OULU 2014
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ACTA UNIVERSITATIS OULUENSIS

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TECHNICA

Ulrico Celentano

DEPENDABLE COGNITIVE WIRELESS NETWORKING

MODELLING AND DESIGN

UNIVERSITY OF OULU GRADUATE SCHOOL;
UNIVERSITY OF OULU,
FACULTY OF INFORMATION TECHNOLOGY AND ELECTRICAL ENGINEERING,
DEPARTMENT OF COMMUNICATIONS ENGINEERING;
CENTRE FOR WIRELESS COMMUNICATIONS;
INFOTECH OULU

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Modelling and design

Academic dissertation to be presented with the assent of the Doctoral Training Committee of Technology and Natural Sciences of the University of Oulu for public defence in Kuusamonsali (YB210), Linnanmaa, on 18 June 2014, at 12 noon

UNIVERSITY OF OULU, OULU 2014

Acta Univ. Oul. C 488, 2014

Supervised by
Professor Matti Latva-aho

Reviewed by
Professor Luiz DaSilva
Professor Petri Mähönen

Opponent
Professor Yevgeni Koucheryavy

ISBN 978-952-62-0418-5 (Paperback)
ISBN 978-952-62-0419-2 (PDF)

ISSN 0355-3213 (Printed)
ISSN 1796-2226 (Online)

Cover Design
Raimo Ahonen

JUVENES PRINT
TAMPERE 2014

Celentano, Ulrico, Dependable cognitive wireless networking: Modelling and design
University of Oulu Graduate School; University of Oulu, Faculty of Information Technology and Electrical Engineering, Department of Communications Engineering; Centre for Wireless Communications; Infotech Oulu
Acta Univ. Oul. C 488, 2014
University of Oulu, P.O. Box 8000, FI-90014 University of Oulu, Finland

Abstract

Radio communication is used in increasingly diversified device typologies. Telecommunications with a reduced detrimental impact on health and environment, and an improved cost-efficiency and working lifetime are expected by institutions, end-users, operators and manufacturers. Moreover, with more networks present or more articulated systems, dependability of the entirety is to be ensured. The related need of efficiency in various compartments – such as in the use energy or the radio spectrum – and of effectiveness in adapting to changing operating conditions can be achieved with cognitive features.

This dissertation addresses network reconfiguration and dependability by cognitive measures from multiple perspectives – each covered by a respective part of this work – providing guidelines for cognitive networks design.

A rationalising view on cognitive networks with related taxonomies and models includes a discussion on the dynamics and interactions in networks operating closely and simultaneously (here, concurrent networks). While cognitive domains are specified for cognitive functions, with a more generic scope control functions are assigned to topological domains. This allows a flexible exploitation of the system design by decoupling the specification of system functions from their mapping onto network devices that will host them.

As interaction plays an important role in many topical scenarios, a model for networked engineered cognitive entities comprising four categories (observation, interworking, consolidation, operation) and two levels (a cognitive frontier and a metacognitive hub) is presented here. Its cognitive phases are considered with regard to the other architectural elements.

Moving the focus down to the levers for exploitation of context awareness, are presented solutions for efficient use of resources and dependability in general, considering the network dynamics. For communication link and network adaptation, the effective capacity is captured by a compact-form expression also considering imperfections, while learning is exploited for reducing overhead, and collaboration for fairly maximising energy save.

Keywords: cognitive radio system, concurrent networks, dependability, energy efficiency, environment awareness, flexibility, modelling, networked cognitive entities, system architecture, topological domains

Celentano, Ulrico, Luotettavat kognitiiviset langattomat verkot: Mallintaminen ja suunnittelu
Oulun yliopiston tutkijakoulu; Oulun yliopisto, Tieto- ja sähkötekniikan tiedekunta, Tietoliikennetekniikan osasto; Centre for Wireless Communications; Infotech Oulu
Acta Univ. Oul. C 488, 2014
Oulun yliopisto, PL 8000, 90014 Oulun yliopisto

Tiivistelmä

Käyttäjät, operaattorit ja laitevalmistajat toivovat tulevilta tietoliikennejärjestelmiltä sekä aiempaa pienempiä haitallisia vaikutuksia terveyteen ja ympäristöön että parannettua kustannustehokkuutta ja toiminta-aikaa. Lisäksi olisi varmistettava useiden verkkojen ja niiden muodostamien monimutkaisten järjestelmien kokonaisuuden luotettava toiminta. Tarvittava tehokkuus energian ja radioresurssien käytössä, samoin kuin kyky sopeutua muuttuviin käyttötilanteisiin, voidaan saavuttaa kognitiivisilla radioteknikoilla.

Tämä väitöskirja käsittelee kognitiivisten menetelmien tuomaa radioverkkojen mukauttamista ja luotettavuutta eri näkökulmista. Samalla esitetään kognitiivisten verkkojen suunnittelun periaatteita ja lähtökohtia.

Väitöskirja sisältää katsauksen kognitiivisiin radioverkkoihin niihin liittyvine luokitteluineen ja malleineen, sekä tarkastelee samanaikaisesti ja läheisesti toimivien verkkojen (rinnakkaisten verkkojen) dynamiikkaa ja vuorovaikutuksia. Työssä määritetään kognitiiviset lohkot kognitiivisine toimintoineen, kun taas topologiset tasot hallintatoimintoineen määritetään yleisemmin. Tämä mahdollistaa järjestelmäsuunnittelun joustavan hyödyntämisen erottamalla järjestelmän toimintojen määrittelyn toteuttavista verkkolaitteista.

Koska vuorovaikutus on merkittävä tekijä useissa sovellusskenaarioissa, verkottuneille keinotekoisille kognitiivisille yksiköille ehdotetaan tässä neljä luokkaa (havainnointi, yhteistoiminta, vakauttaminen, toiminta) sekä kaksi vyöhykettä (kognitiivinen raja-alue ja metakognitiivinen keskus) sisältävää mallia. Mallin kognitiiviset vaiheet käsitellään suhteessa muihin arkkitehtuurin elementteihin.

Järjestelmän kontekstitietoisuuden hyväksikäyttöön liittyen esitetään ratkaisuja resurssien tehokkaaseen käyttöön ja yleisemmin luotettavuuteen ottaen huomioon verkkojen dynamiikkaa. Yhteyksien ja verkkojen mukauttamisesta esitetään analyyttinen ratkaisu saavutettavan tehollisen kapasiteetin määrittämiseksi, huomioiden mahdolliset epäideaalisuudet. Kognitiivista oppimista hyödynnetään hallintaliikenteen vähentämiseksi ja yhteistyötä energiansäästön maksimoimiseksi verkon alueella tasapuolisesti.

Asiasanat: energiatehokkuus, itsemuunneltavuus, järjestelmäarkkitehtuuri, kognitiivinen radiojärjestelmä, luotettavuus, mallintaminen, rinnakkaiset verkot, topologiset tasot, verkottuneet kognitiiviset yksiköt, ympäristötietoisuus

A Silvia,
a Haike Lavinia,
ad Alfredo e Marianne
ed a Marcello e Giovanna

Preface

The research this doctoral dissertation is based upon was carried out at the Centre for Wireless Communications (CWC), now the Department of Communications Engineering (DCE), University of Oulu, Oulu, Finland, in a number of diverse projects.

My foremost thanks go to Professor Matti Latva-aho. First, as the then director, he gave me the opportunity to join CWC: offering multi-fold research opportunities, this has been a great place to work. Then, as my supervisor, Matti pushed me to pack my dissertation: without him, this would have never started and come to a completion. I am grateful to Professor Savo Glišić, who has been available for scientific discussions. I am indebted to Dr. Ian Oppermann who, as the director of CWC some years back, gave me the possibility to enter the area of short-range communications and to look at it from a particular perspective: this further widened my expertise. I appreciate that Dr. Ari Pouttu as the director continued keeping with CWC its peculiar essence that made this such a unique research place during my years there. My thanks also go to Professor Pentti Leppänen, who, as the director of the Telecommunication Laboratory, has been behind all of this.

I would like to express my gratitude to the pre-examiners of this manuscript, Professor Luiz DaSilva, Department of Electronic and Electrical Engineering at Trinity College Dublin, Ireland and Bradley Department of Electrical and Computer Engineering at Virginia Polytechnic Institute and State University (Virginia Tech), Blacksburg, VA, US, and Professor Petri Mähönen, Institute of Networked Systems at Rheinisch-Westfälischen Technischen Hochschule (RWTH), Aachen, Germany, for providing their supportive comments and constructive critics. These comments, together with those of the reviewers of the original contributions, certainly improved the quality of this manuscript. Dr. Timo Bräysy as well as Kirsi Ojutkangas and Dr. Johanna Vartiainen are acknowledged for their contributions to and advices about the Finnish translation of the abstract.

I would like to thank my co-authors, my projects' team members, as well as all the smart people I had the privilege to work with. All those projects' steering board members who gave me their constructive feedback are also acknowledged. A special mention deserves my friend and former colleague Leonardo Goratti: the long discussions with him on more technical and less serious topics gave life and added colour to the project work. Appreciation goes to all present and past colleagues with whom I have spent free-time, or breaks talking about work and life. My special thanks go to Dr. Esa Kunnari and his family, for what they shared with mine.

The help of Jari Sillanpää in maintaining working tools functional and Timo Äikäs in orienting me through the mysteries of financial administration is appreciated. The support of Hanna Saarela, Laila Kuhalampi, Antero Kangas, Elina Komminaho, Kirsi Ojutkangas and Eija Pajunen is also acknowledged. I would like to thank Pekka Räsänen of Research and Innovation Services for his assistance.

While working at CWC, I have been involved in a number of projects and with various roles: doing research in a project task, managing an entire project, or preparing a project proposal and detailing its planning. The diversity of those projects spanned from focused commissioned research to wider publicly funded projects[1]. I was fortunate of having been exposed to such a multifaceted experience.

This research would not have been possible without the funding from the companies Nokia, Nokia Solutions and Networks (Nokia Siemens Networks at the time), Elektrobit, Insta (Instrumentointi at the time), and the institutions the European Commission, the Finnish Funding Agency for Technology and Innovation (Tekes), the Finnish Defence Forces and the Academy of Finland. The personal grants from the foundations HPY:n Tutkimussäätiö, Nokia Oyj:n Säätiö and Telealan Edistämissäätiö are also gratefully appreciated.

My warmest thanks go to my parents Alfredo and Marianne for having infused me with the curiosity of science and interest of technology and to my parents-in-law Marcello and Giovanna for teaching me to always look at the best facet of experience of life. They all and their families also provided support back there and from Italy. My special gratitude goes to my lovely family: my wife Silvia and my daughter Haike gave me the energy I needed. Thank you, Silvia, for all your support, comprehension and encouragement in the *Good Times* and the *Bad Times* I had throughout our years. Thank you, Haike, you are always able to inject joy and happiness, enriching our days; when you pulled me into your world, I was able to forget all the rest.

Oulu, 6 May 2014 Ulrico Celentano

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[1] Tekes projects FUTURA, PANU, WINNER, CROSSNET. Industry projects HRUMAC, FIXWIRE. EU projects QoSMOS (FP7-ICT-2009-4/248454), ULTRAWAVES (IST-2001-35189), NEWCOM (IST-2004-507325). Celtic project MEVICO. Academy of Finland projects JULIET (joint optimisation of full-duplex links and dense networks, grant number 260755), UNICS (langattomien verkkojen monikerroksellinen tilastollinen päättely, grant number 128010).

List of symbols and abbreviations

$\odot$	Hadamard-Schur element-wise matrix product
$\otimes$	modulo 2 bit-wise product
$\lceil \cdot \rceil$	smallest integer not less than the argument
$(\cdot)^\mathsf{T}$	transpose of argument matrix
$\emptyset$	empty set
$\mathscr{A}$	system in an ecosystem
a	availability
$\mathscr{B}$	system in an ecosystem
B	bandwidth
$c(\cdot)$	generic cost function
C_{eff}	effective switching capacity
C_{DB}	capacity loss, database case
C_{SS}	capacity loss, spectrum sensing case
CO_2	carbon dioxide
$\mathbf{D}$	codewords distance matrix
$\bar{d}_\infty$	typical source-destination distance
d_d	distance constraint on database update
$\mathrm{diag}(\mathbf{A})$	vector of diagonal elements of matrix $\mathbf{A}$
$\mathrm{diag}(\mathbf{a})$	diagonal matrix having vector $\mathbf{a}$ on its diagonal
$\mathscr{E}$	ecosystem
e	residual error rate
$e^{(t)}$	transmit energy expenditure
e_A	energy expenditure during active state
e_{amp}	energy expenditure for radio amplifier
e_{comput}	energy expenditure for computation
e_H	energy expenditure during hibernation state
$e_{\max}$	maximum energy expenditure
e_{mem}	energy expenditure for memory
e_{proc}	energy expenditure for radio control
e_t	total energy expenditure
$\mathrm{erfc}(\cdot)$	Gaussian complementary error function

$F^{(\underline{k})}$	failure function of a system with redundancy level k
$F^{(k)}$	failure function of a component of a system with redundancy level k
f	frequency, operating frequency
$f(\cdot)$	generic function; in particular, objective function
G_c	channel coding gain
g	generator polynomial of a convolutional code
$\mathbf{H}^{(d)}$	delayed channel transition matrix
$\mathbf{H}^{(e)}$	mode estimation probability matrix
$\mathbf{H}^{(f)}$	mode acquisition probability matrix
$\mathbf{I}$	identity matrix
K	constraint length of a convolutional channel code
k_f	frequency-domain spreading factor
k_m	carrier repetition factor
k_s	approximated dynamics of the datarate set ($k_s \in \mathbb{N}^+$)
k_t	time-domain spreading factor
K_{trx}	transceiver configuration
I_l	leakage current
L	length
L_b	beacon slot occupied length
L_c	FCS length
L_d	length of a database message
L_h	length of header
L_i	payload length
L_m	mode indicator overhead
L_p	packet length
L_s	PLCP preamble-plus-header length
L_t	tail bits length
$\mathscr{M}$	PHY-modes set
M	cardinality of set $\mathscr{M}$; also memoryless arrival or service process in a queuing system (used for Kendall notation, e.g., $M/M/1$)
m	PHY-mode identifier
M_i	PHY-mode
$\mathbb{N}$	natural numbers set
N	average number of requests in the system
N_c	number of data sub-carriers

N_{dn}	number of power-down transitions (active to sleep)
N_{FFT}	FFT size
$N_i^{\pm}$	expected number of level crossing (resp. upwards and downwards, $\pm$)
N_{up}	number of power-up transitions (sleep to active)
N_z	zero-padded suffix length
n	number of active network nodes
n_m	number of network members
$O()$	limiting behaviour compared to the argument; also order of magnitude
$o()$	limiting behaviour negligible compared to the argument
$\Pr\{\cdot\}$	probability
p	power; also probability
p_A	system availability
$p^{(\text{rx})}$	power consumption during reception
$p^{(\text{tx})}$	power consumption during transmission
p_D	power consumption during deep sleep state
p_{dn}	average power consumption during ramp-down transient
p_E	packet error rate
p_e	bit error rate
p_H	power consumption during hibernation state
p_{hi}	power consumption with high rate mode
p_{low}	power consumption with low rate mode
p_m	power consumption with PHY-mode m
p_R	power consumption during reception
p_S	power consumption during sleep state
p_{ss}	spectrum sensing reliability
p_T	power consumption during transmission
p_{tx}	transmit power
p_{up}	average power consumption during ramp-up transient
$\mathbf{Q}$	state transition rate matrix
$\mathbb{R}$	real numbers set
$R^{(\underline{k})}$	reliability function of a system with redundancy level k
r	useful datarate or informative transmit rate or net throughput
$\mathbf{r}$	throughput vector
R_c	goodput
$\bar{R}_r$	scalar normalised average goodput

$\mathscr{S}$	signal quality regions set
S	cardinality of set $\mathscr{S}$
S_i	signal quality region or channel state
T	average time in the system
T_{BP}	duration of the beacon period
T_{DTP}	duration of the data transfer period
T_d	time period constraint on database update
T_H	time spent in the hibernation state
T_s	symbol duration
T_σ	time period constraint on spectrum sensing update
T_{SF}	duration of the superframe
t	time, time instant
u	utility
$\mathbf{u}$	utility vector; system's control input or observable information
$\tilde{\mathbf{u}}$	perceived information
$\mathbf{u}^{(\mathrm{N,RC})}$	information for resource control at network domain
$\mathbf{u}^{(\mathrm{N,CA})}$	information for context acquisition fusion centre at network domain
V	supply voltage
v_m	speed of a mobile
$\tilde{\mathbf{v}}$	decision
$\mathbf{v}$	system's output
$\mathbf{v}^{(\mathrm{C,SM})}$	spectrum deployed from the co-ordination domain
$\mathbf{v}_i^{(\mathrm{T,RC})}$	resource allocation request from the i-th UE
$\mathbf{w}$	weight vector
$\tilde{\mathbf{x}}$	synthesised instruction
$\mathbf{x}$	spatial position; instruction
$\mathbf{x}_i^{(\mathrm{C})}$	decision of i-th site at co-ordination domain, used in spectrum trading negotiation
$\mathbf{x}_i^{(\mathrm{T,CA})}$	context (acquisition) measurement from i-th sensor, at terminal domain
$\mathbf{Y}$	normalised throughput matrix
$\mathbf{y}$	system's internal state input
$\mathbf{z}$	knowledge
$\tilde{\mathbf{z}}$	learnt knowledge
α	fraction of network devices implementing datarate scaling
α_g	fraction of active gates

γ	signal quality metric in general; also informative-bit-energy to noise-power-density ratio
δ_{ij}	Kronecker delta
δ_s	dynamics of the datarate set ($\delta_s \in \mathbb{R}^+$)
ε_e	estimate error
ε_f	acquisition error
ζ	stochastic process realisation
η_B	bandwidth utilisation
η_c	channel coding rate
η_h	header efficiency
η_m	modulation efficiency
$\boldsymbol{\Theta}$	mode-channel probability matrix
$\boldsymbol{\lambda}$	arrival rate vector
λ_F	failure rate
λ_p	planar point process intensity
$\boldsymbol{\mu}$	service rate vector
μ	service rate (e.g., μ_L and μ_H at low and high datarate mode)
μ_F	repair rate
$\boldsymbol{\Pi}$	diagonal matrix having vector $\boldsymbol{\pi}$ on its diagonal
$\boldsymbol{\pi}$	state probability vector
π_i	state probability
ρ	queuing system load
σ	standard deviation
τ_{dn}	fall time (duration of power ramp-down transient)
τ_e	estimation delay
τ_s	spectrum sensing duration
τ_{up}	rise time (duration of power ramp-up transient)
φ	switching margin
ψ_d	unitary drift
$\boldsymbol{\Omega}$	equivocation matrix
Ω	feasible region of decision variables

3GPP	Third Generation Partnership Project
αCP	collaborative protocol (with a fraction α of devices implementing datarate scaling)

AC	access control
ACM	Association for Computing Machinery
ACT-R	adaptive control of thought-rational
AL	adaptation layer
AMC	adaptive modulation and coding
AP	access point
ARCEP	Autorité de Régulation des Communications Électroniques et des Postes (French postal and electronic communications authority)
AS	application-specific
ATM	asynchronous transfer mode
AWGN	additive white Gaussian noise
BER	bit error rate
BG	beacon group
BLE	Bluetooth Low Energy
BP	beacon period
BPOIE	beacon period occupancy information element
BPSK	binary phase-shift keying
BR	basic rate
BS	beacon slot
C2	command and control
CA	context acquisition
CAHN	cognitive ad hoc network
CapEx	capital expenditures
CCM	configuration control module
CDF	cumulative probability distribution function
CDIS	coexistence discovery and information server
CE	coexistence enabler
CECA	critique-explore-compare-adapt
CEPT	Conférence européenne des administrations des postes et des télécommunications (European conference of postal and telecommunications administrations)
CF	contention full BS
CFMC	cognitive femtocell
CIPC	Companies and Intellectual Property Commission
CH	channel

CM	cognitive manager (coexistence manager, only in Sect. 2.2.4)
CMD	current PHY-mode
CMOS	complementary metal-oxide-semiconductor
CN	core network
COEX	coexistence topological domain
CogNeA	Cognitive Networking Alliance
Col.	colonel
COORD	co-ordination topological domain; also co-ordination in general (as in NET COORD)
CORDIS	Community Research and Development Information Service
CP	collaborative protocol
CPFR	common portfolio repository
CPU	central processing unit
CR	cognitive radio
CRM	cognitive resource manager
CRP	channel reservation protocol
CSG	critical devices sub-group
CSW	contention-based signalling window
CTMC	continuous-time Markov chain
CTRL	control
CUS	collective use of spectrum
CWC	Centre for Wireless Communications
CXWS	cellular extension in the whitespace
DARPA	Defense Advanced Research Projects Agency
DB	database
DCM	dual-carrier modulation
DEV	device
DFS	dynamic frequency scaling
DoS	denial of service
DRP	distributed reservation protocol
DS	direct-sequence
DSA	dynamic spectrum access
DSONPM	dynamic selforganising network planning and management
DSM	dynamic spectrum management
DSP	digital signal processing

DTMC	discrete-time Markov chain
DTP	data transfer period
DVS	dynamic voltage scaling
DySPAN	Dynamic Spectrum Access Networks
EC	European Commission
ECC	Electronic Communications Committee
ECMA	European association for standardizing information and communication systems; originally, until 1994, European Computer Manufacturers Association
EDR	enhanced data rate
EM-DEV	emergency (or critical) device
EM-FRAME	emergency frame
EM-LEV	emergency level
ENIAC	electronic numeric integrator and computer
EPIC	executive process-interactive control
ERR	error message
ESN	energy saving need
EPO	European Patent Office
ETSI	European Telecommunications Standards Institute
FEC	forward error correction
FCC	Federal Communications Commission
FCFS	first come, first served
FCS	frame check sequence
FFT	fast Fourier transform
FH	frequency-hopping
FP	framework programme (FP6, FP7: sixth, seventh FP)
GB	Great Britain
GSM	Groupe Spécial Mobile; now known as global system for mobile communication
GW	gateway device
HIPERLAN	high performance radio local area network
HRG	high-rate group
HRUMAC	high-rate ultra-wideband MAC
HSDPA	high speed downlink packet access

HPY	Helsingin Puhelinyhdistys (HPY Research Foundation is part of Elisa Corp.)
I/O	input/output
IAB	Internet Architecture Board
IBM	International Business Machines
IC-DEV	information collector device
ICT	information and communications technologies
ID	identifier
IE	information element
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IEICE	Institute of Electronics, Information and Communication Engineers
IETF	Internet Engineering Task Force
IND	indication message
inh.	inhabitants
IoT	Internet of things
IP	Internet protocol; sometimes used to refer, in a wider sense, to the entire Internet protocol suite (Braden 1989)
IPO	Intellectual Property Office
IPSO	IP for Smart Objects [Alliance]
IPv6	IP version 6
IRE	Institute of Radio Engineers
ISM	industrial, scientific and medical
ISO	International Organization for Standardization
ISOC	Internet Society
ITU	International Telecommunication Union
ITU-R	Radiocommunication Sector of the ITU
ITU-T	Telecommunication Standardization Sector of the ITU
JRRM	joint radio resource management
LAN	local area network
LC-DEV	low-critical-level device
LCR	level crossing rate
Li-Ion	lithium ion
LOC	spectrum management context localisation
LR	contention-less reduced BS

LRG	low-rate group
LSA	licensed shared access
LSG	large population sub-group
LTE	long-term evolution
M2M	machine-to-machine
MAC	medium access control
MAS	medium access slot
MB	multi-band
MBOA	Multiband OFDM Alliance
MBTI	Myers-Briggs type indicator
MC	mobility control
MGT	management
MIC	Ministry of Internal affairs and Communications
MIPS	millions of instructions per second
MIRAI	multimedia integrated network by radio access innovation
MMITS	modular multifunction information transfer system
MSC	message sequence chart
MTBF	mean time between failures
MTC	machine-type communications
MTTR	mean time to repair
NC	network-domain cognition
NCP	non-collaborative protocol
NET	network topological domain
NFC	near-field communication
NiCd	nickel-cadmium
NICT	National Institute of Information and Communications Technology
NiMH	nickel-metal hydride
NP	network control period
NPRM	notice of proposed rulemaking
NRM	network reconfiguration manager
Ofcom	Office of Communications
OFDM	orthogonal frequency-division multiplexing
OODA	observe-orient-decide-act
OpEx	operating expenditures
OSI	open systems interconnection

OSM	operator spectrum manager
PAL	protocol adaptation layer
PANU	packet access networks with flexible spectrum use
PAWS	protocol to access WS database
PDCA	plan-do-check-act
PDSA	plan-do-study-act
PER	packet error rate
PHY	physical layer
PLCP	physical layer convergence protocol
PMSE	programme making and special events
PSDU	PHY service data unit
QAM	quadrature amplitude modulation
QoS	quality of service
QoSMOS	quality of service and mobility driven cognitive radio systems
QPSK	quadrature phase-shift keying
RA	resource allocation
RAN	radio access network
RBG	regularly beaconing devices group
RC	resource control
RCC	centralised resource control
RCD	distributed resource control
RE	resource exploitation
REP	repository access and management
REQ	request message
RF	radio-frequency
RFC	request for comments (Internet-standards-related specifications or document published by the IETF)
RFID	radio-frequency identification
RGDB	regulatory repository
RM	resource management
RMC	RAN measurement controller
RRAC	rural access
RRC	RAN reconfiguration controller
RRR	resource release request
RRS	Reconfigurable Radio Systems

RS	resource control support
RSP	response message
RSSI	received signal strength indicator
RSW	reservation-based signalling window
RU	resource use
RX	receiver
SBG	specially beaconing devices group
SC	standards committee
SCC	standards coordinating committee
SCTRL	sensor control
SDR	software-defined radio
SE	spectrum engineering
SEL	spectrum selection
SF	superframe
SIFS	short inter-frame spacing
SIG	signal; also special interest group
SINR	signal to interference-plus-noise ratio
SM	spectrum management
SNR	signal to noise ratio
SON	self-organising network
SRC	short-range communication
SRI	Stanford Research Institute
SS	spectrum sensing; also spread-spectrum (as in DS-SS or FH-SS)
SSL	local spectrum sensing
TC	terminal-domain cognition; also technical committee
TDD	time division duplexing
Tekes	Teknologian ja innovaatioiden kehittämiskeskus (Finnish Funding Agency for Technology and Innovation)
TERM	terminal topological domain
TG	task group
TGV	train à grand vitesse (high-speed train)
TMC	terminal measurement collector
TPC	transmit power control
TQM	total quality management
TRC	terminal reconfiguration controller

TRM	terminal reconfiguration manager
TRX	transceiver
TV	television
TVBD	TV-band device
TVWS	TV whitespace
TX	transmitter; transmit
UE	user equipment
UK	United Kingdom
ULYR	upper layer
UMTS	Universal Mobile Telecommunication System
UNIVAC	universal automatic computer
URI	uniform resource identifier
US	Unites States
USAF	US Air Forces
USB	universal serial bus
USPTO	United States Patent and Trademark Office
UTRA	UMTS terrestrial radio access
UWB	ultra-wideband
WG	working group
WInn	Wireless Innovation
WIPO	World Intellectual Property Organization
WLAN	wireless local area network
WNaN	wireless network after next
WPAN	wireless personal area network
WRAN	wireless regional area network
WS	whitespace
WSD	whitespace device
WSDB	whitespace database
WSN	wireless sensor network
XG	next generation
ZA	South Africa

Contents

1 Introduction

> Πάντων γὰρ ὅσα πλείω μέρη ἔχει καὶ μὴ ἔστιν οἷον σωρὸς τὸ πᾶν ἀλλ’ ἔστι τι τὸ ὅλον παρὰ τὰ μόρια, ἔστι τι αἴτιον.
>
> For all of such things as have many parts, and where the whole is not as it were a heap, but is something besides the parts, there is a certain cause [of their being one]. (Taylor 1801, p. 199)
>
> – Aristotle (350 B.C.) *Metaphysics*, H.1045a.8-10.

Radio communication is used by an increasing number of devices. Besides a growing quantity of mobile personal equipments of consolidated use, like cell-phones, smart-phones, tablets, etc., wireless communication interfaces are being included in an enlarging set of communication devices, such as those exploited in short-range communications, wireless sensor networks, etc. This trend by which larger and larger capacities are sought calls for an efficient utilisation of the shared radio resource.

On the other hand, mobile devices need efficient management of their battery energy, and even mains-operated units must be more frugal in energy handling, to reduce both the impact on the environment and the operating expenditures. More advanced and “intelligent” features help in achieving the above targets and benefit adaptive networks with improved use of resources, and increased lifetime and reliability. Various examples in this thesis illustrate how context awareness can be exploited for efficiency and robustness.

Fiercer market competition imposes players readiness and broaden the possibilities of scale economy. The flexible system design discussed here facilitates a more efficient exploitation of the same building blocks over diverse application scenarios.

Communication networks are evolving into large and heterogeneous ecosystems. Emerging phenomena such as the Internet of things, smart energy grids and cloud services, but also current communication networks build on top of interaction of entities. As seen, cognitive methods are enriching communications devices. The novel model for networked artificial cognitive entities proposed in this thesis brings benefits to an effective design of cognitive network devices.

This dissertation discusses dependable cognitive networks under various perspectives and both deepening into details as well broadening the view over the system.

The remainder of this introductory chapter provides a deeper look into the background motivating this work also briefly touching the key historical triggers of the development of cognitive networks. This chapter then illustrates the aim of the thesis and its structure in Sect. 1.2 as well as presents the contributions in Sect. 1.3 together with the thesis outline.

1.1 Background and motivation

The limited availability of the spectrum on one side and the increasing diffusion of mobile radio devices of all kind on the other, pose the need of efficient use of resources, the radio spectrum and energy in particular. Bandwidth-hungrier services and/or larger user population generally require a larger spectrum portion in use. Efficient use of radio spectrum offers to end-users better available experience, and to operators a larger population of simultaneous users, which increases their income. To assess the actual gain, all the related costs needed for the achievement are to be considered. While automatically reconfigurable networks typically introduce most tangible gains in operational expenditures (OpEx), they may be associated with net costs in prior investments or capital expenditures (CapEx). Obviously, a trade-off is needed, similarly to what Lord Kelvin (William Thomson) stated (Thomson 1881) about the economical size of electrical conductors for transmission of energy (Singer *et al.* 1994).

Improved energy efficiency has, in addition to interference control, also other indirect effects. An extended lifetime of a mobile electronic device in principle implies a larger and heavier electric energy storage element. Efficient use of energy in mobile devices moves the operating point in the lifetime-weight plane to a more convenient position.

1.1.1 Telecommunications get mature and adaptive

The fundamental steps towards cognitive radios are shortly reminded in this section and condensed in Fig. 1. The attention will be then focused on the development of cognitive radios and networks in the following Sect. 1.1.2, sketched in Fig. 2.

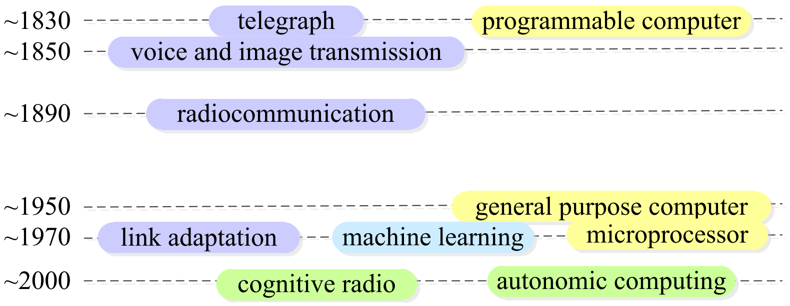

Fig 1. A concise summary of the evolution of modern information transmission and processing. The last step is expanded and continued in Fig. 2. The main inventions at the basis of modern radio communications appeared within a bit more than half a century, but it took about one century to see forms of intelligence consolidated in radio communications, see text.

Fixed radio communication

Starting already in 1849, Antonio Meucci did his first experiments about transmission of voice through his *telettrofono* (Catania 1995, Lucci & Pelosi 2009), invention protected only by a *caveat* filed in US in 1871 (House of Representatives 2002).

Experiments for the transmission of information over distance, wirelessly, took place in parallel in a few places. In 1893, performed by Nikola Tesla in St. Louis, MO, US. In 1894-1895 carried out by Guglielmo Marconi in Pontecchio, Italy, leading to the first transatlantic communication in 1901. In Russia, done by Aleksandr Stepanovič Popov in 1895. (Kuzle *et al.* 2008)

The focus of efficiency in the history of telecommunications has followed the needs of the time. For example, the Morse code (1838) had the aim of reducing average keying time for the telegraph operator, but nowadays it would probably be seen also as an improved spectrum and energy efficiency.

Adaptive radios

Link adaptation is one means for an efficient use of the radio spectrum, as the most appropriate transceiver configuration – e.g., a modulation and error control coding schemes pair, a particular case of what is referred to as *PHY-mode* in Celentano & Glisic (2005, 2006a) – is dynamically selected to adapt to instantaneous operating conditions, namely the channel quality.

Given a hardware technology, energy efficiency in telecommunications may be achieved in basically two ways. One is to improve the use of resources, reducing as much as possible the related overheads, thus the waste of energy, while the device is active. The other way is to just reduce the active time of the device by putting it into a sleeping or hibernating mode (the latter also referred to as dozing). Power consumption and hence energy efficiency is characterised in Sect. 5.2.2 and 5.2.3 and integrated by observations in Sect. 5.4.2 and 6.3.3.

Link adaptation and energy saving decisions, for example, are often based on the operating environment. Metrics such as link channel quality, location (absolute or relative) of nodes, network population, status of neighbouring nodes and networks as well as residual energy level, form the context the communication nodes are operating within. Context awareness is therefore the key requirement for efficient networking. Indeed, link-adaptive systems may be regarded as an early, though simple, form of *cognitive radio* (see Sect. 4.2.2). The concepts of cognitive radio and cognitive network are further discussed shortly below and will be the subject of Chapt. 3 (Sect. 3.3), while a deeper digression on cognition will be given in Chapt. 4.

The way to cognitive radios

In parallel with the evolution of the technologies for the transmission of information, the progress about machinery for the processing of information took place, with those paths eventually converging, see below. From the first mechanical programmable calculator in 1833 (Miller 2003a) through various steps (Miller 2003b), the first civilian fully-electronic computer (Miller 2003b) UNIVAC (universal automatic computer) was commercialised in 1951 (Goldschmidt & Akera 2012).

The main innovative concepts at the foundations of modern radio communications were all generated in a relatively short time (see also Fig. 1): the telegraph and the Morse code (1830's), the Giovanni Caselli's pantelegraph published in 1856 (Lucci

& Pelosi 2009), an early (Lindell 2009) example of *fac simile* (fax) communication (1850's), the telephone (1870's) and the radio (1890's) all appeared within a bit more than half a century.

Communication devices able to exploit context awareness began to be studied at least from the 1960's as the first (Codreanu 2007) link adaptation technique was proposed by Hayes (1968), simultaneously as machine learning had been researched (Thomas *et al.* 2005). Indeed, this was made possible by the advances in automatic computing reminded above. The concepts of software-defined radio and a definition of cognitive radio were introduced by Mitola (1992) and Mitola & Maguire (1999), respectively: it took about one century to see forms of intelligence consolidated in radio communications.

1.1.2 From radio digital switch-over to cognitive networks

The transition from analogue to digital radios (Mitola 1995) was followed by the introduction of software radios (Mitola 1992, 1993). The terms software radio and software-defined radio were initially used interchangeably (Mitola 1995), but later a distinction between the two was laid, where software-defined radio meant a more articulated and modular system (Margulies & Mitola 1998), which also supports multiband operation (Mitola 1999). Jondral (2008) defines software-defined radios as the realisable version of software radios.

Supporting such a development, the Modular Multifunction Information Transfer System (MMITS) Forum was established in 1996. Later (end of 1998) it became Software-Defined Radio (SDR) Forum and finally (end of 2009) Wireless Innovation Forum.

Exploiting the reconfiguration capabilities of software-defined radios, the concept of cognitive radio (CR) is introduced, with a knowledge representation language and a model called cognitive cycle, in Mitola & Maguire (1999) and described in more detail in Mitola (2000).

According to Tuttlebee (1999), the development of software radio started in the US earlier than Europe, due to the presence of multiple standards competing in North America as opposed to the early deployment of a Europe-wide telecommunication standard, the GSM.

Regulation

Mitola (2000) identified spectrum pooling (see Sect. 2.2.1) as a use-case of cognitive radio and cognitive spectrum use is actually among the first applications being addressed in research, standardisation and regulation. The first spectrum portions being released are the TV bands vacant after the digital switch-over, the so-called TV whitespace (TVWS). Other underused spectrum portions have been identified in the UK by the Office of Communications (Ofcom), who committed to release the spectrum currently assigned to the UK Ministry of Defence (Nekovee 2010). In US, the Federal Communications Commission (FCC) sought comments on spectrum use by smart radios in 2003 (FCC 2003), and in 2008 it adopted rules for secondary use of unused TV bands (FCC 2008). In UK, Ofcom (2007) awarded the so-called digital dividend. Whitespace device (WSD) databases were specified in UK (Ofcom 2009b, 2010) and TV bands device (TVBD) databases were made mandatory in US (FCC 2010), where database (DB) administrators were conditionally designated (FCC 2011a,b). Report 159 (ECC 2011), prepared by Spectrum Engineering (SE) project team SE43 on cognitive radio systems operations in whitespaces, and issued by the Electronic Communications Committee (ECC) of the European conference of postal and telecommunications administrations (CEPT), goes beyond the incumbents (sometimes referred to as primary users) of TV and programme making and special events (PMSE), and includes also radioastronomy and radio navigation. ECC (2011) includes requirements on both spectrum sensing and geolocation with databases, but the latter is there deemed more reliable than the former. Recently, the European Commission (2012) issued a communication for promoting shared spectrum access.

Standardisation

To address advanced spectrum management, in 2005 was established the Institute of Electrical and Electronics Engineers (IEEE) P1900 Standards Committee, leading in 2007 to the Standards Coordinating Committee 41 (SCC41) and finally in 2010 to the Dynamic Spectrum Access Networks (DySPAN) Standards Committee (DySPAN-SC). The activities of this committee are organised into six working groups, covering definitions and concepts (WG1), coexistence (WG2), architecture (WG4), policies (WG5) and sensing interfaces and data structures for DSA (WG6). The standard specifications issued by these WGs are named 1900.1, 1900.2, etc. Currently, amendments and derived projects include 1900.1a (new terms and definitions), 1900.4a (whitespace frequency bands), 1900.4.1 (distributed decision-making) and 1900.6a (interfaces to existing spectrum sensing systems and geolocation databases) (Murroni *et al.* 2011). WG3 on dependability and evaluation was dismantled in 2008 (Granelli *et al.* 2010) but its scope possibly only postponed.

In Europe, Reconfigurable Radio Systems (RRS) of the European Telecommunications Standards Institute (ETSI) was started in 2008. Having liaisons with DySPAN-SC and Wireless Innovation Forum, it covers system aspects (WG1), radio equipment architecture (WG2), cognitive management and control (WG3), aspects and requirements for public safety (WG4).

Started in 2005, IEEE 802.22 is a standard for wireless regional area network (WRAN; up to 100 km coverage) released in 2008 (Stevenson *et al.* 2009), which includes cognitive features such as incumbent user detection. Specification of amendments, concerning both physical layer (PHY) and medium access control (MAC), for IEEE 802.11 wireless local area network (WLAN) operation in TVWS started in 2009 under IEEE 802.11af task group.

The Cognitive Networking Alliance (CogNeA), established in 2008, contributed to the ECMA technical committee TC48 task group TG1 standardisation work, which was later consolidated into ECMA-392, released in 2009. ECMA-392 specifies PHY and MAC for a wireless personal area network (WPAN) operating in TVWS, including support of incumbent protection by use of geolocation/database and/or spectrum sensing.

In 2009, IEEE 802.19 started the work on wireless coexistence in TVWS under TG1 (Baykas *et al.* 2010). In July 2010, the license-exempt task group of WG16 of IEEE 802 has released the amendment IEEE 802.16h on improved coexistence mechanisms for license-exempt operation, to support uncoordinated coexistence also specifying an extended quiet period for sensing measurements. In June 2011, within the Internet Engineering Task Force (IETF) has been started the the working group on protocol to access WS database (PAWS), which is assumed to be reachable via the Internet.

Research

In Europe, a number of research projects on cognitive networks research were realised within the sixth framework programme (FP6) funded by the European Commission and boosted with the following FP7. The US Defense Advanced Research Projects Agency (DARPA), with the neXt Generation (XG) programme (McHenry *et al.* 2008) first and with the Wireless Network after Next (WNaN) programme then, addresses dynamic spectrum utilisation, topology and content management with WNaN targeting reduced requirements on system components (Marshall 2009). In Japan, promoted by the Ministry of Internal affairs and Communications (MIC), the National Institute of Information and Communications Technology (NICT) started in 2005 (Ohmori 2011) their Cognitive Wireless Clouds project, aiming at providing support for spectrum sharing and exploitation of heterogeneous wireless networks (Harada *et al.* 2007).

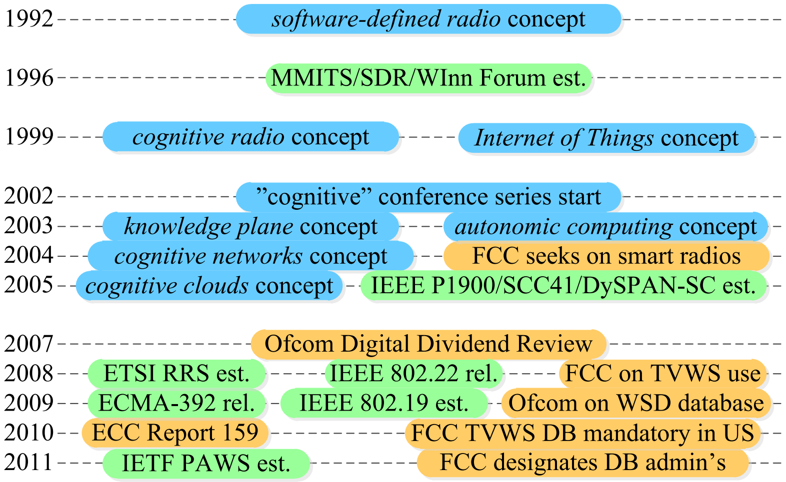

Fig 2. Development towards cognitive networks in research, standardisation and regulation. The historical paths leading to that are summarised in Fig. 1.

Leaning on the concept of a knowledge plane pervasively touching the entire Internet to cope with its complexities (Clark *et al.* 2003), the scope of cognitive domain broadened from the single radio to the entire network (Mähönen 2004). As a parallel path in the computing world, the concept of autonomic computing, by Kephart & Chess (2003) of IBM, arose. These two concepts are further discussed in Sect. 3.3, together with a broader view on cognitive networks research.

Review about cognitive networks development

Good reviews about the developments in research, standardisation and regulation are provided by books (Mahmoud 2007, e.g.) and several review articles. Mitola (2009) tracks the evolution from its first steps; Sherman *et al.* (2008) and Granelli *et al.* (2010) follow the standardisation in US and Europe; Shin *et al.* (2010), Wang & Liu (2011) and Liang *et al.* (2011) cover separate aspects and various protocol layers, including security; Akyildiz *et al.* (2009a,b) consider specifically ad hoc networks; Nekovee (2010), Wang *et al.* (2011), and Pawełczak *et al.* (2011) consider also test-beds. Liang *et al.* (2011) identify as open questions feasible rendez-vous protocols, joint design of access and sensing, definition of flexible architectures, business and commercial aspects. Cognitive networks are sensitive to trust and attacks (Baldini *et al.* 2012, e.g.). Although security is important, those aspects are left out of the scope of this dissertation.

Applications of cognitive radio include cellular (capacity extension and off-loading, including use of femtocells), public safety (improved interoperability) and medical ICT (information and communications technologies) networks (better quality of service than in crowded industrial, scientific and medical, ISM, bands) as well as smart grids.

Fig. 2 summarises the main steps in the development of cognitive networks discussed above, some further treated in Sect. 3.3.1. In particular, Fig. 2 shows the progress from concepts to research, standardisation and regulation on one hand, and from single devices to the entire system on the other hand.

1.1.3 Environmental, economic and safety issues

As noted, efficient use of resources is not limited to spectrum only. Cognitive radio network techniques may also provide means for energy saving, for example through use of reconfigurable base stations in cellular networks and femtocells (Hasan *et al.* 2011). Attention to energy efficiency has however a much broader impact as we will shortly see.

Need of energy efficiency for energy availability

The battery energy density (energy per weight or volume unit) for current technologies is growing slowly (Castillo *et al.* 2004), at least compared with other parameters of wireless mobile communication devices, or it is even possibly saturating (Paradiso & Starner 2005). As a parallel research path, energy harvesting/scavenging by various means (Rabaey *et al.* 2007, Mitcheson *et al.* 2008) is lately receiving increasing attention, but the provided density is currently still limited (Mitcheson *et al.* 2008). Completely energy self-sufficient systems are not currently feasible for all applications (Spies *et al.* 2007), hence energy efficiency in common communication technologies is still required.

Impact of energy efficiency on the environment

As part of the energy requirements along the entire chain and life-cycle of the product (Malmodin *et al.* 2010, e.g.), energy efficiency surely contributes to smaller OpEx and participates to a reduction of carbon dioxide (CO_2) emissions. of which the ICT industry slice is remarkable (Gartner 2007, Mingay 2007, Malmodin *et al.* 2010).

The batteries and accumulators waste generation is around 3 kg per person per year (Eurostat 2013, Average for EU-27 countries, year 2010, all economic activities plus households considered together). Increasingly high target rates for related waste collection and content recycling are set (European Union 2006, e.g.). Therefore, smaller accumulators for given technology allowed by reduced energy requirements imply a reduction in both the impact on the environment as well as on waste processing costs.

Not less important, decreased radiation from mobile appliances, sometimes a side-effect of energy saving, implies reducing the probability of their possible detrimental effects on user's body.

The way to dependability

Indeed, dependability must not be selfishly limited to a device or to a network. *Concurrent networks* – networks operating in relative vicinity and simultaneously with some form of interaction, not necessarily interfering at all or all the time, see Sect. 3.2 – impose to put the view over the entire ecosystem: sometimes a device or a network may need to act altruistically so that another device or network benefits (see Sect. 3.2.2, 5.4.1 and 5.4.2). Increased lifetime of a network, reduced detrimental impact on people and environment, or quality of service of all the parties in concurrent networks users are among the forms, selfish and altruistic, of dependability covered in this dissertation.

1.2 Aim and structure of the thesis

This dissertation aims at covering cognitive networks from various perspectives and at various levels. The contributions presented in this thesis are grouped under chapters of different nature, where theoretical analysis and abstract modelling along with design guidelines, standard enhancements and other innovation, work together towards an holistic view also conscious of underlying constraints of different nature. Thus, this monograph covers how generic cognitive entities are modelled, what knowledge is used and how, and the way reconfiguration is controlled.

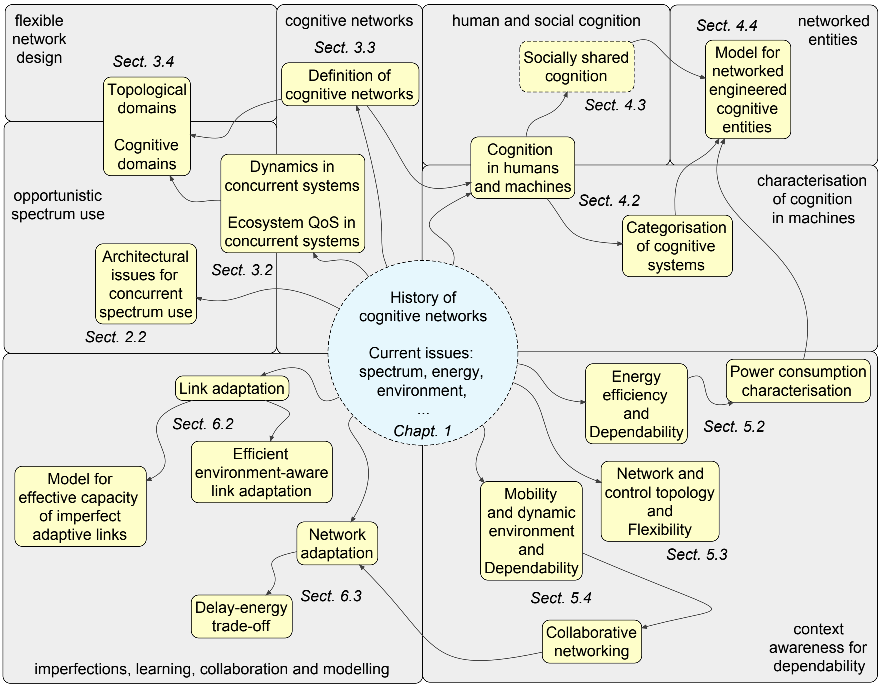

Fig 3. The main topics covered in this dissertation. The introduction chapter is shown at the centre, with the following five chapters proceeding clockwise from the top-left quadrant and covering respectively contributions on: 2) specific architectural issues, and 3) dynamics and domains in flexible network design; 4) cognition and its modelling; 5) context awareness and solutions; 6) efficient adaptation.

Supporting the presentation of the aim of the thesis, Fig. 3 depicts in more details the main topics covered by the thesis. Stemming from the motivation for this work of the introduction (shown at the centre of the figure), the thesis proceeds (top-left quadrant) discussing architectural implications relevant to concurrent spectrum use. Then, the dynamics and the quality of service (QoS) in concurrent systems are considered more generally. Cognitive networks are defined in this part. A framework for flexible design of cognitive networks is completed with the three cognitive domains and the four topological domains, and two realisations of an example concurrent spectrum use system are derived based on them. Departing (top-right quadrant) from the concept of cognitive networks and having seen the requirements and functionalities of such systems, passing through a categorisation of cognitive systems, this third part presents a model for networked cognitive entities, applicable to more general cases than some considered in the second part.

Looking back again at the motivations, energy efficiency and more generally dependability (bottom-right quadrant) are discussed in the fourth part. The exploitation of context awareness is used to obtain flexible networks to cope with some of the dynamics illustrated in the second part, also making use of collaboration. Being one of the tools for reconfigurable networks, adaptation is considered (bottom-left quadrant) in the fifth part, where the analysis of selected aspects is developed, covering both link-level and network adaptation.

1.3 Thesis outline and author's contribution

The discussion in the previous section already gave an outlook of the thesis outline. Here, its presentation is expanded while pinpointing the author's contributions.

This monograph relies on a combination of different kinds of contributions, covering scientific articles and patents, as well as previously unpublished material, to target the goal of the dissertation, summarised in Sect. 1.2.

The discussion on background and motivation included in this Chapt. 1 makes use of an extensive literature review, but the previous work more tightly related to the contributions of this dissertation is commented in the respective chapters, and isolated as much as possible in separated sections.

Chapt. 2 briefly looks into the challenges of future mobile communications and then focuses on one application of cognitive networks: concurrent spectrum use. Along with taxonomies and categorisations that also attempt to clarify sometimes controversial definitions, as well as with the modelling of key issues, this chapter discusses the corresponding requirements. Among them, context information awareness is further investigated there. Chapt. 3 generalises the scope and studies concurrent networks, their dynamics and QoS management. It then moves to cognitive networks, with a definition for the term as used in this dissertation. This chapter presents cognitive and topological domains enabling flexible design by decoupling the specification of the system functionalities from their mapping onto network entities.

Chapt. 4 categorises cognitive networks into three levels and proposes a novel model specifically for networked artificial cognitive entities (thus making use of socially shared cognition). Functions are divided into four categories as well as split into two layers, also with a look at the practical realisation of those entities. The application area of the model includes any system in which cognitive entities interact.

Chapt. 5 presents various solutions that exploit context awareness for efficient use of resources, mainly energy, and dependability in general, including robustness, integrity protection and and flexible network topology. Particular attention is given to feasibility, presenting augmented features both as amendments and as backwards compatible enhancements.

Chapt. 6 analyses selected aspects in link and network adaptation. In particular, it provides the effective capacity of imperfect adaptive links by a compact-form expression, and a solution for efficient link adaptation. For network adaptation, also considering implementation considerations, this chapter analyses by queuing theory the design trade-off.

The framework presented in Chapt. 2 and Chapt. 3, the cognitive entity model presented in Chapt. 4, together with the other considerations in Chapt. 5 and also Chapt. 6 may be regarded as part of a tool-set for the design of cognitive radio networks.

Finally, the concluding Chapt. 7 further discusses these contributions and gives examples of the direct exploitation of them as well as brings a look beyond them.

The introductory Chapt. 1 is entirely made of previously unpublished, original material by the author.

Chapt. 2 and Chapt. 3 mainly include contributions by the author to the European seventh framework programme (FP7) project project QoSMOS, and they are extensively integrated by previously unpublished, original material by the author, partly coming from scientific reports authored under national Tekes project PANU.

All the material presented in Chapt. 2 is either authored or co-authored, with the obvious exclusion of introductory material or short complementary notes clearly labelled under separate sections and where their nature is clearly stated. More in particular, Chapt. 2 starts from an author's taxonomy of access models built upon a rationalisation of the literature. The definition of the requirements for opportunistic spectrum use comes from co-authored work, but the digression on the options on incumbent user presence information acquisition is a contribution solely by the author. Similarly, the specification of the context information structures, coming from collaborative work, founds the basis for the following taxonomy of spectrum resources and for spectrum sensing requirements and configuration, both contributed by the author. For clarity of the presentation of the material, to Chapt. 2 is added a review of the QoSMOS reference model, a co-operative and collaborative effort the author contributed to but of which he is not the sole author, together with an author's comparison with related cognitive architectures.

Chapt. 3 presents the unifying concept of concurrent networks with their dynamics and ecosystem quality of service, the definition of cognitive device and network used in this monograph, the specification of the cognitive domains for decision-making, and finally the specification of the topological domains – adopted by QoSMOS project – and their application examples. All the above are entirely contributions by the author, with the obvious exception of the commented review of the existing definitions of cognitive radio.

The above contributions are previously published as part of the following supporting publications for Chapt. 2 and Chapt. 3: conference and magazine articles Celentano *et al.* (2011a), Mange *et al.* (2011b), Lehne *et al.* (2011b), Ariyoshi *et al.* (2011a,b), MacKenzie *et al.* (2011), Leveil *et al.* (2012), MacKenzie *et al.* (2012), Karla *et al.* (2013), Mange *et al.* (2013), Arshad *et al.* (2014); and public scientific reports Celentano *et al.* (2012), MacKenzie *et al.* (2010), Lehne *et al.* (2011a), Leveil *et al.* (2010), Mange *et al.* (2011a), Mange *et al.* (2012a), Anouar *et al.* (2012), Noack *et al.* (2011), Briggs *et al.* (2012), Bochow *et al.* (2013), Mange *et al.* (2012b).

Chapt. 4 is entirely made of previously unpublished, original material by the author, with the sole exception of Sect. 4.2.1, which summarises relevant parts the author's contribution to edited collection, Celentano (2008). In particular, this chapter presents a three-class categorisation of cognitive systems and a novel model for networked engineered cognitive entities with phases organised into four categories and two layers. The development of this model partly builds upon human learning touched in the above mentioned Celentano (2008) and largely expanded here. All the material presented in this chapter portrays therefore an author's contribution, with the obvious exception represented by the necessary presentation of the earlier related models in a separate section and where clear references to the literature are made.

Integrated by previously unpublished, original material by the author, Chapt. 5 includes contributions by the author to the project HRUMAC, with the obvious exception of the clearly labelled introductory sections and subsections, giving commented literature review integrated with own considerations. In particular, by the author are the conjecture on power consumption and the considerations on energy efficient cognitive functions related to the own model proposed in Chapt. 4. Author's contributions are also the dependable data transmission using beacons with its analysis and applications, and the energy-aware handover of responsible role ensuring a fair energy energy consumption for robustness. The solution for resilience to responsible node unavailability was not originated by the author, but it was adapted by the author to the ECMA-368 standard specification. Spatial reuse is a co-operative and collaborative result, to which the author contributed with support methods based on received signal strength. The solution for network population control is by the author. The contribution on flexible beaconing structure, backwards compatible and efficiently supporting large device populations or extending the datarate support is by the author. Another contribution by the author is the dependability protection under physical mobility of devices. The chapter ends with the author's solution in Sect. 5.4.2, contribution on collaborative datarate scaling. Further contributions are only quickly mentioned in the concluding Sect. 5.5. The above contributions are part of the following supporting publications: granted patents families Celentano *et al.* (2009, 2010, 2011b), Salokannel *et al.* (2008, 2011), Reunamäki *et al.* (2012), Destino *et al.* (2009); and pending patent applications Celentano *et al.* (2008b), Celentano *et al.* (2007), Celentano *et al.* (2008c), Celentano *et al.* (2006), Celentano *et al.* (2008d), Celentano *et al.* (2008a).

In Chapt. 6, the entire contribution on link adaptation leading to the effective capacity of imperfect links with its analysis is by the author; in supporting publications, journal and conference articles Celentano & Glisic (2006a), Celentano & Glisic (2005), and book contribution Celentano & Glisic (2006b), the second author had the role of adviser. The learning method using classification and selection of channel quality metrics with the corresponding signalling options is a contribution by the author, merged together with other material in the joint granted patent family Tirkkonen, Priotti & Celentano (2010, 2011). The rest of the chapter, Sect. 6.3 onwards, on network adaptation is entirely made of previously unpublished, original material by the author. In particular, this part includes the analysis by queuing theory and a discussion of the collaborative datarate scaling presented in Chapt. 5.

This dissertation approaches cognitive networks at different levels, including system-level issues, architecture, protocols and also touching realisation and implementation constraints. Correspondingly, analysis method have been adapted to the context. Compatibly with the desired level of generality and considering the peculiarities of the systems target of the research, qualitative analysis was used when applicable and quantitative analysis adopted when possible.

2 Opportunistic spectrum use and relevant issues

> HAL 9000: “I am putting myself to the fullest possible use, which is all I think that any conscious entity can ever hope to do.”
> – Stanley Kubrick and Arthur C. Clarke (1968) *2001: A space odyssey*.

The introduction to cognitive radio systems, started in Chapt. 1, goes from the present chapter more into the details. The related functionalities needed for a cognitive network are described for a specific example case of cognitive spectrum sharing involving users with different rights. For this, a taxonomy of spectrum sharing models as well as a categorisation of the spectrum resources is given, while message sequence charts are used to illustrate the operations.

A more generic approach is followed in Chapt. 3, where various forms of interaction among networks are discussed. Other forms of cognitive networks are suggested there and also seen also in Chapt. 5.

2.1 Introduction

As outlined in Chapt. 1, telecommunications are becoming more and more pervasive and mobile communication devices of many kinds are a consolidated everyday reality. Technology has dealt with many issues concerning mobility, allowing good quality of experience for homogeneous and static systems operating in such conditions (*static* refers here to the system as a whole, not to its network devices). A recent survey (ARCEP 2011) of French regulator ARCEP about QoS for mobile communications shows that (homogeneous) mobile systems are sufficiently robust still at motorway speeds, with a larger decrease appearing at very high speeds (TGV high-speed trains), see Table 1.

Incidentally, these results suggest that mobile hot-spots may help in those cases, where it may be more feasible to improve the quality of a single link, with predictable mobility pattern, instead of many. Technologies that are exploitable for those use-cases include short-range communications, also discussed in Chapt. 5.

Although under specific aspects there is room for improvements, the challenges of future mobile communication systems are elsewhere. Despite the steady growth of the

Table 1. Average values of successful rates for two-minute voice calls in various environments. Table built using data from ARCEP (2011).

Quality	10000+ inh.	top 12†	motorway	local train	TGV
Successful calls	97,3%	97,0%	92,90%	85,40%	74,20%
Acceptable	97,0%	96,8%	92,50%	84,70%	73,30%
Perfect (fixed-like)	95,9%	95,9%	91,10%	82,80%	69,50%

The three rightmost columns are for purely mobile environments, whereas the first two refer to a mixture of indoor pedestrian ($\approx 50\%$), outdoor pedestrian ($\approx 35\%$, both moving and steady) and urban car ($\approx 15\%$) environments, for cities of different sizes.

†The twelve largest cities (more than 400000 inhabitants) are: Bordeaux, Douai-Lens, Grenoble, Lille, Lyon, Marseille-Aix-en-Provence, Nantes, Nice-Cannes-Antibes, Paris, Strasbourg, Toulon and Toulouse.

bandwidth needs of communication networks, striving for higher datarates appear to be no longer the top design criterion for future networks. Key targets are instead scalability, energy efficiency for both CO_2 footprint and OpEx reduction (see Chapt. 1), as well as consistent quality of service in heterogeneous scenarios (Nokia Siemens Networks 2011).

Radio spectrum is currently a scarce resource – and possibly this will always be, since as new bandwidth is available, more bandwidth-greedy applications face the scene. The shortage of a resource calls for efficiency in its use. The area spectrum efficiency is a measure of the delivered throughput relatively to the amount of spectrum resource used in a given area. The spectrum efficiency is the combined effect of two causes. The first is due to data transmission techniques (e.g., the ability to deliver more data with less stringent spectrum requirements). The second depends on the spectrum utilisation (i.e., the actual use of the spectrum, by any user, over a given time). The latter, more crucial in cognitive radio networks, also implies that the use of spectrum by more users should not decrease the quality of service of any other user, especially incumbents. This means that (all the possibly) available spectrum must be used efficiently and with controlled quality of service.

2.2 Concurrent spectrum use and QoS

As outlined in Sect. 1.1 and in previous Sect. 2.1, a more efficient use of radio spectrum calls for its sharing. This is one of the forms of interactions introduced later in Sect. 3.2.

The management of coexistence among whitespace users, also known as self-coexistence, is often, as done by the FCC, left to the industry (Baykas *et al.* 2010). The observance of the rights of the incumbents is crucial in concurrent spectrum use and for this reason the coexistence of incumbent and opportunistic users is regulated. This latter form of coexistence is in the focus of the first part of this section.

According to the Oxford English Dictionary, the word *opportunism* means (OED 2012b)

> “the practice or policy of exploiting [or the ability or tendency to exploit] circumstances or opportunities to gain immediate advantage, rather than following a predetermined plan”.

Actually, it may be observed that the opportunistic spectrum use, as intended in the present context, even if not following a predefined plan, shall actually follow at least predetermined rules.

Also pushed by the *Internet of things* (IoT) phenomenon, there is a need to allow access with lower barriers than those present in a rigid licensed approach but at the same time of better QoS guarantees than those currently possible in unlicensed bands (European Commission 2012).

Various models of concurrent spectrum use are possible, and they are commented below. The management of the service quality for the involved users, which for some of the spectrum sharing models discussed below includes protection of the incumbent users, is then discussed.

A spectrum hole is a band of frequencies not used at a particular time and location by its assignee (Haykin 2005) and is commonly referred to as whitespace. While in a whitespace only ambient noise is present, in presence of a weak or a strong signal level, a distinction can be made between grey and black space, respectively (Haykin 2005).

A portion of spectrum (or a collection of spectrum portions, aggregated to satisfy datarate requirements) is a spectrum opportunity when its use is allowed to so-called opportunistic users, with possible limitations in time, coverage and waveform used imposed by regulations and/or incumbent users. The limitations in time can be: known, when an incumbent announces its next need of said spectrum portion; estimated, when calculated based on previous knowledge of the spectrum occupation (for example by use of learning); or unknown, when the limitations come from sensing the appearance of an incumbent. The limitations in coverage can be imposed to restrict locally the use of spectrum portions. The limitations in waveform can be imposed to limit the interference to an incumbent.

2.2.1 Access models and their taxonomy

The terminology used in the literature about concurrent spectrum use is not univocal. For the sake of clarity, the existing models are first presented and then a taxonomy of them is discussed together with those issues relevant in this work.

Access models

The simplest spectrum sharing model is the *spectrum commons* model (Zhao & Sadler 2007), which is similar to the spectrum sharing among peers as in ISM bands and does not implement any method for incumbent protection (incumbent protection will be discussed in more detail in Sect. 2.2.2 and 2.2.3). Although some level of control can be imposed (Buddhikot 2007), in general no explicit control is implied.

The opposite of the previous is the *static allocation*, where the assignee exclusively uses the resource, which is controlled by a regulator according to a command-and-control philosophy (Buddhikot 2007). A further step is represented by the *use-or-trade* model (in Zhao & Sadler (2007) called spectrum property rights), by which a licensee has an option to sell or lease "its" spectrum. In a more flexible way, the *dynamic allocation* allows following, although only slowly, spatio-temporal traffic variations and reallocating the spectrum correspondingly.

In between the above two major classes, a hierarchical access (Zhao & Sadler 2007) with which license holders and non-licensed users (Buddhikot 2007) interact can be identified. This use of spectrum by opportunistic users with no or limited detrimental effects on the incumbent service can be further classified into three major categories: underlay model, overlay model and interweave model (Srinivasa & Jafar 2007). With the *underlay* model, the emissions by the opportunistic transmitter are calibrated in such a way that reception at incumbent receivers is not or negligibly affected, i.e., the caused interference is kept below a given threshold therefore not sufficient to degrade the correct reception at incumbent destination sites (Zhao & Sadler 2007). A corresponding maximum interference-free transmit power (Do & Mark 2009) can be identified locally and hence with this model we can talk of a spatial spectrum hole (Do & Mark 2009).

Under the assumption of sufficient knowledge at its site, an opportunistic transmitter can in principle emit without harm to (or, more exactly, with known and controlled interference at) an incumbent receiver (Srinivasa & Jafar 2007). The *overlay* model does not impose limitations on the transmit power, nevertheless the opportunistic user causes no interference to the incumbent communication by use of proper coding[2] (selfish approach), or it even relays the known incumbent message together with its own message (selfless approach) (Srinivasa & Jafar 2007). The *interweave* model is based on interference avoidance: when no activity of an incumbent transmitter is in place (in practice, when a spectrum portion is assessed to be unused), an opportunistic transmitter may interpose in time its transmissions, using the available whitespace, which can be referred to as a temporal spectrum hole. However, clearing the spectrum at the instant of start of activity of incumbent transmitter cannot always be guaranteed (Srinivasa & Jafar 2007) if sensing is used and therefore the detrimental effects of opportunistic transmitter on the incumbent user cannot be determined accurately. As seen, hierarchical models can be regarded as a hybrid as far as control is concerned.

Concurrent networks accessing spectrum may make use of more than only one of the previously presented models. For example, even when the channel is not assessed as unused, an opportunistic user may still continue transmitting, provided that its interference on the incumbent is controlled and subject to applicable policies. This case of hybrid interweave/underlay model can be referred to as use of spatio-temporal spectrum holes. An example of spatio-temporal spectrum sharing is presented in Kang *et al.* (2009). Spatio-temporal spectrum sharing is also applicable when performance degradation on incumbent receivers is considered for potential trade-off with the performance of the opportunistic users, i.e., when incumbent performance constraints are soft.

As outlined earlier, the terminology used in the literature about concurrent spectrum use is not univocal. The overlay and interweave models defined above, are sometimes jointly referred to as overlay model, or opportunistic spectrum access (Zhao & Sadler 2007), usually used as a synonym for interweave model only, as in (Xiao *et al.* 2009), where on the other hand the more generic spectrum sharing term is used to refer to the specific underlay model. The interweave model is called spectrum pooling by Mitola (2000) and opportunistic spectrum access by Liang *et al.* (2011), where the concept of

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[2] The overlay model exploits dirty-paper coding (Caire & Shamai 2003, e.g.), whose details are out of scope of this thesis.

underlay is referred to as spectrum sharing by Haykin (2005) and concurrent spectrum access by Liang *et al.* (2011).

Taxonomy and discussion

It is interesting to outline commonalities and distinguishing peculiarities of the previous paradigms. The spectrum sharing models reviewed above models are here classified and put in the taxonomy illustrated by Fig. 4, whereas Table 2 summarises some features of the main models.

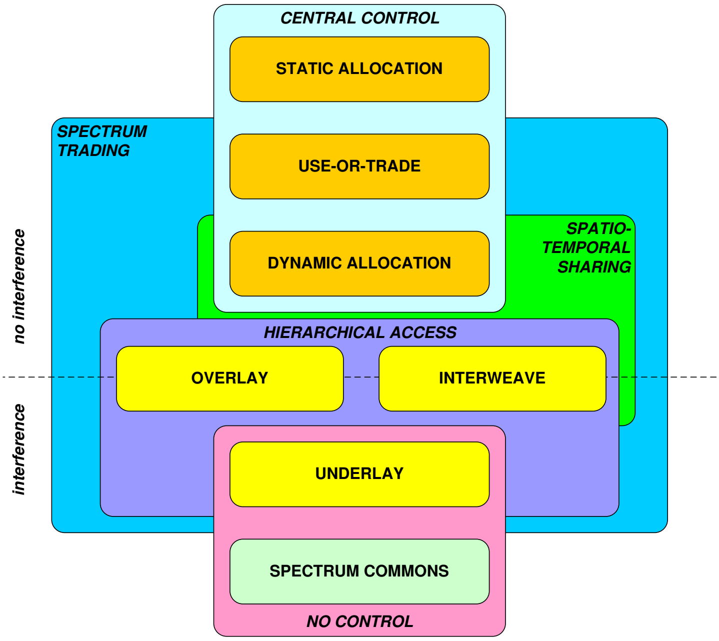

Fig 4. Taxonomy of concurrent spectrum use models.

From top to bottom of Fig. 4, the level of flexibility increases, but with it, also the level of interference potentially grows. The two models at top, static allocation and use-or-trade, do not involve any spatio-temporal variation. The allocations in the latter may change with time, but these changes are ruled by other mechanisms and are not necessarily related to the actual spectrum utilisation. The two models at bottom, spectrum commons and underlay, do not take into consideration the instantaneous channel occupation. For this reason, these two models do not require any control, whereas the three models at top are ruled by a rigid central control. From the uppermost (central control) class, the control is less centralised and less strict going down; similarly, from the lowermost (no control) class, the constraints are stricter going up.

A major split of the access modes can be done regarding absence or presence of interference. These two classes roughly coincide with the two macroclasses for shared spectrum access defined by the European Commission: the licensed shared access (LSA) and the collective use of spectrum (CUS), both with variety of implementations. Correspondingly, the Radio Spectrum Policy Group 2011 (2011) identifies as access models the administrative model, the market-based model, the licensed shared access model, and the collective use model. These approaches match how the models are mapped top down in Fig. 4.

Table 2. Spatio-temporal spectrum sharing models and their main limitations.

Model	Interference	Main challenge
Dynamic allocation	no interference	slowly follows predicted (not actual) variations
Overlay	interference control	channel gains and incumbent transmission non-causally known at opportunistic transmitter (intrusive, potentially harmful)
Interweave	interference avoidance†	instantaneous incumbent detection and spectrum vacation; impact on QoS: capacity/delay
Underlay	interference mitigation	limited transmit power (intrusive, possibly non-invasive); impact on QoS: limited coverage/rate

†See text.

The idea behind the underlay spectrum sharing model is similar to the interference mitigation or avoidance and dates back to direct-sequence spread-spectrum (DS-SS) techniques (Simon *et al.* 1985, e.g.) and ultra-wideband (UWB) systems (Oppermann *et al.* 2004, e.g.). Similarly, with an interwave model the system behaves somehow similarly to a frequency-hopping spread-spectrum (FH-SS) (Simon *et al.* 1985, e.g.), with interference ideally avoided. Although the underlay model does provide integrity of incumbent spectrum use, it may fail in providing an adequate reliability to opportunistic users, due to its main drawback: the constraint on spectral emissions limiting the possible coverage of underlay approach.

The most interesting models are those at the centre of Fig. 4. As seen, dynamic spectrum allocation, although avoiding interference, is not able, due to its design, to follow quick variations. The overlay model is based on the assumption that all channel gains and incumbent user transmission are known non-causally at the opportunistic transmitter, which is not easily satisfied in practical cases. Overlay and interweave do not cause interference in ideal situations, but in practice complete avoidance or mitigation is impossible to be achieved. Compared with the overlay model, the interweave model imposes design requirements that are probably closer to what can be achieved in general cases by practical systems. One challenge in mobile networks is to react in time to spectrum use variations, where variations differ with spatial location.

Depending on the model, spectrum can be shared without specific trading with a possible spectrum owner. Trading is explicitly needed in use-or-trade, but it can occur also in other cases, as for example in dynamic allocation or interweave models, or even underlay, where the incumbent user, upon trading, may actually free resources for opportunistic users by rearranging its own services or accepting a decrease in performance (see also the discussion in Sect. 3.2.2). In addition to trading, other forms of direct interactions among players can be needed. For example, in the overlay model, the incumbent user could provide the opportunistic user the knowledge needed for the coding algorithms, to ease bridging the model feasibility gap discussed above.

Almost any of the above sharing models, is governed by a set of parameters. Adjustment of relevant parameters can be done considering either the temporal or the spatial domain, but it is clear that both approaches can be jointly used, enhancing the effectiveness in capacity increase. The performance of both the incumbent service, namely its integrity, and the opportunistic user, in particular its reliability, as well as the necessary overhead and complexity to support the cognitive features, depend on those settings, which can be adjusted with regard to performance and/or overhead and complexity. For example, the opportunistic transmission under an underlay model is penalised by a limited coverage, which can be possibly traded with datarate.

It is clear that in order to be able to manage all those constraints, a number of requirements on the system stem and a properly structures architecture is needed. This will be the subject of the following sections.

2.2.2 Architectural implications in opportunity exploitation and incumbent protection

Motivation for protection of incumbent users and description of the situations in which such measures are needed have been described in the previous sections. In this and the following sections the focus is on how this can be enforced together with the opportunistic service quality management. In this context, the problem of spectrum sensing is addressed without entering into the details on the spectrum sensing *methods and algorithms* themselves, which are broad research topics themselves and out of the scope of this work. Rather, the topic is treated here to derive the implications on the *system architecture*.

Requirements

The fundamental constraints about QoS provision to opportunistic users and protection of incumbents are represented by the internal and external constraints, respectively, for the opportunistic system; they are the two starting boxes at the top of Fig. 5. From those derive the challenges, which depend on the relevant concurrent spectrum use model, and the main requirements for opportunistic networks, as illustrated in Fig. 5. This sets the corresponding, multi-faceted resource management problem.

The main requirements relevant here – for a broader view see Lehne *et al.* (2011a), Mange *et al.* (2011b) – are the following:

- *Awareness*. A cognitive system shall be environment-aware and able to act accordingly (see Sect. 3.3.2). For opportunistic systems, this in particular means vacating a operating channel, change the transmit power, etc., according to the model (Sect. 2.2.1), to ensure protection of an incumbent and coexistence with other opportunistic systems. To further improve coexistence, an opportunistic communication system should be able to detect also signals from other electromagnetic field sources. To this end, and depending on the relevant regulations, the opportunistic system should support spectrum sensing, and when this is done, without affecting the QoS of opportunistic users. The opportunistic system also shall support geolocation databases and be capable of interworking with these and other relevant external systems, such as those needed for trading.
- *Robustness*. A working opportunistic communication system shall support QoS (datarates, traffic classes, etc.) for opportunistic users, to cope with the effects of

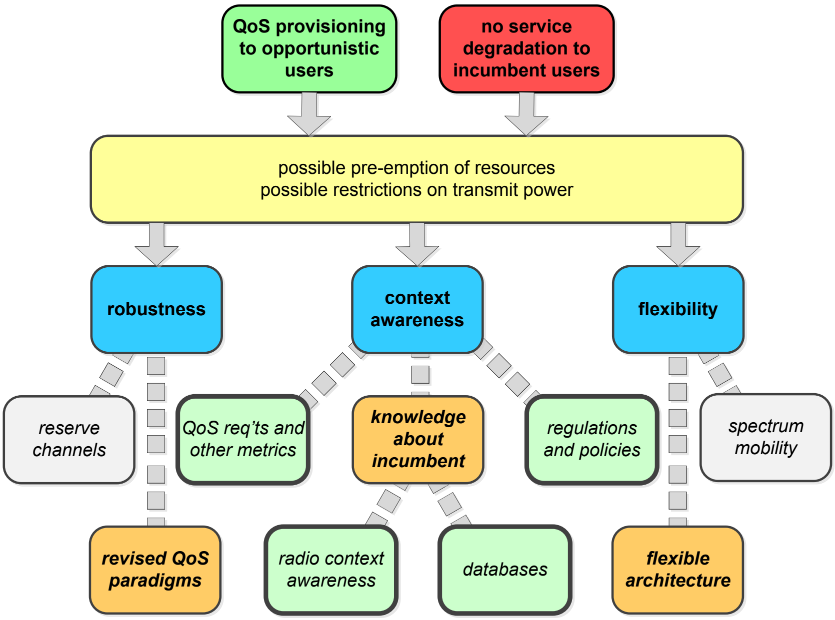

Fig 5. Constraints about QoS provision and incumbent protection, derived challenges depending on concurrent spectrum use model, and requirements for opportunistic network. They include capability to continue operations in other spectrum portion when needed and the supporting cognitive functionalities. Incumbent user presence information acquisition, QoS paradigms, and flexible architecture are further discussed in Sect. 2.2.2, Sect. 3.2.2, and Sect. 3.4, respectively. Revised from Arshad *et al.* (2014).

incumbent appearance in the scene. To this end, the system also maintains a proper set of reserve channels, together with the related measurements. Mobility shall also be supported when relevant to the scenario.

- *Flexibility*. An opportunistic communication system shall of course be flexible in the use of spectrum and possibly also be capable of supporting different radio access technologies. Moreover, an opportunistic system shall be capable of obeying relevant regulations in different regions. More generally, the capability (see Sect. 3.4.2) of being applicable to scenarios different in topology, range, etc. expands the exploitability of a system.

In addition to the above, are also relevant to these systems other dependability issues, such as those related to security. They are mostly out of scope of this thesis. See Lehne *et al.* (2011a) for some related requirements and Chapt. 1 of this dissertation for short discussions on the subject.

The remainder of this section focuses on the acquisition of the knowledge about the presence of the incumbent user. Sect. 3.2.2 further discusses QoS paradigms and Sect. 3.4 focuses on flexible architecture.

Incumbent user presence information acquisition

In order to enforce protection of incumbent users, knowledge about their activity and usage of assigned spectrum portions is required. The incumbent user presence information acquisition, i.e., the awareness about the current presence or imminent appearance of an incumbent, can be achieved in two ways (Lehne *et al.* 2011b). One way is by using *a priori* knowledge of upcoming occupation at a given location and time of a given spectrum portion. The planned usage of spectrum resources can be anticipated by their incumbent and this information can be conveyed by an authorised database. The other way is to acquire *a posteriori* knowledge of incumbent user presence by using spectrum sensing.[3]

The terms *a posteriori* and *a priori* in this context – where the focus is on the system architecture, see also the text at the beginning of this Sect. 2.2.2, and here in particular on incumbent user *presence information acquisition* – refer to the actual *presence* of the incumbent. In other words, *a posteriori* means here that the incumbent is already present when the information on its presence is assessed. Conversely, *a priori* refers to the fact that this information is acquired already beforehand. In the literature on spectrum sensing – i.e., as is the case of incumbent user *detection* – the term *a priori* is sometimes used with reference to the *information* on the signal needed to perform the detection algorithm. See for example Vartiainen (2010, Sect. 2.3) for a digression on the need and use of a priori information in signal detection, and on the major classes of

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[3] A third method is the use of beacons (Nekovee 2010) sent by the incumbent or a delegated party to announce the channel as available. As with the database method, the information about the activity is not necessarily or tightly linked to the actual use of the resource. On the other hand, it is implemented similar to incumbent detection by sensing, as it requires detection of a signal (but the beacon can be out-of-band). For these reasons, beaconing can be regarded as a hybrid of the two. This method, initially considered together with sensing and geolocation, was later disregarded by ECC (2011). Indeed, the method may not allow high resource utilisation, while being prone to inaccuracy (e.g., hidden node) and inefficiency (detection).

detection methods from energy detection to matched filtering through feature-based (semi-blind) and blind methods. In the context of the present Sect.2.2.2, any signal detection method is classified as a posteriori *presence information acquisition* method, regardless of the amount and nature of the information about the signal to be detected.

Short and long-term views, and integrated methods

In the memorandum FCC (2010) issued by the Federal Communications Commission (FCC) of the United States of America, for the operation in TV whitespace, access to database information is required. Whitespace databases for use by whitespace devices are also discussed in the UK by Ofcom (Ofcom 2009b, 2010) and in the US, TV bands device database administrators are already identified and conditionally designated (FCC 2011a,b).

While requirement on spectrum sensing is eliminated by FCC, its further study is at the same time encouraged for the possible improvements brought by it and for its possible need for other bands (actually, memorandum FCC (2010) concerns TV whitespace only). Indeed, Ofcom (2009a) does not see detection-only devices (ECC's term for FCC's sensing-only devices) impossible, although they are not seen as a feasible option in the short-term. The above facts provide the motivation for what presented in this section.

If not already dictated by regulation, the most appropriated method depends on the incumbent user's activity dynamics, on requirements about promptness vacation of the spectrum and on the overhead imposed by the necessary protocols over the incumbent and opportunistic systems. In any case, both methods open up a set of requirements on the opportunistic system and bring possible trade-offs for discussion, where reliability and efficiency of spectrum sensing methods play a fundamental role.

The use of only geolocation databases is a viable solution for the short-time deployment of opportunistic systems, since its guarantees of lack of harm to incumbents are undoubtedly higher. However, a database may exhibit poor resource use efficiency due to the smaller dynamics it can efficiently support in a scalable manner. Improving the utilisation ratio of database solutions requires an increased update rate. Quick updates of databases may be complex in terms of transmission overhead (if the whole portfolio, see Sect. 2.2.3, of interest is to be downloaded each period) or in the management of the updates (to keep track of individual deployments of portfolios). Moreover, taking into account each and any opportunistic user in such a dynamic database may not be feasible for complexity reasons. This means that collisions among opportunistic users may not be avoided by using databases only and spectrum sensing capabilities should be therefore present in opportunistic systems. Moreover, spectrum sensing is needed to detect those users not registered to databases.

Overhead is associated with spectrum sensing as well. Measurements may be as small as binary outcomes and they can be carried with reduced overhead, so a major component of inefficiency is represented by the quiet periods needed for sensing, whose duration depends on the sensing algorithm.

Depending on the aforementioned limitations, in some scenarios sensing could be used to integrate the database approach and to improve the spectrum utilisation. Spectrum sensing may enable a more dynamic use of the spectrum and it may come in place in the mid-long term, when lack of spectrum resources due to poor utilisation of whitespaces would be faced and more efficient reliable spectrum sensing techniques would be available. In addition to the above considerations, another aspect to look at is the kind of whitespace (i.e., the kind of incumbent associated with it and the use of such whitespace: the kind of opportunistic user going to use it). Some incumbent users – e.g., military: in addition to the above scenario, FCC (2012) opens a 3.5 GHz band currently utilised for military and satellite communication – may temporarily release spectrum (for example to emergency users), but may still want prompt and unplanned access to their bands and refresh rate of portfolios may not allow this. On the other hand, spectrum sensing must be very reliable in those cases, and this is a key issue as already stated.

Table 3 summarises the differences between the two methods in efficiency and design challenges, and some of those are expanded in the following.

A discussion about a priori and a posteriori knowledge

A more quantitative discussion can be made by limiting the scope to the capacity loss implied by the methods and using realistic values, such as those provided with FCC regulations. Of course, such a comparison simplifies some aspects, such as those summarised in Table 3.

A fixed TVBD must access the DB at least once a day, whereas a mode I TVBD must contact at least once every minute a fixed or a mode II TVBD. Mode II devices (as well as fixed devices) are capable of determining their location and the locally available channels. Mode I TVBDs are not, and therefore they may only operate under the control

Table 3. Comparison of *a priori* and *a posteriori* incumbent protection.

	a priori	a posteriori
Means	database (provided by an external entity)	spectrum sensing done at one or more nodes
Availability	uncertain (depends on an infrastructure)	certain (independent of infrastructure)
Integrity‡	perfect (anticipated avoidance) and accurate	imperfect (vacation upon appearance) and potentially inaccurate
Speed of reaction†	potentially slow (upon database update), depending on database access rate	potentially fast (upon incumbent appearance), depending on sensing algorithm
Spectrum utilisation	potentially low (imperfect interweave), depending on incumbent's policy	potentially high (perfect interweave), but affected by sensing overheads
Overhead†‡	potentially large (but can be out-of-band); small, when incumbent's activity is easily predictable (e.g., TV broadcast)	potentially small (but mostly in-band due to quiet periods); large for reliable sensing; may depend on frequency band

†In the a priori case, speed can be improved at the expense of an increased overhead (database access).

‡In the a posteriori case, accuracy can be improved with an increase in overhead (sensing rate).

of one of the above. As seen, for all TVBDs, spectrum sensing is optional and database access mandatory.

Let us focus here on a so-called mode II device. According to FCC (2010, 2011a), a mobile TV band device must access a database at least once every 60 s or after a dislocation of more than 100 m, whereas a sensing-only device must sense an operating channel at least once every 60 s. Despite the FCC one-minute sensing period, the channel must be evicted within two seconds upon appearance of an incumbent. Ofcom sets the sensing period for detection-only whitespace devices to one second (Ofcom 2009a). A sensing-only device must demonstrate not to harm incumbent services and also has stricter power emission limits.

Assuming that those limitations are compatible with the target application and that the sensing reliability also responds to regulations, a comparison can be made as efficiency is concerned. The capacity loss for any operating channel for the two cases are

$$C_{\mathrm{DB}} = L_d \max\left(\frac{v_m}{d_d}, \frac{1}{T_d}\right) \tag{1}$$

$$C_{\mathrm{SS}} = r\frac{\tau_s}{T_\sigma} \tag{2}$$

where L_d length of the database message, v_m speed of the mobile device, d_d distance imposed by regulations, T_d database access period imposed by regulations, r useful datarate capacity, τ_s sensing duration depending on target signal and sensing algorithm, T_σ sensing period imposed by regulations. In (2), an additive term L_s/T_σ due to collection of distributed measurements and delivery of the decision, making a total length of L_s may be needed depending on the sensing method. The corresponding traffic may be carried over a possible out-of-band control channel and may be negligible compared with the other. ‘ On the other hand, the latency possibly needed to access a remote (Internet) database is not considered. For a cellular network, this traffic can be supported by the core network, but in the case of ad hoc networks (see in the following a remark on opportunistic ad hoc networks) this occurs on the wireless component, either in-band or out-of-band. Parameters as imposed by the above FCC regulations are $d_d = 100$ m, $T_d = 60$ s, $T_\sigma = 60$ s. The speed range for a terrestrial mobile is approximately $v_m = (1 \div 160)$ m/s, from pedestrian to high-speed train. Considering the term $\max(v_m/d_d, 1/T_d)$, the discussion can be split around $v_m = 100/60 \approx 1.67$ m/s, hence between pedestrian and non-pedestrian mobiles.

Under the above conditions, spectrum sensing is beneficial for

$$\frac{r\tau_s}{L_d} < \frac{T_\sigma}{T_d}, \quad \text{pedestrian } (v_m < 1.67\ \mathrm{m/s}) \tag{3}$$

$$\frac{r\tau_s}{L_d} < \frac{v_m T_\sigma}{d_d}, \quad \text{non} - \text{pedestrian } (v_m \geq 1.67\ \mathrm{m/s}) \tag{4}$$

The order of magnitude of the scenario-dependent right-hand-side terms are units and units to hundreds, respectively. The order of magnitude of the design-related quantities on the left is as follows. A typical sensing duration time τ_s is of the order of the millisecond[4], but wider ranges such as $(10^{-5} \div 10^{0})$ s are also specified for clear channel assessment (IEEE 2007). The order of magnitude of L_d can be assumed of the tens (one or a few bytes). Under these assumptions, spectrum sensing may be more efficient than database access for lower bitrate applications, see Table 4, as it was expected, since the major inefficiencies of sensing and database approaches are in time and data, respectively. The values at the bottom-left corner of the table may be infeasible, since

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[4] The IEEE 802.22 standard allows a fast sensing (e.g., by energy detection) and a fine sensing (e.g., by feature detection). For those, indicative values are 1 ms and 25 ms, respectively (Benko *et al.* 2006, Cordeiro *et al.* 2006). Values within this range are suggested in Liang *et al.* (2008).

fast sensing should be possible at a high mobile speeds. This, together with the possible weaknesses in reliability of sensing results justifies the choice of database approaches as the preferred method, at least for the short-term.

Table 4. Overhead and theoretical order of magnitude of the break-even point for pedestrian ($v_m = 1$ m/s), car/urban ($v_m = 15$ m/s) and high-speed train ($v_m = 160$ m/s) scenario. Spectrum sensing is profitable (more efficient) than database approach for maximum system datarate r smaller than the indicated magnitude.

τ_s	$\approx 10\,\mu$s	≈ 1 ms	≈ 10 ms	≈ 1 s
Pedestrian	≈ 1 Mbit/s	≈ 10 kbit/s	≈ 1 kbit/s	≈ 10 bit/s
Car	≈ 10 Mbit/s	≈ 100 kbit/s	≈ 10 kbit/s	≈ 100 bit/s
Train	≈ 100 Mbit/s	≈ 1 Mbit/s	≈ 100 kbit/s	≈ 1 kbit/s

The above discussion is valid for database validity updates and for already established communications between sensing-only devices. At establishment phase, a database length is much larger and aforementioned regulations impose a thirty-second listening time before starting transmissions. On the other hand, depending on the scenario, sensing-only devices do not necessarily need to rely on continuous availability of an infrastructure, and due to a smaller portion of the protocol stack to be travelled (spectrum sensing is possible at lower layers), vacation might be faster in this case[5].

About opportunistic ad hoc networks

An ad hoc network is a network of devices that does not rely on external entities for its control. In compliance with regulations, an ad hoc network may need to exchange information with external entities. This is to acquire, when needed, mandatory regulatory constraints, including access to databases, if required. The connection with external entities is not needed continuously, but shall be compliant with regulation (for example, with at least a given periodicity, if needed). A gateway device is a device in such a network with the role of this interfacing. The gateway device can be selected statically or dynamically (see also Sect. 5.3.2 on this).

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[5] In principle, if opportunistic devices are equipped with full-duplex radios (Jain *et al.* 2011), the opportunistic node could detect an incumbent user while using the spectrum (Choi *et al.* 2010), without the need of quiet periods and with the vacation message that could be promptly sent.

Note on devices rendez-vous

The interconnection of network devices implies the existence of a means for coordination, sometimes called rendez-vous (Theis *et al.* 2011) and realised in some cases with a common control channel, like the cognitive pilot channel in Tiemann *et al.* (2009) or the common signalling proposed in MIRAI (multimedia integrated network by radio access innovation) project of e-Japan programme (Ohmori 2011). Dependence on a common control channel realised by unreliable (non-dedicated) resources may prove challenging, especially in the case of need of an immediate vacation of the operating channel, called reactive spectrum handover by Lee & Akyildiz (2012). To avoid such a need, Theis *et al.* (2011, e.g.) propose probabilistic methods for (re)establishing a link between a pair of cognitive devices.

Theis *et al.* (2011) observe that in absence of a single common control channel, the rendez-vous process for cognitive devices shares commonalities with the neighbour discovery of ad hoc networks. More generally, neighbour discovery can be considered the dual of opportunity detection: they roughly are about making sure to find a target device and being sure that no other device is present, respectively. (Compare this with the categorisation into two types, or use-cases, of cognitive radio identified by Harada (2010), Ohmori (2011): the so-called *heterogeneous type*, able to find a connection among many, and the *spectrum sharing type*, able to exploit vacant spaces.)

A common control channel can be global (presenting scalability issues) or local, and it can be either in-band or out-of-band (Akyildiz *et al.* 2009a,b). Sometimes, in the latter case a common control channel, which presents low-rate needs, can be available with reduced requirements on the overall system. The problem discussed in this note is not specifically addressed in the present dissertation.

2.2.3 Context information in opportunity exploitation and incumbent protection

As also shown in Fig. 5, exploitation of context information is a key requirement for opportunistic spectrum use. The previous section discussed two approaches that can be followed, and the discussion deepens in this and the following sections.

The foremost aspect to consider in opportunistic use of spectrum portions are the regulatory constraints imposed for its use. Therefore, the minimal information an opportunistic system is required to manage consists in the required regulatory constraints. Those are typically static in time but may be different at different locations. For this reason, whitespace devices may be required to be capable of positioning. Depending on the use-case and sharing model, also trading-related and/or other policies possibly attached to the spectrum portions are among the active constraints. More, the contents of such a repository can be enriched with measurement reports about service quality experienced by opportunistic users, spectrum sensing providing refined information about incumbent user's activity and coverage, etc. Finally, the repository can be used to share information about the current use of the spectrum resources.

This can be called spectrum portfolio. Different components and levels, at the different network equipments and the different topological domains (defined later in Sect. 3.4.2), respectively, can be identified. For example, a global portfolio has a broader and slower scope compared to a local portfolio, closer to the operational site. Moreover, there are an active portfolio, deployed for use to an opportunistic user, as opposed to an inactive portfolio. The repository at the highest level can be called common spectrum portfolio[6]. The spectrum portfolio (a database or more generally a repository) conveys the information corresponding to the four boxes with thicker frame at the bottom of Fig. 5.

Fig. 6 illustrates the portfolio operations across elements at coexistence, co-ordination and networking domains and Fig. 7 example portfolio operations. The above topological domains (Celentano *et al.* 2011a) are defined in Sect. 3.4.2. The functional blocks shown in the figure are part of the reference model developed within the QoSMOS project and further described later (see Sect. 2.2.4 and references therein). The functions of the cognitive manager for spectrum management (CM-SM) are here split between two macro-blocks for repository access and management (REP) and for spectrum management context localisation (LOC) and spectrum selection (SEL). The cognitive manager for resource management (CM-RM) is also shown in the figure. At the coexistence domain, for example in the Internet, are located the repositories, the regulatory (RGDB) and the common portfolio (CPFR). The network elements at the

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[6] Similar concepts are for example the data archive of IEEE 1900.6 (Murroni *et al.* 2011) or the available resource maps (da Silva *et al.* 2008).

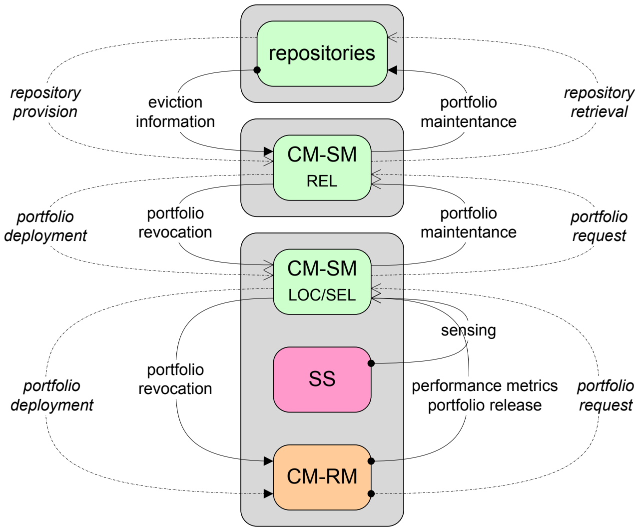

Fig 6. Portfolio operations across elements at coexistence, co-ordination and networking domains (background boxes from top down). Operations originate at dot-headed lines, proceed through open arrowheads and end at filled arrowheads. An outer path proceeds through dash-dotted lines marked with slanted font labels, whereas three inner paths go along solid lines marked with upright font labels. Revised from Karla *et al.* (2013).

co-ordination domain are in the core network in a cellular case, or at a gateway device (GW) in an ad hoc network (see the remark on p. 60 in Sect. 2.2.2 about this), whereas the elements at the network domain are the base station or access point (AP), or the gateway device, respectively.

The portfolio operations involve elements at coexistence, co-ordination and network domains (Sect. 3.4.2), respectively, in Fig. 6. Internet, core network (CN) and base station, in a cellular example. Operations originate at dot-headed lines, proceed through open arrowheads and end at filled arrowheads. An outer path proceeds through dash-dotted lines marked with slanted font labels, whereas three inner paths go along solid lines marked with upright font labels. For example, sensing measurements made available by the spectrum sensing (SS) block are exploited at the CM-SM and propagated up to a common portfolio repository.

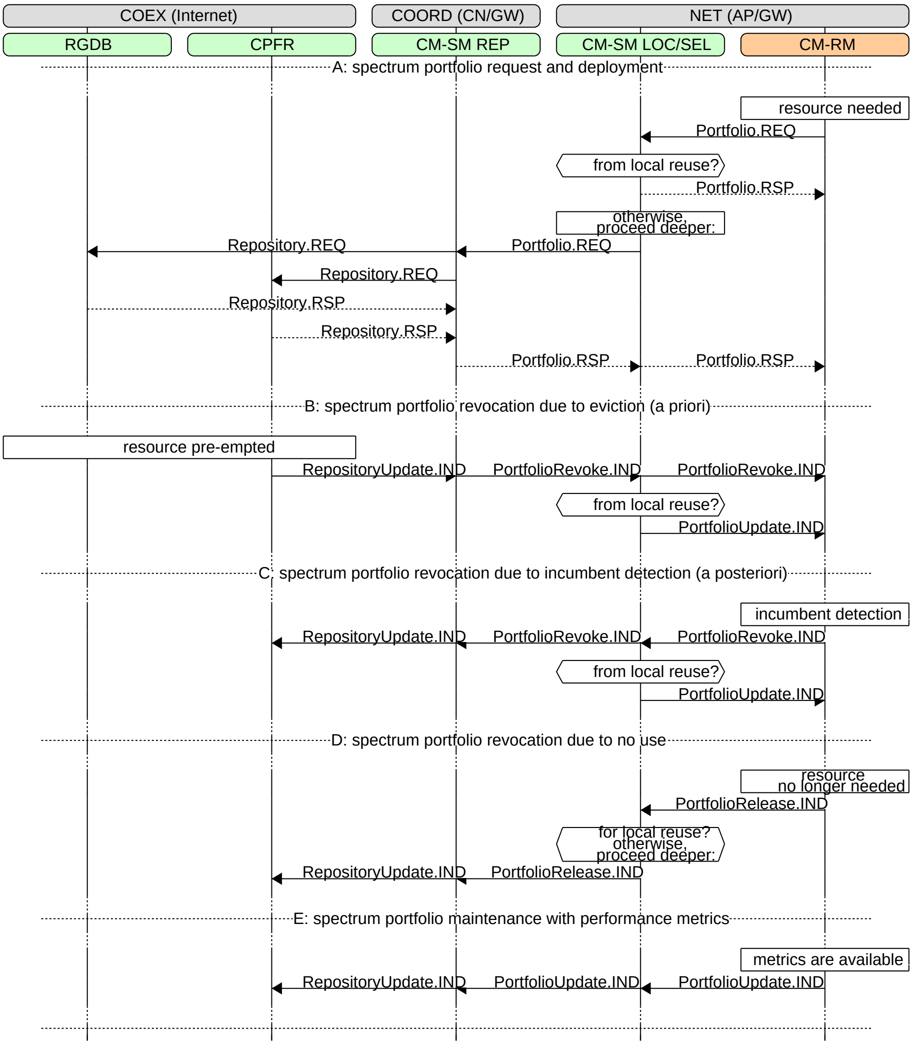

Fig 7. Portfolio request and deployment, revocation and maintenance. Revised from Mange *et al.* (2012b).

Fig. 7 shows the request and deployment of a spectrum portfolio (A) with different deepness of intervention. The portfolio revocation due to eviction (B) always implies the revocation of the relevant portion, but in case alternative resources are available, a portfolio update may be triggered. In the portfolio revocation by incumbent appearance

(C), the process starts at the opposite side. In both cases (B and C), alternative resources may also be found at the co-ordination domain. A process similar to the latter, but with different effects, is followed in case of release due to no use (D). The repository may also be integrated or updated with measurements, such as performance metrics (E).

The information about the context concerning the spectrum resources depends on their nature. This aspect is addressed in the following section.

Taxonomy of spectrum resources in opportunistic use

The spectrum portions (in this section referred to as *channels* for simplicity) of possible interest for an opportunistic system, the portfolio channel set, can be categorised according to different perspectives (Leveil *et al.* 2010).

One viewpoint is related to *why* the information is gathered (e.g., the spectrum is sensed), i.e, what is the use of the gathered information (e.g., a sensing decision). Hence, a distinction can be done between *active* and *inactive* channels[7]. Within the former category are possible different levels of activity. So, its elements can be further divided into *operating* and *reserve* channels, depending on whether the spectrum is in use almost all the time or more rarely, or the channel is not currently in use but it may turn to be used in the short period upon unavailability of current operating channel, e.g., due to appearance of incumbent.

Being aware of the current or upcoming presence of an incumbent in the operating channels is of course of primary importance, but in order to avoid or reduce service interruptions to opportunistic users, the status of reserve channels should also be carefully tracked. For example, FCC requires sensing-only devices to sense a channel for 30 s before its possible use and mode II devices to possess database information not older than 60 s. Therefore, both operating and reserve channel are included in an active set, while the remaining portfolio channels are categorised as inactive. For inactive channels, information is gathered for example with the purpose of identification of alternative reserve channels or more generally other active portfolios.

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[7] Despite the terminology used here, when spectrum resources refer to formally specified channels, all the guard channels that possibly need to be included to account for leakage (e.g., adjacent TV channels), as for example IEEE 802.22 categorisation does, should belong to the same category of the related main channel. For example, a spectrum portion affected by the use of an operating channel must be considered as (part of) an operating channel, even if not really in use.

Another viewpoint is related to *what* is the kind of the spectrum resource, from a transceiver perspective. The distinction in this case is between *in-band* and *out-of-band* channels, i.e, those in use at an opportunistic device and those not. The distinction is important because out-of-band sensing can be performed simultaneously with data reception, if the hardware allows it. On the contrary, in-band sensing and (in-band) data communication are, in general (see footnote on p. 60), not possible at the same time, and sensing needs to be scheduled properly.

Table 5. Channels for opportunistic spectrum use. Based on Leveil *et al.* (2010).

Channel	Description		
Operating	in use almost all the time or more rarely	active set	in-band
Reserve	may be used in the near future	active set	out-of-band
Inactive	of possible interest on a longer time scale	inactive set	out-of-band
Other	of no interest	inactive set	out-of-band

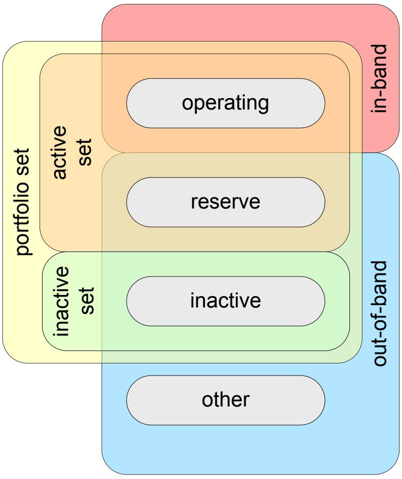

Fig 8. Taxonomy of channels for opportunistic spectrum use. Revised from Leveil *et al.* (2010).

The two above dichotomies (i.e., active/inactive and in-band/out-of-band), summarised in Table 5 do not coincide, as Fig. 8 shows.

Spectrum sensing requirements and configuration

As seen, spectrum sensing can be needed for detecting the presence of an incumbent user[8] in concurrence with opportunistic spectrum use, or for building or enriching a map or database used for opportunistic spectrum management. These two forms of spectrum sensing can be associated with two distinct cognitive domains described in Sect. 3.4.1. Nevertheless, spectrum sensing results can be shared between those domains, see Mange *et al.* (2011a, e.g.) and Fig. 20 and 21.

The implications of the different *channel* categories discussed above on spectrum sensing and the relationships between these categorisations are here commented. Depending on *why* the spectrum is sensed, the descending sensing requirements (e.g. required sensitivity) do have an impact on the sensing method and topology used (see sensing topologies in Sect. 3.4.2; sensing parameters are discussed here in the following). Requirements on sensing are tighter for operating channels than for reserve channels. However, for the entire active set, fast and up-to-date sensing is needed. Sensing for spectrum management support can be collected proactively before the actual use of the resource. This type of sensing does not need to be fast; therefore more precise (or otherwise more exhaustive) sensing schemes can be affordable.

For incumbent protection, the timely decision about the presence or absence of an incumbent in a spectrum portion is a requirement. Correspondingly, important parameters of the spectrum sensing are sensing result delivery latency and sensing reliability.

The *sensing result delivery latency* includes always the duration of the sensing measurement(s) at lower layers and the processing of the decision. Depending on the sensing topology (see Sect. 3.4.2), the contribution due to the exchange of commands and measurements to/from all involved devices and to the distribution of the decision to the requesting entity may be smaller or larger. *Sensing reliability* depends on the specific spectrum sensing method and algorithm used. Metrics related to spectrum sensing reliability can be probability of detection and probability of false alarm or derived/related metrics.

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[8] Potentially, an opportunistic transmitter creates interference at an incumbent *receiver*. The detection of a receiver is much more difficult than identifying the presence of a transmitter. Often, spectrum sensing has as target the detection of a transmitter. For the reason above, spectrum sensing is called by Liang *et al.* (2011) *indirect* when the target is the transmitter, where the term *direct* is used when the target is the receiver.

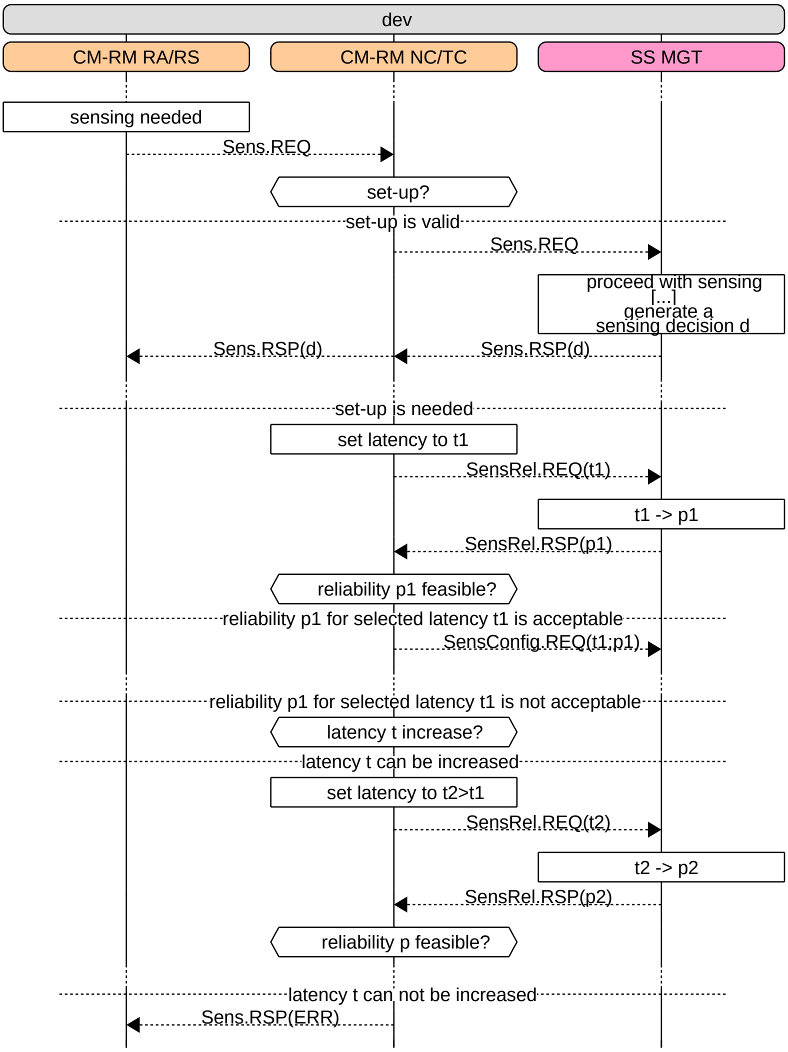

Fig 9. Example of sensing configuration negotiation. The functional blocks in the figure (the CM-RM blocks for resource allocation and resource control support, the network domain and terminal domain cognition blocks, and the spectrum sensing management block) are introduced in Sect. 3.4.2. For simplicity, the quantities referred to in the text as τ_s, d_s and p_{ss} are indicated in the figure as t, d and p, respectively.

Based on these parameters, proper settings (including method and algorithm) may be selected at the entities responsible for spectrum sensing. However, there may be trade-offs between sensing result delivery latency and sensing reliability and the selection of the most appropriate settings may imply negotiations. An example negotiation between a cognitive manager (CM) and the spectrum sensing block, may proceed through the following steps:

1. The CM issues a request to the SS with the latency constraint, τ_s;
2. The The SS may respond with the reliability p_{ss} that can be provided, corresponding to proper settings of the sensing method and algorithm that the SS would use;
3. The CM may do another attempt issuing a request with another latency value (e.g., $\tau_{s,2} > \tau_{s,1}$, corresponding now to $p_{ss,2}$), or the CM can accept the set-up;
4. The SS then proceeds by issuing the proper messages to set-up the sensing.

Fig. 9 shows first a sensing request and the reply with the corresponding sensing decision d_s. In need of set-up, the above configuration steps are illustrated (except for the last one, involving the SS and possibly the lower layers of the transceiver).

The specific CM block that triggers the process depends on the cognitive domain involved. For example, spectrum sensing could be needed for resource management and the process could start at network domain, thus involving a resource allocation (RA) and a network domain cognition (NC) block, or at terminal domain and going through a resource control support (RS) block and a terminal domain cognition (TC) block, depending on the sensing topology used (see Sect. 3.4.2) and the channel (operating/reserve) in question. See also Sect. 3.4.2 and Fig. 15 in particular.

2.2.4 Review of cognitive management architectures

The reference architecture developed by the FP7 QoSMOS project is used for illustration purposes in some parts of this and the following chapter. Here, a brief review of selected parts of it is provided, together with a comparison with related models (Celentano *et al.* 2011a) with regards to the issues touched in the aforementioned parts of this thesis.

The QoSMOS reference model

The QoSMOS project introduced its reference architecture for cognitive management. A complete presentation of this reference architecture can be found in sources cited below or e.g. in Celentano *et al.* (2011a), Mange *et al.* (2012b) and an overview of some parts of it is provided in the course of the previous Sect. 2.2.3. This section limits its scope to the way cognitive management is organised.

As seen, the QoSMOS reference architecture is based upon a two-tier cognitive management (Leveil *et al.* 2010), with a cognitive manager for resource management, CM-RM (Mange *et al.* 2011b), and a cognitive manager for spectrum management, CM-SM (Noack *et al.* 2011), having a shorter-term and a longer-term scope, respectively. These blocks are split according to the functionalities they incorporate and to the topological domain they pertain to. The partition of the CM-SM is outlined in Sect. 2.2.3, whereas the subdivision of the CM-RM is discussed in Sect. 3.4.2.

Comparison with related architectures

Some related architectures rely on a single cognitive manager, as is the case of the one proposed by FP7 ARAGORN project (Mähönen *et al.* 2010) – see also Mähönen *et al.* (2006) – in which a cognitive resource manager (CRM) embeds functionalities similar to those distributed among the above CM-RM and the CM-SM.

Other architectures, such as those developed by ETSI RRS (Dimitrakopoulos *et al.* 2009, Mueck *et al.* 2010, 2009), IEEE P1900, namely IEEE P1900.4 (Houze *et al.* 2009, Filin *et al.* 2010) and IEEE802.19.1 (Baykas 2010), discussed shortly below, assign functions to separate blocks. A comparison with those is shown in Fig. 10, where the functions are also mapped onto the topological domains defined in Sect. 3.4.2.

Although there is no precise correspondence of the respective blocks, roughly the CM-RM corresponds: to configuration control module (CCM) plus joint radio resource management (JRRM) of the ETSI RRS architecture; to the terminal reconfiguration manager, reconfiguration controller and measurement collector (TRM, TRC and TMC) and its network and radio access network (RAN) counterparts (NRM, RRC and RMC) of IEEE P1900.4; and to the coexistence enabler (CE) of IEEE802.19.1.

Similarly, the functionalities provided by the CM-SM are somehow equivalent approximately to: dynamic spectrum management (DSM) plus dynamic self-organising network planning and management (DSONPM) of ETSI RRS; to operator spectrum manager (OSM) of IEEE P1900.4; and to coexistence discovery and information server (CDIS) of IEEE802.19.1, but with coexistence manager (CM) spanning across both CM-RM and CM-SM. The IEEE P1900.4a for whitespace operation includes a cognitive base station RM, CBSRM (with CBSRC and CBSMC) and a whitespace manager

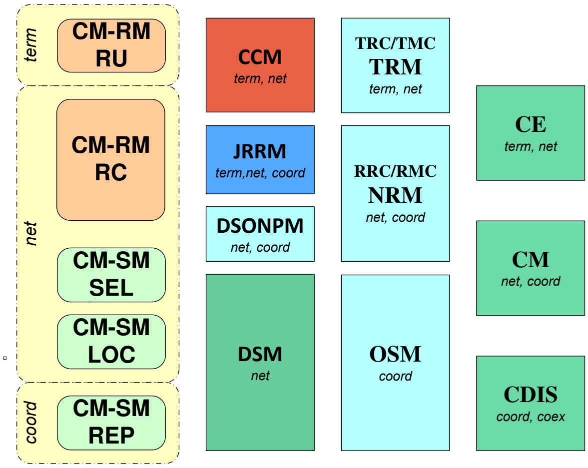

Fig 10. Comparison of scopes of functional blocks of QoSMOS functional architecture with, from left to right, ETSI RRS, IEEE P1900.4, and IEEE 802.19.1. Revised from Celentano *et al.* (2011a).

(WSM), equivalent to NRM and OSM, respectively, of IEEE P1900.4, but tailored for whitespace operation.

One comment, relevant to the discussion of flexible design coming in Sect. 3.4, is how those functional blocks map to the topological domains, specified in the section cited above. Indeed, ETSI RRS and IEEE P1900.4 architectures have been specified for specific applications primarily: the former mainly targets centrally controlled systems (3rd Generation Partnership Project, 3GPP, long-term evolution, LTE, but also emergency and defence systems) (Dimitrakopoulos *et al.* 2009, Mueck *et al.* 2010, 2009), whereas the latter envisages partial distributed control (Houze *et al.* 2009). This is reflected by the mapping; for example, the TRM of IEEE P1900.4, although assigned to a specific network device, covers duties (Houze *et al.* 2009) that pertain to both terminal and network domain as defined here.

2.3 Discussion

The scarcity of spectrum resources, or more generally an improved exploitation of them, calls for more flexible use models. The existing access paradigms are reviewed and rationalised in this chapter. Concurrent networks (Chapt. 3) are networks operating in relative vicinity and simultaneously with some form of interaction. One of them, concurrent spectrum use, is addressed in more details in the present chapter, where various access models are rationalised. The obvious related challenge is the basic requirement on incumbent protection and quality in the opportunistic (sub)system, and the chapter discusses how this can be supported, centring on gathering and communication of knowledge and context information. Architectural implications, were presented here, together with the relevant taxonomies, especially for the particular case of spectrum sharing and opportunistic spectrum use, which represents an important and realistic short-term application of cognitive networks concepts.

3 Concurrent and cognitive flexible networks design

> Of course, there will always be those who look only at technique, who ask *how*, while others of a more curious nature will ask *why*.
> – Man Ray (Èmmanuèl' Radnickij)

Spectrum sharing, covered in the previous chapter, is one form of interaction among networks. Other forms, such as those deriving from mobility or traffic are covered in the remainder of this dissertation. All these are grouped under the unifying concept of concurrent networks developed in Sect. 3.2, where their dynamics are studied. As seen throughout this monograph, cognitive features can be exploited in those cases, to properly reconfigure the network.

The ability to reconfigure a network relies on the possession of corresponding functionalities, which sometimes need to be located at different places (network devices) of the system. Special attention is granted here to the network devices those functionalities are located at, so that the flexibility of the system can be brought up to its design. This shows how the same architecture can be exploited in different use-case scenarios, including an improved support for future use-cases, approach applicable also to communication networks in general. To this end, the concept of topological domains is introduced.

3.1 Introduction

This chapter is made of three parts. Concurrent networks are defined in Sect. 3.2, where their dynamics and related QoS management are studied. Sect. 3.3 derives a definition for cognitive networks adopted in this work. Cognitive entities are then more generally treated in Chapt. 4 and cognitive systems are categorised is Sect. 4.2.2. Finally, Sect. 3.4 provides a digression on decision-making in the special application-case of cognitive networks of Chapt. 2 and then generalises and widens the scope to define the topological domains used to bring flexibility in the network design.

3.2 Concurrent networks

Networks operating in the same area, in relative proximity, or neighbouring, using simultaneously the same spectrum resources are here referred to with the term coexisting networks. Concurrent networks include so-called coexisting networks, i.e., operating in the same geographical area, simultaneously, and using the same spectrum resources. Coexisting networks interact therefore with potential or controlled interference. Examples include, respectively, colliding networks or network operating below the noise floor (underlay operation, see Sect. 2.2), e.g., using ultra-wideband technology.

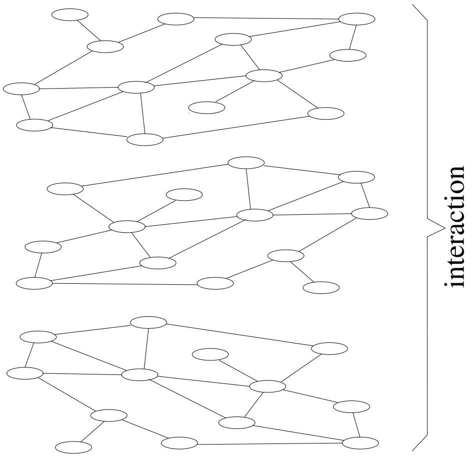

Fig 11. Concurrent networks operate in relative vicinity and simultaneously with some form of interaction. The various forms of interaction are explained in the text.

When resources are instantaneously used exclusively, resources from a set are shared among players according to rules and/or negotiations. In this case, the interaction is in spectrum. Examples include negotiations among operators, interaction between incumbent and opportunistic users (Sect. 2.2), the latter sometimes referred to as secondary users, joining/merging of networks (see discussion in Sect. 5.3.5), etc. Interaction as effect of negotiations is direct, whereas the above interference case can be regarded as a form of indirect spectrum interaction. When users move or are moved (either physically or virtually) from one network to another, the interaction is in traffic. Also in this case, interaction can be indirect, if following physical users' mobility (e.g., following daily or weekly time patterns), or direct, when users are moved from one network to another, as in the case of the spectrum mobility discussed in Sect. 3.2.1, or simply moved out, as in Sect. 5.4.1.

As seen, networks can operate in different spectrum portions but still be linked by some kind of interaction, see summary in Table 6. All these, together with the earlier coexisting networks are here referred to as *concurrent networks* (Fig. 11). Concurrent networks, may operate in the same area and simultaneously, but due to various forms of interactions they do not necessarily interfere at all or all the time[9]. A particular case of concurrent networks is the interaction between an incumbent and an opportunistic network. As seen in Sect. 2.2, different forms of spectrum sharing are associated with different forms of interaction.

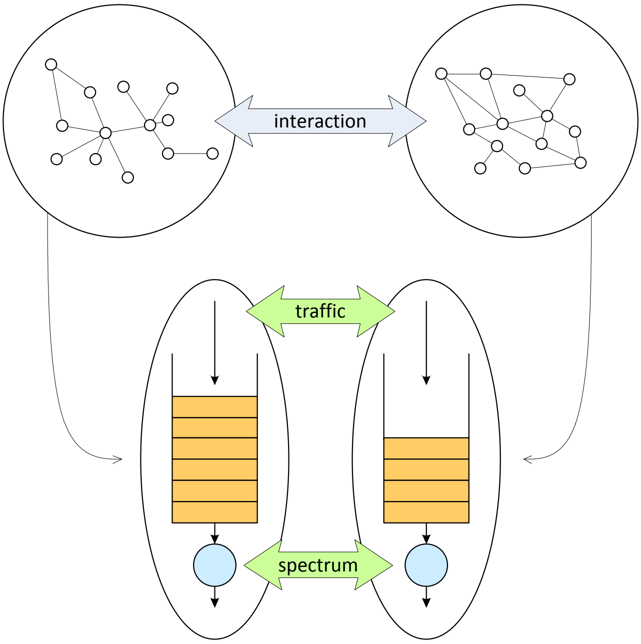

Fig 12. Concurrent networks with spectrum and traffic interaction.

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[9] This differs from the concurrent spectrum access term used by Liang *et al.* (2011) for a controlled interfering condition, denoted here as underlay spectrum sharing, see Sect. 2.2.1. Another term for them could be conflicting networks.

Table 6. Examples of interactions between concurrent networks.

Interaction		Example
In spectrum	direct	spectrum sharing with rules or negotiations
	indirect	interference
In traffic	direct	spectrum mobility or similar forced actions
	indirect	physical (user) mobility or activity

For example in the cellular case, negotiations may occur among operators. However, especially when pricing comes into the scene, actors may directly include also end-users (decisions based on rate, quality, etc.). Interactions occur therefore both at resource use and possibly also at input traffic, see Fig. 12.

As seen, particular cases of concurrent networks include spectrum sharing and opportunistic spectrum use.

3.2.1 Dynamics in concurrent networks

Dynamics in concurrent networks has various forms. Depending on its specificities, it poses specific challenges to the system. Some of them are covered in this chapter and in Sect. 5.4.

The *physical mobility* of a network node has impacts at lower layers (e.g., due to fading and Doppler spread) as well as at upper layers (e.g., variable effective capacity, delays and topology). The latter are more relevant to this thesis (for example, for effective capacity, see Sect. 6.2).

Peculiar to opportunistic networks is the need to support in them the eviction from the currently used resource upon appearance of an incumbent user. This *spectrum mobility* may occur also with physically static devices. Despite being caused by different triggers and therefore being characterised by different temporal patterns, for example, some of the required functionalities needed for physical mobility support can be used also to support spectrum mobility: in both cases the maintenance of the service while moving it from one site to another is needed, as it has to be managed the appearance of new devices at the new site. However, even physical mobility only brings new challenges for a cognitive network. For example, the context acquired at certain time and location may no longer be relevant and valid at the new reached location. This is taken into consideration by regulations by imposing requirements in both time and space concerning context acquisition, see Sect. 2.2.2.

Other forms of dynamics in the time domain include the previously mentioned changes in the activity (of user or application, hence traffic) and the management of hibernating devices, i.e., devices going or put into a lower activity mode. Some related issues are discussed in Chapt. 5.

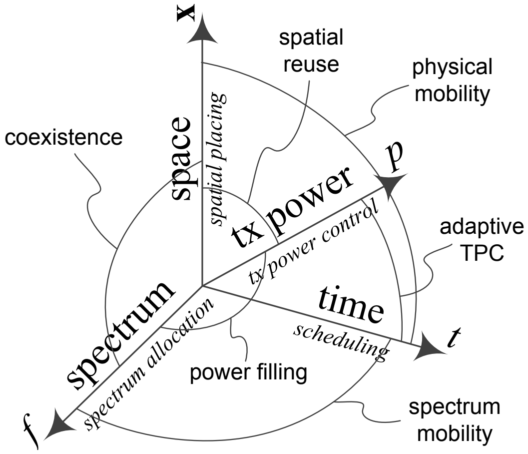

Fig 13. The domains of dynamics in concurrent mobile networks in a four-dimensional space with old and new implications. Scheduling, transmit power control, spatial planning and spectrum allocation problems are given by fixed $(\mathbf{x},f,p)$, $(t,\mathbf{x},f)$, (t,f,p) and $(t,\mathbf{x},p)$, respectively. On the other hand, phenomena involved when moving on the $(t,\mathbf{x})$, $(\mathbf{x},f)$, (t,f), (t,p), $(\mathbf{x},p)$ or (f,p) planes are physical mobility, coexistence, spectrum mobility, adaptive transmit power control, spatial reuse or power filling, respectively.

Fig. 13 illustrates the domains of dynamics in concurrent mobile networks in a four-dimensional space. The axis are time t, spatial position $\mathbf{x}$, spectrum f and transmit power p_{tx}, referred to in the figure as p for simplicity. Problems or phenomena like physical mobility, spectrum mobility, adaptive transmit power control, spatial reuse or networks planning are identified by fixing one or more quantities and working in the corresponding subspace.

Obviously, the above system dynamics have an impact on the experienced level of the quality of service, and for concurrent networks this applies to all the involved players. These aspects are covered in Sect. 3.2.2.

3.2.2 Quality of service in concurrent networks

The scope of communication systems is to deliver information from a source to a destination. It is clear that the usability of the information delivered to the destination is crucial. For example, a remote-control command must arrive in time and not corrupted, whereas an interactive message must satisfy the user's needs, otherwise, the cost of delivery and the utilisation or resources, including energy, for the scope is vain. Resource allocation must be done properly in order to exploit the resources without wasting them. QoS support techniques are needed to exploit at best scarce shared resources in presence of heterogeneities in the system. In fact, when resources (spectrum, processing) are abundant, all services can receive the service they expect, without any additional effort. Even with scarce resources, there is no need of sophisticated schemes – the need of QoS arises as networks are loaded by different types of traffic or more networks with different levels of importance or rights are sharing the same resources. When the network is loaded by homogeneous traffic, there is no need of particular scheduling schemes, since simple fair disciplines like first-come, first-served (FCFS) and round-robin perform just well, with the possible limitations. As resources become scarce and some services or systems are more important (in some sense), they must be served better. Indeed, by using QoS support techniques, networks can be optimised so that they are efficiently utilised whilst achieving the various needs.

Legacy QoS models

Historically, quality of service has been used in relation to specification of requirements and constraints for applications such as voice and video. QoS management and related traffic classes are specified in ATM (1988) and in IEEE 802.1p (1997), later incorporated in a revision (1998) of IEEE 802.1D standard, originally published in 1993 and further revised in 2004. QoS classes belong to two major groups: those whose carried information becomes useless after a certain maximum tolerable delay, called real-time applications in the ATM model and inelastic applications in the Internet model, whereas those whose carried information is useful regardless of the delay, though if smaller delays may be beneficial, are called non-real-time applications and elastic applications, respectively.

Implementation of QoS support follows two main approaches: absolute and relative QoS provisioning (Chua *et al.* 2007). Absolute QoS refers to quantitative service guarantees to traffic classes, which implies the existence of hard limits the performance metrics must be kept in. Relative QoS refers to offering relatively better service to privileged services over others, by traffic differentiation and without specifying guarantees or performance bounds. The former view is followed for example in the integrated services architecture IntServ (Braden *et al.* 1994, Seaman *et al.* 2000), whereas the latter is followed in the differentiated services architecture DiffServ (Blake *et al.* 1998), both proposed within the IETF.

While delay-intolerant applications may be loss-tolerant (e.g., voice or video) or loss-intolerant (e.g., remote control), loss-intolerant applications (e.g., file transfer) have been typically considered delay-tolerant. Nowadays, those application are also becoming delay-sensitive: (many) seconds of delay are no longer acceptable by users in a number of cases. Quality of service constraints should be therefore applied to almost all supported services, obviously taking into account the context and with different values for the requirement parameters, including priorities. Indeed, quality of service can be defined as done by the Telecommunication Standardization Sector of the International Telecommunication Union (ITU-T) as (ITU-T 2002):

> “the collective effect of service performances which determine the degree of satisfaction of a user of the service”.

A look at the entire ecosystem

Quality of service in concurrent networks, for example in conjunction with opportunistic spectrum use and more generally in presence of shared resources is seen here in the bigger picture of *dependability* of the entire ecosystem.

In an opportunistic system, resources are shared between incumbent and opportunistic users but also among opportunistic users, scenarios sometimes referred to as vertical and horizontal sharing, respectively (Kruys 2009). On one hand, *integrity* of the incumbent service must be guaranteed regardless of the operations of opportunistic users. On the other hand, *reliability* of the service provided to opportunistic users should be pursued even in presence of possible interruptions caused by the presence of incumbents. Together with the two aforementioned, other primary and secondary attributes of dependability (Eusgeld & Freiling 2008, Avižienis *et al.* 2004), availability, safety, confidentiality and robustness, are touched, with different deepness, also in the following chapters.

A dependable system not necessarily is completely faultless. According to Avižienis *et al.* (2004),

> “dependability of a system is the ability to avoid service failures that are more frequent and more severe than is acceptable”.

Applied to our case, this means that the protection of (all) incumbent users may not necessarily be a hard constraint in every case. Indeed, performance degradation for incumbent users has been considered for potential trade-off with the performance of the opportunistic users (Pawełczak *et al.* 2008). The above mentioned problems of incumbent integrity and opportunistic reliability can in this case be jointly addressed for example by considering the incumbent users as a special QoS class, with the QoS management moving from an absolute to a relative model.

Consider the entire ecosystem $\mathscr{E}$ involved. An ecosystem can be represented by a telecommunication service provider possibly managing or influencing, either directly or indirectly, both incumbent and opportunistic users. Another example of ecosystem is the combination of a public or safety service and a concurrent telecommunication network.

In both the above examples and in more general cases, two subsets of systems or users $\mathscr{A} \subseteq \mathscr{E}$ and $\mathscr{B} \subseteq \mathscr{E}$, $\mathscr{E} = \mathscr{A} \cup \mathscr{B}$, $\mathscr{A} \cap \mathscr{B} = \emptyset$, are defined. The global utility may be modelled as: $u_{\mathscr{E}} = c_{\mathscr{A}}(\mathbf{u}_{\mathscr{A}}) + c_{\mathscr{B}}(\mathbf{u}_{\mathscr{B}})$, where $\mathbf{u}_{\mathscr{A}}$ and $\mathbf{u}_{\mathscr{B}}$ are the vectors of user utilities. When considering the global utility of concurrent networks, it is clear that the significance of users to the ecosystem must be considered. This significance may be intrinsic in the user type, dictated by economics[10] or by other ecosystem issues (like in Sect. 5.4.1). To take this into account, the global utility may be modelled as a weighted sum of the utilities per user over all the elements of the ecosystem: $u_{\mathscr{E}} = \mathbf{w}_{\mathscr{A}}\mathbf{u}_{\mathscr{A}} + \mathbf{w}_{\mathscr{B}}\mathbf{u}_{\mathscr{B}}$

When focusing on one of the subsets, the influence on it from the other can be beneficial or disruptive, and consequently to the definitions of the subsets, the weights in a subset can take all the same sign. The weights for $\mathscr{A}$ can be taken positive. For $\mathscr{B}$, they can be positive in a scenario in which $\mathscr{A}$ and $\mathscr{B}$ are co-operating/collaborating, or negative when they collide (e.g., interfere). In any case, the magnitude of the weight represents how much the intervention of another type of user is beneficial or detrimental.

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[10] Where a number of considerations is to be taken into account (Nguyen *et al.* 2011, e.g.).

The utility at the user in general is a function of performance and efficiency metrics (e.g., QoS metrics such as goodput or delay, energy-related indicators like the consumption rate of the residual energy, etc.) as well as of the price paid. At the network domain, the utility includes for example the revenue from the provided service (e.g., the income coming from a user minus the cost of the resources allocated to that user) the transmit power allocations, etc. All the above metrics are functions of the allocated resources.

Utility functions are often assumed monotonically increasing and with a decreasing marginal utility. When the utility is a function of the allocated spectrum and for the former of the above examples, it intuitively follows that it may be beneficial to a service provider to (re)sell or lease its resources (decrease $u_{\mathscr{A}}$ and increase $u_{\mathscr{B}}$). This is one of the options of spectrum sharing investigated in Sect. 2.2, where total QoS is addressed in more details.

3.3 Cognitive networks

While opportunistic spectrum use, which has as goal to cope with spectrum scarcity, is just one, although important, application of them, as outlined in Chapt. 1 and reminded in Sect. 2.1, the targets of cognitive networks also include addressing other issues such as energy efficiency – which also impacts positively on environment and profitability – and flexible networking – to enforce other dependability measures, including safety, and, in the end, to enhance user experience. In a word, cognitive networks are a means to improve networks operation in general.

According to the Radiocommunication Sector of the International Telecommunication Union (ITU-R), an adaptive system is a “radiocommunication system which varies its radio characteristics according to channel quality” (ITU 2012). Cognitive networks can be regarded as an enhancement of adaptive systems, in both the used triggers and the controlled targets. All exploit, at different levels, their awareness or the environment: in order to achieve or approach the targeted goals, they perceive the context they operate within, gain knowledge from those observations and act accordingly.

In the rest of this section, definitions related to cognitive networks are discussed. The cognitive process behind is the subject of Chapt. 4, where also a novel model for networked cognitive entities is proposed.

3.3.1 Related concepts

The complexity of systems in ICT is growing and ways of dealing with it are searched. With the scope of self-management (configuration, optimisation, healing and protection), the approach selected for *autonomic computing* is to get inspired by the human nervous system that allows control without *conscious* intervention (Kephart & Chess 2003). Autonomic computing is a first step to simplify complex information-technology systems (Dobson *et al.* 2006). *Autonomic communications* add self-organisation, i.e., the capability to also evolve without external intervention. Both the above concepts are also considered together, as autonomic communications and computing (Boutaba *et al.* 2005, Peddemors *et al.* 2005). From the same concept, also stem autonomic network management (Samaan & Karmouch 2009). The autonomic manager is discussed in Sect. 4.4.2, where is covered the related work on cognitive process modelling.

To manage complex networking systems, so that networked elements are capable of self-managing, self-configuring and self-regulating, and of working totally unsupervised, with co-operation among them encouraged, control is distributed (Dobson *et al.* 2006). As Saracco (2003) observed, intelligence of the network is drifting towards its edge and into terminals. In other words, self-governing systems are regarded as a further step from centralised to distributed (Leibnitz *et al.* 2007). As seen, these distributed systems are inspired by organisation of complex natural systems (Bicocchi & Zambonelli 2007): molecular processes, artificial immune systems, evolutionary systems, swarm intelligence (ant-colony optimisation, etc.) (Leibnitz *et al.* 2007). However, Bicocchi & Zambonelli (2007) commented that “reverse-engineering” of natural systems does not provide straightforward mapping onto networks. The above concepts of self-configuration, self-optimisation and self-healing are brought by the 3GPP to LTE as self-organising networks (SON) capabilities (ETSI 2011).

Dobson *et al.* (2006) put under the umbrella of autonomic communications the concept of cognitive packet networks. Cognitive packet networks (Gelenbe *et al.* 2004) are thought to be integrated in the Internet to offer adaptive quality of service (QoS). To achieve the goal, smart packets are used to collect measurements. Related to both the idea of using the packets flowing into a network as a tool, and the distribution of control is the concept of *active networks*, which envisages routers working up to application layer and code injected by users through packets (Tennenhouse *et al.* 1997). The above cognitive packet networks differ here in that the network is not programmable by packets (end-users) to reduce security risks (Gelenbe *et al.* 2004).

Clark *et al.* (2003) propose a distributed cognitive system permeating the Internet called *knowledge plane*, able to learn (accumulate knowledge) and reason (infer and interpret). This complements the information provided by control plane and data plane and aims at combining and carrying information from the edges as well as from inside of the network. A more conservative approach is followed by Strassner (2007), who adds an *inference plane* having the role of aiding the management plane with cognitive functions.

A *software-defined radio* is a radio capable of operating over multiple air interfaces and protocols and controlled, whenever possible and beneficial, by a software running on general-purpose processors (Mitola 1999). *Cognitive radios*, term coined by Mitola at MITRE Corp. and Royal Institute of Technology KTH (Kungliga Tekniska Högskolan), exploit the software-defined radio concept but have a broader scope. A cognitive radio is a radio employing model-based reasoning and using a cognitive cycle (Mitola 1999). This cognitive cycle, with main phases being *observe*, *orient*, *plan*, *decide*, *act* as well as *learn*, is discussed in Sect. 4.4.2.

The concept of cognitive radio has been extended to *cognitive networks* by Mähönen (2004) at the RWTH (Rheinisch-Westfälische Technische Hochschule) Aachen University, leaning on the knowledge plane concept, and by Thomas *et al.* (2005) at the Virginia Polytechnic Institute and State University (Virginia Tech), see also Thomas *et al.* (2006). Broadening the scope from a single radio or link and considering an entire network, the latter authors emphasise that a cognitive network is not (necessarily) a network of cognitive radios, and also abstract from the access technology that is not restricted to wireless. The cognitive network defined by Thomas *et al.* (2005), relies upon a software-adaptable network, corresponding to the role SDR has in the context of cognitive radios. Doyle & Forde (2007) model the cognitive process involved in cognitive ad hoc networks applying the cited Mitola's cognitive cycle to the entire system. A different approach is followed in the model proposed in Sect. 4.4.3.

Example applications of cognitive networks

As outlined in Sect. 1.1.2, applications envisaged for cognitive radio networks include smart grids, public safety networks, cellular networks and healthcare applications (Wang *et al.* 2011). Cognitive features can be exploited to improve QoS support and security and in heterogeneous networks (Thomas *et al.* 2005), such as the IoT, see Sect. 5.1.

Due to the awarding of the so-called digital dividend (Ofcom 2007), opportunistic spectrum use in one important application of cognitive radios ad cognitive networks. Various issues concern resource management in cognitive networks (Akyildiz *et al.* 2008, e.g.). Some of them are addressed in this chapter, together with a look at the functionalities cognitive network devices may need to include. Nevertheless, the scope of cognitive networks is not limited to flexible spectrum use only, as seen above.

3.3.2 Cognitive networks and their definition

Cognitive communication networks are approached more closely from now and defining some terms is appropriated here. A related discussion, focusing more on learning and with a categorisation of cognitive networks, is present in Chapt. 4 (Sect. 4.1 and 4.2).

Background

According to the Oxford English Dictionary (OED 2012a), cognition is

> "The action or faculty of knowing taken in its widest sense, including sensation, perception, conception, etc., as distinguished from feeling and volition.".

Encyclopædia Britannica (2012a) defines cognition as

> "The process involved in knowing, or the act of knowing, which in its completeness includes perception and judgment. Cognition includes all processes of consciousness by which knowledge is accumulated, such as perceiving, recognizing, conceiving, and reasoning. Put differently, cognition is an experience of knowing that can be distinguished from an experience of feeling or willing."

whereas for Enciclopedia Treccani (2012) the cognitive process is the

> "Process through which a system acquires information on the environment and process it as knowledge in function of its own behaviour (perception, imagination, problem-solving)."

In all the above definitions we can recognise cognition as a derivation of conclusions based on perception, or, so to say, adaptation depending on experience. This can indeed be regarded as learning in its general meaning. Nonetheless, a cognitive radio system is defined by ITU-R (2009) as

> “A radio system employing technology that allows the system to obtain knowledge of its operational and geographical environment, established policies and its internal state; to dynamically and autonomously adjust its operational parameters and protocols according to its obtained knowledge in order to achieve predefined objectives; and to learn from the results obtained.”

Albus (1991) defines intelligence as the ability to act in an uncertain environment to increase the success probability in the achievement of a goal, with learning being an optional feature capable of increasing the intelligence itself by experience. Langley *et al.* (2009) consider strictly required capabilities only recognition and decision-making. A few other definitions are reported by Neel (2006).

Comparing all these definitions, it appears that awareness of the environment is indicated as a peculiar feature, but learning is not always explicitly mentioned. The environment includes the entity’s own internal state. In particular, as Thomas *et al.* (2005, 2006) note, within the scope of cognitive networks also fall cross-layer design ideas, so that context information from and actions to more layers is also exploited.

Definition

In this thesis, the term cognitive network refers to a network capable of adaptation, exploiting internal and external environment awareness and with possibly some level of learning, even if very simple[11]. To this end, a cognitive device is therefore capable of perceiving and understanding the context (awareness). It is also able to decide (decision-making), to (re)act (adaptation) and (possibly) to learn. (On learning and its levels, see Sect. 4.2.) Examples of the environmental context a communication device or a network operates in, such as those considered in this chapter, Chapt. 5 and 6, may include a metric of signal quality, the presence of a signal or of a network device, relative distance and relative and absolute position, service requirements and QoS, buffer occupation and delay, or residual energy level. Actions may happen at any device or at

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[11] When all the previous properties are present but there is lack of learning, i.e., in presence of memory-less adaptation, Thomas *et al.* (2006) categorise this as simple cross-layer design. More exactly, according to these authors, one of the main advantage of learning is not limited to the generation of the best decision, but it resides in the possibility to support *proactive* instead of just *reactive* behaviour.

any protocol layer and targets for it include for example efficiency (spectrum, energy, etc.), robustness, service performance, etc. Clearly, a cognitive system may possess a range of levels of cognition, as Albus (1991) has suggested for intelligent systems and Mitola (2000) for cognition tasks.

Adapting [12] those given by Haykin (2005), Jondral (2005) and Thomas *et al.* (2006), a definition of cognitive network, and cognitive device in square brackets, adopted here is:

> A cognitive network [or device] is a reconfigurable network [or device] aware of its environment, capable of understanding it, adapting its parameters and configuration, learning at some level from past perceptions (possibly including the effects of own actions), to achieve a goal[, and of exchanging information and commands].

Various cognitive levels (see Sect. 4.2.2) depend on presence and complexity of capabilities such as perception, interaction, processing and learning capabilities. A model for a cognitive entity is presented in Sect. 4.4.

3.4 Cognitive and topological domains

The flexible communication networks subject of this dissertation are able to adapt according to the changes of the operating environment and of the own internal status. System specifications are often tailored for a specific application scenario. While this has obvious advantages, it also brings rigidity to the system and its applicability to different scenarios is not always possible or it is not efficient. The flexibility of the system can be brought at a further level, where the design itself of the network is made exploitable over a wider range of application scenarios. Among the applications of cognitive communication networks, opportunistic spectrum access is an important and short-term one, and this is why it is taken as an example in this chapter. Nevertheless, the present considerations, and especially those regarding the topological domains, are mostly applicable also to other kinds of cognitive networks or even common communication networks.

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[12] The word *surrounding/outside*, given in Haykin (2005), is left out since, in this definition, awareness covers both network's and device's own environment, which is what Mitola (2000) calls self-awareness. Examples are QoS requirements of local traffic, buffer occupation, residual energy, connectivity, etc. Moreover, the scope is extended here beyond spectrum sharing use (see also the following chapters). For this reason, to the term cognitive user, sometimes used in the literature in this context, opportunistic user is preferred here.

Sect. 3.4.1 provides a rationalisation of the cognitive domains specific for opportunistic communication networks, whereas Sect. 3.4.2 defines the topological domains exploitable for flexible system design. Again, without loss of generality, opportunistic communication networks are taken as an illustrative example.

3.4.1 Decision-making and cognitive domains

Ensuring a controlled level of quality of service to opportunistic users requires an appropriate resource management. Ensuring proper coexistence of the involved players implies a corresponding spectrum management. These cognitive domains are used in the functional architecture defined in the cited FP7 project QoSMOS, which adopts a two-tier cognitive manager (see Sect. 2.2.4). When considering also the context sensing that aids the above functionalities, it can be seen that the decision-making spans over three tiers.

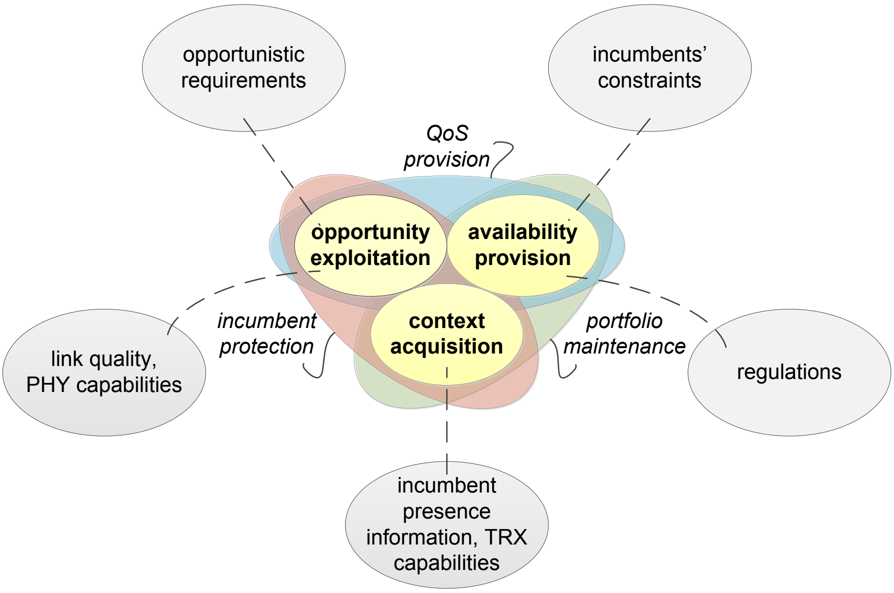

Fig 14. Decision-making in cognitive spectrum access, at the centre, their interactions, and the environmental context.

Fig. 14 shows the three cognitive domains, summarised in Table 7, and some of their interactions. The opportunity exploitation domain is in this example in charge of resource management, the availability provision domain is here responsible for spectrum management, and context acquisition domain also gathers other capabilities, e.g. from the transceiver (TRX).

With reference to Fig. 14, context acquisition may provide spectrum management with the knowledge of the radio scene in order to let it capable of maintaining an enhanced spectrum portfolio information. Sect. 2.2.2 discussed the major options for context acquisition relevant in this case. Context acquisition may provide resource management with the radio context information required to ensure protection of the incumbent users. The combined interaction of resource management and spectrum management targets the satisfaction of QoS requirements of opportunistic users whilst guaranteeing the observance of the mandatory incumbent protection constraints.

Table 7. Cognitive domains and their roles.

Cognitive domain	Role	Stimuli
Opportunity exploitation	applies various levels of cognitive methods for efficient use of deployed spectrum resources (resource management)	based on: resource availability; QoS requirements; radio context; network load; link quality; TRX capabilities; spatial position
Availability provision	applies various levels of cognitive methods for efficient deployment of spectrum resources (spectrum management)	based on: regulations and policies; performance and usage reports; radio context; spatial position
Context sensing	applies various levels of cognitive methods in order to provide knowledge of the radio scene (spectrum sensing)	based on: measurements; service constraints; target signals

The context these cognitive entities operate with is constituted by the perceived stimuli and the information they provide and exchange (the aspect of networked cognitive entities is addressed under a more general perspective in Sect. 4.4.3, where a related model is proposed). In this particular example, the context includes quantities and structures needed to enforce incumbent user protection, ensure opportunistic QoS and mobility support, and provide the above functionalities.

3.4.2 Topological domains and mapping

For a flexible (reusable) system design, the system functional blocks should be located at the network device these functionalities pertain, irrespective of the other characteristics a device may posses. When the system design is done partitioning the system functionalities according to the role, it is made possible realising systems with diverse characteristics from the same architecture. Reusing its protocols may allow reduction of design costs over a range of use-cases. One tool for this is represented by the introduction of topological domains (Celentano *et al.* 2011a). The following four topological domains can be defined.

- The *terminal domain* (TERM) covers entities at the wireless *border* and it is thus associated with the radio at a user equipment or mobile node and at a base station or access point, for example.
- The *network domain* (NET) is the place in which reside those entities in charge of the control of lower hierarchical level entities within an interconnected network (e.g., a network or cell).
- The *co-ordination domain* (COORD) includes the entities responsible for the co-ordination of neighbouring and related networks.
- The *coexistence domain* (COEX) is associated with the entities responsible for larger-scale coexistence.

Table 8. Topological domains and their roles.

Topological domain	Example roles
Terminal domain	data transmission and reception, resource use, support to resource control, terminal-domain cognition, measurements
Network domain	resource control, decision using multiple measurements, network-domain cognition, local policies
Co-ordination domain	networks co-ordination, spectrum trading, access to external repositories
Coexistence domain	regulatory repositories, common repositories (portfolio, providers)

Example roles of the above domains are summarised in Table 8 and their use is then presented with examples in the following[13]. Fundamentally, cognitive functionalities

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[13] Loosely related concepts are the node-level (or unilateral) and network-level (or multi-lateral) cognitive processing in Doyle & Forde (2007). The approach followed for the two categorisations is different, coming

are defined depending on the topological domain they refer to instead of assigning them directly to a specific network node, such a base station or a user equipment. The functional blocks defined for a topological domain are assigned to a network node only in a second step, and only at this time depending on the topology a specific scenario assumes.

Resource control topologies

A communication network may exhibit a centralised resource control (RCC), normally used in cellular networks, for example, or a distributed resource control (RCD) topology (also called flat, which can be single or multiple hop), with hybrid alternatives in between, sometimes (Jurdak *et al.* 2004, e.g.) referred to as decentralised, semi-distributed or clustered. The discussion about those, further continues from a different viewpoint in Sect. 5.3.2.

It is appropriate to separate the cognitive functions for resource management according to the distinct topological domains (Fig. 15; see also Table 8). At the terminal domain occurs the resource use (RU), i.e, the actual exploitation of the resources to provide upper layers (ULYR; application at a UE, or transport at the CN) with the service, whereas the resource control (RC) belongs to the network domain. Fig. 15 also shows the internals of the cognitive manager. The blocks emphasised with thicker frame are those in charge of resource allocation (RA) and resource control support (RS), as well as those for network domain cognition (NC) and terminal domain cognition (TC), used for the example in Sect. 2.2.3 (Fig. 9). A full description of the internal blocks[14] is out of scope here, where the emphasis is on the domain split, but can be found in Leveil *et al.* (2012), Anouar *et al.* (2012).

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from a different scope. In order to be able to understand the wisdom of crowds, Doyle & Forde (2007) discuss the mapping of the phases of the cognitive cycle proposed by Mitola (2000) to the network, making use of a two-level cognition scheme. In the present categorisation, the functionalities of network devices are organised over four topological domains, in order to enforce flexibility in the system design. The way a networked cognitive entity is thought and modelled is also different, and is illustrated in Chapt. 4.

[14] Namely, in addition to the other mentioned here, the remaining blocks appearing in Fig. 15 are access control (AC), mobility control (MC) and resource exploitation (RE).

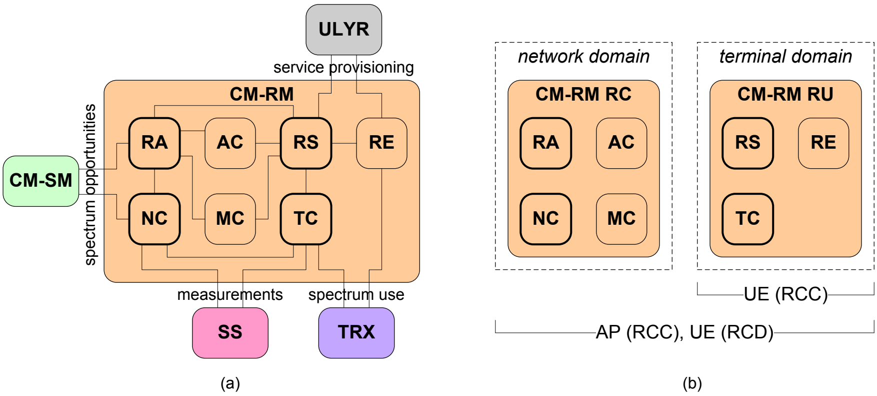

Fig 15. Cognitive resource management and topology mapping. The internal functional blocks (a) are divided into those pertaining to the network and terminal topological domains (b), responsible of resource control and resource use, respectively. For example, a base station or access point (under centralised resource control) includes both domains, whereas the corresponding user equipment is limited to the terminal domain. With distributed resource control, all peers cover both domains. Revised from Leveil *et al.* (2012).

Spectrum sensing topologies

Also spectrum sensing functions can be split according to the topological domains. In fact, centralised (SSC) and distributed (SSD) spectrum sensing topologies may be used, along with a local spectrum sensing (SSL) alternative; all these are described shortly below, together with the corresponding mapping of the internal functional blocks. Two macro-blocks can be defined. The spectrum sensing management (MGT) is in charge of generating a decision about the radio context, such as the presence or not of an incumbent, whereas the sensor[15] control (SCTRL) is assigned to a separate functional block, having the task of controlling the actual measurements. The related aspect of the configuration of the spectrum sensing service has been discussed in Sect. 2.2.3. Differently from resource control, for spectrum sensing the terminology is not univocal. For this reason, a brief digression on this is provided in the following.

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[15] The term sensor is used in the context of spectrum sensing with the meaning of a device in charge of spectrum sensing measurements. This is not (necessarily) a member of what is commonly known as a wireless sensor network.

Different sensing topologies are possible and a recent survey of them is given in (Yücek & Arslan 2009, e.g.). In opportunistic communication systems, spectrum sensing may be duty of opportunistic communication devices themselves or alternatively assigned to devices dedicated to this. These options are referred to as internal and external sensing, respectively. External sensing may improve the communication device's efficiency from both communication (reduced overhead) and energy perspectives. Also, it can overcome the lack of sensors in scarcely populated areas. In what follows, the focus is on topological aspects of the spectrum sensing. This means that despite the above efficiency considerations, signalling and topology aspects are similar for both internal and external sensing. In other words, the only difference is in the type of device performing the sensing and possibly on the placement of those sensors in the network (mobile vs. fixed, location, etc.). Different physical channels may be used, though.

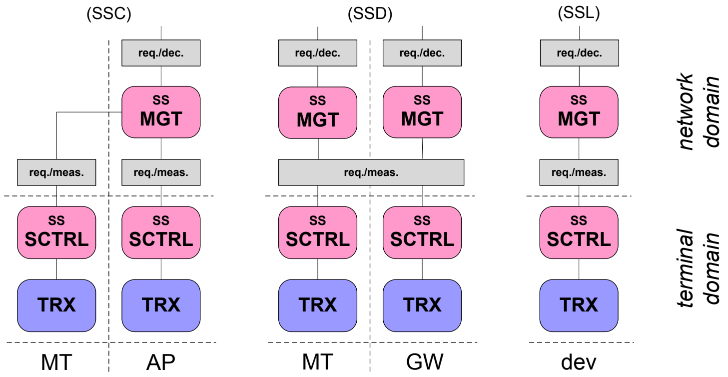

Fig 16. Centralised, distributed and local spectrum sensing topologies and their mapping to a generic device, a mobile terminal, a base station or a gateway device. Revised from Celentano *et al.* (2012).

The following three sensing topologies, illustrated in Fig. 16, are identified. Further insight is provided by the message sequence charts in Fig. 17 and Fig. 18.

With *local* sensing, the opportunistic node (for example a mobile terminal or a base station), performs sensing and also generates the decision. The sensing request proceeds down from the MGT block to the SCTRL, which then provides its measurement(s) by interfacing the lower layers of the transceiver. Once the measurements reach the MGT, it can generate a decision, often Boolean, about the radio context. In SSL, The entire process takes place at a single device.

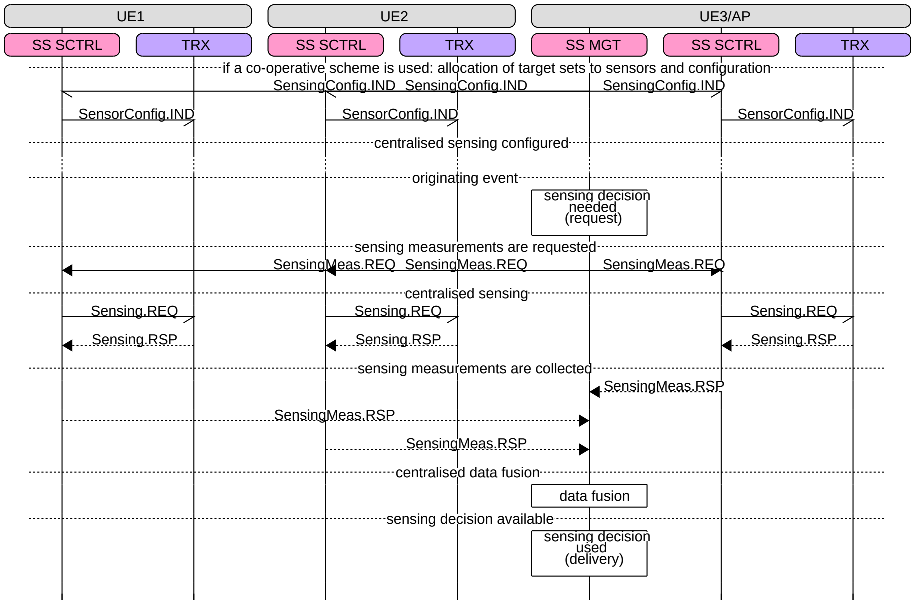

Fig 17. Centralised spectrum sensing. Revised from Leveil *et al.* (2010), Celentano *et al.* (2012).

In the case of *centralised* sensing, the scattered sensing nodes (they could be user equipments in a cellular scenario) provide the sensing measurements, which are then gathered by a central device (naturally located at the base station in the previous example), which then generates a sensing decision based on those measurements. Depending on the allocation of sensing duties to the sensors, centralised sensing may have a collaborative or a co-operative nature[16]. With centralised collaborative sensing, the individual measurement outcomes are different instances of the same measurement. The scope is to mitigate the hidden incumbent problem and to compensate for the effects of noise, fading and shadowing, thus improving the sensing reliability. With centralised co-operative sensing, the individual measurement outcomes are complementary, i.e., the sensor nodes do not measure the same set of targets (e.g., channels or incumbent). This helps reducing the overhead (sensing and communication) on individual sensing nodes, but with no gain in diversity.

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[16] Although in normal language the two terms carry similar meanings and are nearly synonyms, the terminology follows here the meaning used in cognitive science (Hurme 2010, e.g.), see Sect. 4.3.

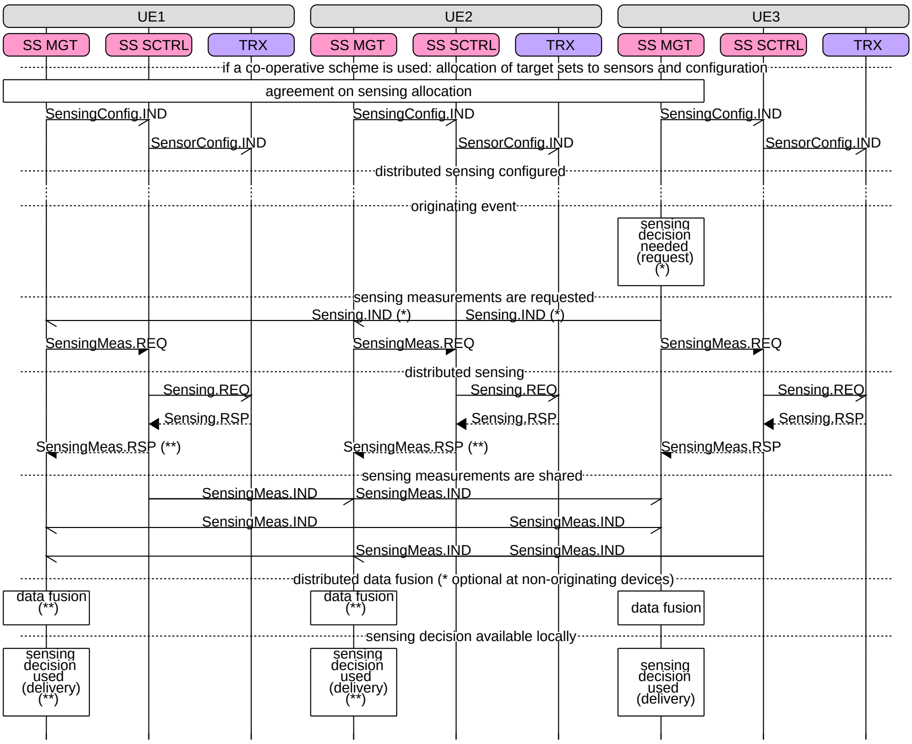

Fig 18. Distributed spectrum sensing. In this example, the triggering event occurs at device UE3 (and the trigger shared by `Sensing.IND` commands, see (*) in the figure), but it could occur at all peers simultaneously, depending on the protocol and originating event. Accordingly, a sensing decision be generated and the originating device or at all of the peers (see (**) in the figure), but in any case the measurements are shared among peers. Revised from Leveil *et al.* (2010), Celentano *et al.* (2012)

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Distributed sensing is in some respects similar to the centralised cases but the main difference is that in this case the sensing decision is generated at each peer. The triggering event may be simultaneously generated at each peer or at any of them, see Fig. 18. Scattered nodes perform sensing measurements and share their outcomes with (broadcast or multicast to) the other peers. All peers are then able to perform the decision in a distributed fashion. In ideal conditions, all nodes will come to the same decision, although the presence of transmission errors at some node may not guarantee this. However, due to the lack of a central fusion node, this scheme is more robust to its possible disappearance (since all peers will have a sensing decision available, independent of the availability of the decision from a central fusion node or of the link from it) and does not need any agreement for the selection of a replacing fusion centre.

In the literature, the terms collaborative and co-operative are sometimes used interchangeably. Moreover, introducing confusion with the use of terms, they are also sometimes referred to with the term distributed sensing to reflect that sensors are distributed over an area; still, the decision is done in those cases at the fusion centre. Actually, distributed sensing could be regarded as a centralised sensing with distributed decision-making. Here, the focus is on the cognitive functions and therefore on the spectrum sensing decision-making. Therefore, distributed sensing refers to a scheme using scattered[17] sensors, but with the decisions taken at many, potentially all, network nodes.

Spectrum management topologies

The third element described in Sect. 3.4.1 and Fig. 14 concerns the management of another portion of context, discussed in Sect. 2.2.3 and concerning spectrum management. Also these corresponding functions are subject to mapping onto the topological domains, as clear from Fig. 6.

As resource control needs access to spectrum management information, at least part of the functionalities related to the spectrum selection need to be located at the network domain and at any network node in charge of resource control. The gathering of the context relevant to the network happens through a gateway device, see note on p. 60 in Sect. 2.2.2. This role is taken by one or more of the capable devices (see also Sect. 5.3.2) having access to the coexistence domain in case of distributed resource control, or in the case of centralised resource control the corresponding functionalities may be split between the base station and the core network, as in the cellular case.

Mapping for example application scenarios

The mapping of resource management, spectrum management and spectrum sensing functions to topological domains with indication of the network devices possibly incorporating those has been covered above separately. Here, two example scenarios

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[17] The meaning of *scattered sensors* is the same of the term *distributed sensors* in IEEE P1900.6 specifications.

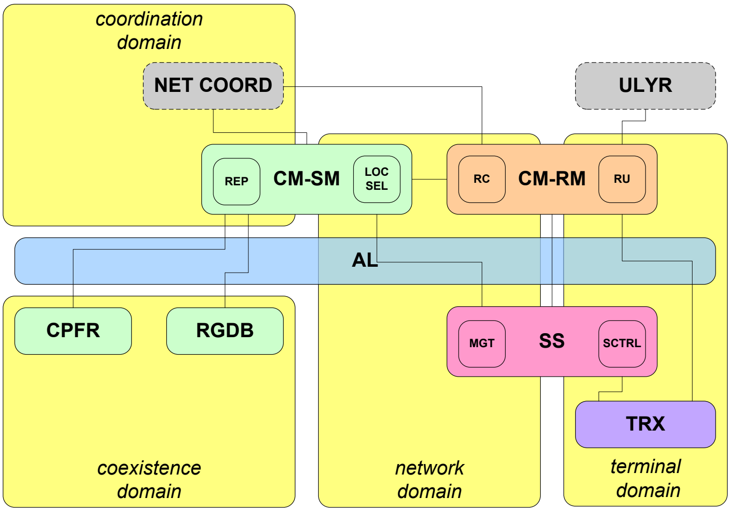

Fig 19. Topology mapping of QoSMOS reference model functional blocks. Revised from Celentano (2012).

combining together the above mappings are presented. These examples also further illustrate the use of the topological domains.

In a specific realisation and according to the architectural choices, not all the functional blocks discussed in this section may be present. In particular, following the discussion in Sect. 2.2.2, spectrum sensing blocks may be missing. Nevertheless, for completeness of the presentation, all are incorporated in the examples of the remainder of this section.

Fig. 19 shows a generic topology mapping summarising the main functions previously seen. As seen, to the terminal domain belong the sensor control and the resource use functions, whereas the network domain covers the above spectrum sensing management and resource control functions as well as the spectrum management functions for localisation of the spectrum management context and for spectrum selection. To the co-ordination domain belong the repository access and management, while the repositories are placed at the coexistence domain. Depending on the scenario, a network co-ordination block may support the operations from the co-ordination domain (e.g., from the CN). An adaptation layer (AL) provides the communication among remote entities[18].

Table 9. Promising scenarios for cognitive radio networks: cognitive ad hoc network, cognitive femtocell, cellular extension in the whitespace and rural access, with some characteristics. Revised from Ariyoshi *et al.* (2011a,b), MacKenzie *et al.* (2010).

Scenario	Application	Range (order of magnitude)	Environment
CAHN	cellular, WLAN/WPAN-type, machine-to-machine (M2M)	$(1 \div 1000)$ m	inside, outside
CFMC	cellular, WLAN-type	$(1 \div 100)$ m	inside, inside-to-outside
CXWS	cellular	$(0.1 \div 10)$ km	outside
RRAC	broadband, M2M	$(1 \div 10)$ km	outside

The availability of new spectrum at lower frequencies, such as the TVWS, with better penetration properties, may support new applications, thus enabling new business cases. Promising scenarios for cognitive radio networks include[19] cognitive ad hoc network (CAHN), cognitive femtocell (CFMC), cellular extension in the whitespace (CXWS) and rural access (RRAC). Although they do possess diverse characteristics, see Table 9, a proper design may still allow multiple realisations from the same system of origin.

For the illustration purposes of this section, two of them and in particular settings, are considered here. Further options are considered in Leveil *et al.* (2010), Mange *et al.* (2011a).

A cellular network is governed by a centralised resource control scheme. In such a case, a centralised spectrum sensing with fusion centre located at the base station seems a natural choice. The mapping for this RCC-SSC option is shown in Fig. 20.

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[18] The pale blue discs in Fig. 20 and 21 represent the AL shown also in Fig. 19. For its functionalities, not relevant to the present context of topology mapping, see Leveil *et al.* (2010), Mange *et al.* (2011a, e.g.). In few words, the AL has two roles: of dispatcher, taken in the upper disc of the cited Fig. 20 and 21 and in the rightmost part in Fig. 19, as well as of interfacing, taken in the part represented by the lower one in the mapping figures and in the leftmost part of Fig. 19.

[19] The cited QoSMOS project identified, after a rationalisation process, six scenarios (Ariyoshi *et al.* 2011a,b, MacKenzie *et al.* 2010), which then underwent an additional analysis of the related business cases (Lehne *et al.* 2012). Part of the above rationalisation process is expanded in the text.

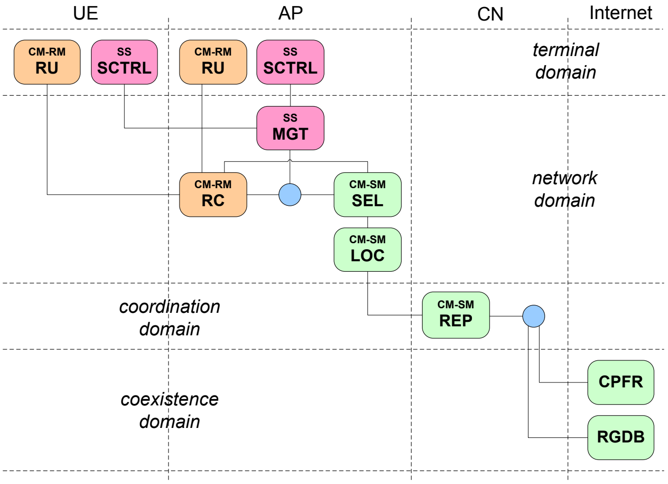

Fig 20. Mapping of the functional architecture onto topological domains for an example cellular network, with centralised resource control, adopting a centralised spectrum sensing method. Revised from Celentano *et al.* (2011a).

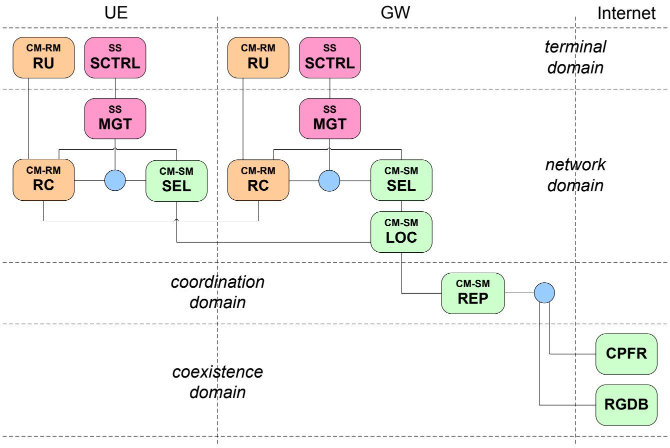

Fig 21. Mapping of the functional architecture onto topological domains for an example ad hoc network adopting a distributed resource control together with a local spectrum sensing method. Revised from Celentano *et al.* (2011a).

The second example is represented by an ad hoc network. While both resource control topologies are applicable here, a distributed resource control is assumed together with a local spectrum sensing topology. Among all peers, a gateway device can be elected, statically or dynamically among all the capable devices for such a task, to take the responsibility of accessing the repositories, as demanded by applicable regulations. The mapping for this RCD-SSL option is shown in Fig. 21.

3.5 Discussion

Lying on the knowledge brought by the introductory Chapt. 1, this chapter started presenting a view on the current trends in system design and on the background motivations behind those. Two important driving forces are represented by the need of reduction of operating expenditures to increase the profit margins in growingly competing markets on one hand, and on the necessity of more environmental-friendly communication systems on the other. Both call for efficiency and flexibility, and cognitive networks, introduced in this chapter, are a possible answer.

Concurrent networks operate simultaneously and in mutual proximity. The necessary simultaneous and global QoS provision to all players/users must be taken into account. The chapter continued presenting the interactions in those systems, together with the displayed dynamics and quality of service framework for such an ecosystem,

Finally, the chapter concluded with an analysis of the decision-making process and the derivation of the corresponding cognitive domains. The topological domains were defined with the aim of rising the flexibility of the system up to its design, and their use was illustrated by applying them to two different example application scenarios.

This chapter together with the previous Chapt. 2 contributes to a rationalised system design. The rationalisation process continues in the following chapter, in more general terms but with a narrower focus.

4 Modelling networked artificial cognitive entities

Nur erst, wenn dir die Form ganz klar ist, wird dir der Geist klar werden.	Only when the form is entirely clear to you, will become clear to you the spirit.

– Robert Alexander Schumann (1845) *Musikalische Haus- und Lebensregeln*.

The previous chapter presented some example functionalities required by the entities that are part of a cognitive network. More, they showed that some fundamental interactions happen across the cognitive domains and across the topological domains. In addition, the interaction of these cognitive entities may occur *during* the cognitive process, i.e., between the perception of the first inputs and the generation of a final action.

Networked cognitive entities can be found in various forms of distributed decision-making, which may occur among peers, among co-operating parties, or among entities at different hierarchical levels, involving one or more steps. Forms of it are found in the cognitive communication networks of the previous chapters, in the Internet of things, whose scope covers the focus of the following Chapt. 5, in smart energy grids, where electrical energy producer, consumer and producer/consumer nodes are networked, and, on a smaller scale, in car networks, where various sensor and actuator systems interact.

Many of the above examples concern cognitive *radio* network, meaning a set of cognitive entities interworking using wireless links. The concepts subject of the present chapter have however a scope, addressing cognitive network, a network of cognitive entities in general.

While it is possible to build a single cognitive model for a networked system in its entirety, its design proceeds down to its individual components, so a corresponding detail level for the model is useful. Indeed, there is also correspondence between the nature of the *phases* of the cognitive entity (the components active in the cognitive process) and the role they have in relation to the environment they operate in, and in terms of interfacing with the corresponding blocks (of the architecture or of the circuitry), see Sect. 4.4.3.

It is therefore clear that a model specific to networked engineered cognitive entities is needed. This is the subject of this chapter, which proposes such a model.

4.1 Introduction

Before proceeding to the cognitive entity, the meaning that cognition, knowledge and its processing, learning, have as terms is presented next, and, in the following, those concepts are expanded in the specific context of cognitive networks, thus completing the discussion of Sect. 3.3.2.

The term *cognitive* comes from the Latin *cognoscĕre*, i.e. *to know*, or “to learn and retain a notion” (Vocabolario Treccani 2012). In turn, *learning* is “the alteration of behaviour as a result of individual experience” (Encyclopædia Britannica 2012b). Interestingly, *to know* corresponds in Finnish to *tietää*, which may come from *tie*, i.e. *way*, and means “to be able to follow the way” (Häkkinen 2007). We may say that the knowledge is what is used to take a direction, i.e., to take decisions to approach a goal.

Cognition and learning are discussed in Sect. 4.2 with a look at both humans and machines. While what said there is valid also in the case of isolated cognitive entities, Sect. 4.3 addresses social interaction in cognition, thus providing with the insight needed to build the model for networked artificial cognitive entities proposed in Sect. 4.4.

4.2 Learning: from humans to machines

An artificial cognitive entity not necessarily has to mimic human intelligence. Nevertheless, a look at human learning is beneficial in order to understand how the perceived inputs, the stimuli, can be exploited and what are the mechanisms involved with that. Moreover, humans themselves are sometimes part of the overall ecosystem, and in some studies it is beneficial considering them explicitly.

4.2.1 Humans

Although it is difficult to capture and categorise the characteristics of a complex system such as the human being, with many hidden mechanisms, there have been studies that produced models of the human learning looking at it from different perspectives.

Bloom’s taxonomy (1956) is a hierarchy in which more advanced cognitive functions make use of the previous ones. They are: knowledge, comprehension, application, analysis, synthesis, and evaluation (Wankat & Oreovicz 1993). In many of the models discussed in this chapter, the process iterates through *phases*, representing cognitive functions similar to the above. In some of these models, phases are always iterated in a predefined order, thus identifying proper *cycles*.

The discussion on the cognitive phases will continue later in Sect. 4.4.2 and 4.4.3 and will also cover models for human learning. For the proposed model presented later, it is of interest to broaden the scope to cover also the interaction with the environment.

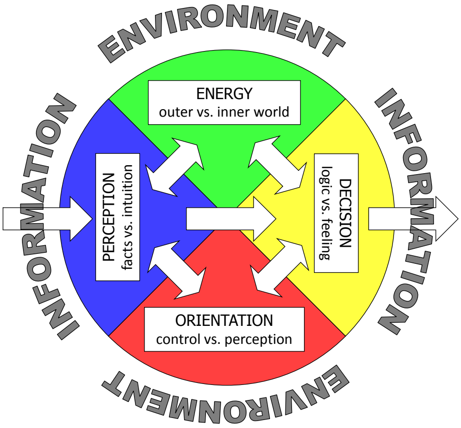

Fig 22. The four dimensions in the Myers-Briggs personality model. From Celentano (2008).

Different learning styles related to psychological types have been classified by the Myers-Briggs type indicator (1961), MBTI. The MBTI actually defines sixteen personality types, categorising their use of *perception*, *inclination*, *interaction* and *decision-making*[20]. The MBTI personality model is based on Carl Gustav Jung's theories dating back from 1921 (Wankat & Oreovicz 1993). The model aims at capturing, with limitations in its general validity (Boyle 1995) such as those outlined at the beginning of this section, the impact of different types in in persons' different performance in distinct jobs and tasks as wells as their career (Devito Da Cunha & Greathead 2004). Types move in a binary four-dimensional space and are categorised according to interaction with the environment (Extraverted/Introverted; Perceiving/Judging) and perception and actions (Sensing/iNtuitive; Thinking/Feeling), see Fig. 22.

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[20] These categories are partly adapted here for our use. They are *sensing vs intuition*, *extroversion vs introversion*, *thinking vs feeling*, and *judgement vs perception*, respectively.

4.2.2 Machines

An extensive review on machine learning techniques is out of the scope of this section. Reviews on relevant learning techniques can be found in the literature (Dietterich & Langley 2007, Friend *et al.* 2007, e.g.). Rather, the scope is here to understand the role of learning and cognition in a cognitive entity so to derive a model for it.

Different levels of cognition

From what discussed in Sect. 4.1, it can be extrapolated that an artificial cognitive system may possesses increasing levels of "intelligence": acquisition of information of its environment (see definition in Sect. 3.3.2, p. 86), its processing or elaboration, and more advanced exploitation of the gained knowledge.

Mitola (2000) identifies nine levels of cognition for radios, ranging from only pre-programmed capabilities to fuller awareness, planning and adaptation capabilities at protocol level. Albus (1991) analyses learning and identifies three types: repetition learning (without any feedback from the results of the actions), teacher learning (with a teacher explicitly correcting the actions), and reinforcement learning[21] (with feedback from the actions and a more independent learning); as a consequence, learning is slow in the first case, faster in the second, and somewhere in the middle for the third case.

To keep the categorisation compact and possibly more general, the focus may be put on aspects related to the architecture of the system and its interfaces and environment, and on the complexity of the implemented functionalities. A simple characterisation is provided in Table 10. Although it seems difficult to name the categories in the leftmost column with a clear and univocal significance also consistent with the literature, their meaning is obvious from the rest of the table.

In the following, inputs are distinguished between stimuli, assumed to be based on perception with no relation to the own actions, and feedback from actions.

Simpler adaptive systems make use of *instantaneous* inputs to change parameters or configuration. Inputs can be stimuli only or they may include also feedback from own actions. Learning implies the exploitation of the *experience* accumulated by the entity. Again, the experience can be based on stimuli only (as in supervised learning, repetition

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[21] In reinforcement learning the performance improves as an effect of the rewards received as a consequence of the actions. A reinforcement scheme provides an update (reinforcement) of the rule underlying the learning automaton actions, for example, using reward-penalty schemes based on the history of the environment outputs, i.e., the automaton inputs (Najim & Ikonen 2002).

Table 10. A categorisation of cognitive systems.

System	Characteristic	Example notation†
Memoryless adaptive	fixed behaviour using instantaneous inputs	$\mathbf{v} = f(\mathbf{u})$; $f(\cdot)$ fixed
Learning	fixed behaviour using accumulated experience	$\mathbf{v} = f(\mathbf{u}, \mathbf{y})$; $f(\cdot)$ fixed
Developing	adaptive behaviour using knowledge processing	$\mathbf{v} = f(\mathbf{u}, \mathbf{y})$; $f(\cdot)$ adaptive

†See text.

learning and simple average estimation[22]), or also use feedback from actions (like in teacher learning, reinforcement learning and or tracking[23]). Hence, different levels of learning can therefore be identified. An example is given in Sect. 6.2.9.

Developing systems, are characterised by advanced adaptation strategies, may be able to form concepts out of perceptions, and targets and plans can also be adapted depending on stimuli and/or experience[24].

Where simpler adaptive systems typically exhibit reactive behaviour, more evolved systems may possess a proactive attitude. The distinction between a reactive and a proactive behaviour depends on how the decision-making algorithm uses its information rather than on the kind of information that is used. In order to be proactive, a system need to anticipate. Predictive algorithms make an adaptive system proactive.

Cognitive systems, including the simplest adaptive systems, modify their actions and possibly their behaviour depending on the changes in their environment. These can be seen as the control inputs of the systems and its actions as the outputs. Let $\mathbf{u}$ be the system's control inputs, $\mathbf{v}$ its outputs, $\mathbf{y}$ the internal state and $f(\cdot)$ a generic function of its arguments. Given an environment, if the algorithms are fixed and memoryless, an adaptive system behaves always in the same way whenever put under the same conditions: $\mathbf{v} = f(\mathbf{u})$. If the system has memory, the actions of this system may improve, due to a better knowledge, so the behaviour of a *learning* also depends on its state, which condenses part of its experience: $\mathbf{v} = f(\mathbf{u}, \mathbf{y})$. A memoryless adaptive system (and in general a learning system) has a fixed $f(\cdot)$ function (or a set of them), whereas in a

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[22] Examples are the cumulative running average at step $n+1$, $\bar{x}_{n+1} = (n\bar{x}_n + x_{n+1})/(n+1)$, or the moving average (Law & Kelton 1991, e.g.), $\bar{x}^{(m)}_{n+1} = (m\bar{x}^{(m)}_n - x_{n-m+1} + x_{n+1})/m$, for some fixed m.

[23] Tracking algorithms are identified as a simple form of learning also by Thomas *et al.* (2005).

[24] The regulation of cognitive processes pertains to metacognition (see Sect. 4.3). McGregor (2007) identifies five metacognitive levels, including awareness, evaluation, reflection and the capability of transferring knowledge to different context.

developing system the function $f(\cdot)$ can itself be adaptive. In other words, a developing system can be regarded as an adaptive, adaptive system.

The decision-making and the learning processes, together with their feedback loops, are depicted in Fig. 23. The feedback loop that we see in machines is also present in human learning, as represented for example by assessments for students (Celentano 2008). As clear from the above discussion, not all the parts are always present in an artificial entity.

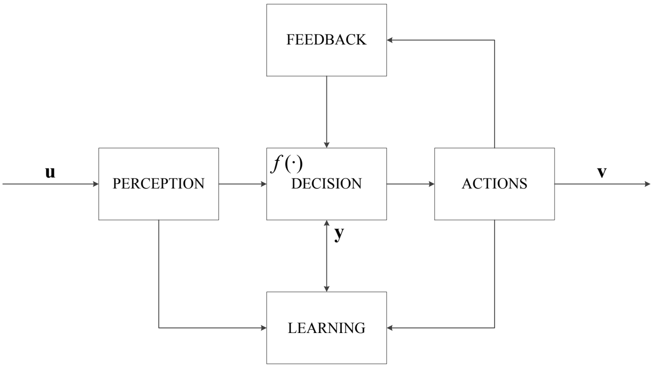

Fig 23. The decision-making and the learning processes with their feedback loops. Revised from Celentano (2008).

Example cognitive systems with different cognition levels are discussed and approached from different angles in Chapt. 3, 5 and 6.

Final remarks

Learning and cognition are potentially intensive processes and therefore it may be appropriate to assign them, whenever possible, to otherwise idle[25] periods. When a cognitive entity is free from other duties, it can perform more resource-consuming

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[25] These are what Mitola (2000) calls *sleep* epochs, in analogy with known mechanisms of the human cognitive process. We prefer to reserve the word *sleep* to states associated with reduced energy consumption (see Chapt. 5). The term *idle*, also present in the above context, is used here in its more general meaning.

processing of the acquired information with less onerous requirements on system capabilities, such as on the hardware, and on energy[26].

According to Piaget and Perry learning theories, learners build their knowledge when exposed to *moderate disequilibrium* between the already consolidated knowledge and the new (Wankat & Oreovicz 1993). The same assumption applies to machines as well (e.g., classification, clustering, tracking).

4.3 Socially shared cognition

The considerations in the previous sections concern (also) isolated cognitive entities. Here the scope is broadened to cover their interaction.

Metacognition is the knowledge about the cognitive phenomena (or *knowledge of cognition*) and the *regulation of the cognition processes*; in short, cognition about cognition (Artz & Armour-Thomas 1992, Garofalo & Lester 1985, McGregor 2007, Hurme 2010)[27].

Metacognition is not just about own cognitive processes but it concerns also those of others. Socially shared metacognition in problem solving eases the problem itself (Hurme 2010) by exploiting the interaction and the reciprocal participation of more entities. With *co-operative* learning, the work is divided among group members and the final result comes from merging the intermediate solutions whereas with *collaborative* learning, group members work together towards a common goal (Hurme 2010). Interaction among entities may follow also different schemes. Other examples include co-ordination and negotiations among entities, see Sect. 2.2.3, 3.2 and 5.3.4.

From the above discussion it is clear that, when exploiting distributed cognitive functionalities, the cognitive process takes place *while* those entities interact. A model for networked artificial cognitive entities is proposed in the following section.

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[26] As shown in Chapt. 5 (Sect. 5.2.2 to 5.2.4), in this way can be avoided both unnecessary power level changes, which represent a source of energy waste, and requirements on higher clock rates that could be needed for coping with more simultaneous tasks.

[27] See for example: Brown and Palincsar (1982) in Garofalo & Lester (1985) and Roberts & Erdos (1993) in McGregor (2007); Flavell (1976) in Garofalo & Lester (1985), McGregor (2007); and Flavell (1981) in Artz & Armour-Thomas (1992); respectively. See also McGregor (2007, cap. 10) for more definitions and thoughts.

4.4 Cognitive process modelling

4.4.1 Introduction

In the scope of this chapter are the cognitive processes a cognitive entity networked with others is involved in, and a model for such artificial entities, which also considers some implications related to the realisation of artificial entities, see Sect. 4.4.3. As seen in Sect. 4.2.2 (e.g., Table 10), a cognitive system is reconfigurable and perhaps developing, but not necessarily an intelligent artificial entity, for example as the one supposed to pass a Turing test[28](Turing 1950, Guccione & Tamburrini 1988, Saygin *et al.* 2000).

Although quite efficient to solve specific tasks, artificial intelligence has not been able yet to cover all the complexities of the human brain. As Kolker (2006) observed, the difficult tasks for a computer are generally not those that humans consider difficult, but everyday easy activities such as common-sense reasoning.

As noted by Patrick Hayes and Kenneth Ford (Saygin *et al.* 2000), the ultimate goal of artificial intelligence should not be the imitation of the human intelligence. Indeed, for what we are concerned here, one should not imitate but rather get inspired by humans. The following Sect. 4.4.2 gives an overview of the relevant models related to cognitive entities, and the subsequent Sect. 4.4.3 proposed a model for networked cognitive entities.

4.4.2 Related models

Observing a process, learning from it and controlling it, are functions common with several branches, from quality control, which has the scope of continuous improvement of the production process, to cognitive networks. There are similarities in some of the phases of those models, with bigger differences in the details of the phases and how they are navigated. Models range from proper cycles, with phases visited with a pre-defined sequence, to more elaborated models, possibly mimicking the human cognition process, in which the use of the phases and therefore the order they are visited depend on the cognitive process.

The models are first presented here below and then discussed in Sect. 4.4.4, where they are compared with the proposed model of Sect. 4.4.3, see Table 12 and Fig. 27.

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[28] The scope of the Turing test is to asses the intelligence of an entity by recognising, through conversation and the analysis of given responses, the impossibility for a human to distinguish between a machine and another human.

Models for quality control

In his first version, Walter Andrew Shewhart defined the three fundamental steps of *specification*, *production* and *inspection*, corresponding to the case in which no corrective actions are identified at inspection, thus originating a linear model (Shewhart 1939). In the above three steps, tolerance limits are specified, action limits are adopted, and finally correspondence with the aimed-at value is checked. When corrective actions show to be needed after step three, a further step appears after the last one and proceeding back to the first, thus basically originating the *plan-do-check-act* (PDCA) cycle. The cycle was later formalised and further developed by William Edwards Deming as the PDSA cycle, where a more profound *study* replaces the *check*. The above model referred to as PDCA, PDSA, Shewart or Deming cycle, is a component of total quality management programmes[29] (Grisham 2011) for process improvement, for example to reduce variability in production.

Shewhart (1939) observes that the above steps[30] also constitutes "a dynamic scientific process of acquiring knowledge", going through the steps of *hypothesis*, *experimentation* and *testing*, respectively.

Models for problem solving and human cognition

The Polya's cycle (Polya 1957)[31], modelling the problem-solving process, is also characterised by four phases: *understanding* the problem, *devising a plan* for its solution, *carrying out the plan*, and *look back*. Note that this last step includes learning, since its evaluation is also done thinking at its possible future re-use.

According to Ernest (1991), Polya's cycle resembles the model of philosophy of discovery developed by William Whewell a century earlier, by which a theory should go through three verification criteria (Snyder 2006): prediction (of other cases of the same kind), consilience (with cases of a different kind), coherence (of hypotheses over time).

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[29] See Curkovic *et al.* (2000, e.g.) for definitions of total quality management (TQM). In brief, TQM is holistic quality provision over all business chains (production, supply, etc.), such as *kaizen* (1986). The term *kaizen* is Japanese for *improvement*, often used to mean continuous improvement. For kaizen, see Ashmore (2001, e.g.).

[30] In the reference, he says this for the original three steps, but the same applies to the four-phase model, where the corrective phase is also usually present.

[31] Polya's book *How to solve it: A new aspect of mathematical method* was first published by Princeton University Press in 1945, so we use this date in the following Sect. 4.4.4.

Schoenfeld broadens the model, and identified *reading*, *analysis*, *exploration*, *planning*, *implementation* and *verification* as the cognitive phases, or episodes, as he called them (Garofalo & Lester 1985). One key difference with Polya's model is Schoenfeld's *explore* episode, which can be seen as an inner cycle within decision-making.

Garofalo & Lester (1985) propose a cognitive-metacognitive framework with four categories or activities, related to Polya's phases but having each a broader scope: *orientation* (analyse and comprehend); *organisation* (identify goals and subgoals, global and local plans); *execution* (perform, monitor and fine-tune); *verification* (of the previous three).

The Kolb-McCarthy learning cycle (Wankat & Oreovicz 1993), obtained combining together the models developed by David A. Kolb and Bernice McCarthy, describes the cognitive information processing and has four phases: concrete *experience*, reflective *observation*, abstract *conceptualisation* and active *experimentation* (Kolb, 1984), leading to the self-questions on why, what, how and what if (McCarthy, 1987), respectively.

Models for robotics and autonomic systems

Early robotic models, like *Shakey*, developed at Stanford Research Institute (SRI) in 1969, (Nilsson 1984), were based on a goal-oriented, or deliberative approach, in which steps are executed according to a *sense-plan-act* (Simmons 1994, e.g.), also expanded as sense-model-plan-act-control (Brooks 1986) loop. A reactive, or behaviour-based approach adopting a functional decomposition of the above steps (called subsumption architecture) was proposed (Brooks 1986), where behaviours are such as: plan changes, identify objects, build maps, monitor changes, explore, wander, avoid objects. Hybrid approaches have then been proposed (Simmons 1994, e.g.). A goal-oriented reactive system in Riekki (1998) has sense-behave-(arbitrate)-act chains co-ordinated to a common goal.

The first model in robotics has continued its life in neighbouring areas. Albus (1991) identifies as functions of an intelligent system, *sense*, *judge* and *behave*, with a *model* function interacting with all of the previous ones. As seen in Sect. 3.3, autonomic computing is a first step to attack complexity of evolved information-technology systems. The autonomic element by Kephart & Chess (2003) has a *monitor*, *analyse*, *plan* and *execute* loop, together with a shared *knowledge* function. The autonomic communications concept also includes capabilities of the system to self-organise, and the autonomic manager that controls its functional units follows an autonomic control loop: *collect*, *analyse*, *decide*, *act* (Dobson *et al.* 2006).

Models from cognitive sciences

Cognitive architectures have been developed within cognitive sciences – whose birth is conventionally set in 1978 (Legrenzi 2012) with the first conference on the topic held in La Jolla, California – bridging various disciplines from psychology and human cognition to artificial intelligence. The architecture mostly relevant to the proposed model are discussed in this section. The interested reader may find a review given by Langley *et al.* (2009). Some are computer-like models of the human mind; this helps in analysing human-computer interactions, since the two models can then be easily juxtaposed, as done by Kieras & Meyer (1997).

Allen Newell attempted to build unified theories of cognition (1990) and with Langley *et al.* (1987) developed the Soar architecture, later updated (Lehman *et al.* 2006, e.g.) and used for robots and robot-human interaction (Langley *et al.* 2009) in a number of scenarios (Lehman *et al.* 2006). Serving *perception*, *action* and *decision*-making, two kinds of *memory* are identified: working (relevant to current situation) and long-term (procedural, for rules and used e.g. in reinforcement learning, semantic, for learnt facts, and episodic, for experiences).

The adaptive control of thought-rational (ACT-R) architecture was developed by Anderson & Lebiere (1998), for humans but also applied for human-machine interaction (Anderson *et al.* 2004, Langley *et al.* 2009). ACT-R shares with Soar an unifying view, but is partly also inspired by EPIC (Anderson *et al.* 2004). Along with *perceptual* and *motor* modules, this architecture includes explicitly a *goal* module, a long-term declarative knowledge and a procedural system (used for decision-making).

The executive process-interactive control (EPIC) model of human cognition developed by Kieras & Meyer (1997) does not consider learning but focuses on task execution and perceptual-motor aspects (Kieras & Meyer 1997). Although noting that a single-processor is traditionally assumed, Kieras & Meyer (1997) assume a multi-processor structure to support the assumption of human's multi-tasking capabilities. EPIC includes therefore interconnected specialised processors: *perceptual*, *motor* and *cognitive* processors, as well as distinct working and declarative *memory*. Working memory is actually manifold: dedicated to processors with one dedicated to current goals and plan's steps. The cognitive processor cycles through read-write phases of the working memory and may process production-rules in parallel.

Models for decision-making in military operations

A model for decision-making to be applied to military operations (i.e., to command and control, or C2), developed by USAF Col. John Boyd (1986) to understand adversaries, is made of an *observe-orient-decide-act* loop, also known as OODA loop.

A newer proposal is the *critique-explore-compare-adapt* (CECA) model proposed by Bryant (2004). The last three phases have similar duties as the *observe*/*orient* with *decide* and *act* of the OODA model, but a *critique* phase – a double one, actually – constitutes a model to guide the perception process (in *compare*) and to prepare the ground for the *explore* phase, thus the entire cycle. This makes the model more proactive than reactive.

Models for cognitive radio

One notable model for cognitive radios has been proposed (together with a representation of the cognitive process through the radio knowledge representation language) by Mitola (2000). As Thomas *et al.* (2005) noted, Mitola's model introduces the *plan* and *learn* phases over the OODA model. Mitola's cognitive cycle is therefore made of *observe*, *orient*, *plan*, *decide* and *act* in a loop, with *learn* fed by most of the previous phases.

Whereas in Bryant (2004) *plan* serves as a sort of initialisation phase before the context acquisition takes place, in Mitola (2000) it is used to take further actions as a consequence of the acquired context information. We may observe that OODA regulates the actions, CECA regulates the plan.

Haykin (2005) proposes a cognitive cycle for cognitive spectrum sharing, modelling the entire reconfiguration process. The three-phase model includes *analyse*, *model* and *configure*, with the first two carried out at the receiver and the latter at the transmitter.

Mitola's model has been widely adopted in the literature on cognitive radios and networks. Four-phased models (such as observe-orient-decide-act or collect-analyse-decide-act) are also commonly used. For example, an *observe*, *analyse*, *decide* and *reconfigure* cycle is mapped onto protocol layers by Nasreddine *et al.* (2010).

4.4.3 A model for networked cognitive entities

As we have seen, some of the models realise proper cycles, other not. Indeed, a cognitive *process* makes use of the cognitive *phases* in a sequence that is peculiar to that specific process and instantiation. The specification of the sequence of phases may not be general. Also the model presented in this section does not implement a cycle.

This model for networked cognitive entities introduces new phases, missing from the existing models, and organises all phases into two layers.

Categorisation and layering

It is clear that distinct cognitive phases belong to distinct – though interrelated – domains. Schoenfeld (1983) identifies categories of knowledge and behaviour as resources (facts and competences), control (decision-making and metacognitive acts) and belief systems (about self and environment). For our purpose, the latter two are closely interconnected, thus two classes are identified: functionalities dealing with exchanging facts and implementing competences, and those in charge of processing knowledge, making decisions and learning.

Some notion of inside-versus-outside, although sometimes implicit, is present also in some of the previously cited models (but with the social aspect missing). Albus (1991), Mitola (2000) and Haykin (2005) as well as Anderson & Lebiere (1998) all have (only) two interfaces to the outside world: one for observing and one for acting (sensors and actuators, observe and act, analyse and transmit, visual and manual, respectively). Sutton *et al.* (2004) classify the phases of Mitola's (2000) cognitive cycle assigning *observe* and *act* phases to a *reconfigurable node* domain and the remaining phases to a *cognitive engine* group. Wang (2010) identifies forms of intelligence regarding the input (called experience, transforming actions into information), the output (wisdom, transforming information into actions) and internal (knowledge, transforming information into information).

As it will be seen, the model proposed here follows, for the definition of its interfaces, logical, topological and design considerations, so that cognitive functions can be assigned to specific elements/units. The phases of the cognitive entity, i.e., the components instantaneously active in the cognitive process, are defined considering also their role in relation to the environment they operate in. It will be then clear that this has implications on implementation issues concerning the interfaces. In other words, the proposed model looks at the possible functional blocks constituting or being controlled by a cognitive entity. In particular, functions related to input/output (I/O) are separated from those likely to be stand-alone tasks.

Interworking and new phases

Interaction of a cognitive entity with its environment by observing and acting is certainly one form, but interaction is not limited to that: a cognitive network is constituted of more interacting cognitive entities.

In principle, it is possible to model the entire network as a single entity and adopt one of the existing models – for example Doyle & Forde (2007) apply Mitola's cognitive model to the entire system. For design purposes, it may be useful to think instead at cognitive networks as a system of cognitive entities. Hence, there is a need to model those entities. In addition, their individual behaviour can be analysed; otherwise, their role would be shaded by the overall model (see also Sect. 4.5).

There are also other reasons why a different approach is beneficial. It is obvious that what is an action for one entity may be a perception for another, but there are also other important forms of interaction. Sect. 4.3 showed us that cognitive entities should make use of the information made available by the others. In case of co-operating or collaborating entities or in the more general cases discussed shortly below, the interaction with their environment occurs *during* the cognitive process and not (necessarily only) at its start or end (i.e., at perception or action, respectively). In other cases, as the outcome of a decision, an action may occur locally at a cognitive entity or it may trigger another entity of the cognitive network. This sharing of information or knowledge, or sometimes commands, takes possibly place *before* the actual actions are taken and therefore cannot be modelled as *act-perceive* interactions. New cognitive phases are needed for that.

Two layers and four categories

As seen in Sect. 4.3, metacognition is the knowledge about the cognitive phenomena (or *knowledge of cognition*) and the *regulation of the cognition processes*. Or, as Garofalo & Lester (1985) summarise, cognition is *doing*, whereas metacognition is *controlling* what to do and monitoring what is being done.

Table 11. The cognitive and metacognitive phases in the four categories.

	Cognitive frontier	Metacognitive hub	
Perceive	acquiring information	processing information	analyse
Remember	storing/fetching knowledge	building knowledge	learn
Share	sharing instructions†	preparing instructions†	synthesise
Apply	actuating decisions	generating decisions	decide

† An instruction can be a piece of information or knowledge, or a command, see text.

The phases of the model presented in this section are grouped under *two layers*:

- a **cognitive frontier**, in charge of interaction with external entities in the process of:
  - acquiring (raw) information (sometimes referred to as data),
  - storing and fetching accumulated knowledge,
  - sharing instructions, and
  - actuating decisions;
- a **metacognitive hub**, in charge of controlling cognitive phenomena and cognitive actions, i.e., of the interwork of the internal processes in:
  - processing the acquired information,
  - building knowledge from experience (both from outside information/knowledge and own decisions),
  - preparing instructions, and
  - generating the needed decisions.

The phases belong to the following *four categories*, shown in Fig. 24:

- **observation** (*perceive*, *analyse*),
- **consolidation** (*learn*, *remember*),
- **interworking** (*synthesise*, *share*) and
- **operation** (*decide*, *apply*).

The phases are respectively linked across the cognitive frontier and the metacognitive hub, as summarised in Table 11. The above phases are further described throughout the remainder of this Sect. 4.4.3, together with a deeper insight into their interrelation.

Following and extending the notation introduced in Sect. 4.2.2, we can say that the cognitive entity has observable information $\mathbf{u}$ that is used to store knowledge $\mathbf{z}$ and

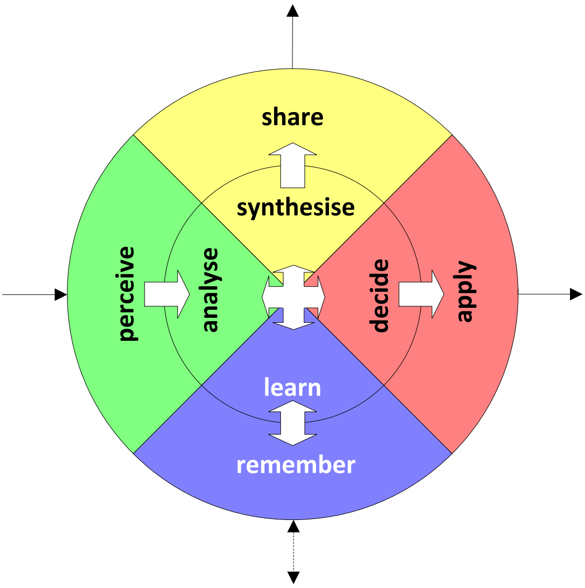

Fig 24. Model for a networked cognitive entity. Four categories span across two layers.

operate instructions $\mathbf{v}$. Instructions, i.e., information, knowledge or commands $\mathbf{x}$ can be externalised. All the above are outside the cognitive entity. The internal steps, occurring at the boundary between the cognitive frontier and the metacognitive hub, imply the presence of, respectively, perceived information $\tilde{\mathbf{u}}$, learnt knowledge $\tilde{\mathbf{z}}$, decision $\tilde{\mathbf{v}}$ and synthesised instructions $\tilde{\mathbf{x}}$. Everything within the core of the metacognitive hub realises the internal state $\mathbf{y}$ of the cognitive entity.

Fig. 25 illustrates in a more detailed way the cognitive processes also with the above notation. The figure also shows the split of the functionalities into an informative half-plane and an operative half-plane, as well as into a living knowledge half-plane and a consolidated knowledge half-plane. The flow of observations, information, knowledge and commands, or instructions, within a networked cognitive entity is shown in Fig. 26. For example, through the *interworking* category can be shared information, knowledge or commands. Similarly, those can be exploited for *operation*. The *metacognitive hub* oversees these tasks.

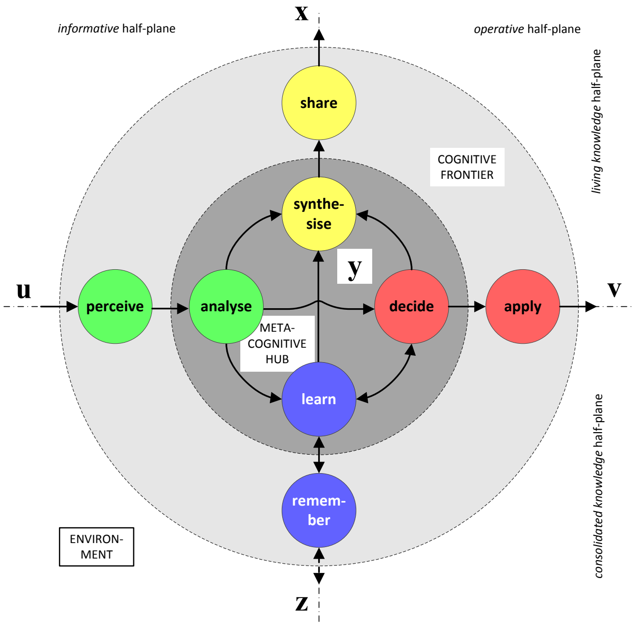

Fig 25. The interactions among the phases of the metacognitive core and the cognitive frontier. The environment includes other related cognitive entities.

The nature of the modelled systems has an impact on the architecture of the cognitive frontier. The differentiation among memoryless adaptive, learning and developing pertains to the metacognitive hub.

A more detailed description of the metacognitive hub to further distinguish its functionalities, to be done while keeping generality, is left as a subject of further studies.

Instantiation of a cognitive entity

The interaction of a cognitive entity with other entities or its environment occurs with different directions in different phases, which has an impact on the realisation of those phases in a cognitive device.

The cognitive entity gathers inputs or stimuli from an outside entity or the environment, in the *perceive* phase, whereas it actuates taken decisions in the *apply* phase. In the *share* phase, a cognitive entity communicates instructions, i.e., information, knowledge or commands, as needed. In the *remember* phase, it remembers the learnt or consolidated knowledge and provides both ways access to it. All the above phases posses interfaces to the outside of the cognitive entity. The latter, *remember*, may not necessarily have such, but in general it can. For example, this is needed when access to information is distributed as in clouds, whereas a working memory is likely to be local to the entity. The four outer phases above represent the interfaces towards the entity's outside world, the *cognitive frontier*. Those interfaces are used as inputs and outputs for commands, ports for communication and data storage and retrieval.

While the outer phases of each category exchange information with their corresponding inner phases only, the four inner phases exchange their own inputs and outputs among themselves, so they form what we call the *cognitive hub*. In the *analyse* phase, inputs are filtered, converted and analysed. Conversely, in *synthesise*, instructions are selected and adapted for the specific sharing use. So, in the *learn* phase, the cognitive entity processes commands (actions are not directly observable at metacognitive hub, but

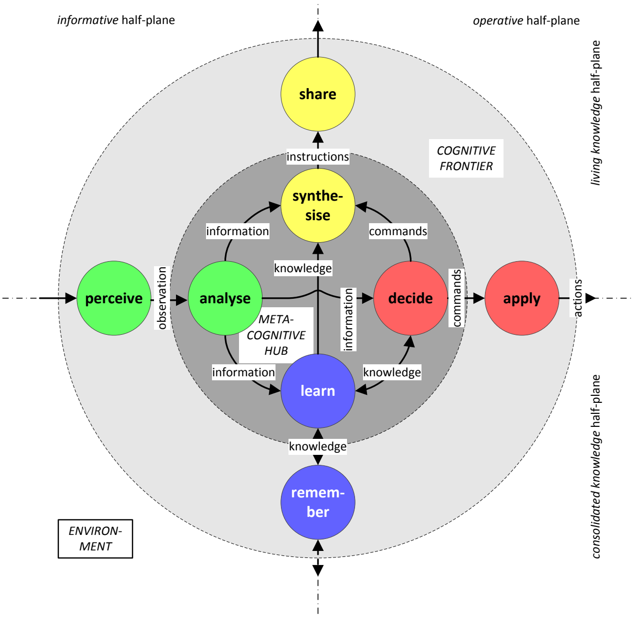

Fig 26. Observations, information, knowledge, commands and instructions within a networked cognitive entity.

decisions are) and information (including the feedback from actions, when available), to build knowledge. Learning may also be exploited for preprocessing incoming stimuli or process instructions for a specific sharing scope. All the above is exploited to take decisions (including prioritisation and planning of actions) in the *decide* phase.

The phases *synthesise-share-perceive-analyse* form the communication (direct interaction) path between the metacognitive hubs of interworking entities. Interaction may also occur indirectly through actions. Hence, thinking at a possible implementation of a cognitive entity part of a communication, *perceive* represents the acquisition port for control and data (including measurements), *share* is the delivery port for control and data, *remember* is an interface for possibly external data I/O, whereas *apply* depends on the nature of the considered system.

The generic model described here incorporates all the functionalities of a cognitive entity. Clearly, in a given cognitive entity, only a subset of those may be present (or, equivalently, be active)[32].

Examples

To further illustrate the application of the above model, few simple examples are given in the following. Consider first data fusion for context acquisition (this is the case of a centralised spectrum sensing scenario, see Sect. 3.4.2), where a fusion centre makes a decision based on several measurements gathered from scattered sensors. In this case, the information used at network domain (see Sect. 3.4.2), $\mathbf{u}^{(\mathrm{N,CA})}$, is

$$\mathbf{u}^{(\mathrm{N,CA})} = f\left(\mathbf{x}_1^{(\mathrm{T,CA})}, \ldots, \mathbf{x}_n^{(\mathrm{T,CA})}\right) \tag{5}$$

where $\mathbf{x}_i^{(\mathrm{T,CA})}$ is the measurement from *i*-th sensor at terminal domain, which possibly includes a decision made on more measurements done at that sensor.

Another example is a centralised resource allocation problem. The information used at network domain for resource control, $\mathbf{u}^{(\mathrm{N,RC})}$, is

$$\mathbf{u}^{(\mathrm{N,RC})} = f\left(\mathbf{v}^{(\mathrm{C,SM})}; \mathbf{v}_1^{(\mathrm{T,RC})}, \ldots, \mathbf{v}_n^{(\mathrm{T,RC})}\right) \tag{6}$$

where $\mathbf{v}^{(\mathrm{C,SM})}$ is the spectrum made available for the network from the co-ordination domain , and $\mathbf{v}_i^{(\mathrm{T,RC})}$ is the resource allocation request from the *i*-th UE, which may take

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[32] For example, paraphrasing Artz & Armour-Thomas (1992), the application of a fixed algorithm involves no metacognitive actions, whereas the solution of a previously unknown problem does require it. Indeed, metacognitive episodes are related to the actual solution of a problem, whereas cognitive episodes are critical in the case of group interaction (Artz & Armour-Thomas 1992).

into account UE-local decisions on service requirements, backlog, residual energy level, etc.

Similar examples can be drawn. For example for spectrum trading decision-making, where decisions at co-ordination domain $\mathbf{x}_i^{(\mathrm{C})} = f\left(\ldots, \mathbf{x}_j^{(\mathrm{C})}, \ldots\right)$ are negotiated, here at i-th and j-th site.

4.4.4 Collation

Similarities and differences among the models have been partly discussed previously, and the novelties introduced with the proposed model have been already highlighted. The scope of this final section is to put the all the previous models, the proposed and the related ones, side by side, also with the aid of a summarising table and a figure.

A comparison in terms of their phases of the proposed model for networked cognitive entities and the related models is not always easy due to some differences in their definitions (see more below).

Nevertheless, Table 12 reports the phases present in the above models. For compactness of the table, some *distinct* phases are grouped under the same column and this is denoted by a separating comma. A slash indicates a joint phase and in parentheses are reported phases or portions of phases not explicitly or not always present in that model. The cognitive functions corresponding to the columns of Table 12 are related to:

A. collecting the inputs,
B. evaluating the inputs,
C. interworking (sharing instructions),
D. decision-making (deciding on the course or actions, and planning the actions[33]),
E. implementing the decisions,
F. verifying and generalising the lessons learnt.

Often the allocation of phases to one of the six columns is natural but, as the definitions of the phases in different models are not always easily comparable, it is obvious that truth has been sometimes strained, as usual in these cases. One example is *orient* in Mitola (2000). It evaluates a stimulus, thus being comparable with our *analyse*, but it does possess (possibly context dependent) features of decision-making, like the selection among immediate, urgent or normal. In other cases, phases hide in them somehow evolved functions, like for Garofalo & Lester (1985), where the

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[33] The boundary between planning and decision-making is not always neat.

Table 12. A summary of the model† proposed in this thesis for networked cognitive entities, together with related‡ models. For compactness of the table, some *distinct* phases are grouped under the same column of this table. A comma denotes distinct phases that are grouped, whereas a slash indicates a joint phase. In parentheses are indicated phases or portions of phases not explicitly or not always present in that model. For the meaning of the columns, see p. 120.

Model	A.	B.	C.	D.	E.	F.
Shewhart (1939)	do(/collect)	check	–	act, plan	–	–
Polya (1945)	–	understand	–	plan	carry-out	look back
Schoenfeld (1983)	read	analyse	–	explore, plan	implement	verify
Garofalo & Lester (1985)	–	orient	–	organise	execute	verify
Kolb (1984)	experience	reflect	–	conceptualise	experiment	–
Artz & Armour-Thomas (1992)	read	understand, analyse	watch/listen(/talk)	explore, plan	implement	verify
Nilsson (1984)	sense	(model)	–	plan	act	(learn)
Albus (1991)	sense	(process)	–	judge	behave	model
Kephart & Chess (2003)	monitor	analyse	–	plan	execute	(knowledge)
Dobson *et al.* (2006)	collect	analyse	–	decide	act	–
Boyd (1986)	observe	orient	–	decide	act	–
Langley *et al.* (1987)	perceive	–	–	decide	act	memory
Anderson & Lebiere (1998)	perceive	–	–	goal, decide	act	knowledge
Bryant (2004)	explore	(filter)	–	compare (plan)	adapt	critique
Mitola (2000)	observe	orient	–	plan, decide	act	learn
†Celentano (2014)	perceive	analyse	synthesise, share	decide	apply	learn, remember

‡ Related models by Shewhart (1939) for quality control, by Polya (1945) for problem-solving, by Schoenfeld (1983) and by Garofalo & Lester (1985) as a cognitive-metacognitive framework, by Kolb (1984) for learning cycle, by Artz & Armour-Thomas (1992) as a cognitive-metacognitive framework for social groups, by Nilsson (1984) and by Albus (1991) for robotics or intelligent systems, by Kephart & Chess (2003) and by Dobson *et al.* (2006) for the autonomic element and the autonomic control loop, respectively, by Langley *et al.* (1987) and Anderson & Lebiere (1998) for cognitive sciences (Kieras & Meyer (1997) using dedicated processes not shown), by Boyd (1986) and by Bryant (2004) for decision-making in military operations, and by Mitola (2000) for the cognitive cycle.

execution phase does include *apply*, but with feedback, also to fine-control the process with trade-off decisions.

Although, as observed before, related models are found even from nineteenth century, the earliest model can be identified as the one by Polya (1945). The Polya's model is a reference for the other human-related models (Schoenfeld, 1983; Garofalo & Lester 1985; Artz & Armour-Thomas 1992), although in them the learning phase gets smoothed across more phases. Learning appears in some robotics-related models (Albus 1991; Kephart & Chess 2003; Langley *et al.* 1987; Anderson & Lebiere 1998), but it disappears then (Dobson *et al.* 2006) or it is kept out (Kieras & Meyer 1997). Indeed, as also already seen, learning is possibly the key addition in Mitola (2000) when contrasted with Boyd (1986). Compared with previous models, one key difference introduced with the model proposed here are the phases devoted to interworking.

As anticipated in the introduction to Sect. 4.4.2, the proposed and the related models can be put under different classes. A possible categorisation can be made as follows by looking at the organisation of the phases[34]:

- strictly cycle-based models (with phases visited according to a pre-defined order): Shewhart (1939) (cycle may be terminated at act phase), Polya (1945), Kolb (1984), Nilsson (1984), Dobson *et al.* (2006), Boyd (1986);
- nested loops or parallel loops: Bryant (2004);
- cycle-based models with a shared phase (all phases except one are visited in a pre-defined sequence, but they all interact with one of the phases): Kephart & Chess (2003), Albus (1991);
- branched cycles with a shared phase (a cycle is somehow defined, but short-cuts can be taken): Mitola (2000);
- purely phase-based models (phases are visited with a pattern depending on a specific instantiation or condition): Langley *et al.* (1987), Anderson & Lebiere (1998), Kieras & Meyer (1997), Artz & Armour-Thomas (1992), Celentano (2014).

A taxonomy obtained by considering more characteristics is presented in Fig. 27.

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[34] Some models (Schoenfeld, 1983; Garofalo & Lester 1985) are not explicitly categorised but may be regarded as belonging to the latter class.

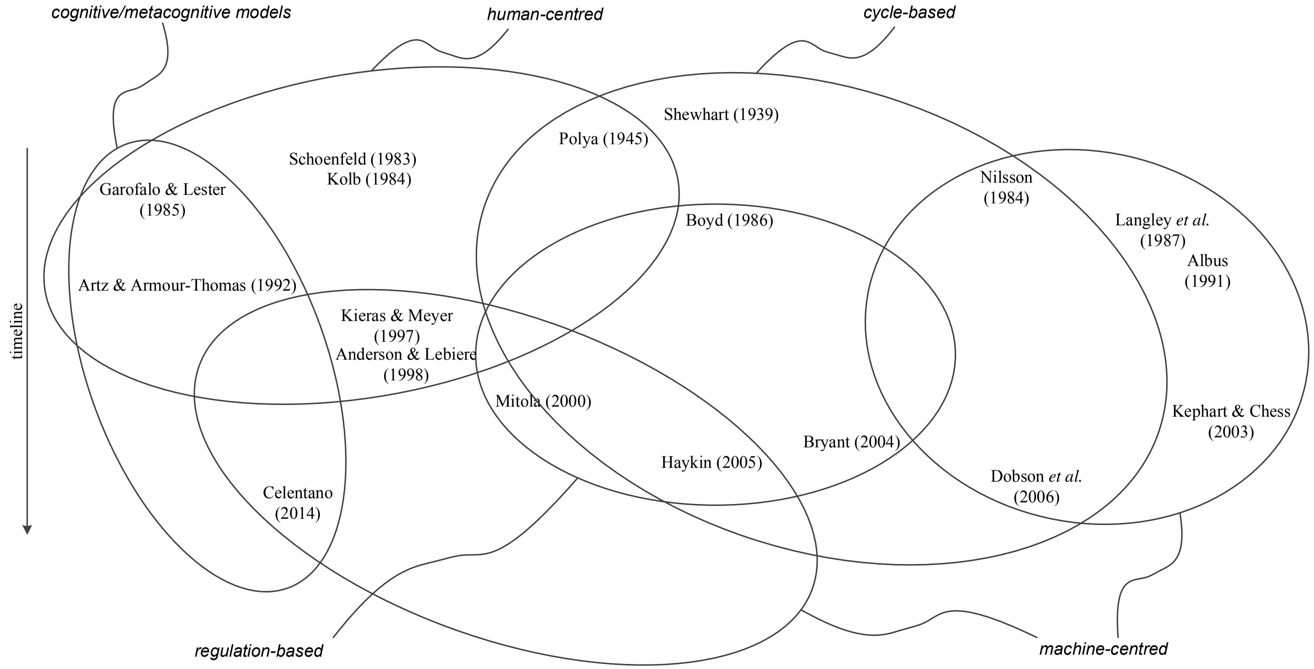

Fig 27. A taxonomy of the models summarised in Table 12.

4.5 Discussion

The previous chapters discussed, at system level, aspects of cognitive networks. Exploiting the gained understanding of them, this chapter presented a model for networked artificial cognitive entities. Before entering the details of that discussion, the chapter presented previous research on human cognition and learning as well as the corresponding studies for machines, where a categorisation of cognitive systems was also given. After the importance of socially shared cognition was discussed, this chapter presented in details the proposed model, contrasting it with exiting related models developed across a range of disciplines, and emphasising the introduced novelties. Considerations about instantiation of cognitive entities was finally given, thus preparing for the following chapters, which will present detailed solutions.

The framework presented in the previous chapter (in particular, Sect. 3.4.2) and the cognitive entity model presented in this chapter form together a possible design framework for cognitive radio networks.

Sect. 4.4.3 showed examples of how a cognitive entity interacts with other in some example cases considered in Chapt. 3. Where systems with few or many *independent* entities can be studied with elementary or statistical methods – total order and total randomness are the most simple mathematical models (San Miguel *et al.* 2012) – in the case of the networked cognitive entities considered here, i.e., in presence of *interdependencies* among adaptive entities, the result is what is called a complex system.

Complex systems may be shortly described as articulated compounds constituted of elementary entities. As Anderson (1972) observes, "at each level of complexity, entirely new properties appear". The presence of these emergent behaviours that the system exhibits when its components (together with their individual characteristics and actions) interact and that are not evident from the analysis of these components (Christakis *et al.* 2010) is the peculiar characteristic of complex systems.

These emergent properties are possibly not seen separating or obscuring those entities from the context they live in, and this is one reason for creating a model of the individual cognitive entities (Sect. 4.4.3), especially when their design is of interest. To gain understanding of the entirety $U_s = (\bigcup_{\forall e \in \mathscr{E}} U_e) \cup (\bigcup_{\forall x \in \mathscr{X}} U_x)$ it is sometimes not sufficient to just study its entities ($\mathscr{E}$), ignoring how they interwork ($\mathscr{X}$). These developments are left for possible future work.

5 Dependable context-aware networking

> I am enough of an artist to draw freely upon my imagination. Imagination is more important than knowledge. Knowledge is limited. Imagination encircles the world.
>
> – Albert Einstein (1929) *The Saturday Evening Post*, 26 Oct.

Chapt. 2 and Chapt. 3 illustrated a framework for cognitive communication networks design, capturing many related aspects. Chapt. 4 presented a model for generic networked engineered cognitive entities, where also some implementation issues are captured. Opportunistic spectrum use, within the focus of Chapt. 2 and Chapt. 3, is just one of the possible applications where context awareness can be beneficially exploited. Broadening the scope of the dissertation, this chapter discusses how context awareness can be exploited to improve system performance or its dependability, or to introduce new capabilities into it.

5.1 Introduction

With electronics becoming more powerful and cheaper, more and more appliances are integrating extra capabilities, including connectivity technologies. Communication devices include often more than one communication technology – for example, current cellular terminals include a short-range communication (SRC) technology, such as Bluetooth and increasingly also a near-field communication (NFC) interface – and objects that were until yesterday "inanimate" are now starting to "talk" with their environment. A large number of wirelessly interconnected, heterogeneous devices is usually referred to with the term Internet of Things[35]. How large it could be, is suggested by the definition for Internet of things given by Botterman (2009) as a world-wide network of interconnected, uniquely addressable objects; this is made possible by IP

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[35] Term first used by Kevin Ashton in 1999 (Ashton 2009, Botterman 2009). Related terms are smart objects (used by the Internet Architecture Board, IAB, a committee of the IETF and an advisory body of the Internet Society, ISOC, and also used within the IPSO Alliance), networked objects (Kortuem *et al.* 2010), smart utility networks (Sum *et al.* 2011), or wireless embedded Internet (Shelby & Bormann 2009). A related concept was anticipated by Weiser (1991), see also Want (2000), for ubiquitous computers generalised for their use but mainly intended for human interaction; still, such that they "disappear [and] weave themselves into the fabric of everyday life until they are indistinguishable from it."

version 6, IPv6 (Deering & Hinden 1998). Actors here range from very simple printed electronics, radio-frequency identification (RFID) tags or sensors, to more capable devices. Example application are tracking of people and goods, remote control and other forms of interaction of the objects with their environment, including M2M or, more generally, machine-type communications (MTC). More complex systems are possible on a longer time-scale, considering the progress in integration and also the possibilities offered by nanotechnologies, for example (Haykin 2005). The idea of "anything" interconnected, even its dimensional scale may be even world-wide, is indeed made of smaller-scale components. These are within the scope of this chapter.

Fixed appliances can be connected to the Internet directly by cabled connections, but mobile devices need (and even fixed may take advantage of) wireless connections, which can supported by cellular technologies, such as LTE, or shorter-range network, like WLAN or WPAN, for example (despite the name, a WPAN technology may serve diverse applications, including remote control, machine-to-machine, etc.). This chapter presents some solutions mostly developed for short-range communication network, possibly viable for such an application scenario. Solutions are often presented with realisation examples for selected technologies, mostly WiMedia, but they may sometimes be applicable to other technologies as well, although with due differences.

The IoT supports, and is composed by, machine- and/or human-driven applications. M2M or MTC communication typically, but not always, has strict delay requirements but is flexible in bandwidth needs. Due to this, system robustness is a key aspect and appropriate service topologies and carriers suitable to the target scenarios need to be identified. For some business cases, in which devices are battery-operated, energy efficiency is a fundamental aspect impacting system's lifetime and therefore its reliability. Aziz *et al.* (2013) collect a set of definitions for network lifetime. Our scope is to have all the relevant nodes alive and connected.

Interaction with the environment, including context awareness, is a key requirement. Moreover, with simple devices, efficiency, energy efficiency in the first place, is extremely important and this is addressed in this chapter.

The use humans make of these devices is in some of the following cases crucial. Indeed, as Kortuem *et al.* (2010) observe, the Internet of things is a human-centred system that cannot be decoupled from them. The mobility in networks formed by battery-operated (energy-constrained) devices brings a number of design problems to be solved: energy efficiency, interference avoidance, robustness, security and safety protection, to name a few. Some of these will be addressed in more details in the following sections, others represent too a wide domain and are therefore left out of the scope of this work.

In a continuously evolving area as ICT it is difficult, if not impossible, to identify clear points in which a technology is really mature and complete, thus ready to be definitively consolidated in an immutable standard. This means that sometimes improved features need to be added on top of pre-existing technologies and retro-fitting existing standards with improved features is a method to keep them up-to-date. This causes new problems, like backward compatibility as well as consistent behaviour. This aspect is addressed in this chapter.

As seen above, and on the basis of Chapt. 2 and Chapt. 3, it is clear that exploitation of context awareness is often beneficial. This information could be about the environment, own energy level and location, etc. In those first chapters, context related to opportunistic spectrum use has been covered, and in the following Chapt. 6, specific context metrics will be covered from a different perspective.

According to von Neumann (1966),

> "In building complex computing machines, unreliability of components should be overcome not by making the components more reliable, but organizing them in such a way that the reliability of the whole computer is greater than the reliability of its parts."

(Sreevijayan *et al.* 1994). Improvements of system reliability – for instance considerations regarding the choice of the topology (e.g., centralised or distributed) and the role of a network controller as well as robustness to its unavailability, enforcement of protection of sensible devices – are approached in this chapter from this viewpoint. The emphasis in this chapter is on the feasible realisation of the proposed solutions. Always, improvements over existing standards would be realisable through amendments, but in some cases they can also be added as enhancements in full compliance with legacy standard specifications. Feasibility of improvements over existing standards is discussed here. Implementation details are not reported here in their entirety, but they are available from the cited contributions.

Underlay access has been introduced in Chapt. 2 and the wide-spread presence of SRC has been highligthed above. The use of UWB signalling for such SRC networks started within IEEE 802.15 working group as Task Force 3a. One of the proposals was based on multi-band orthogonal frequency-division multiple access (MB-OFDM) technology and supported by the Multiband OFDM Alliance (MBOA). After debate in

IEEE 802.15.3a, no agreement was reached and that proposal, developed further within WiMedia Alliance, was eventually published by ECMA as High rate ultra wideband physical layer (PHY) and medium access control (MAC) standard, ECMA-368 (ECMA 2005), and then also as ISO and IEC standard ISO/IEC-26907 (ISO/IEC 2009). While PHY and MAC specifications reached version 1.5 (WiMedia Alliance 2009b,a) with rates up to 1024 Mbit/s, WiMedia Alliance transferred its UWB specifications to wireless USB and Bluetooth applications[36].

ECMA-368 has its channel-time divided into superframes (SF), in turn having a period dedicated to the control part, called the beacon period (BP) followed by a portion referred to as data transfer period (DTP). As also discussed below, associated devices are called the beacon group (BG). In Sect. 5.3.6, the ECMA-368 SF structure is enhanced.

Many of the features of ECMA-368 specifications have been incorporated into recent MAC and PHY for operation in TV whitespace, ECMA-392 (ECMA 2009) and High rate 60 GHz PHY, MAC and PALs, ECMA-387 (ECMA 2010). This makes the above technology more interesting and topical. In some sections of this chapter, ECMA-368 is used as an example target system, but for what seen above, some of those solutions could be applicable as well at least to ECMA-392 or ECMA-387 (ECMA 2010).

In addition to improved hardware technologies (Hasan *et al.* 2011), the techniques at protocol level for energy saving generally present in communication standards are mainly transmit power control and power management – with longer time scale (hibernation and similar) or shorter time scale (discontinuous mode).

This chapter is structured into three parts. Energy consumption and energy efficiency are introduced in Sect. 5.2, but being energy efficiency a background target throughout this chapter, it will come out again also in the following. Under Sect. 5.3 is discussed topology control, whereas various forms of dynamic environment, also including collaborative networking, are covered in Sect. 5.4.

There exists a vast research on the topics covered in this chapter. Broader literature reviews are available in publications and are not repeated here, but sharper discussion of articles more closely related to the work presented here appears in the following sections. Generic literature review on energy efficiency, being it one aspect addressed in many parts of this dissertation, is discussed earlier in Sect. 1.1.3. A recent review on topology

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[36] In March 2009, specifications were transferred to USB Promoters Group, USB Implementers Forum (USB-IF), and Bluetooth SIG (USB Implementers Forum 2009). Bluetooth version 4.0 for its BR/EDR (basic rate, enhanced data rate) has, as version 3.0 had, the possibility to use an alternative MAC and PHY (AMP), for example for higher rates.

control is made by Li *et al.* (2013) also providing their design guidelines. The taxonomy by Li *et al.* (2013) categorises the literature as covering network coverage and network connectivity issues. The former refers to the field monitored by the sensors and is not relevant here. The latter category, pertinent to this chapter, is about power management by use of energy saving states such as sleep or hibernation, and transmit power control. For network connectivity, Aziz *et al.* (2013) add clustering as a third class.

5.2 Energy efficiency

5.2.1 Introduction

As observed in Sect. 1.1.3, the growth of battery capacity is slower than the one of silicon density or bandwidth (Havinga 2000). This means that, in order to keep the pace, better energy efficiency and seek of alternative sources of energy, including harvesting (Paradiso & Starner 2005, e.g.), are needed. As outlined, energy efficiency gains can be searched in hardware and protocols.

On the protocol side, forms of energy waste include (Demirkol *et al.* 2006, Bachir *et al.* 2010) retransmissions, protocol and signalling control overhead (sending packets carrying control only with no data, or control information within a packet), idle listening (vainly listening a channel for possible relevant information), overhearing (listening to irrelevant transmissions not intended to a given node), over-emitting (sending when destination is not available). Strategies to improve energy efficiency include making better use of energy in busy states, reducing awake time (going into sleep) and active time (going into hibernation when possible).

Improvements in efficiency and energy efficiency in particular have been pursued also in standards. Efforts to facilitate M2M support in 3GPP cellular networks started in ETSI (2006), issued in ETSI (2007). This standardisation activity is ongoing also supported by research projects (Nitzold *et al.* 2012, e.g.). A low-energy version of Bluetooth (referred to as BLE) has also been specified and included in version 4.0 (released in June 2010), with a simpler state machine and the capability of handling larger networks up to 2^{32} devices, although at the cost of reduced topology flexibility: no scatternets are possible in BLE as they were in BR/EDR (Mackensen *et al.* 2012). BLE has been evaluated by Siekkinen *et al.* (2012) as more energy efficient than IEEE 802.15.4 (ZigBee), although Wong *et al.* (2013) noted that where BLE seems still efficient for episodic transmissions, IEEE 802.15.6, released February 2012, seems otherwise outperforming.

Since the MAC controls the radio component, it is among the main targets for energy efficiency improvements (Bachir *et al.* 2010). Energy efficiency for various MAC protocols is thoroughly covered in the literature and is not repeated here. The review article by Gummalla & Limb (2000) follows a classical categorisation, while Jurdak *et al.* (2004) and Bachir *et al.* (2010) follow categorisations according to the features or problem targeted, focusing on ad hoc networks and wireless sensor networks (WSN), respectively. Demirkol *et al.* (2006) provides also a survey on MAC protocols for WSN and Ray & Turuk (2009) a review on energy-efficient protocols for WLANs.

The remainder of this chapter addresses energy efficiency together with other goals. Here, specific problems are identified and solutions for them are presented, often in the form of enhancements to existing standards with augmented features, whilst preserving consistent behaviour of legacy devices.

5.2.2 Characterising power consumption

Energy consumption in a wireless communication device is mainly due to communication interface or wireless network interface (MAC and power amplifier within RF front-end), and computation or host central processing unit (CPU) (Havinga 2000, Rantala *et al.* 2009). The memory footprint, used for example to store the network status (Bachir *et al.* 2010), consumes a significant amount of power (Mudge 2001), for both access (dynamic) and just storage (leakage).

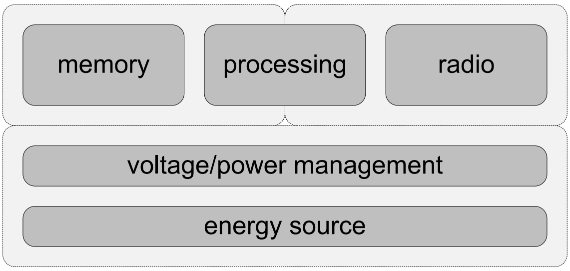

Fig 28. Main blocks of a communication device with related energy management.

Four contributions to power consumption can be identified in a cognitive radio device, see Fig. 28: two for the radio part, RF (power or low-noise amplifier) and its control (signal processing, error correction, MAC, etc.), and two for the calculations component, information processing or computation and storage: $e_t = (e_{\mathrm{amp}} + e_{\mathrm{proc}}) + (e_{\mathrm{comput}} + e_{\mathrm{mem}})$.

The energy cost for encoding is negligible but decoding contribution is not (Sankarasubramaniam *et al.* 2003), so the second term in the above expression is larger during reception. On the other hand, the first term depends in transmission on link distance and path-loss exponent, so it is dominant for longer range (Havinga 2000).

Transmit and receive (together denoted as busy), and idle states are dictated by the communication phases. They are characterised by different power consumption rates, as seen. Other activity states can be introduced in order to save energy by switching off unneeded components (called power gating). The device's power states are defined in Table 13. A qualitative relation of power consumption rate is given in Fig. 29, illustrating how power consumptions increases with the activity states.

The first four states in Table 13 are a smooth generalisation of the definitions given in ECMA-368 (ECMA 2005) and ECMA-392 (ECMA 2009). The last two states are added and apply to active devices only. Similar definition of busy and idle are usually related to a channel being used or not. Note that while a device is busy, the channel it is using may not necessarily be continuously busy, due to the used protocol, so the two definitions for channel and device state do not necessarily match (i.e., they will not, in general).

The power consumption of complementary metal oxide (CMOS) logic circuitry is composed by its dynamic and static (leakage) components: $p = p_{\mathrm{dyn}} + p_{\mathrm{sta}} \approx \alpha_g C_{\mathrm{eff}} V^2 f + V I_l$ (Mudge 2001, Kim *et al.* 2003), where α_g is the fraction of active gates, C_{eff} is the effective switching capacitance, V is the supply voltage, f is the operating frequency and I_l is the leakage current.

Reduction of capacitance is mainly related to chip design. Reducing f itself does not necessarily reduce energy consumption since the task lasts longer and the power gain is linear. Reducing voltage does imply a reduction in performance, but the power gain is quadratic. (Havinga 2000) The means to reduce power consumption are reducing the activity and reducing the voltage (Mudge 2001).

Chip frequency may be related to processing or operating radio frequency. About half of a receiver consumption directly depends on the RF frequency (Enz *et al.* 2004).

Table 13. Power and activity states.

State	Definition
awake	the device receives and sends signalling traffic (e.g., beacons) and able to receive and transmit data traffic
sleep	the device is not able to receive or transmit for a relatively short time (e.g., within a superframe)
active	device either awake or sleep; not hibernating
hibernating	the device does not receive or transmit for a relatively long time (e.g., multiple consecutive superframes); not active
idle	device (active and) not involved in data communication (only signalling)
busy	involved in data communication

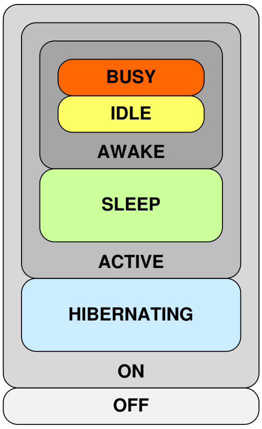

Fig 29. Power and activity modes. Power consumption increases from bottom up.

Hence, operating at a lower frequency such those in TV bands (see Sect. 1.1.2), already generates an energy save.

When the task allows, dynamic voltage scaling (DVS) and dynamic frequency scaling (DFS) can be used to save energy (Dargie 2011). If the task duration is to be preserved, DVS can be compensated with parallelism, as typically done in digital signal processors (DSP), to achieve a higher figure of instructions per second per power unit, or MIPS/W (Mudge 2001), although this is associated with an increase of the silicon area (Havinga 2000). However, a reduced voltage implies an increased leakage power, which otherwise is negligible (Mudge 2001). See Mudge (2001), Kim *et al.* (2003), e.g., for trade-off among supply voltage, maximum operating frequency and leakage. Havinga (2000) discusses in more detail dynamic power reduction by considering its four terms separately.

Havinga *et al.* (2000) observe that energy state transitions are associated with significant overhead. On the other hand, Havinga & Smit (2000) report that intermittent drain may benefit batteries, since during the relaxation time, lost voltage may be partially recovered. This is however true only for alkaline batteries, since for nickel-cadmium (NiCd) and nickel-metal hydride (NiMH) the behaviour is opposite and lithium ion (Li-Ion) are insensitive to that (Castillo *et al.* 2004). It is beneficial to have prompt move to low-power modes in presence of rare traffic or high mobility (Puttonen *et al.* 2012). Also the selection of the most appropriate energy saving state has its impact. In fact, Puttonen *et al.* (2012) observe that the transition of an LTE UE to awake from deep sleep costs about fifty percent more than a transition from light sleep.

The characterisation of the power consumption in a communication device continues in Sect. 5.2.3, where transition between power states and PHY-modes are considered.

5.2.3 A conjecture on power consumption

Fig. 30 reports a *conjecture* (Celentano *et al.* 2008b) about the power consumption during device operation when moving to awake (and busy) state using a higher-rate mode, to a sleep state and again awake (and busy) but now using a lower-rate mode. For simplicity of the description, two rates are considered in this example. Moreover, for the time being, those periods may include transmission or reception or both, but distinct contributions will be considered in the following. We limit to the active device, so other measures for power saving, like hibernation, are not considered in this section.

The device shall be awake for the first time between t_2 and t_3. In order to be fully awake at t_2, some guard time may be set and the target awake time start is specified as t_1. To be awake at t_1, some transceiver parts are put in awake mode and therefore a first power-on ramp may be seen. The shape of all the ramps depends on the hardware and may exhibit peaks not shown here. The power level moves from the lowest value p_D (deep sleep) to the operating value p_{hi}. After the first awake period, a first power-off ramp may be seen. The power goes to a lower value p_S, possibly slightly larger than p_D. This is due to fact that the device is ready to go awake again in a shorter time.

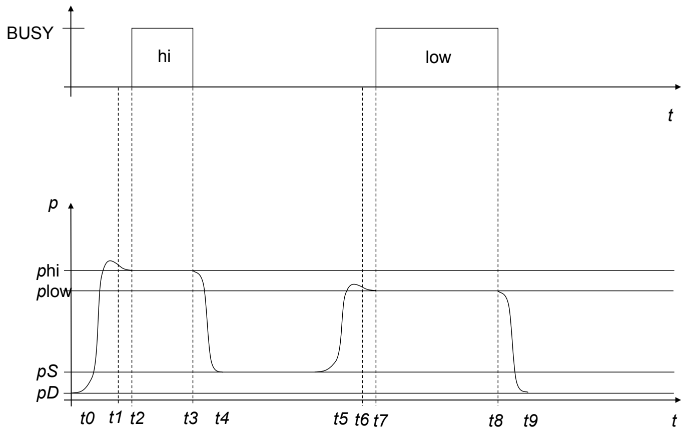

Fig 30. Example power consumption during various activity states. In the figure two distinct PHY-modes are used in the two intervals shown. When distinct modes are used, different values for power consumption may be assumed. Between the two busy periods, sleep is assumed (at p_S in the figure) for fast activity set-up compared to a lower power, deep sleep mode (at p_D in the figure). Levels are indicative to illustrate an example behaviour. Revised from Celentano *et al.* (2008b).

Alternatively, the power goes to the lowest value p_D, depending on the time the device expects to stay in that sleep or deep sleep mode.

The device shall be awake again between t_7 and t_8. Similarly, some guard time may be set and the target awake time start is specified as t_6. To be active at t_6, some transceiver parts are put in awake mode and therefore a second power-on ramp may be seen. The power moves from the intermediate value p_S (or alternatively from the lowest p_D) to the operating value p_{low}. After this second active period, a second power-off ramp may be seen. The power goes to the lowest value p_D (or alternatively again to p_S, depending on the scheduled activity).

Different receiver configurations may be needed with different PHY modes (due to the possibly different demodulator and decoding architectures, antenna configuration, etc.). Correspondingly, also the power consumption in reception may depend on the rate used. For short-range communication systems, power consumption is larger in

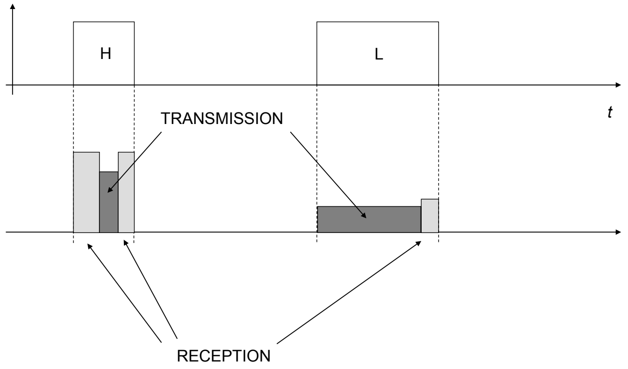

Fig 31. Example operations of a device. In a first awake time, the device is using a transceiver mode H and is engaged on both reception and transmission. This may be for example the beacon period, in which devices of a distributed network send their beacons. In a second awake time, the device is engaged again in both transmission and reception. This may be for example the data transfer period, in which exchange of data is performed. Transmission may be for sending data and reception may be for an acknowledgment and/or other feedback information. Revised from Celentano *et al.* (2008b).

reception than in transmission; for example, $p^{(\mathrm{rx})} = 1.26$ mW and $p^{(\mathrm{tx})} = 0.72$ mW is used in Goratti, Celentano & Salokannel (2006).

The busy phases shown in Fig. 30 may be associated with different periods, such a network control or beacon period and a data transfer period. In those, both transmission and reception occur, as shown in Fig. 31.

Fig. 32 details the power consumption levels and the activity phases seen before in Fig. 30 and 31, respectively. The effective values p_{up} and p_{dn} shown in Fig. 32 depend on the duration of the transients and the shape of the ramps and may be defined using $p_{\mathrm{up}} = \frac{1}{\tau_{\mathrm{up}}} \int_{t_0}^{t_2} p(t)\mathrm{d}t$ and $p_{\mathrm{dn}} = \frac{1}{\tau_{\mathrm{dn}}} \int_{t_3}^{t_4} p(t)\mathrm{d}t$, where $\tau_{\mathrm{up}} = t_2 - t_0$ and $\tau_{\mathrm{dn}} = t_4 - t_3$ are the rise time and fall time, respectively.

The above applies, as said, to an active period. When also hibernation is considered, the total energy consumption is obviously $e_t = e_H + e_A$, where the contribution due to hibernation is simply $e_H = p_H T_H$, where p_H is the power consumption rate and T_H is the time spent, both during hibernation. In more details, the energy consumption for

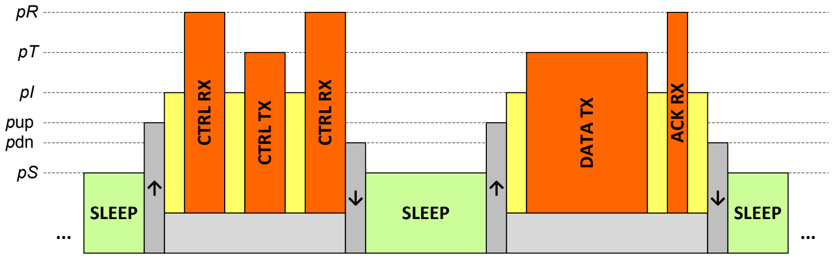

Fig 32. Example of operations for an active device. The activity phases power states are shown for a device involved first in a network control phase (beacon period) and then in a data transfer period. In this snapshot, one PHY mode is used.

an active device can be obtained by summing all the contributions shown in Fig. 32 (Celentano *et al.* 2008b), giving:

$$e_A = p_S T_S + N_{\mathrm{up}} p_{\mathrm{up}} \tau_{\mathrm{up}} + p_I T_I + \sum_{m \in \mathscr{M}} p_m^{(\mathrm{tx})} T_m^{(\mathrm{tx})} + \sum_{m \in \mathscr{M}} p_m^{(\mathrm{rx})} T_m^{(\mathrm{rx})} + N_{\mathrm{dn}} p_{\mathrm{dn}} \tau_{\mathrm{dn}} \qquad (7)$$

where p_S and p_I are power levels during sleep and idle states, respectively; p_{up}, p_{dn}, τ_{up} and τ_{dn} are defined above; $p_m^{(\mathrm{tx})}$ and $p_m^{(\mathrm{rx})}$ are power levels at transmission and reception, respectively, with PHY mode m in the supported set $\mathscr{M}$; T_S, T_I, $T_m^{(\mathrm{tx})}$ and $T_m^{(\mathrm{rx})}$ are durations of the time spent in the respective phases during a reference time; and N_{up} and N_{dn} are the number of transitions (deep) sleep to active and active to (deep) sleep, respectively, during the same reference time. An expression similar to (7) but for a single-mode transceiver is given by Bormann (2011).

5.2.4 Energy-efficient (meta)cognitive functions

From what seen, it is clear that a device – in general, not a cognitive one specifically – should pursue as long as possible at lower consumption states, but the state transitions should be carefully evaluated to actually achieve an energy gain. In other words, a self-aware device may improve battery lifetime, but this should be done with no or minimal calculations, to save CPU consumption. Certainly, processing and memory consumption tend to be more important in cognitive radio systems, so for an energy-efficient cognitive device, the cognitive part should be properly designed. (Cognitive and meta-cognitive functions have been distinguished and defined in Chapt. 4. Where such a distinction is not needed, the term cognitive refers in this chapter for simplicity to meta-cognitive functions as well.)

We have seen in Chapt. 4 that a human-like cognitive entity processes the gathered information to generate knowledge during less activity-intense periods (see footnote 25 on p. 106). This may be not necessarily the best choice for an artificial entity. Low-power states should exploit frequency scaling, thus processing power is correspondingly decreased. This means that computationally intensive operations, thus requiring high clock frequency, may not be energy-efficiently done during communication-inactive periods: if able to do so, these might be best allocated just to full-clock states. On the other hand, state switching eats power and static power consumption does not depend on frequency. Hence, a *learning* power state can be identified, with processing subsystem running on higher power and communication subsystem possibly on a lower one.

5.2.5 Dependable data transmission using beacons

Along with high-rate, a number of low-rate applications are becoming more and more important. Lower-rate service may also coexist with higher-rate traffic in the same appliance. One example could be a remotely controlled mobile equipped with a high resolution vision system. Another example of mixed rate sub-systems is given in Sect. 5.3.6.

Many relevant applications, such as remote control and M2M, while having loose requirements on datarate, they have very tight latency constraints requirements. Whereas technologies dedicated to low-rate systems such as IEEE 802.15.4 do exist, due to the variety of service demands, parallel use of more radio access technologies may not always be recommended. For example a user or a machine could be otherwise equipped with a high-rate communication system, which could potentially be exploited also for low-rate application. This may reduce complexity in some devices.

Carriage of low-rate data is often inefficient, due to the protocol overhead caused by header, preamble, etc. Considering that for some application even few bits or few tens of bits may be sufficient, this may represent a source of huge inefficiency. Relevant examples include, in addition to remote control[37] service, also distributed or centralised sensing traffic, see Sect. 3.4.2. Those services can be efficiently served with the method presented here.

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[37] Remote control traffic is not to be confused with control traffic, needed for network control and pertaining to the control plane. Indeed, the method described here can be regarded as cross-plane service.

Beaconing systems rely on beacons for maintaining network connectivity and therefore all associated devices always send their beacon when active (non-hibernating) with given periodicity. In those cases, data that could fit inside an information element (IE) as part of the beacon (Celentano *et al.* 2008c), can be transferred at virtually zero overhead.

Cross-plane data transmission for efficiency

Data transmission over beacons allows prompt and efficient transfer of small data payload. The transfer is prompt because there is no need to gain a slot in the data part. It is also efficient since, as seen, overhead is drastically reduced and collision is avoided[38].

Consider the example system ECMA-368. The maximum beacon size in bits is here referred to as `MaxBeaconSize`. Using the values from the specifications[39], its duration is calculated as

$$\begin{aligned}&\texttt{MaxBeaconSize} = \\ &= (\texttt{mBeaconSlotLength} - \texttt{pSIFS} - \texttt{mGuardTime})\,\texttt{pBeaconTransmitRate} = \\ &= (85 - 10 - 12)53.3 \approx 3357\ \text{bit} = 419\ \text{octet}\end{aligned} \tag{8}$$

Now let us see which part of the above quantity is available for data to be sent by the proposed Data-IE (Celentano *et al.* 2008c). Actually, Celentano *et al.* (2008c) specify a set of information elements for set-up, data and acknolwedgements.

According to ECMA-368, some IE shall always be sent, while other should or may be sent depending on certain circumstances or are left optional. The maximum amount of room available for data depends therefore on the IEs that need to be transmitted. In principle, the entire beacon slot (BS) or almost all of it could be used. In practice this is not the case and in the following we will consider some example scenarios. In dynamic conditions, devices send some beacons during the transients. In the example scenarios considered here, static conditions are assumed. Clearly, in dynamic conditions, the room for data may be smaller for the time needed for performing the relevant IE exchange. The only IE listed in the specifications which is explicitly stated to be sent always is the beacon period occupancy information element (BPOIE).

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[38] With a different approach, (Sheu *et al.* 2011) propose to improve efficiency of MTC over LTE by embedding the data into the authentication messages, thus avoiding the need to establish a bearer after authentication.

[39] The parameters starting with letter `m` are the MAC parameters and those starting with letter `p` are the PHY-dependent parameters.

Table 14 shows the beacon occupation in octects in some example scenarios. In the standard, the DRP IE is used by the distributed reservation protocol (DRP), similar to the channel reservation protocol (CRP) of ECMA-392, and the hibernation IEs are used to manage hibernation. Further details are in the specifications ECMA (2005, 2009).

Table 14. Beacon slot occupation in octets in example scenarios. A: two non-power-sensitive devices. B: two power-sensitive devices. C: twelve devices, the two corresponding devices are not power-sensitive. D: twelve devices, the two corresponding devices are power-sensitive and the rest are all hibernating.

	A	B	C	D
beacon parameters	8	8	8	8
BPOIE	10	8	33	8
DRP IE	8	8	8	8
Hibernation mode IE	-	4	-	4
Hibernation anchor IE	-	-	-	32
Total	26	28	49	60

The minimum overhead of the above protocol is one octect (Celentano *et al.* 2008c). Using now (8) and L_b from Table 14, and since the superframe period is $T_{\mathrm{SF}} = 256\, \mathtt{mMASLength} = 65.536$ ms, it is found that the maximum sustainable capacity with the Data-IE is

$$r_{\mathrm{Data-IE}} = \frac{1}{T_{\mathrm{SF}}} \left(\mathtt{MaxBeaconSize} - L_b\right) \approx 48\ \mathrm{kbit/s} \tag{9}$$

(this applies to scenario A; for scenario D $r_{\mathrm{Data-IE}} \approx 44\ \mathrm{kbit/s}$). The above datarate should be enough for some application. As a reference, consider that IEEE 802.15.4 provides $(20 \div 250)\ \mathrm{kbit/s}$ (Shelby & Bormann 2009).

Some standards specify information elements whose use is not ruled by the specification, and must be safely ignored by generic standard-compliant devices. For example, ECMA-368 specifies the so-called application-specific information elements (AS-IE). An implementation using those IEs allows the addition of enhanced features to a standard without the requirement of any amendment but still in a robust way in that any legacy device not implementing the added feature shall, according to specifications, ignore and discard those unspecified information elements (e.g., AS-IE) or information elements otherwise not recognizable.

Virtual transmission of payload for efficiency

When the special IE discussed here does not contain any address, the intended destination is any receiving device (*implicit addressing*). Otherwise, if needed to distinguish recipients, the target address can be explicitly added to the IE (*explicit addressing*).

Corresponding devices are the information source and the related destinations. Prior to the data exchange, there may be a set-up phase between a pair of devices (or among more devices) on the creation of such a data service between or among them. At set-up, corresponding devices may agree on the Data-IE length. All Data-IEs that are sent are therefore agreed to be of known length, further improving overhead reduction. Otherwise, to support variable data size, the Data-IE shall include a Length field.

Any recurrent payload content may be considered as a well-known payload. To further reduce the required size of the Data-IE payload, at set-up, a code may be associated with a corresponding well-known payload, or to an action or more generally to any meaning of the carried information. After a set-up phase, only those codes are actually sent with this *virtual transmission of payload* (Celentano *et al.* 2008c).

The corresponding needed set-up information may be represented by a look-up table. The codes are in this case addresses to that table, used at destination side to fetch the intended information. This is represented by at least the device addresses (destination address), in case of explicit addressing, and the stream index specifying the information stream the payload refers. The payload may be as small as a few bits.

In addition to the above information, also the payload may be coded into the address, so that the table includes basically the actions for all possible destination devices participating the set-up phase. The set-up phase may be performed once per session. Therefore, the amount of information exchanged during set-up has possibly little effect on the final efficiency of the entire communication session[40]. Moreover, the set-up information may be retained for possible use in a future session.

Virtual transmission of payload for security (confidentiality)

With virtual transmission of payload, the exchange of a code corresponds to a virtual exchange of the entire record addressed by that code. These are like keywords for some

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[40] The set-up phase may be performed with or without the use of data transfer period. The use of DTP may be needed in case the set-up information to e exchanged is so large to not fit into the information element payload of one or a few beacons.

information to be transmitted. Source and destination agree on a set of well-known payload they may exchange in the future. Actual payload samples may be exchanged at set-up time while building the table. Otherwise, they may be, e.g., hard coded or pre-programmed into devices. In practice, the MAC receives from upper layer some well-known payload to be transferred. If not known in advance, the table may be built dynamically, forming a sort of caching. After some processing/search at source side, that payload is coded into an address previously agreed with the destination. Instead of really transferring the payload, the source device sends the code. The destination gathers the actual payload from the table and sends it to upper layer. Basically, exchange of codes/addresses represents the virtual exchange of payload between source and destination. Virtual transmission of payload is comparable to source coding.

The actual payload exchanged during the set-up phase may be a string of data, possibly recurring with some frequency in transmissions. Indeed, any possible payload could be coded regardless of its actual recurrence rate. In this way, the set-up table could be exchanged using secure transmission (Celentano *et al.* 2008c). The following data transmission does not need to be secure, since the address alone does not offer any use to possible eavesdroppers[41].

5.3 Flexible network and topology control

5.3.1 Topology selection

The topology of a communication network may be selected considering the role the network nodes have. If one of the node has a central role, such as a gateway, for example, and possibly is more powerful than others, a centralised control may be appropriated. On the other hand, a distributed control is generally more robust to controller node unavailability. To improve efficiency, a network may also realise a mixed topology. For example, IEEE 802.15.3 WPAN has a star control topology and a mesh data topology.

One goal of topology control is minimising interference. Connecting always to the nearest neighbours not necessarily represents the best choice for interference efficiency (Burkhart *et al.* 2004). However, an optimal topology generally requires knowledge of

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[41] The actual security level depends on the way the encryption is done; details are beyond the scope of this method. Simple monoalphabetic ciphers can be broken by cryptanalytic attacks by observing the encrypted stream and exploiting for example language redundancy (observing their statistics). Polyalhpabetic ciphers flatten the frequency distribution and therefore make encryption stronger. More complex ciphers protect better. See Stallings (2010, e.g.).

the network beyond the one locally available. As network size grows, costs (overheads) associated with global knowledge are prohibitive. Knowledge about the network impact effectiveness of topology control. Komali *et al.* (2010) and Komali & Mähönen (2009) analysed the price of ignorance – a special case of a more generic price of feature in Thomas *et al.* (2007) – i.e., the performance loss due to partial knowledge compared to global knowledge, finding preferable deepness (in the number of hops) of knowledge that guarantees optimal performance.

In the remainder of this section are covered issues related to robustness and fairness in central network control, to clustering, and to flexible topology control.

5.3.2 Network control and dependability

Centralised and distributed control

With a centralised topology, the network controller has full view of the status of the entire network and manages the resources the network uses. Whereas it brings some advantages such as simplicity of control and clear hierarchy of network devices, a centralised topology has some disadvantages as well. The most important is probably the dependency of the entire network on the availability of a single device. A centralised network is also referred to as a star topology (Baran 1964).

The other extreme is distributed network control, sometimes called also grid or mesh topology (Baran 1964) or flat, regardless of being it single or multi-hop (Jurdak *et al.* 2004). Moving from a centralised to a distributed topology, observability of the global view may suffer, thus introducing a trade-off between controllability and scalability (Leibnitz *et al.* 2007).

It is however clear that distributed networks have advantages over centralised topologies. The former do not rely on a single co-ordinator, but rather all devices act as distributed co-ordinators. In other words, a distributed network introduces redundancy, which provides improved robustness to disappearance of one of the devices in dynamic or noisy environments or to a single node destruction. A node destruction could be due to failure of the node or an attack to it, mainly differentiating in the probability distribution of such event (Baran 1964).

Despite its benefits, a distributed system does also have some disadvantages. Clearly, this solution brings additional network overhead due to distributed network management. In addition to that, all awake (non hibernating) devices are generally required to either beacon at fixed intervals or to scan common channels, which in either case adds energy requirements on those.

As a compromise between the two, hybrid solutions present a few, instead of just one “central” node, leading to a clustered topology (Jurdak *et al.* 2004), sometimes referred to as decentralised (Baran 1964).

In the problems considered in the remainder of this chapter is identified a responsible role, of which the above case of resource control is one example. That role can be taken in the two extreme cases by one or all network members, or more generally by a smaller number of capable devices.

Reliability and availability of redundant configurations

In a system with one component having failure function $F^{(k)} = F^{(k)}(t)$, the system reliability function is here denoted as $R^{(\underline{1})} = 1 - F^{(\underline{1})} = 1 - F^{(1)}$. With a redundancy level n and under the assumption of independent failures, the system reliability function is $R^{(\underline{n})} = 1 - \prod_{i=1}^{n} F_i^{(n)}$.

It has been observed that the failure rate[42] for a component $\lambda_F(t)$ decreases during the initial burn-in and increases at the final wear-out, but it is almost constant during the useful lifetime, which justifies the commonly accepted assumption of Poisson failures or exponential distribution of the time between failures, which gives the mean time between failures[43] (MTBF).

The system is unavailable until repaired. Assuming also constant repair rate μ_f, the system availability is

$$p_A = \frac{\mu_F}{\mu_F + \lambda_F} = \frac{\text{MTBF}}{\text{MTBF} + \text{MTTR}} = a \tag{10}$$

where $\text{MTBF} = 1/\lambda_F$ and $\text{MTTR} = 1/\mu_F$ is the mean time to repair.

Discussion

Clearly, even with a relatively small number of redundant components, the allowable component failure probability $F_i^{(n)}$ can be orders of magnitude larger than $F^{(1)}$ allowed

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[42] The failure rate is found (Gross & Harris 1998, e.g.) from $\lambda_F(t) = f(t)/(1 - F(t))$, where $f(t)$ is the failure probability density function. The probability of a failure during the interval $(t, t + \mathrm{d}t)$ is $f(t)\mathrm{d}t = \Pr\{t \le T \le t + \mathrm{d}t | T \ge t\}$, and the right-hand-side can be written as $\Pr\{t \le T \le t + \mathrm{d}t, T \ge t\}/\Pr\{T > t\} = f(t)\mathrm{d}t/(1 - F(t))$.

[43] Under this assumption, the MTBF of the parallel system is $\sum_{i=1}^{n} (-1)^{i+1} \binom{n}{i} \frac{1}{i\lambda_F}$ (Ha 1990).

for a simpler architecture. Repairing or replacing a responsible device at any feasible location for a distributed system may be easier than replacing a central responsible device at its location prescribed for operations. Hence, a redundant system may exhibit also a smaller MTTR, thus further improving the system availability.

5.3.3 Robustness and fairness in wireless connectivity

As seen above, a centralised topology relies on the availability of the *central co-ordinator* or *controller*. This could be the co-ordinator of a centralised network or any other similar role, such as a piconet master or a cluster-head, or as the *information collector* or the *hibernation anchor* discussed in Sect. 5.3.6 and 5.3.3, respectively. Any possible measure increasing the reliability of a central co-ordinator translates into a more robust network as a whole. The role of co-ordinator is not necessarily to be linked to a single physical device, but can be dynamically selected among all capable network member devices. For example, in a centralised ad hoc network, more powerful devices may act (always or more often) as co-ordinator, to relief the other devices from the related energy consumption overhead. Similar central roles are found also in distributed controlled network, for instance in presence of hibernating devices.

Energy-aware handover of responsible role

To increase the network lifetime of centrally controlled networks, the role of the co-ordinator may be shared among capable devices imposing fairness on energy availability (Salokannel *et al.* 2008, 2011), see Fig. 33, thus also improving network reliability by increasing the lifetime of the network as a whole.

When the energy level of a battery-operated controller falls below a threshold, handover of such a role can be initiated. More generally, as the energy level of a device falls below a threshold, this information can be shared with the rest of the network, so that appropriate actions can be taken. For example, a residual energy level may be indicated by four levels and associated with the interpretation as the capability to act as co-ordinator; for example (Salokannel *et al.* 2008, 2011): 3 (mains-operated): co-ordinator role always possible; 2 (battery almost full): co-ordinator role now possible; 1 (battery half or less): co-ordinator role not desirable; 0 (battery almost empty): co-ordinator role not possible. A solution with three classes, 3, 2 and 1 merged, and 0 is realisable with *regular* IEs of IEEE 802.15.3 MAC (Salokannel *et al.* 2008, 2011).

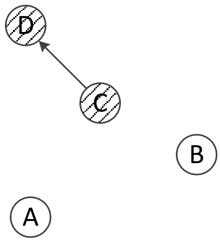

Fig 33. Handover of controller/collector/anchor from device C to D. Revised from Salokannel *et al.* (2008, 2011).

The weighted clustering algorithm by Chatterjee *et al.* (2002) selects the cluster-head based on the minimum of a weighted sum, in which one addend takes into account the cumulative time the node acted as cluster-head, related to energy consumption, assuming all nodes having equal batteries, initial charge, etc. The present approach takes into account the real condition of the batteries; moreover, in Salokannel *et al.* (2008, 2011) the current co-ordinator can, if needed, request handover of the co-ordinator role, based on the gathered awareness of battery levels of capable devices in the network.

Resilience to responsible node unavailability

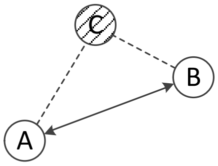

Fig 34. Re-establishment of connectivity between devices A and B upon disappearance of a central controller or hibernation anchor C. Revised from Reunamäki *et al.* (2012, 2005).

With a centralised topology the disappearance of the central co-ordinator may imply the immediate loss of connectivity among all associated devices. As seen, a similar case occurs in presence of hibernating devices in distributed control networks. This problem may be corrected by automatic renegotiation of co-ordinator/responsible and allowing associated devices to continue communication during negotiation (Reunamäki *et al.* 2012, 2005).

In a network with distributed control and hibernating devices[44], such as ECMA (2005, 2009, 2010), one device, a hibernation anchor, must remain active to keep network status. The hibernation anchor carries relevant information of hibernating devices, to avoid that hibernating devices completely disappear from the network. In ECMA (2005) the anchor includes this information in a dedicated information element. Devices coming back from hibernation shall re-synchronise and wake one superframe before the planned communication.

In case of failure of the hibernation anchor and especially in case critical applications are served, those re-activating devices may be allowed to keep the previous scheduling, see Fig. 34, and send their beacons together with a special field and re-start quickly the network (Reunamäki *et al.* 2012, 2005), which should be possible if the accumulated clock drift is not excessive. This solution improves the network availability by reducing the mean time to repair.

5.3.4 Supporting spatial reuse in distributed control

As its title suggests, this section is not about the improvement of capacity by spatial reuse. Rather, it discusses how such an improvement can be supported.

It is known that spatial spectrum efficiency expressed in terms of bit/s/Hz/m^2 can be improved by reusing channels. While in cellular networks this is achieved by planning cells and radiation patterns of base stations as well as controlling transmit power levels, in distributed networks, knowledge about the network topology must be obtained by the member devices.

Simultaneous transmissions are allowable when the signal to interference ratio, or the ratio of the distances at receiver of corresponding and interferer transmitter, is above a threshold; these are the physical and protocol model, respectively, in Gupta & Kumar (2000). In practice, the needed information is whether a certain connection between a pair of corresponding devices can be considered “local”. This knowledge can be obtained by absolute positioning algorithms, providing the co-ordinates of devices in a reference

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[44] Reunamäki *et al.* (2012, 2005) also give a basic solution for centrally-controlled networks, providing resilience to network controller unavailability.

co-ordinate system, or relative methods that exploit ranging capabilities. Due to possible presence of obstacles, such as walls, methods using information on position or mutual distances may not be effective unless they are coupled with additional information about propagation characteristics, such as terrain information or a geolocation database.

Since the signal strength between pair of devices is the key factor, a practical metric is the received signal strength indicator (RSSI). Usually, RSSI of neighbour nodes is available at a device with no overhead and a vector of those can be built locally. In distributed control networks, beacons are usually transmitted at known (maximum allowed) power to ensure the largest coverage. If this is not the case, information on transmit power is also needed.

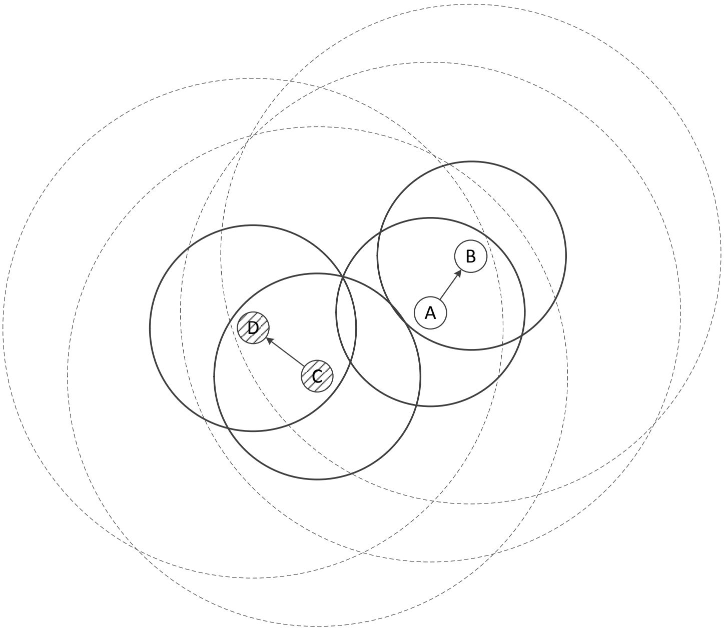

Fig 35. Data clustering (solid lines) between pairs A-B and C-D. Control topology (dashed lines) is also shown for the case described in Sect. 5.3.4, whereas a smaller coverage may be used also for control in the case of Sect. 5.3.5.

The above vectors may be exchanged (periodically or triggered by topology update events) so that any device is able to maintain a connectivity table of RSSI values providing the needed vicinity information. As a device announces its plans to send data to its destination using a given spectrum resource (channel and time slot), the collision resolution protocol ran at devices may use this information together with the RSSI table to decide upon the feasibility of simultaneous transmissions. Instead of exchanging RSSI vectors, devices may send the RSSI of their used link while announcing their transmissions, thus building the RSSI table is made possible by learning (cumulated knowledge). (Destino *et al.* 2009).

Fig. 35 shows control as well as data topologies for the scenario described here. In this case, control and data topologies are distinct: the network topology is a disconnected graph in the data plane but still a connected graph in the control plane. A different control topology choice is considered in the following section.

5.3.5 Network population control

The main target in previous Sect. 5.3.4 is an increase in resource utilisation, but a reduction in transmit power also implies an energy save[45]. As personal networks operate in a device-dense environment, the problem of efficiency arises. For example, in distributed MAC networks as ECMA (2005) (and similar, see Sect. 5.1), the network group size, and the associated energy consumption with it, may grow unacceptably. Methods for controlling the network population, may be beneficial to improve efficiency, especially in terms of energy.

Network devices need to be connected before actual communication may occur. In centralised networks, devices associate with the network co-ordinator and in distributed networks, devices associate with each other and this is achieved in some systems by the use of beacons. To ensure connectivity, all devices must in general pursue reciprocal exchange of uncorrupted beacons, irrespective of propagation conditions.

Concurrent networks should avoid destructive collisions whilst allowing possibility of communication among devices. In order to reduce collisions and improve coexistence, merging of neighbouring and potentially interfering networks may be imposed: as originally distinct network come in proximity, i.e., as devices are able to listen each other, a merging procedure is started, causing all the devices merging as members of the same, larger network. According to some standard specifications such as the above ECMA (2005), devices are not allowed to ignore other devices they may be connected to.

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[45] This depends on the application scenario. For example, for sensor networks with duty cycle of one percent or smaller, transmit energy is not the most important parameter (Enz *et al.* 2004).

However, especially in crowds, not all the network members are actually corresponding devices, and network merging cannot always be completed in mobile scenarios.

The device filtering procedure in BLE specified by Bluetooth SIG (2010) allows avoiding responding to devices outside a white list. The solution described in the following is more drastic.

Neighbour population size may be reduced by including only the really needed neighbours (i.e., the corresponding source-destination pairs/groups)[46]. The minimal neighbour subset is defined by the natural clusters identified for example when information about associated or paired devices is explicitly available. In lack of this information, a similar knowledge may be gathered cognitively by looking at the traffic streams, or from specific and relevant device capabilities. However, when selecting the minimal neighbour subset, one aspect to consider is the availability of neighbours capable of acting as hibernation anchor.

Differently from what seen in the previous Sect. 5.3.4, a pure clustering is then obtained, as disjoint clusters are now disconnected also for control. The reduction of the neighbourhood size brings a two-fold benefit in energy consumption due to *both* transmit power *and* network control signalling reduction. One possibility to achieve this, consistent with specifications, is to move to another channel, which brings an energy gain due to the reduced BP length. Another possibility is to reduce beacon transmit power so that also control topology gets smaller, bringing an additional saving contribution. Once a network is smaller, further energy gain may be achieved by exploiting datarate scaling as described in Sect. 5.4.2. If occasional connection with the previous larger group is needed, the methods of following Sect. 5.3.6 can be applied. The burden is then put on a selected, possibly more energy-robust device.

5.3.6 Efficient and flexible beaconing structure

A disadvantage of a distributed control is the fact that all awake devices are generally required either to scan common channels, or to beacon at determined intervals (a device is otherwise disassociated if is not heard in a specified interval; for example, in ECMA (2005) this time is `mMaxLostBeacons` $\approx$ 197 ms). The redundancy intrinsic in distributed control implies that each member device must replicate at least part of the status of the entire network, such as the information on connectivity and possibly on hibernation (see Sect. 5.1 and 5.3.2). First, there could be strict limits on the number

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[46] In Sect. 6.4 is discussed the source-destination distance in infinite crowds.

of network members (e.g., in ECMA (2005) the maximum number of beacon slots is 96), and in any case this method does not scale well, as any member of the BG needs a dedicated BS in the BP, which eventually could take a good portion of the SF, also because beacons must be transmitted with the strongest mode, which is also the less spectrum-efficient. Second, beaconing may cause an intolerable energy consumption for some devices.

When tight beaconing periodicity is not tolerable for resource or energy efficiency reasons, and regular hibernation is also not appropriated for service purposes, a hybrid topology may be adopted, for example with a centralised sub-network embedded into a distributed larger group (Celentano *et al.* 2007). In such as layered architecture, described in this section, the role of the co-ordinator/gateway may be shared, as seen for example in Sect. 5.3.3.

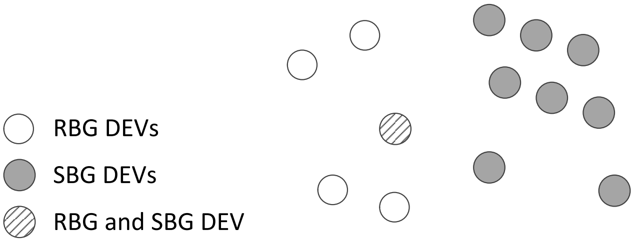

Fig 36. A hybrid topology network. One part of the devices (with clearer filling) are member of a distributed network and another part (with darker filling) of a centralised one. The controller of the centralised network (with patterned filling) is member of both. Revised from Celentano *et al.* (2007).

For the generic topology of Fig. 36, two cases are presented in the following. In the first scenario, are present a critical devices sub-group (CSG) and a large population sub-group (LSG). The second scenario concerns a high-rate group (HRG) and a low-rate group (LRG). For what discussed above, the CSG and HRG can be regarded in some cases as legacy devices, and are both referred to as the regularly beaconing devices sub-group (RBG). Correspondingly, the LSG and LRG are therefore called special beaconing devices sub-group (SBG).

Where in the first scenario CSG-devices and LSG-devices are possibly part of the same BG, in the second case the HRG and LRG possibly form disjoint networks, depending on the different PHY-mode set. This issue is further discussed later.

Support of large population

As the network population grows, regular and full beaconing of all devices starts getting resource and/or energy inefficient. A solution to this is to reduce the need of beaconing for some devices (Celentano *et al.* 2007).

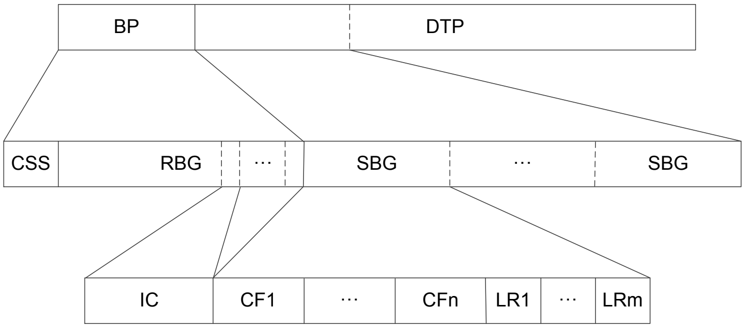

Fig 37. Example for support of large population with contention-based full beaconing and contention-less reduced beaconing depicted. Revised from Celentano *et al.* (2007).

In some applications, a subset of devices does not need tight beaconing. An example is given by a multicast application with a large number of sink devices, like in audio or multimedia content distribution. For them, the source device represents naturally a candidate for a central reference device. The information pertaining to those devices can be collected and possibly fused (removing redundancy) at a delegated information collector device (IC-DEV).

LSG devices do not need frequent updates of their information, and updates can be done for example in contention-based slots, the contention full (CF) BS shown in Fig. 37. As an alternative solution, associated LSG devices may optionally have assigned a very short slot, also to acknowledge by a flag that the information sent by the IC-DEV is correct, and/or to announce the need of an update or correction. In this case, the contention-less reduced (LR) BS in Fig. 37 are used. These may also serve to show that those devices are still alive. Additionally and optionally, an LSG device may send a bitmap for correctly/erroneously received BSs sent by other LSG DEVs. In case more LSGs are present, corresponding SBG portions of the SF are allocated, as shown in Fig. 37. The number of CF-BSs and LR-BSs can be changed during the lifetime of the network.

The remaining regular CSG devices may need timely delivery of beaconing information or need its information to be updated frequently, for example for renegotiation of channel allocations.

Support of lower datarates

A standard may envisage a large set of datarates for flexibility, but, for reduced complexity and cost, with disjoint sets of required modes, leaving the rest as optional. (The availability of a larger mode set, with a reduced part active is addressed from another viewpoint in Sect. 6.2.9.) Lower datarates are more robust and provide a larger coverage. Therefore, for reliability, the strongest strongest PHY-mode is usually adopted for beaconing.

Considering the previous example application of a high-rate video, as will be clear when discussing shortly below about realisation, it may be beneficial to enhance the high-rate technology to serve also a low-rate audio component. For given transmit power, the audio subsystem may have the better coverage needed by such less controllable links. Alternatively, the reason for using of lower-rates is a smaller energy consumption for given coverage. (It is obvious that a smaller transmit power implies a smaller total *power* consumption. Even considering the longer transmit time needed with a lower transmit power communication, it can be seen that the total effect is a decrease in *energy*, see Sect. 6.3.3. This is exploited also in Sect. 5.4.2 and 6.3.1.)

Such simpler devices, could not be possibly members of the same BG as the more powerful high-rate device, since what is the strongest mode for the latter is not for the former group, and the strongest mode for the former (enhancement) may not be supported by the latter (legacy).

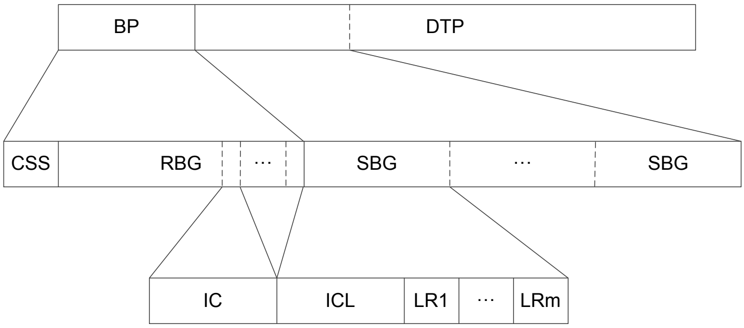

Fig 38. Example for support of support of lower rate (non-legacy) devices with lower datarate beacon and contention-less reduced beaconing depicted. Revised from Celentano *et al.* (2007).

Fig. 38 shows a SF structure similar to the one used for the previous scenario. The LRG devices may use a different PHY-mode set than the one used by HRG devices. The IC-DEV is selected among the devices capable of being member of both groups. Again, role handover for fairness is possible.

Another example of a hybrid high/low-rate system is the enhancement of proximity services (Celentano *et al.* 2008d) discussed in Sect. 5.5.

A note on the realisation

The information included in the SBG portions illustrated above pertains to the control plane, hence those portions could be part of the BP (Celentano *et al.* 2007). For the example implementation with the standard ECMA-368 system, backward compatibility is ensured by allocating the SBG portions to the DTP instead, preferably as so-called private reservations (Celentano *et al.* 2007).

Despite the fact that the SBG portion may be part of the DTP, by allocating the IC slot at the end of the BP, the beaconing period for the SBG group (i.e., the IC slot plus the SBG portion) may be made contiguous for one group, since as seen this is more energy-efficient.

In lack of a natural central device for the SBG, the IC-DEV may be elected among capable devices and its role handed over, if needed, to improve fairness, as in Sect. 5.3.3.

It has been observed that, especially in the lower-rate scenario, the RBG and the SBG are disconnected apart from the role the IC-DEV has. Almost equivalently the same scenario could be realised with the use of two distinct technologies for RBG and SBG networks. Some form of coexistence, if not of co-ordination, between the two systems should be anyway put in place, and the use of separate technologies may make this more cumbersome, at least at the co-ordinator node. The presence of gateways obviously poses additional constraints at the gateway for example avoiding time conflicts with signalling and communication channel portions in the used networks.

Another reason to have more networks at one (more powerful) device could be because of splitting a larger group of devices as seen in Sect. 5.3.5 to improve energy saving.

Comparison with parallel work

A similar SF structure is specified by ECMA-392, ECMA (2009). Table 15 summarises those similarities. By comparing the recurrent structure of the SF of ECMA-368 and ECMA-392, it can be seen that the signalling slots of the former are placed in a contention-based signalling window (CSW).

Table 15. Comparison of the SF of Celentano *et al.* (2007) and ECMA (2009).

Celentano *et al.* (2007)	ECMA-392	notes
CSS	CSW	signalling slots
RBG	BP	“regular” beacon slots
SBG	RSW	of variable length
	RSW schedule IE	reservation of RSW portion

However, between the approaches in Celentano *et al.* (2007) and ECMA (2009) there are some key differences, discussed below.

- In ECMA (2009), a reservation-based signalling window (RSW) may be appended after the BP to support master-slave connections and non-beaconing slave devices . Celentano *et al.* (2007) introduce a solution for less-frequently beaconing devices that

is backwards compatible with legacy ECMA-368 operations, whilst adding scalability, radio resource efficiency and energy efficiency.
- Slave devices in ECMA (2009) still access the regular BP. For example, slave devices request a slot in the RSW by signalling in the CSW. In Celentano *et al.* (2007), the "master" IC-DEV takes care of the "slave devices" in the SBG, thus allowing lower-rate modes for them, adding flexibility.
- As seen, in ECMA (2009) control and management information is sent in contention-based slots. In Celentano *et al.* (2007) there is the possibility of having very short beacons in small contention-less slots.

5.4 Mobility and dynamic environment

Various forms of dynamics in concurrent networks are discussed in Sect. 3.2.1, see also Fig. 13 therein. In this section are covered some issues concerning dependability and efficiency related to physical mobility (Sect. 5.4.1) and other network dynamics in time (Sect. 5.4.2).

5.4.1 Dependability protection

Regulations pose limits on the allowed emission masks of transmitting devices. In some cases, sensitive appliances may need to be protected more strongly. Anyway, emitting devices designed to comply in conformance with regulations, may emit above or outside limits, for example due to damage or malfunction.

Those mobile devices may be let aware of such conditions by special devices, in order to power down or power off their potentially dangerous emissions (Celentano *et al.* 2006).

In order to protect the above sensitive areas, a special device, referred to as emergency device, EM-DEV, co-located with the sensitive appliance or area to be protected and/or within its surroundings, may scan, periodically or continuously, the wireless medium. Once detected, a foreign device, referred to as low-critical-level device, LC-DEV, can be silenced by putting it into hibernation for a predefined time, pausing it for an indefinite time ending with a resume signal, or stopping it virtually forever, see Fig. 39.

A `stop` is indicated for example when the risk duration is indefinite or very long. A `pause` is appropriated when the risk is temporary, and its duration is unknown or long (relatively to the maximum hibernation duration of the target system). A pause

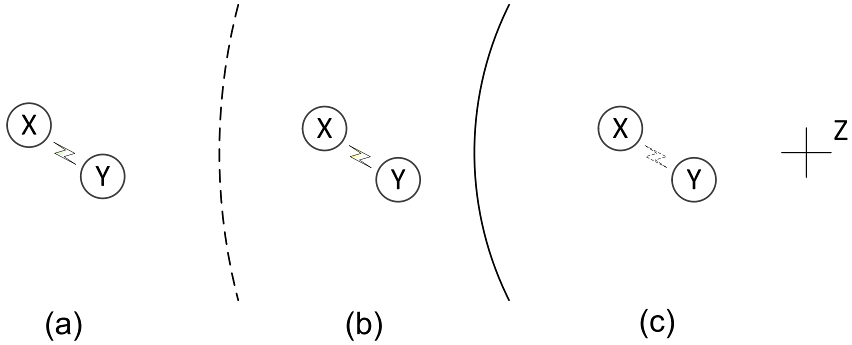

Fig 39. Devices (X and Y) approaching (a) and entering a protected area (including Z). As the devices are close to the sensitive area, they receive a `warning` message (b): they may decide to step backwards or they can prepare to shut-down. If actually entering the area, the devices may receive a `hibernate`, `pause` or `stop` message (c).

period ends with a `resume` message. A `hibernate` is used when the risk duration is known and compatible with the maximum hibernation duration of the target system. Hibernation and pausing are also useful to control the number of devices when a single interfering device is not detrimental but the cumulative effect could. The above actions may be requested for all emissions or may be restricted to specific frequency band or signalling methods indicated in an optional EM-SIG field, if present.

To reduce impact on the device object of the operation, these measures can be anticipated by a `warning` message to let the user (human or not) leave the sensitive area, move to the frequency bands or signalling methods left available by the EM-SIG option, if present, or to let the application complete some tasks in time. The information included in the EM-SIG allows anticipating the knowledge of the residual grade of service available, if any, in the protected area. Target devices can be explicitly addressed or a broadcast address can be used instead.

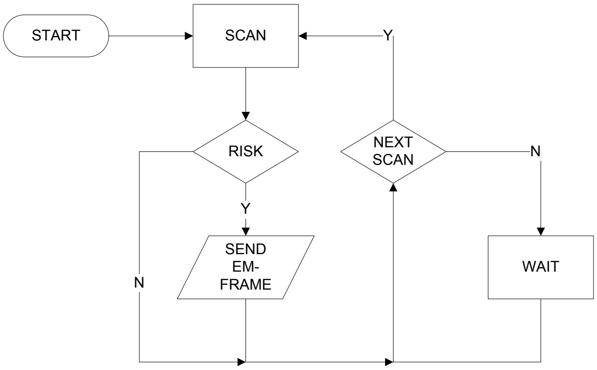

Fig 40. Protocol for detecting and controlling foreign devices at an EM-DEV. If a risk is detected at scanning, a properly formatted emergency frame (EM-FRAME) is sent. After sending or after negative assessment of risk, the condition for next scan is checked. Eventually, the next scanning operation is performed. This condition (delay) may be different depending on the previous step (transmission of EM-FRAME or no risk detected). Revised from Celentano *et al.* (2006).

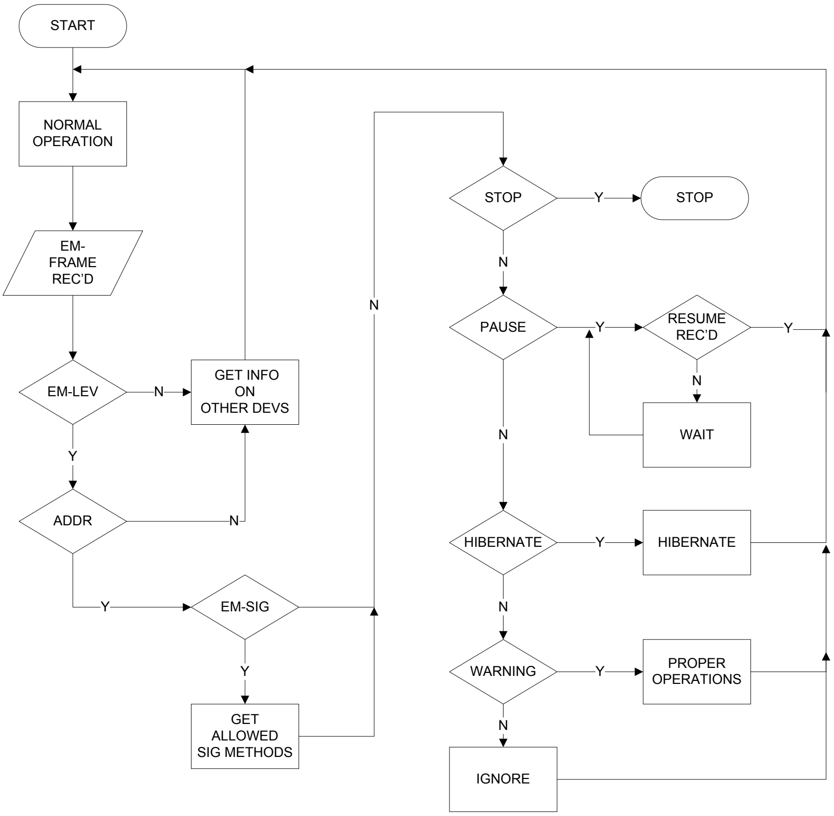

Fig 41. Protocol for processing received EM-FRAMEs at an LC-DEV. As an EM-FRAME is received, the (possible) LC-DEV checks EM-FRAME's and own EM-LEVs. If positive, if the command is broadcast or if own address matches the one in EM-FRAME, the type of command is further checked and the device behaves accordingly. In the GET INFO step, information in commands sent to other DEVs, known to the DEV is question, is gathered (e.g., to be aware of stopped neighbours). Revised from Celentano *et al.* (2006).

Sensitive areas can be classified according to levels and silencing signals can carry the level of the site issuing the signal. In this way, properly using different emergency levels, can be protected areas such as libraries, theatres, churches, etc. Also devices target of silencing commands may have an emergency level (EM-LEV) associated explicitly or by default, to properly introduce priorities and to make possible decisions on the needed actions (priority is checked before executing the command)[47].

Fig. 40 and 41 depict the protocol for a critical device (EM-DEV) and a low critical-level device (LC-DEV), respectively. Information included in the frame can be used also by devices not targeted by that message. For example, a stopped device shall be considered as disassociated from the others, and the hibernation duration imposed by the EM-DEV shall be properly used.

A note on denial of service attacks

Denial of service (DoS) attacks can be suffered for example when a carrier or other noise signal with proper frequency and transmit power are sent. Prone to DoS attacks is also a device processing the above silencing frames. Therefore, such messaging needs to be certified properly and/or their use put under applicable restrictions.

A level of protection from misuse may be achieved for example by avoiding access of user or application to the EM-FRAME transmission capability. For example, the mentioned feature could be activated only in a specific family of chip-sets, whose commercialisation undergoes specific controls.

5.4.2 Collaborative datarate scaling

Fig. 42 shows error rate curves for an example system. Curves for other systems differ but they have a similar *relative* behaviour[48]. From those curves, it can be seen that a lower-rate mode has better performance in terms of error rate, which allows for smaller transmit power (a smaller signal to noise ratio, SNR, is required for given error rate). This fact is general – this is the reason why figures in Sect. 5.2.3 indicate at lower rates a lower power consumption rate – and it is expressed also by (23) in Sect. 6.3.3, where it is highlighted that the decrease in the required transmit power at a given transmit rate, $p_{tx}(r)$, is faster than the effects of the increase in the required transmission time, thus

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[47] Considering the utility for the entire ecosystem discussed in Sect. 3.2.2, due to the potential danger caused by the mobile users approaching the sensitive area, the weight for them are clearly $w^{\mathscr{B}} \to -\infty$, so that the they are basically put off, independently of the $\mathscr{B}$-user QoS requirements $\mathbf{v}_q^{\mathscr{B}}$, by the solution to the problem $r^{\mathscr{B}} = 0$.

[48] For example, curves for ECMA-368 are provided by Kim *et al.* (2009).

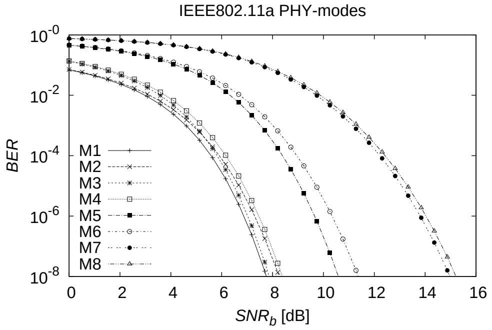

Fig 42. Bit error rate vs. signal to interference-plus-noise ratio (SINR) per bit for modulation and channel coding pairs in additive white Gaussian noise (AWGN) channel. Curves for an example system IEEE 802.11a are shown. Rates are: 6, 9, 12, 18, 24, 36, 48, 54 Mbit/s. Revised from Celentano *et al.* (2008b).

bringing a net gain. [49] When datarate is decreased, DVS/DFS (see Sect. 5.2.2) may be applied to part of the circuitry, to further improve energy efficiency.

Rate adaptation is used in a number of communication systems and specified in some standards. The metrics used to select among multiple PHY-modes available at a device have been often limited to the link between transmitter and receiver, mainly throughput or error rate. For example, as channel conditions change, the mode is selected to provide the highest possible datarate while keeping the error rate within requirements. These could be called *link-based*, *error-rate-triggered* rate adaptation methods.

Efficient use of energy has recently received more interest, also in this area. As seen, from the energy efficiency perspective it is beneficial to use the slowest admissible datarate. Note that support of slower modes may also be introduced by the enhancement described in Sect. 5.3.6.

Overview

Since for a given payload the required transmission time obviously increases as the transmit rate decreases, and an increased portion of the data carrier channel time is correspondingly used, other users cannot be neglected.

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[49] Ebert *et al.* (2002) show for IEEE 802.11 that higher bit-rates are also associated with a larger *receive* power consumption.

In this section (Celentano *et al.* 2008b), a *network-based*, *energy-efficiency-triggered* adaptation method is presented, in which PHY mode together with transmit power control are selected, also considering other devices in the neighbourhood. Mode switching is done not limiting the scope to the transmitter-receiver link, but considering the entire network instead. A network device selects a lower-rate mode as possible, but reverts to a faster one as needed, to allow other devices to access the common medium, bringing together energy efficiency and fairness. Devices decide in a distributed manner who may save energy and also decide to proactively start freeing resources by increasing their datarate or they select a target for relinquishing resources.

Distributed protocol

With the present distributed protocol, an active mode set[50], a sub-set of the supported modes, is identified considering traffic as well as target error rate and channel conditions. Devices switch to a lower-rate mode provided that there are free channel resources left and they are entitled to do so. In fact, devices may be categorised according to their priority to save energy[51] and advertise an energy saving need (ESN) indicator so that those with a higher priority are (first) allowed to occupy more resources to save their energy. Accordingly, to free resources, devices may switch to a higher-rate mode proactively as newcomers join the group or hibernating devices wake up (i.e., active population grows). A rate change may be realised as a jump to a declared mode or stepwise in a declared direction. Change may be immediate from the following frame, or according to a switch countdown.

In case of need, resources can be requested by a device under certain conditions and rules. Announcing an ESN value higher than those of the other network members is an *implicit* resource release request (RRR) when it also indicates the amount of resources needed. Considering own energy saving need level and margins to satisfy the request without service degradation, device release allocations. If the freed resources are not enough or they are not promptly made available (see switch countdown above), an *explicit* RRR may be issued. ECMA-368, ECMA (2005), specifies safe and unsafe reservations, the former being strictly needed for a service and the latter being additional resources. If such an information is available, the owner of unsafe reservations may be a

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[50] A slightly different definition of active set is followed in Sect. 6.2.9. The method described there may however be applicable to this case as well.

[51] The residual energy level described in Sect. 5.3.3 may be combined with traffic or backlog information.

selected target for an explicit RRR (an explicit RRR may use the relinquish request procedure specified by ECMA (2005), which also specifies a reason code that can be used here as a priority level). Otherwise, information about the current mode (CMD) used and the highest mode in the available set may be used to select it. In addition or alternatively to the above rules, the device selected as the target of an explicit RRR may be the one suffering the smallest energy loss, although this requires in some form the knowledge about the power consumption as a function of the mode.

Discussion

Specific energy consumption, and thus the gain, can be evaluated with (7) if the necessary information on the hardware is available. A more abstract analysis is done in Sect. 6.3. Related work is also discussed in the following chapter, in Sect. 6.3.2.

In this section, the capacity of the system is fixed and users adjust their datarate depending on the expected network load. Of course, the larger the network load, the smaller the margin for energy gain. By making the available capacity breathing, possibly using the methods discussed in Chapt. 3, energy gain can be preserved for some users. Again, combining energy gain with spectrum cost or any loss for other players, may make use of the framework of Sect. 3.2.2.

5.5 Discussion

Awareness is a key functionality in the cognitive network and entities covered by previous Chapt. 2 to Chapt. 4. Environment awareness, such as knowledge about the presence or properties or status of itself and/or surrounding devices, can be exploited. This chapter looked into energy efficiency and dependability, from the viewpoint of feasibility of solutions and their realisation. The present section provides an outlook of what covered, together with additional considerations.

Power consumption in transceivers was covered and some considerations concerning cognitive devices were drawn. Solutions for energy efficient data transmission and robustness were illustrated, together with flexible topologies extending the applicability of enhanced standards.

As seen, energy saving measures include hibernation. The use of lower datarates was also exploited as a measure to reduce power consumption rate, if channel time allowed it. Indeed, being energy the product of power and time, either factor may be reduced to save energy. A longer sleep or hibernation period may be achieved by speeding up communication with higher datarates. This choice should be considered together with the use of lower datarates, since as observed also power state switching does bring its energy overhead. Another aspect related to hibernation is the temporary unavailability as destinations of hibernating devices. To help in that, a neighbour node may altruistically store the information intended for those, and forward it as those nodes are back active[52].

Dynamic environment was also covered in this chapter, again from the aspect of dependability protection and energy efficiency, and included exploitation of collaboration. Among the possible applications of short-range communications are proximity services. In the more general case of approaching devices, subsequent phases can be identified for detection, association, probing and actual data exchange[53]. The above association phase, or joining operation, of newcomers poses its challenges. As association is obtained by accessing a common channel with a contention-based protocol, it is obvious that a large channel time portion always available represents an overhead for existing group members, while a smaller one impacts negatively on access effectiveness. Temporarily opening a larger portion, beyond the duration the devices would normally need to listen to, as in Celentano *et al.* (2009, 2010, 2011b) may help[54].

Some details of aspects covered in this chapter are further analysed in the following Chapt. 6.

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[52] ETSI HiperLAN Type 1 (ETSI 1998) envisages so-called p-supporter nodes that act as deputy destinations for neighbouring p-savers, exploiting mutual knowledge of activity periods. Similar functionalities are provided by the power save mode (PSM) for IEEE 802.11 or the automatic power save delivery (APSD) for the QoS-capable access points and stations (IEEE Computer Society 2012). Celentano *et al.* (2008a) propose a solution for distributed control networks, in which a forwarder node can be selected by destination prior to hibernation or by the source once this already happened. A forwarder may also propose itself, for example as devices announce their hibernation (Celentano *et al.* 2008a). The procedure may also be exploited to cope with other forms of temporary unavailability, such as bad channel, broken link or asymmetric link (Celentano *et al.* 2008a). Obviously, as also Bachir *et al.* (2010) observed, packets backlogged at intermediate nodes may lead to overflow, so fairness measures (Sect. 5.3.3, e.g.) are appropriate.

[53] Earlier detection may be achieved for example by using the lower datarate modes discussed in Sect. 5.3.6 to allow preparing for the communication, and probing allows a more conscious decision about the modes to be used. (Celentano *et al.* 2008d)

[54] Not yet included in MBOA MAC draft specifications version 0.95 by MBOA Alliance (2005), such a procedure is found from release 1.0 by MBOA Alliance & WiMedia Alliance (2005), also published by ECMA (2005) as ECMA-368. As other MAC parameters, the adopted value `mBPExtension` is fixed and is 8 BS duration long. Various alternative values for this extension are considered by Vishnevsky *et al.* (2008).

6 Efficient link and network adaptation

> Quelli che s'innamorano della pratica senza la diligenza, ovvero scienza, per dir meglio, sono come i nocchieri ch'entrano in mare sopra nave senza timone o bussola, che mai non hanno certezza dove si vadino. Sempre la pratica deve essere edificata sopra la buona teorica, della quale la prospettiva è guida e porta, e senza questa nulla si fa bene, così di pittura, come in ogn'altra professione.
>
> Those who are captivated of practice without diligence, or better said, without science, are like helmsmen who put to sea in a vessel lacking rudder or compass; they never know for certainty where they are going. Practice must always be founded on good theory, of which the perspective is the guide and gate and, without it, nothing is well done, so in painting as in any other profession.
>
> – Leonardo da Vinci (1651) *Trattato della pittura*, Cap. XXIII.

Before the solutions presented in the previous Chapt. 5, Chapt. 3 introduced cognitive networks and Chapt. 4 gave a categorisation of them with the different levels of their behaviour. Chapt. 5 continued discussing the exploitation of context awareness. Following the concluding remarks in Sect. 4.5, it is clear that the full comprehension of the entire system involves the understanding of underlying details. This chapter focuses on the analysis of selected issues in matter of adaptation.

6.1 Introduction

Selected problems related to link and network adaptation are further studied in this chapter, where analytical expressions are derived for selected metrics. Effective and efficient resource allocation should consider characteristics of the context, including channel quality and some of its dynamic properties, network load, also due to newcomers into the scene, service requirements, energy conditions, etc.

Sect. 6.2 starts with link adaptation in presence of imperfections. The lower layer characteristics are abstracted for upper layer analysis, and a compact form for the effective capacity is found. Efficient environment-aware link adaptation is also presented.

In Sect. 6.3 the focus moves to network adaptation, and a queuing theory interpretation of the collaborative datarate scaling of Sect. 5.4.2 is studied. The delay-energy trade-off is discussed and approximations are validated for an example implementation. Finally, related to some scenarios covered in Chapt. 5, a discussion on the source-destination distance in infinite Gaussian clusters is given in Sect. 6.4.

6.2 Link adaptation

In wireless systems, the channel reliability is affected by several phenomena, such as propagation properties of the environment, and mobility of the terminals. Moreover, to compensate for these impairments, various techniques, including adaptive schemes, are used at the physical layer, to dynamically modify the transceiver structure. As a consequence of varying channel conditions and dynamically changing transceivers structures, the available informative data rate at the link layer is in general time varying.

The channel seen from above the physical and link control layer, which will be referred to as MAC channel, must be characterised with sufficient accuracy but still by a simple and treatable model. In the resulting MAC channel model used in the sequel, physical layer characteristics, as well as the physical channel and some implementation losses, are taken into account. The efficiency of the model is improved avoiding bit level or signal level, and detailed channel statistics calculations. The result is a model that can be easily used for analytical purposes, as well as for efficient modelling of the MAC channel behaviour in network simulators. Due to the modular structure of the model, the analysis can be extended to more general and possibly complicated systems.

In general the physical layer, or Layer 1 (L1), provides a virtual link of unreliable bits. For the sake of simplicity, the term *physical layer* will be used to refer to the protocol stack portions in which no distinction is made regarding the information carried by the bits. The portions in which such distinction is done will be referred to as *upper layers*, which correspond to L2-L7 of the open systems interconnection reference model of the International Organization for Standardization (ISO-OSI) model and to the Internet protocol suite, in addition to the data link part of the technology, for IP networks.

The received signal quality can be measured, e.g., with the signal to interference-plus-noise ratio, but in the following γ will denote a generic metric for the quality level. The signal quality is a function of a number of contributions, related to both the transceiver structure and settings, and the communication environment. Changes in the time-varying signal quality are due to various causes and they reveal themselves with different time scales. Changes of rate comparable with bit rate with duration $O(T_{\text{bit}})$, or shorter, are dealt typically with diversity gain. Slower changes of $O(T_{\text{pkt}})$ are handled by changing PHY scheme and possibly with proper scheduling. Changes of $O(T_{\text{frame}})$, and longer, are handled typically with scheduling or renegotiations and reconfigurations at higher layers. In addition to diversity gain and multiplexing gain (Paulraj *et al.* 2004), link adaptation techniques are used to enhance performance.

In link adaptive systems, as a response to the received signal quality γ, the transceiver configuration K_{trx} (*PHY-mode* or *mode*) is changed so that a performance metric e is kept between certain boundaries: $e(K_{\text{trx}}, \gamma) \in \{\text{acceptable values}\}$. An example of metric e is the error rate[55], but other metrics may be used instead. Link adaptation strategies may include adaptive modulation and coding (AMC), power control, or both (Chung & Goldsmith 2001).

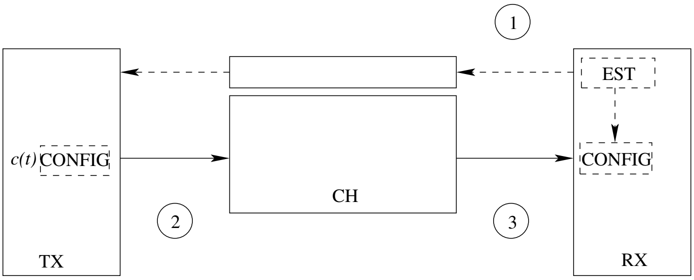

Fig 43. Adaptive radio with receiver-controlled link adaptation, or closed loop control of mode switching. The receiver does the estimation and signals the quality or directly commands the transmitter the mode to be used. Since the used mode may be known at receiver side, the transmitter can avoid sending information on the used mode. Numbers indicate the sequence order of operations; solid lines are data transmission, whereas dashed lines are control signalling. The metric used as a control signal $c(t) = \hat{\gamma}(t - \tau_e)$ is a delayed estimate of the true value, possibly affected by errors in the feedback channel. From Celentano & Glisic (2006b).

At the basis of adaptive systems, is the definition of the reference and input signals that are fed into the adaptation algorithm. These are the target quality and the actual

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[55] The error rate used for expressing QoS requirements is usually the packet error rate (PER) since it is closer to user's perception of quality. Generally, distinct channel coding schemes can be adopted for the header and for the payload, since the information included in the packet is of primary importance for the rest (in addition, the correct reception of the header only may already provide some information). In case different channel coding schemes are adopted, the outcome of the packet reception is a ternary error process: header and payload successful, header successful and payload corrupted, header and payload corrupted. In the following, the same channel coding scheme is assumed to be applied to both parts.

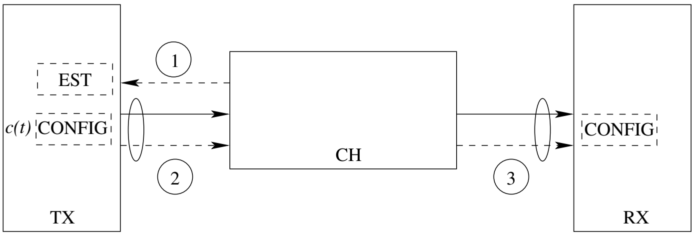

Fig 44. Adaptive radio with transmitter-controlled link adaptation, or open loop control of mode switching. The transmitter first estimates for the future transmission the state of the channel based on received signal and then transmits data. Some coded information about the chosen mode must be sent, denoted with circles, or complexity at the receiver must be added. Numbers indicate the sequence order of operations; solid lines are data transmission, whereas dashed lines are control signalling. The metric used as control signal $c(t) = \tilde{\gamma}(t)$ is an approximated estimate of the true value. The value is further approximated, e.g., due to lack of reciprocity. From Celentano & Glisic (2006b).

signal quality, respectively. Basically, there are two possible methods for the definition of the control signal (Celentano & Glisic 2006b). The first is to let the transmitter know what the measured quality at the receiver is (Fig. 43). Being a closed loop solution, it has the drawback that the signal that is used by the algorithm does not reflect the channel conditions at the transmission time. The other possibility is that the transmitter autonomously estimates the channel, based on the quality measured at its side (Fig. 44). This open loop scheme assumes reciprocity of the direct and feedback channels (which may be approximated in time division duplexing, TDD, systems).

In both cases, a related problem is how transmitter and receiver agree their configuration. With closed loop, the channel state information is sent from the receiver to the transmitter, e.g., by piggybacking the information on outgoing packets. In this receiver-controlled scheme, the PHY mode will be obviously known at the receiver side. Conversely, in the open loop case, the mode can be either sent by the transmitter, causing overhead, or obtained blindly from the receiver, leading possibly to an increase in complexity and to PHY mode acquisition errors.

It must be emphasised that with both open and closed loop schemes, it is practically impossible for the transmitter to know what the actual channel state will be at the transmission instant, and hence the actual conditions that will be experienced at the receiver. Imperfections in the adaptation chain have impact on the effectiveness of the algorithm. Indeed, the closed loop scheme is affected by delay, which is not less than the round trip delay, and possibly by estimate error. Conversely, the open loop case is affected by a much smaller estimation delay, but the estimate may not match the state at reception time. In addition to that, the information signalled from the receiver to the transmitter is prone to errors in the communication channel. All these aspects are taken into account in the proposed model for imperfections described in following sections.

6.2.1 Modelling link-adaptive systems

As seen above, several phenomena affect the wireless link capacity. Primary effects are essentially propagation properties of the environment and mobility of terminals. Secondary effects include dynamic adaptation of transceiver techniques to actual conditions. Transceivers reconfiguration, introduced to compensate for the primary impairments, must be operated at both sides, consistently. Imperfections, intrinsic in real adaptive systems, affect system performance. Those aspects must be characterised with sufficient accuracy but still with a simple and tractable model that can be used in the analysis of the higher network layers (Celentano & Glisic 2006a).

For design and performance analysis of upper layer protocols, it is important to characterise the actual link service capacity. The MAC channel model discussed further below in this chapter, includes physical channel and the physical layer, see Fig. 45 (Celentano & Glisic 2005). The same portion of the protocol stack is covered in a link layer model, called effective capacity link model (Wu & Negi 2003), which models directly few *link layer parameters* used in queuing analysis, without including *imperfections* of the physical layer or *adaptation* in link layer. A similar definition of MAC channel is given in Liebl *et al.* (2000), where a model for *packet losses* is included, taking into account physical channel, modulation and channel coding, and some other functions of the data link layer, but only for transceivers with *fixed* structure. Performance of adaptive radio links has been studied in presence of AWGN channel (Qiao & Choi 2001), or fading channels but *without* channel coding (Ericsson 1999), or for coded systems with *specific* channel coding schemes and decoding methods (Goldsmith & Chua 1997, Vishwanath & Goldsmith 2003).

The goal of the model is not to capture effects of higher frequency fading, but rather to represent the behaviour of the signal quality level in terms of presence in a region, and to link it to the behaviour of the service offered by the PHY in terms of data rate and error rate, with a granularity given by the number of PHY modes of the system. When the number of regions is small, e.g., less than eight, the quality level exhibits lower frequencies due to practical constraints discussed in the following.

The true quality level is modelled here as a continuous-time Markov chain (CTMC)[56], with state transitions are associated with boundary crossings of the metric, instead of discrete-time model sometimes used for symbol or packet error models (Wang & Moayeri 1995, Tralli & Zorzi 2002). A more extended literature review on Markovian models is in Celentano & Glisic (2006b).

The benefit of this model is threefold: the model may be integrated better in some analytical models, and the simulation model that can be derived from it can be naturally and efficiently integrated in event-driven simulators, which usually are more efficient. Second, the proposed model integrates both channel model and link adaptation in a flexible way open to generalisations. Third, some imperfections (estimate error, estimation delay, feedback error), as well as implementation implications (like switching hysteresis) are included in the model.

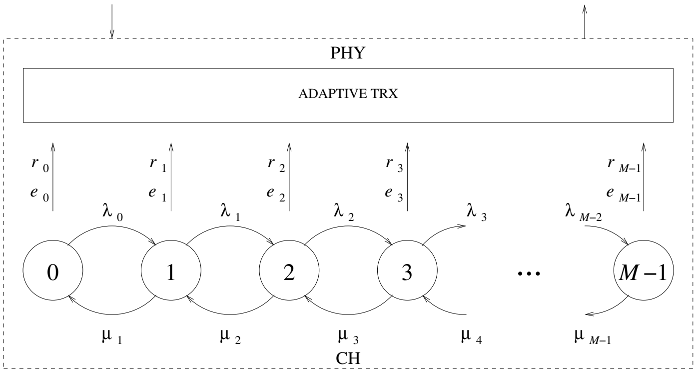

Fig 45. The MAC channel that includes the overall behaviour of the physical channel and the PHY. According to the channel state, the PHY mode is chosen. As a consequence, in each state, data rate r_i and error rate e_i are defined. The model includes imperfections in the implementation of the adaptation method. From Celentano & Glisic (2005, 2006b).

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[56] Typical fading channels exhibit correlation between successive values and therefore the system cannot be considered as memory-less if samples of those values are analysed. In the present continuous-time model, the system does not sample the specific value of the quality metric, but rather the region in which the quality metric falls. It is clear that for small number of states the higher frequency correlation in the physical channel is smoothed out when considering the jumps from one state to another.

A model for the service capacity of wireless adaptive links is presented in the following. The effective quantity of service provided at upper layers is measured by the goodput. The goodput is actually a stochastic process $R_c(t;\zeta)$, which depends on the PHY mode in use selected depending on the signal quality level estimate $\hat{\gamma}(t;\zeta)$. In the notation to follow, unless otherwise specified, the dependence on time t and realisation ζ will be omitted. The average goodput will be shown to be expressed in compact form as $\bar{R}_c = \tilde{\mathbf{r}}^{\mathsf{T}}\mathrm{diag}(\mathbf{Y}\boldsymbol{\Theta}^{\mathsf{T}})$. The dependence of $\bar{R}_c$ on the impairments is then discussed using analytical, numerical, and simulations results. Illustrative examples show that the modelled imperfections should not be neglected for realistic performance analysis at upper layers.

6.2.2 The Markovian model

As we will see, net throughput r and residual error rate e summarise the contributions of the configuration to the effective link capacity.

In our framework, a *mode* may be associated with a wider set of transceiver configuration parameters, as enabled by a software-defined radio, as long as that mode is represented by an (r,e) pair. Non-adaptive systems, having a single, unchangeable transceiver configuration (modulation scheme, channel coding scheme, etc.), are called here *fixed* systems. In those systems, the error rate absorbs the variability of the channel. Conversely, with link adaptation, the PHY mode from a set $\mathscr{M}$ is chosen so that the error rate is kept bounded, whereas the bit rate changes with the state. The proposed model describes the dynamics of those metrics, including the physical channel and the PHY characteristics, as well as imperfections in the link adaptation (Fig. 45). This is referred to as MAC channel model.

The cardinality of the *modes*' set $\mathscr{M} = \{M_0, M_1, \dots, M_{M-1}\}$, $M = |\mathscr{M}|$, is typically small. For example, M is up to six in IEEE 802.16a, seven in the high speed downlink packet access (HSDPA) of the UMTS terrestrial radio access (UTRA) and ETSI HiperLAN/2, and eight in IEEE 802.11a.

Let us consider a continuous-time finite Markov chain obtained by a stochastic process $\gamma(t;\zeta)$ *defined over a time interval* $T \subseteq (-\infty,+\infty)$ *that assumes values on a continuous set* $\Gamma \subseteq \mathbb{R}$ *split in a finite number of contiguous, non-overlapping intervals. This process is a birth-death process, if the process is continuous.* The new value assumed by a continuous function after an infinitesimal time interval Δt can only belong to the same or a neighbouring interval. For our purpose, it is sufficient to assume that the process is continuous *almost surely*[57], or with probability 1. So, looking at the time instants in which γ crosses the target levels, the process can jump only to neighboring states.

The framework is this section is intended to be applicable to generic channel processes that are continuous, and that can be represented by a small number of states.

According to QoS requirements (target error rates), the domain of the signal quality metric is divided into M contiguous, non overlapping regions: $\mathscr{S} = \{S_0, S_1, \ldots, S_{M-1}\}$, $S_i \Leftrightarrow [\gamma_i, \gamma_{i+1})$ (Celentano & Glisic 2005). Each region is associated with a state of the CTMC, and each of the M *modes* is associated with a region of the quality metric. Each state is therefore characterised by its bit rate and error rate: $S_i \Rightarrow M_i \Rightarrow r_i,\ e_i$. The set of the threshold levels, i.e., the mode switching points, is defined so that:

$$\begin{aligned} \gamma \in [\gamma_i, \gamma_{i+1}) &\Rightarrow S_i \Rightarrow M_i,\ 0 < i \leq M-1 \\ \gamma \in (\gamma_0, \gamma_1) &\Rightarrow S_0 \Rightarrow M_0, \end{aligned} \tag{11}$$

where $\gamma_0 = -\infty$ and $\gamma_M = +\infty$. The generic elements of the *state transition rate matrix*, **Q** can be written as

$$\begin{aligned} q_{k,k+1} &= \frac{p(k,k+1;t,t+\Delta t)}{\Delta t} = \frac{\Pr\{\text{crossing upwards in } \Delta t | S_k\}}{\Delta t} \\ &= \frac{N_{k+1}^{+} \Delta t}{\pi_k} \frac{1}{\Delta t} = \frac{N_{k+1}^{+}}{\pi_k}, \end{aligned} \tag{12}$$

where N_k^+ is the expected number of times level k is crossed upwards in a second, the level crossing rate (LCR), and π_k is the probability of state S_k. Similarly

$$q_{k,k-1} = \frac{p(k,k-1;t,t+\Delta t)}{\Delta t} = \frac{N_k^-}{\pi_k}. \tag{13}$$

Switching points can be defined also using other methods, including optimisation methods (Hanzo *et al.* 2002). Quantities in (12) and (13) can also be evaluated from observation of measurement traces or from simulations of complicated systems. If switching hysteresis is adopted (see the following), definition of LCRs must be properly modified using the modified levels, see Sect. 6.2.3. Our model is independent of the method used to define the set $\mathscr{S}$.

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[57] A stochastic process $\gamma(t;\zeta)$ defined over at time interval $T \subseteq (-\infty, +\infty)$ is said continuous almost surely (with probability 1) over T if the function $\gamma(t;\zeta_i)$ is continuous over T for each result except for a subset of results having probability zero, i.e., if $\gamma(t;\zeta_i) \in C(T), \forall \zeta_i \in Z - Z_0, \Pr\{\zeta_j = 0, \forall j : \zeta_j \in Z_0\}$.

Note that by rewriting (12) as $p(k,k+1;t,t+\Delta t) = q_{k,k+1}\Delta t + o(\Delta t)$, replacing $\Delta t = T_u$, where T_u is the time unit of a discrete-time model, we obtain the expression of the transition probability of the discrete-time Markov chain representing symbol or packet errors, used (without the concept of hysteresis) in Wang & Moayeri (1995) and related papers.

6.2.3 Switching thresholds and hysteresis

To avoid too frequent mode switching around thresholds, *switching hysteresis* can be introduced by fixing distinct values for falling, γ^-, and rising, γ^+, thresholds (see Fig. 46): $\gamma_i^\pm = \gamma_i \pm \varphi_i^\pm$, $\varphi_i^\pm \geq 0$. The width of the hysteresis region is $\varphi_i^+ + \varphi_i^-$. Margins φ_i^+ and φ_i^- can be equal, or set so that the cumulative probability distribution in the hysteresis regions is the same at both sides:

$$\Delta_{\mathrm{CDF}}^{(i,-)} = \int_{\gamma_i-\varphi_i^-}^{\gamma_i} p_\gamma(\gamma)\mathrm{d}\gamma = \int_{\gamma_i}^{\gamma_i+\varphi_i^+} p_\gamma(\gamma)\mathrm{d}\gamma = \Delta_{\mathrm{CDF}}^{(i,+)} \tag{14}$$

Alternatively, an effective definition could be done imposing an upper limit on the probability of spurious switching in a given time.

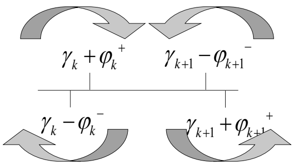

Fig 46. Switching thresholds hysteresis.

Although not exactly an imperfection, switching hysteresis is also related to the implementation of link adaptation in real system and its effect will be addressed in Sect. 6.2.7 together with the imperfections described in Sect. 6.2.5.

6.2.4 Effective capacity of the ideal adaptive link

The goodput is defined as the net bit rate, i.e., the rate at which error-free information is transmitted through the channel, thus excluding overhead of headers, redundancy of forward error correction coding, and errors that occur in the communication channel. Adapting an expression for the link service rate from Kim & Li (1999), we write the goodput for an ideal *fixed* system as $R_c(t) = [1 - e(t)]r(t)$, where $r(t)$ is the informative bit transmit rate or net throughput, and $e(t)$ is the residual error rate at reception. For an ideal reconfigurable system, each state is associated with, and characterised by, its transmit rate and error rate: $S_i \Rightarrow M_i \Rightarrow r_i, e_i$.

The informative bit transmit rate depends on the transceiver configuration (*mode*). For mode M_j, we have $r_j = \eta_h \eta_{c,j} k_j / T_s$, where $\eta_h = L_i/L_d$ is the header efficiency, $L_d = L_i + L_h$ is the total size of payload plus header, $\eta_c = L_d/(L_d + L_o)$ is the channel coding code rate, including redundancy L_o, k_j is the number of bits per symbol of the j-th mode modulation scheme, and T_s is the symbol duration. A received packet is valid if no error is present or all errors have been corrected. Therefore, the residual error rate after reassembling e has the same value of the packet error rate (PER): $e = p_E$.

The *effective capacity* of the link is obtained by averaging the goodput over the modes:

$$\bar{R}_c|_{\text{ideal}} = \sum_{i=0}^{M-1} [1 - e_i]\, r_i \pi_i, \tag{15}$$

where π_i is the probability of the channel being in the i-th state *and* using the i-th mode.

An adaptive system has a *reference* quality and a *control*. The control (actual measured quality) can be defined at the receiver (closed loop) or at the transmitter (open loop). In either case, it is impossible for the transmitter to know what the actual quality will be at the reception instant and site.

6.2.5 Model of imperfections

A real adaptive communication system is prone to erroneous determination of the transceiver configuration suitable for the instantaneous channel quality at transmission time. Estimate errors and estimation delay have been so far neglected and will be now introduced. parameters estimation is a broadly researched subject. The properties of the transceivers configuration set-up errors depend on the particular system. It is out of scope of this research the study of specific algorithms, but rather here is built a flexible model open to generalisations.

The effective channel condition is hidden. A non-exact, and possibly delayed and corrupted by noise version of it is available instead, and based on that, the *mode* is actually chosen.

The metric used for mode switching can be expressed as $\hat{\gamma}(t) = \gamma(t - \tau_e) + \varepsilon_e + \varepsilon_f$, where γ and $\hat{\gamma}$ are the true and the estimated value, respectively, ε_e is the estimate error, ε_f is the acquisition error, and τ_e is the estimation delay. Among these three terms, the first has more important effect in the open loop case, whereas in the closed loop case, the other two terms are dominant. At estimation time t, the *true* channel quality metric falls in the k-th region, $S(t) = S_k$, and the metric is *estimated*: $\hat{S}(t) = S_h$. The estimator or mode selector may be implemented at transmitter or receiver side. The estimate or command is sent to the other side, and M_i is finally *acquired*, and used for transmission (with closed loop) (or reception, with open loop). During the estimation delay τ_e, the channel quality metric may move to its *effective* region, $S(t + \tau_e) = S_j$. The final effect is that mode M_i is used at transmission time, when the channel is in effective state S_j. The probability of this event, see Fig. 47, can be written as $P(M_i, M_h, S_k, S_j)$. The estimation process and the channel process are assumed independent; this relates mainly to the estimation algorithm. It is also assumed that the acquisition channel is independent of the direct channel; this relates to the adaptation scheme, duplexing scheme, MAC frame structure, terminals speed, etc. Under these assumptions, we can write[58]

$$
\begin{aligned}
&P(M_h, S_k, M_i, S_j) = \\
&= P(S_k) P(M_h \,|S_k\,) P(M_i \,|M_h\,) P(S_j \,|S_k\,).
\end{aligned}
\tag{16}
$$

The three last terms in (16) are treated separately in the sequel.

The *mode estimation probability matrix* $\mathbf{H}^{(e)} = \{h_{hk}^{(e)}\} \in \mathbb{R}^{M \times M}$ models the effects of the imperfections in the estimation process due to noise. The probability of selecting mode M_h with the true channel in state S_k at estimation time is $h_{hk}^{(e)} \doteq \Pr\{M_h | S_k\}$. This is the second term in (16).

The *mode acquisition probability matrix* $\mathbf{H}^{(f)} = \{h_{ih}^{(f)}\} \in \mathbb{R}^{M \times M}$ models the probability of errors in the exchange of set-up information between transmitter and receiver. The set-up information is the identifier of the *mode* or, equivalently, of the related signal quality region. Hence, $h_{ih}^{(f)} \doteq \Pr\{M_i | M_h\}$. This represents the third term in (16).

The *delayed channel transition matrix* $\mathbf{H}^{(d)} = \{h_{kj}^{(d)}\} \in \mathbb{R}^{M \times M}$ models the effects of estimation delay. The probability that given the true channel was in state S_k at estimation

---

[58] From the definition of conditional probability: $P(M_h, S_k, M_i, S_j) = P(M_h, S_k) P(M_i, S_j \,|M_h, S_k\,)$. The last term $P(S_j, M_i \,|M_h, S_k\,) = P(S_j, M_i, M_h, S_k)/P(M_h, S_k)$ can also be written, applying the chain rule, as: $P(S_j \,|M_i, M_h, S_k\,) P(M_i \,|M_h, S_k\,) \cancel{P(M_h, S_k)} / \cancel{P(M_h, S_k)} = P(M_i \,|M_h, S_k\,) P(S_j \,|M_i, M_h, S_k\,)$. Since estimation process and channel process are independent, the last two terms become: $P(M_i \,|M_h, \cancel{S_k}) P(S_j \,|\cancel{M_i, M_h}, S_k\,) = P(M_i \,|M_h\,) P(S_j \,|S_k\,)$. Finally, again from the definition of conditional probability, the first term in the first expression in this note can be written as: $P(M_h, S_k) = P(S_k) P(M_h \,|S_k\,)$.

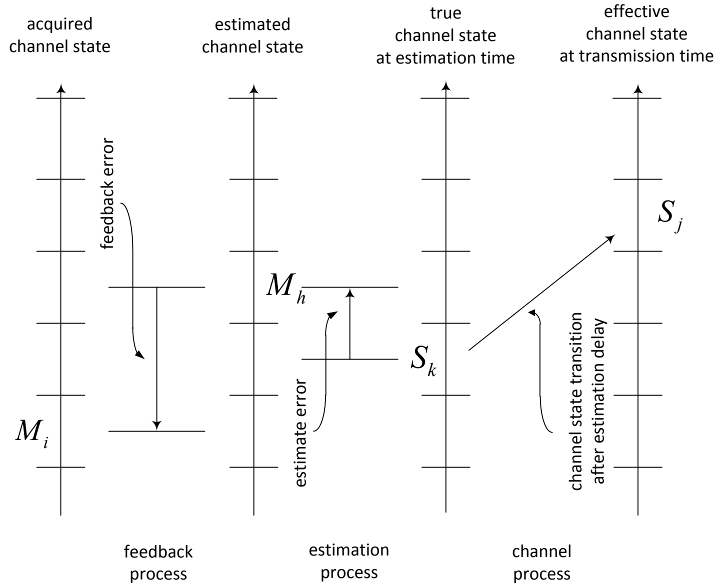

Fig 47. The model of imperfections in the adaptation chain. Based on the true channel state at estimation time, an estimate subject to estimation error is obtained. Its identification code is sent through the error-prone feedback channel and is acquired as the selected state. During the estimation delay, the channel state may change following its dynamics. Revised from Celentano & Glisic (2005, 2006b).

time, at transmission time (after τ_e) the channel is in state S_j is $h_{kj}^{(d)} \doteq \Pr\{S(t+\tau_e) = S_j | S(t) = S_k\}$. This represents the last term in (16).

6.2.6 Effective capacity of imperfect adaptive links

The service capacities can be represented in (15) by a vector because the effective state and chosen mode by assumption coincide: $S_i \Leftrightarrow M_i$. In case of imperfect systems, the bit rate depends on the *used* mode whereas the error rate depends on both the used mode and the *effective* state. The following definitions are needed to extend the expression to imperfect systems.

The *throughput vector* $\mathbf{r} = \{r_i\} \in \mathbb{R}^M$ is defined as $\mathbf{r}^\mathsf{T} \doteq [r_0, \ldots, r_{M-1}]$ with r_i defined above. The *normalised goodput matrix* is $\mathbf{Y} = \{y_{ij} \doteq (1-e_{ij})\} \in \mathbb{R}^{M\times M}$, where

e_{ij} denotes the error rate when the mode M_i is used and the channel is in effective state S_j (see Sect. 6.2.5). Matrix $\mathbf{Y}$ expresses the useful bit rate normalised to the transmit rate in each case. The sojourn probabilities in the signal quality regions are denoted with the *state probability vector* $\boldsymbol{\pi}$, $\boldsymbol{\pi} \in \mathbb{R}^M$. Matrix $\boldsymbol{\Pi} = \operatorname{diag}(\boldsymbol{\pi})$ is the diagonal matrix having vector $\boldsymbol{\pi}$ on its diagonal.

The effective capacity, in presence of the imperfections modeled in Sect. 6.2.5, is

$$\begin{aligned}\bar{R}_c &= \sum_{i=0}^{M-1} h_{ii}^{(f)} r_i \sum_{j=0}^{M-1} (1-e_{ij}) \sum_{k=0}^{M-1} h_{ik}^{(e)} \pi_k h_{kj}^{(d)} \\ &= \tilde{\mathbf{r}}^{\mathsf{T}} \operatorname{diag}(\mathbf{Y}\boldsymbol{\Theta}^{\mathsf{T}}),\end{aligned} \tag{17}$$

where $\tilde{\mathbf{r}}^{\mathsf{T}} \doteq [h_{ii}^{(f)} r_i] = \mathbf{r} \odot \operatorname{diag}\mathbf{H}^{(f)}$ ($\odot$ denotes the Hadamard-Schur element-wise matrix product) and $\boldsymbol{\Theta} = \{\vartheta_{nj}\} \in \mathbb{R}^{M\times M}$. $\boldsymbol{\Theta} = \mathbf{H}^{(e)}\boldsymbol{\Pi}\mathbf{H}^{(d)} = \boldsymbol{\Pi}\mathbf{H}^{(d)}\mathbf{H}^{(e)}$: $\vartheta_{nj} = \sum_{k=0}^{M-1} h_{hk}^{(e)} \sum_{m=0}^{M-1} \pi_{km} h_{mj}^{(d)} = \sum_{k=0}^{M-1} h_{hk}^{(e)} \pi_{kk} h_{kj}^{(d)}$ models the probability of using mode M_n with the channel in the effective state S_j (*mode-channel probability matrix*). The operator $\operatorname{diag}(\mathbf{A}) \doteq [a_{ii}]$ extracts the vector of diagonal elements of matrix $\mathbf{A}$.

The *scalar normalised average goodput* corresponds to the average goodput of a system adopting a hypothetical set of *modes* all having unitary transmission rate:

$$\bar{R}_r = \left\| \operatorname{diag}(\mathbf{Y}\boldsymbol{\Theta}^{\mathsf{T}}) \right\|_1 . \tag{18}$$

The use of this quantity will be clear in the analysis.

Let us now see how the expression of the effective capacity specialises in few special cases. Under the assumption of *additional blind mode detection*, a mode acquisition error does not imply information loss but only mismatch in the used *mode*. In this case

$$\begin{aligned}\bar{R}_c &= \sum_{i=0}^{M-1} r_i \sum_{j=0}^{M-1} (1-e_{ij}) \sum_{h=0}^{M-1} h_{ih}^{(f)} \sum_{k=0}^{M-1} h_{hk}^{(e)} \pi_k h_{kj}^{(d)} = \\ &= \mathbf{r}^{\mathsf{T}} \operatorname{diag}(\mathbf{Y}\tilde{\boldsymbol{\Theta}}^{\mathsf{T}}),\end{aligned} \tag{19}$$

where $\tilde{\boldsymbol{\Theta}} = \mathbf{H}^{(f)}\mathbf{H}^{(e)}\boldsymbol{\Pi}\mathbf{H}^{(d)} = \boldsymbol{\Pi}\mathbf{H}^{(d)}\mathbf{H}^{(f)}\mathbf{H}^{(e)}$. In this case, $\tilde{\boldsymbol{\Theta}} = \boldsymbol{\Pi}\boldsymbol{\Omega}$, where $\boldsymbol{\Omega}$ is the *equivocation matrix*, which includes all the imperfections of link adaptation processes.

In the ideal case of *perfect link adaptation*, in which M_i timely follows without errors S_i, $\mathbf{H}^{(e)} = \mathbf{H}^{(d)} = \mathbf{H}^{(f)} = \mathbf{I}$, and (17) reduces to

$$\bar{R}_c\big|_{\text{ideal}} = \sum_{i=0}^{M-1} r_i (1-e_{ii}) \pi_{ii} = \mathbf{r}^{\mathsf{T}} \operatorname{diag}(\mathbf{Y}\boldsymbol{\Pi}). \tag{20}$$

Fixed systems are considered in this model as a special case with $\mathbf{H}^{(f)} = \mathbf{I}$, $\mathbf{H}^{(d)} = \mathbf{I}$, and static mode selection leading to a matrix $\mathbf{H}^{(e)}$ having as non-zero elements all 1 in the i-th row, if mode M_i is implemented in the system: $h_{hk}^{(e)} = \delta_{hi}\delta_{kk}$, where δ_{ij} is the Kronecker delta.

6.2.7 Illustrative examples

For illustration purposes, the above analysis tool is applied to a sample system to investigate the sensitivity to imperfections and implementation constraints. The purpose is to show how imperfections influence the effective capacity and the importance to include those into the model. It is here out of scope to provide performance analysis of a specific system.

Assumptions

Consider a five-mode link-adaptive system with binary and quadrature phase-shift keying (BPSK and QPSK, respectively), 8QAM (quadrature amplitude modulation), and 16QAM modulation schemes, and a no-transmission mode for insufficient signal quality. The same channel code ($g_0 = 133_8, g_1 = 171_8, K = 7$) is used for all modes (Celentano & Glisic 2005). With independent bit errors at link layer (achieved, e.g., with sufficiently long interleaver), the PER is $p_E = 1 - (1 - p_e(\gamma G_c(\gamma)))^{L_p}$, where $p_e(\gamma)$ is the bit error rate of the uncoded system, $G_c(\gamma)$ is the coding gain, γ is the SINR per bit, and L_p is the packet length in bits. The assumption of independent bit errors and the use of $G_c(\gamma)$, used in this example, are not needed in the generic model of Sect. 6.2.6.

Expression for the performance of uncoded modulations are in Proakis (1989). The values of the coding gain for a half-rate code (Jacobs 1974) and punctured versions having $\eta_c = 2/3$ and $\eta_c = 3/4$ (Haccoun & Bégin 1989) are fit to a coding gain curve G_c.

Markov models are widely adopted in the literature for channel modelling, since they lead to tractable models. The validity of first-order Markov models is addressed in Tan & Beaulieu (2000), Zorzi *et al.* (1997, e.g.). Continuous time models may integrate better with other fluid analytical models and are efficiently implemented in event-driven simulators. The presence in the M signal quality regions $\mathscr{S}$ is modelled with a continuous time Markov chain with *infinitesimal generator* $\mathbf{Q} \in \mathbb{R}^{M \times M}$ (Celentano & Glisic 2005). The assumption of Markov chain is however not needed in the generic model of Sect. 6.2.6, since only the stationary state probabilities appear in the formula of the effective capacity.

Switching thresholds are obtained from a required PER of 10^{-5} for a packet length of 2048 bits. Although both multipath fading and shadowing are generally superimposed, only one at a time affects link adaptation (Goldsmith & Chua 1997). Here are assumed Ricean fading process (Rice 1944, 1945), line-of-sight component with zero Doppler frequency, uncorrelated Gaussian noise components, and Jakes shaped Doppler power spectral density or isotropic scattering (Pätzold & Laue 1999, Beaulieu & Dong 2003) and the corresponding expression of the LCR is given in Pätzold *et al.* (1998). Replacing them into (12) and (13) gives the expressions and the CTMC parameters in Celentano & Glisic (2006b).

Sensitivity of state probabilities to hysteresis region width

By looking at levels $\gamma_i^{\pm} = \gamma_i \pm \varphi_i^{\pm}$, the stationary state probabilities after introducing the hysteresis can be written (Celentano & Glisic 2005) as $\pi_i^{(h)} = \pi_i - \Delta_{\mathrm{CDF}}^{(i-1,+)}\pi_{i-1} - \Delta_{\mathrm{CDF}}^{(i+1,-)}\pi_{i+1} + \Delta_{\mathrm{CDF}}^{(i,-)}\pi_i + \Delta_{\mathrm{CDF}}^{(i,+)}\pi_i + o(\Delta_{\mathrm{CDF}})$, where $\pi_i^{(h)}$ and π_i are the stationary state probabilities with and without hysteresis, respectively, and $\Delta_{\mathrm{CDF}}^{(i,\pm)}$ is the half width of the i-th hysteresis region at upper (+) and lower (-) side, respectively. In case of equal and symmetric hysteresis regions and neglecting higher order infinitesimals we have $\pi_i^{(h)} \approx \pi_i + \Delta_{\mathrm{CDF}}(2\pi_i - \pi_{i+1} - \pi_{i-1})$. For larger values of Δ_{CDF}, the states with a larger probability have their probability further increased by the introduction of hysteresis.

From Fig. 48, it can be observed that up to about $\Delta_{\mathrm{CDF}} = 10^{-3}$, state probabilities are almost unaffected.

Sensitivity of effective capacity to estimation errors

The distribution of the estimation error depends on the specific adopted estimation technique. Analytical and/or empirical distributions for estimation error are generally unknown (Goldsmith & Chua 1997). For this illustrative example, no assumption is made on the structure of the estimator, and Gaussian distributed error is assumed. In this case, the elements of $\mathbf{H}^{(e)}$ are $h_{hk}^{(e)} = 0.5\{\mathrm{erfc}[(\gamma_h - \bar{\gamma}_k)/\sigma_e] - \mathrm{erfc}[(\gamma_{h+1} - \bar{\gamma}_k)/\sigma_e]\}$, where $\mathrm{erfc}(\cdot)$ is the Gaussian complementary error function, σ_e^2 is the estimation error variance, and $\bar{\gamma}_k$ is the nominal value of the metric in S_k. The nominal value may be

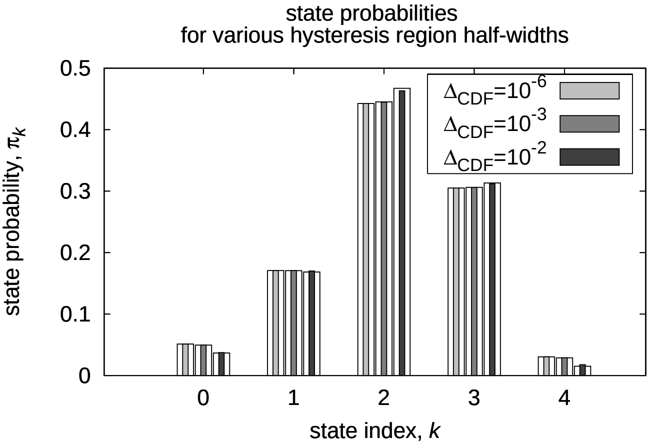

Fig 48. Sensitivity of stationary state probabilities to hysteresis region width. Filled bars are simulated values, whereas empty background bars are the theoretical values. Up to about $\Delta_{CDF} = 10^{-3}$, state probabilities are unaffected. For larger values of Δ_{CDF}, states with large probability, the central ones in our case, have their probability further increased by the introduction of hysteresis. Revised from Celentano & Glisic (2005, 2006b).

the average value in the region. With $\tau_e = 0$ and error free acquisition channel, the sensitivity of $\bar{R}_c$ to estimate errors is studied.

In Fig. 49, $\bar{R}_c$ exhibits a maximum for variance larger than zero. This behaviour is explained by the fact that, in the expression for $\bar{R}_c$, the success rate is weighted by the bit rate. The scalar normalised average goodput $\bar{R}_r$, defined in 18, takes into account only the effects of the error rate e and is independent of the transmit bit rate r. As expected, $\bar{R}_r$ is monotonically decreasing. The maximum of $\bar{R}_c$ is due to a small gain in using a larger r even if combined with a slightly larger e.

Sensitivity of effective capacity to estimation delay

To simplify the analysis, in this example the estimation delay is assumed negligible compared to the minimum inter-transition time (time between state changes): $\lambda_i \tau_e = q_{i,i+1}\tau_e \ll 1$ and $\mu_i \tau_e = q_{i,i-1}\tau_e \ll 1$. Under this assumption, it is straightforward to see

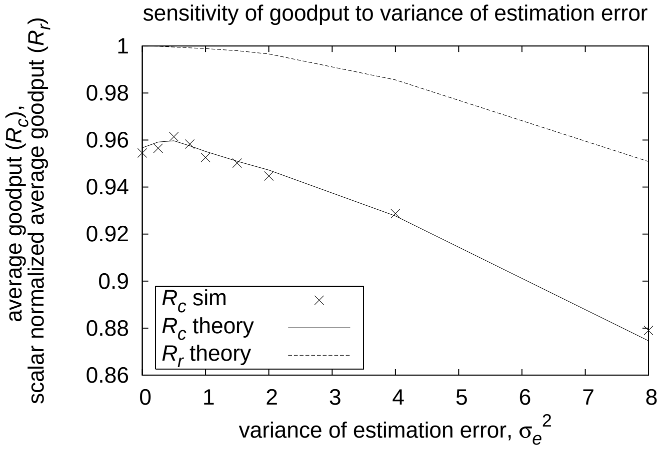

Fig 49. Sensitivity of effective capacity to variance of estimation error. Effective capacity $\bar{R}_c$ (solid line), scalar normalised average goodput $\bar{R}_r$ (dashed line), and simulations (crosses). The curve of the scalar normalised average goodput $\bar{R}_r$, which is independent of the transmit gross bit rate, is monotonically decreasing, The curve of the effective capacity $\bar{R}_c$ exhibits a maximum due to a small gain in using a larger bit rate even if combined with a slightly larger error rate. From Celentano & Glisic (2006a); revised from Celentano & Glisic (2005, 2006b).

that $\mathbf{H}^{(d)} = \mathbf{I} + \mathbf{Q}\tau_e$ (Celentano & Glisic 2006b). In this case,

$$\begin{aligned}\bar{R}_c(\tau_e) &= \mathbf{r}^\mathsf{T}\mathrm{diag}(\mathbf{Y}\boldsymbol{\Theta}^\mathsf{T}) = \mathbf{r}^\mathsf{T}\mathrm{diag}[\mathbf{Y}(\mathbf{I}+\mathbf{Q}^\mathsf{T}\tau_e)\boldsymbol{\Pi}] \\ &= \mathbf{r}^\mathsf{T}\mathrm{diag}(\mathbf{Y}\boldsymbol{\Pi}) + \tau_e\mathbf{r}^\mathsf{T}\mathrm{diag}(\mathbf{Y}\mathbf{Q}^\mathsf{T}\boldsymbol{\Pi}) \\ &= \bar{R}_c(0) + \tau_e\Psi_d \end{aligned} \tag{21}$$

with $\bar{R}_c(0)$ given by (20) and where

$$\Psi_d = \frac{\partial \bar{R}_c}{\partial \tau_e} = \mathbf{r}^\mathsf{T}\mathrm{diag}(\mathbf{Y}\mathbf{Q}^\mathsf{T}\boldsymbol{\Pi}) \tag{22}$$

is the unitary drift of the effective capacity from the ideal conditions due to the estimation delay.

Sensitivity of effective capacity to acquisition errors

To identify a *mode*, a control message with $\lceil \log_2 M \rceil$ bits is used. The distance in bits among all pairs of codewords is given by a symmetric matrix having null diagonal,

$\mathbf{D} = \{d_{ij}\} \in \mathbb{N}^{M\times M}$, $d_{ij} \doteq \sum_{n=1}^{m} w_i^{(n)} \otimes w_j^{(n)}$, where $w_i^{(n)}$ is the n-th bit of the i-th codeword and $\otimes$ denotes the modulo 2 bit-wise product. For our five-mode system, the element of matrix $\mathbf{H}^{(f)}$ can be written as $h_{ih}^{(f)} = p_{e,f}^{d_{ih}}(1-p_{e,f})^{\lceil \log_2 M \rceil - d_{ih}}$, where $p_{e,f}$ is the residual bit error probability in the feedback channel, given by $p_{e,f} = p_e^{(f)}(\gamma G_c(\gamma))$. Mode identifiers may be coded with the Gray code. Assume that the message is transmitted always using the strongest mode.

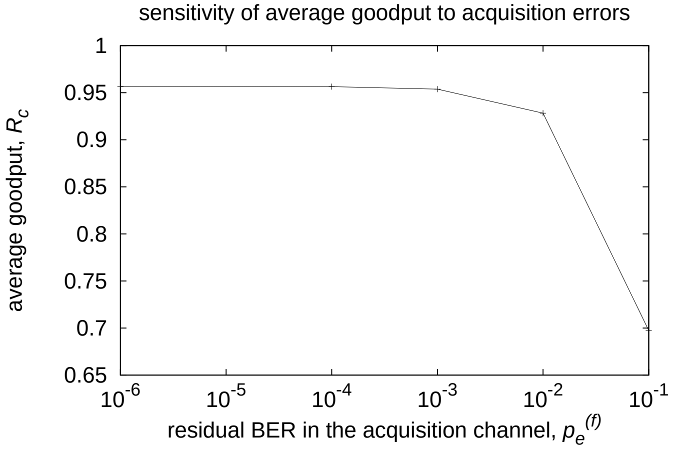

Fig 50. Sensitivity of effective capacity to acquisition errors. In this figure, the residual bit error rate in the acquisition channel is assumed fixed and independent of the state of the direct channel. The impact is no longer negligible only for values of $p_e^{(f)}$ so large to be out of range in adaptive systems and often in communications systems in general. From Celentano & Glisic (2006a); revised from Celentano & Glisic (2006b).

It has been seen that the effect of acquisition errors is negligible. In fact, as shown in Fig. 50, in which the bit error rate in the acquisition channel, $p_e^{(f)}$, is assumed fixed and independent of the channel state, the impact is no longer negligible only for $p_e^{(f)}$ out of useful range for adaptive and communications systems in general.

6.2.8 Discussion

A model for the service capacity at link layer has been presented. At link layer, resource allocation protocols manage resources made available by the physical layer and assign those to services offered at their upper layers. A good metric for characterizing the available resources, and therefore the effective link service capacity, is the goodput. The presented effective capacity model incorporates a number of characteristics, including link adaptation with its imperfections. Illustrative examples showed that aspects above should not be neglected for realistic performance analysis at upper layers.

The effective capacity is expressed also in a compact form including the impact of imperfections and implementation losses. The characteristics of the adaptive system are independently represented by separate matrices, for the lower layers ($\mathbf{Q}$, $\boldsymbol{\pi}$, $\mathbf{r}$, $\mathbf{Y}$) and for the imperfections in the transceivers set-up ($\mathbf{H}^{(e)}$, $\mathbf{H}^{(d)}$, $\mathbf{H}^{(f)}$). Therefore, the model can be flexibly adapted to a number of systems. Consistent comparison of different scenarios can be done by using the same model and changing properly the model's matrices. Mobility may be included in the model by averaging over the channel conditions represented by distinct matrices $\mathbf{Q}$. The proposed model can also be incorporated into network simulators, implementing the separate look-up tables (matrices). In a multi-user scenario, distinct matrices for each user are used. For the realisation of a parametric simulation model are useful the considerations in Sect. 6.2.6.

6.2.9 Efficient environment-aware link adaptation

As seen, with either the receiver-controlled (Fig. 43) or the transmitter-controlled (Fig. 44) scheme (i.e., in non-blind systems), there is the need to exchange between source and destination a coded representation either of the environment's quality metric or of the selected mode. Moreover, mode signalling must be protected well against noise, thus possibly further increasing the overhead. It is important to keep as small as possible the additional information (overhead) that needs to be added to the informative units. Obviously, the overhead reduction need to be particularly efficient when a wide range of modes is available and/or in case of fast adaptation, when the modes are subject to frequent changes, such as with symbol-by-symbol adaptation.

This section presents a method for overhead reduction by means of classification and selection included in Tirkkonen, Priotti & Celentano (2010, 2011).

Overhead reduction

Given the operating conditions (channel properties), a specific transceiver configuration, such as a modulation and channel coding scheme pair or a more general set of parameters, may perform best among a set of available configurations. Communication devices may be designed to be able to operate in a wide range of environments. An example is a personal communication device that can be used in a very static scenario (e.g., fixed) with good coverage, or in quite challenging conditions (e.g., in high-speed trains), with a number of intermediate conditions. In order to allow that device to operate optimally in most of situations, a large set of transceiver settings should be available. The agreement of those settings at both sides must be done dynamically to reflect the actual link conditions[59].

It can be identified a time-window during which the operating conditions exhibit the same characteristics, i.e., they be static or they may change, but with almost static characteristics, for example with a metric within a given range. In such a period, a restricted configuration set may be used. This is referred to as *active set* (a slightly different definition is followed in Sect. 5.4.2). Still, the use of a limited set of settings may not imply significant performance losses in some common situations. For example, an active set size as small as two may represent already a good compromise (Tirkkonen, Priotti & Celentano 2010, 2011).

According to changes in the operating conditions, a new set of configurations is agreed. Within the lifetime of a particular agreed set, only the code (relative identifier) *in that set* needs to be exchanged. While the capability of operating in diverse scenarios is kept, the addressing space of the modes is reduced and fast rate adaptation is made affordable with a smaller overhead.

The active set is defined according to the observation of the environment and the modes may be chosen to maximise the average goodput across the entire range. The classification and selection method used for supporting transceiver structure codes signalling is illustrated in the following with example adaptive modulation and coding schemes.

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[59] In blind methods, the receiver estimates the mode that was used for transmission. Although this does imply additional overhead to allow mode detection, this overhead does not carry explicitly any mode coding and is therefore not considered here. When instead an indicator is given, this is done by explicitly commanding the mode to be used or communicating the mode used, or implicitly, exchanging a metric regarding channel conditions.

Classification

Assume that a signal quality metric is observed and measured (either at receiver or transmitter side), and its values are collected to estimate the state probability for the regions associated to each available PHY-mode implemented in the system. This classification is a learning phase, as discussed in Sect. 4.2.2. The above statistic is the discrete representation of the probability density function and is realised as a histogram. An outer algorithm iterates through the following steps (Tirkkonen, Priotti & Celentano 2010, 2011):

1. Collect values and dynamically update environment statistics.
2. Select the modes of the active set (periodically run the selection algorithm below).
3. If there are changes, signal the new active set.

Selection

The inner algorithm selects the modes corresponding to the "best" regions as follows. Modes within the active set are ideally selected so that the two extremes of the state probabilities have small, non-zero values, implying that the whole dynamics of the channel is exploited, and having in the middle region large values, implying that the mode selection is done in a way that modes that are optimal for most of the time are within the active set.

Given the state probabilities for all implemented modes, built and updated according to the outer algorithm described above, the active set is selected according to the following algorithm (Tirkkonen, Priotti & Celentano 2010, 2011):

1. Discard all higher rate modes until the one having "non-zero" probability.
2. Discard all lower rate modes until the one having "non-zero" probability.
3. Decimate the modes until the desired set size is reached (optional step).

Indeed, two basic sub-methods for building the active set can be implemented, with and without decimation.

1. **Selection without decimation**. Modes in the active set are contiguous also in the implemented set. Two possibilities for the information to be sent:
    a) first mode code and last mode code are sent;
    b) first mode code and active set size are sent.

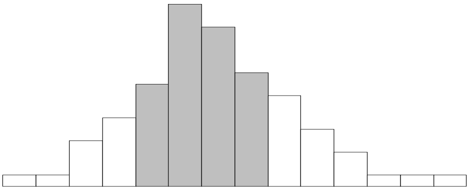

Fig 51. Selection without decimation. All modes between lowermost and uppermost are included in the active set. Revised from Tirkkonen, Priotti & Celentano (2010, 2011).

In this case the entire dynamics of the metric may be not represented or the active set size required to cover that may be large. Both sub-cases are illustrated by Fig. 51.

2. **Selection with decimation**. Contiguous modes in the active set are not contiguous in the implemented set. Two possibilities for the information to be sent:

   a) first mode code, step size, active set size are sent (even step size);
   b) explicit list of codes of the modes in the active set is sent (uneven step size).

   These two sub-cases are illustrated in Fig. 52 and 53, respectively.

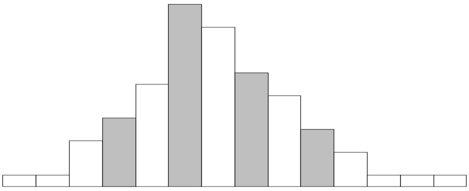

Fig 52. Selection with decimation with even step size. The subset between the first and last useful modes is decimated until it reaches the required size. Revised from Tirkkonen, Priotti & Celentano (2010, 2011).

Since the requirement on the performance must be respected, the elimination of one mode implies associating its signal quality metric interval to the lower neighbouring, more error resistant, PHY-mode.

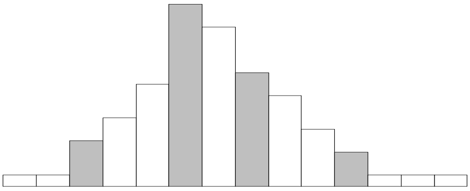

Fig 53. Selection with decimation with uneven step size. The subset between the first and last useful modes is decimated until its reaches the required size. Revised from Tirkkonen, Priotti & Celentano (2010, 2011).

Signalling and complexity

Different levels of signalling overhead are associated with each of the above methods. The complexity of those methods is compared below in terms of required binary digits.

Table 16. Overhead with different methods for signalling the active set. Revised from Tirkkonen, Priotti & Celentano (2010, 2011).

Method	Overhead, L_m
1a	$2\log_2 M_i$
1b	$\log_2 M_i + \log_2 M_a$
2a	$\in [\log_2 M_i + \log_2 M_a, \log_2 M_i + 2\log_2 M_a]$
2b	$M_a \log_2 M_i$

With M_i available modes implemented in the transceiver, an active set of M_a modes is identified with the overhead L_m listed in Table 16. The overhead L_m for all the four methods is plotted in Fig. 54 against the active modes set size ($M_i = 128$ assumed). Obviously, overhead for method 1a is independent of the size M_a, whereas for method 2b the overhead rapidly explodes compared with the others, as modes are explicitly listed. For case 2a, note that the step size ranges between 1 and M_a, so its curve lies between the one for method 1b and the one plotted in the figure.

The above control information must be sent each time the set is changed. During operations, to represent and identify a mode in the active set, a code $\log_2 M_a$ binary digits long is required, and is sent for example with each information unit (e.g., a packet or a symbol). This code is used as an address of an active set mode look-up-table used to obtain the absolute mode identifier.

Discussion

The threshold used at steps 1 and 2 of the selection algorithm for assessing irrelevancy of a histogram class (i.e., “zero” value), or the threshold for detecting a change in the statistics at step 3 of the classification algorithm are design parameters.

The choice of the selection mode can be fixed or done adaptively. In light of what seen above (Fig. 54 and Table 16), this can further reduce the overhead. When the addressing mode is adaptive, a first field may indicate the addressing method and thus the length of the remaining fields, a second field (always $\log_2 M_i$ bit long) is for the first mode identifier, and the remaining fields are according to the selected signalling method.

The active set size M_a depends in many ways on the dynamics of the observed metric. Not only it should cover the useful range for a given time, it also may be taken large enough to avoid frequent active set updates caused by too small values of M_a.

Actually, if the conditions in the environment exhibit temporarily limited dynamics, this method may significantly reduce the overhead. If conversely the conditions in the environment exhibit large dynamics, the active set may be selected in such a way that

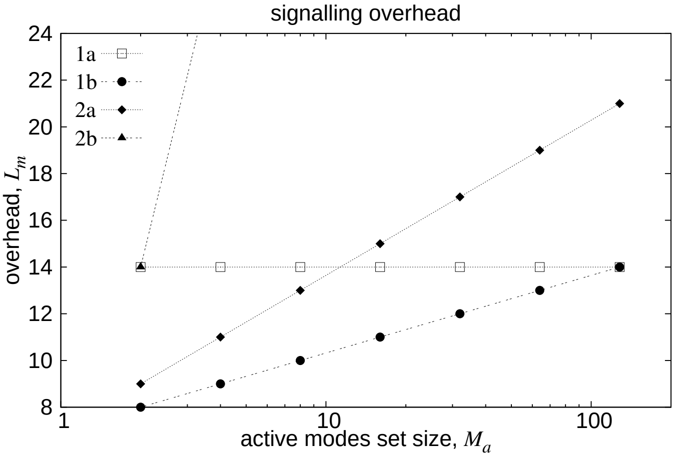

Fig 54. Required address size L_m in bits versus the active set size M_a. (Example for $M_i = 128$.)

the dynamics is covered, but with lower resolution, due to the reduced set of available modes.

The disadvantage is an increased complexity in memory requirements due to the storage of the channel statistics used to select the set, and in the computation for building the statistics, but these may not be important when an efficient use of the spectrum is crucial.

6.3 Network adaptation

6.3.1 Collaborative datarate adaptation

The collaborative datarate scaling protocol introduced in Sect. 5.4.2 is here further analysed. In link adaptive systems, energy efficiency improves when using slower, more robust transmission modes, at the cost of a longer channel occupation. Therefore, network devices are allowed to reduce their datarate to save energy but collaborative measures allow sharing the energy gain among more nodes. The delay-energy trade-off is discussed making use of the results obtained by queuing theory. The analysis in this part gives further insight into the energy costs in transceivers.

6.3.2 Related work

Often, rate adaptation and energy efficiency are addressed focusing on a single link. For energy-efficient rate adaptation targeted by Kompella & Snoeren (2003), WLAN stations obtain the network status either from the access point combining load information from individual stations and sharing this global view, or by snooping network traffic. Considering that especially for shorter-range applications reception is expensive, the latter distributed approach eats at least partially the achieved gain. In the present protocol (Celentano *et al.* 2008b), the required information is announced to the network as information elements in anyway transmitted beacons, with potentially smaller overhead. Yeh *et al.* (2007) combine DVS/DFS with adaptive modulation and study the energy consumption of a sensor network. Since all sensors are assumed to process the same tasks, the effects on the traffic load of the network are not considered. Wang *et al.* (2007) consider an IEEE 802.11 multi-hop network in which nodes first exchange their link information (required channel time and power in each mode), then select for improvement the link with the largest benefit ratio, defined as the ratio of the power consumption gain over the channel time loss, and finally send messages with those new rates to neighbours, which accept them if they are feasible. Meshkati *et al.* (2006, 2009) study joint power and rate control for a DS-CDMA distributed system. Heliót *et al.* (2012) consider the downlink of a cellular scenario and minimise the ratio of the total power per cell over the total sum-rate per cell, subject to transmit power up to a limit and fairness above a limit; upper layer issues are out of the scope of that paper and in particular delay is not considered there. Amin *et al.* (2013) consider spectral efficiency, fairness and estimated residual battery lifetime as attributes for a resource allocation procedure in a centrally controlled network of reconfigurable devices.

6.3.3 Energy efficiency of link adaptive systems

A common non-collaborative protocol for link adaptation often selects preferably the highest speed mode, compatibly with quality of service constraints. In this way, the smallest fraction of the shared resources is used by the device and therefore more resources are left available for others. However, this strategy is not energy-efficient, as also observed in Kompella & Snoeren (2003, e.g.).

The required signal to noise ratio at the receiver, and hence the transmit power $p_{\mathrm{tx}}(r)$, is monotonically increasing in the rate r, with given bandwidth B fixed. This is due to the use of weaker channel coding and closer modulation constellation points. From the well-known Shannon capacity limit, the required information-bit-energy to noise-power-density can be obtained as (Dahlman *et al.* 2008):

$$\gamma = (2^{\eta_B} - 1)/\eta_B. \tag{23}$$

where $\eta_B = r/B$ is the bandwidth utilisation obtained dividing the datarate by the bandwidth. Eq. (23) tells that the decrease in the required transmit power at a given transmit rate, $p_{\mathrm{tx}}(r)$, is faster than the effects of the increase in the required transmission time. The property applies to practical systems, as it is easily verified when theoretical performance expression for modulation and coding schemes are available.

6.3.4 Collaborative protocol

Datarate is changed varying channel coding, modulation scheme and other parameters thus defining a specific PHY-mode (Celentano & Glisic 2006a), see Sect. 6.2 and following. From what seen above, the use of a slower mode, compatibly with traffic requirements and load constraints, is preferable in terms of energy efficiency. Since this strategy will extend the use of the channel time, to be fair towards other users, it requires collaboration among users.

According to the collaborative protocol described here, devices transmit preferably with their slowest feasible mode and therefore occupy the channel longer. To allow other network devices to use the shared data channel, busy devices collaboratively free resources. This rule can be called an *energy-triggered, network-targeted* rate adaptation, contrasted with the *error-rate triggered, link-targeted* rate adaptation, as the non-collaborative protocol described above in Sect. 6.2 and following, see Celentano & Glisic (2006a, 2005, e.g.).

Network-wide rate control is clearly easier in centralised systems. In distributed networks, control information is generally available at each node. For example, devices know the associated devices and possibly their traffic requirements by listening at control channel. In this case, the information needed for fairness operation is available at legacy devices and often with no additional cost in term of resource usage, see Sect. 6.3.9.

In its simplest version, resources are freed by the collaborative protocol as more traffic is expected to arrive to the network because more devices activate (newcomer devices join or devices wake up from hibernation). In some distributed protocols, such as ECMA-368 (ECMA 2005), this fact is known at all devices from the list of associated devices and their status.

Not all network devices may have stringent energy saving needs. The fraction of the devices allowed or intending to lower their datarate may indicate this by an energy saving need indicator included in the beacon. This information, with the possible addition of the knowledge of energy consumption curves (needed explicitly only in case of heterogeneous devices and possibly not in a single-standard network) may rule a distributed decision on devices allowed to decrease or devices asked to increase their rate.

The collaborative protocol is compared with the reference non-collaborative protocol. The third case outlined above, with only a fraction of devices adopting network-triggered rate adaptation, is also considered.

6.3.5 System model

As seen in Chapt. 5, a device may be *hibernating* or non-hibernating (active). An *active* device may be *sleeping* or *awake*, and in this latter state, it can be *busy* (i.e., transmitting or receiving data) or *idle*. Devices may want to get active for purposes other than related to data transfer, for example for refreshing network state information. Before being able to transmit, a device needs to associate to an existing network (or to create a new one). This is done for example gaining a slot in the network control channel.

Devices go active either after joining the group or coming back from hibernation. The analysis of the network control period (NP, see e.g. Fig. 59) and the slot acquisition by newcomers is a separate problem itself and out of the scope of this study: a device is here assumed to enter and exit instantaneously the corresponding associating state in null contention time. Channel time allocation in distributed systems requires in general collision resolution protocols. Similarly, instantaneous reservation collision resolution is assumed in this paper.

Consider a population of $2n_m$ devices with unicast traffic instantaneously paired as n_m source-destination pairs, with $n \leq n_m$ sources simultaneously busy.

A device selects a transmit rate r in a finite set $\mathscr{M}$. The maximum feasible rate depends on service requirements (tolerable error rate) and link quality (see e.g., Sect. 6.2 and following) whereas the minimum value may depend on user throughput requirements. As we will see, with the collaborative protocol, the instantaneous minimum feasible rate depends on the system state (number of requests in service). Without loss of generality we can denote with $\delta_s \in \mathbb{R}^+$ the dynamics of the feasible rates: $\mu_H = \delta_s \mu_L$, where μ is the service rate. Also assume link quality good enough so that devices may select the fastest mode (only parameter δ_s will change).

In general, see Sect. 5.4.2 and Celentano *et al.* (2008b), PHY-mode transition may be done from the current superframe (possible if the control part comes prior to the data part), or the following, or even delayed according to a count-down counter; PHY-mode transition may be done in a single step or in up/down-steps of one mode among those commonly available at transmitter and receiver side, Here we assume that the rate is changed immediately.

6.3.6 Queuing model

The channel time of many practical systems is divided into segments, see e.g., Fig. 59. However, in some practical systems the timing structure can be ignored, see Sect. 6.3.9. Based on this and on the assumptions in Sect. 6.3.5, we approximate the system with a Markovian queuing model.

To evaluate the collaborative protocol, we want to isolate from the effects of limited buffering and infinite queues are therefore assumed. Activity of devices is assumed Poisson with an aggregate arrival rate $\lambda_n = \lambda$. For the analysis below we approximate $\delta_s \approx k_s$, for some $k_s \in \mathbb{N}^+$.

In order to allow service for other possible users, with the reference non-collaborative protocol (NCP), users always select the highest possible rate regardless of the users population: requests are served by the system using the fastest possible rate $\mu_H = k_s\mu_L$, therefore the system service rate is $\mu_n = k_s\mu_L$.

With the collaborative protocol (CP), users select the slowest rate compatibly with users population: requests are served by the system with a rate increasing with the number of requests in service. The service rate increases with the state until the maximum datarate is used: $\mu_n = n\mu_L, 1 \leq n \leq k_s$, and $\mu_n = k_s\mu_L, n > k_s$.

Hence, appropriated queuing models are a single server with server of capacity $k_s\mu_L$ ($M/M/1[k_s\mu_L]$), and a multi-server with servers of capacity μ_L ($M/M/k_s[\mu_L]$), for NCP and CP respectively. (We use the Kendall's (1951) notation with the addition of the server capacity, which is important in this comparison, in square brackets.)

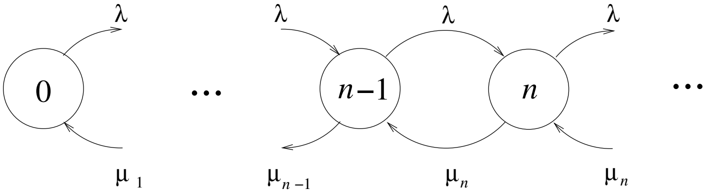

Fig 55. Queuing model of both non-collaborative (NCP) and collaborative (αCP) systems. The service rate is given by (24), with $\alpha = 0$ and $0 < \alpha \leq 1$, respectively.

Let us now consider a third system. Not all devices may need energy saving feature or some devices may not tolerate the small additional delays associated with it. In a more generic system (αCP), only a fraction α of devices adapts transmit rate according to network conditions.

Since systems NCP and CP behave the same for $n \geq k_s$, consider here the αCP model for $n < k_s$ only. As seen, NCP can be modelled with a single-server $M/M/1[k_s\mu_L]$, and CP as a multi-server $M/M/k_s[\mu_L]$. The CP system can also be seen as a single-server system with state-dependent service rate. For the αCP case with FCFS discipline and in stationary conditions, the total service rate for the αCP system is therefore $k_s\mu_L$ with probability $(1-\alpha)$ and $n\mu_L$ with probability α; rearranging terms:

$$\mu_n = \begin{cases} [k_s + \alpha(n-k_s)]\mu_L, & 1 \leq n \leq k_s \\ k_s\mu_L, & n > k_s \end{cases} \tag{24}$$

With the αCP system (24), network-triggered rate-adaptive devices (αCP requests) adjust rate according with n, regardless of the fraction α of devices. This is reasonable, since this additional information may not always be available, or may change with time depending on local device state.

The $M/M/1$ system with state-dependent service rate (24) is a more general model that also fits NCP and CP systems: obviously, letting $\alpha = 0$ or $\alpha = 1$, the system reduces to the special cases NCP ($M/M/1[k_s\mu_L]$) or CP ($M/M/k_s[\mu_L]$), respectively. We can therefore limit the study to this system only.

Model (24) tells that, because of the memoryless service distribution, a stationary Markovian multi-server queue can be regarded as a particular Markovian single-server queue with state-dependent service rate.

The equilibrium conditions of model (24) give the steady state probabilities $\boldsymbol{\pi}(\alpha,\lambda) = \{\pi_n\}$ as follows[60]:

$$\pi_n = \begin{cases} \pi_0 \left(\frac{\lambda}{\mu_L}\right)^n \prod_{i=0}^{n-1} \frac{1}{k_s+\alpha(i+1-k_s)}, & 1 \leq n \leq k_s \\ \pi_0 \frac{(\lambda/\mu_L)^n}{k_s^{n-k_s}} \prod_{i=0}^{k_s-1} \frac{1}{k_s+\alpha(i+1-k_s)}, & n > k_s \end{cases} \tag{25}$$

where as usually $\pi_0 = (1 + \sum_{n=1}^{\infty} \pi_n/\pi_0)^{-1}$.

The probability of zero energy gain is the probability of finding the system in any state n, $n \geq k_s$: $\sum_{n=k_s}^{\infty} \pi_n$ (similar to the Erlang's (1917) C formula):

$$\begin{aligned} \Pr(e_{\max}) &= \sum_{n=k_s}^{\infty} \pi_n = \\ &= \pi_0 \prod_{i=0}^{k_s-1} \frac{1}{k_s+\alpha(i+1-k_s)} k_s^{k_s} \sum_{n=k_s}^{\infty} \left(\frac{\lambda}{k_s\mu_L}\right)^n \\ &= \pi_0 \prod_{i=0}^{k_s-1} \frac{1}{k_s+\alpha(i+1-k_s)} k_s^{k_s} \frac{(\lambda/k_s\mu_L)^{k_s}}{1-\lambda/k_s\mu_L} \\ &= \pi_0 \frac{(k_s\rho)^{k_s}}{1-\rho} \prod_{i=0}^{k_s-1} \frac{1}{k_s+\alpha(i+1-k_s)} \end{aligned} \tag{26}$$

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[60] For $1 \leq n \leq k_s$, we have $\frac{\pi_n}{\pi_0} = \prod_{i=0}^{n-1} \frac{\lambda_i}{\mu_{i+1}} = \prod_{i=0}^{n-1} \frac{\lambda}{[k_s+\alpha(i+1-k_s)]\mu_L} = \left(\frac{\lambda}{\mu_L}\right)^n \prod_{i=0}^{n-1} \frac{1}{k_s+\alpha(i+1-k_s)}$. For $n > k_s$: $\frac{\pi_n}{\pi_{k_s}} = \prod_{i=k_s}^{n} \frac{\lambda}{k_s\mu_L} = \frac{(\lambda/\mu_L)^{n-k_s}}{{k_s}^{n-k_s}}$, and $\frac{\pi_n}{\pi_0} = \frac{\pi_n}{\pi_{k_s}} \frac{\pi_{k_s}}{\pi_0} = \frac{(\lambda/\mu_L)^n}{k_s^{n-k_s}} \prod_{i=0}^{k_s-1} \frac{1}{k_s+\alpha(i+1-k_s)}$.

where $\rho = \lambda/(k_s\mu_L)$ is the load. Eq. (26) suggests a design criterion, the minimisation of $\Pr(e_{\max})$, alternative to those considered in the following sections.

When $\alpha = 0$ (NCP model), clearly $\Pr(e_{\max}) = 1$, whereas for $\alpha = 1$ (CP model), (26) gives $\Pr(e_{\max}) = \pi_0 \frac{(k_s\rho)^{k_s}}{k_s!(1-\rho)}$, the same as the cited Erlang-C formula.

6.3.7 Delay-energy trade-off

The average number of requests in the system is found as $N = \sum_{n=0}^{\infty} n\pi_n$ with π_n given by (25), and using Little's formula we get the average time in the system $T^{(\alpha CP)} = N/\lambda$, which is our delay metric (delay cost). Fig. 56 shows $T^{(\alpha CP)}$ versus load $\rho = \lambda/(k_s\mu_L)$ for various values of the fraction α, using $k_s = 10$. It can be seen that for small values of α, delay performance is closer to the NCP case ($\alpha = 0$), especially for smaller values of ρ. For lightly loaded system, α can be relatively large without affecting much delay performance.

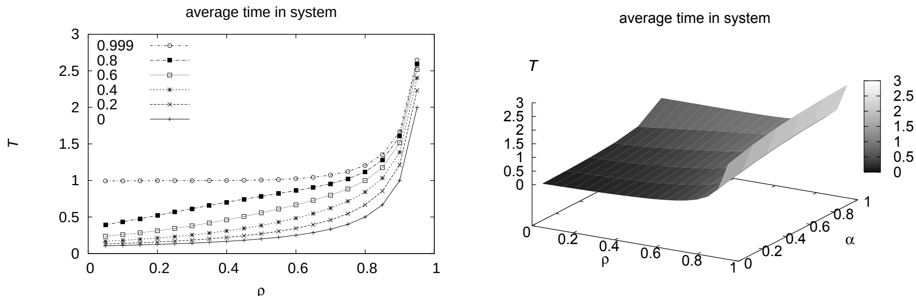

Fig 56. Average time in system $T^{(\alpha CP)}$ versus load ρ for various values of network-triggered rate-adaptive devices ratio α.

Limiting to the cases $\alpha = 0$ and $\alpha = 1$ (corresponding to $M/M/1$ and $M/M/k_s$, respectively), the delay performance comparison is well-known (Bertsekas & Gallager 1992, e.g.): NCP system has k_s times better delay performance when lightly loaded, with the difference vanishing as the load increases, since the service is the same for $n \geq k_s$.

The required information bit energy to noise power density (23) is used as energy expenditure metric:

$$\gamma_n = B(2^{\mu_n/B} - 1)/\mu_n \tag{27}$$

where μ_n is given by (24). The average transmit energy expenditure for the energy-saving requests (energy cost) is

$$e^{(t)} = \sum_{n=1}^{\infty} \gamma_n \pi_n \tag{28}$$

where π_n are given in (25).

Fig. 57 shows $e^{(t)}$ versus load ρ for various values of the fraction α, again with $k_s = 10$.

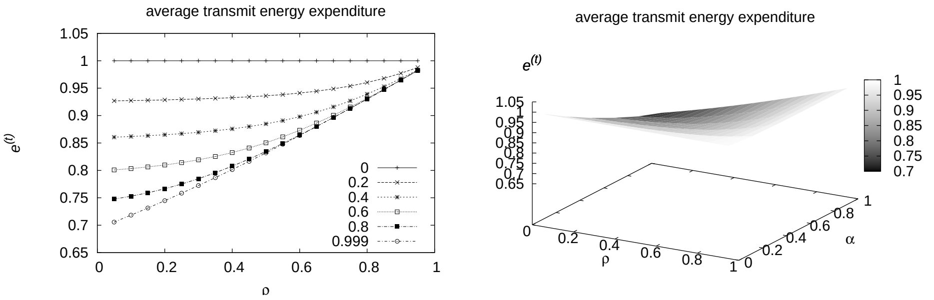

Fig 57. Average transmit energy expenditure versus load ρ for various values of network-triggered rate-adaptive devices ratio α.

Objective functions $T^{(\alpha CP)}(\rho, \alpha)$ and $e^{(t)}(\rho, \alpha)$ defined above are continuous in the feasible region of decision variables $\Omega = (0,1) \times [0,1]$. Consider the closure $\bar{\Omega} = [0,1] \times [0,1]$. It is known that extrema of any linear combination of objective functions exist and are achieved in $\bar{\Omega}$ (Kolmogorov & Fomin 1980). The minima for energy and delay costs studied separately are achieved at opposite extremes of the domain of α: delay is traded-off for the energy gain. It is easy to see that the Pareto front of $\min_{\boldsymbol{\pi} \in \Omega} \boldsymbol{f}(\boldsymbol{\pi}), \boldsymbol{f}(\rho, \alpha) = [T^{(\alpha CP)}(\rho, \alpha), e^{(t)}(\rho, \alpha)]^{\mathsf{T}}$ is achieved at $\rho \to 0$, see Fig. 56 and 57, which corresponds however to a small system utilisation. Higher values of ρ correspond obviously to less opportunities for energy save and to larger values to the delay. The trade-off region covers therefore the central part of the support and avoids the extremes for ρ. As α increases, $e^{(t)}$ decreases but $T^{(\alpha CP)}$ increases; as ρ increases, both objective functions increase. This was expected: for a light system the delay is obviously smaller and the larger available capacity brings a larger margin energy gain as well. In other words, the delay and energy costs are minimised by over-dimensioning the system. Including in the cost function a related metric, like the utilisation, ρ, to be maximised, we get:

$$\min_{\boldsymbol{\pi}\in\Omega} \boldsymbol{f}(\boldsymbol{\pi})$$
$$\boldsymbol{f}(\rho,\alpha) = [T^{(\alpha CP)}(\rho,\alpha), e^{(t)}(\rho,\alpha), (1-\rho)]^{\mathsf{T}} \tag{29}$$

with the same support for $\boldsymbol{f}$ as above.

Problem (29) has been solved implementing in Matlab a weighted Čebyšev programme (Klamroth & Tind 2007), which does not require assumptions on convexity (Klamroth & Tind 2007). Opposed to the weighted-sum approach, the weighted Čebyšev programme is able to find all Pareto points and therefore to generate Pareto fronts (Chen *et al.* 2000).

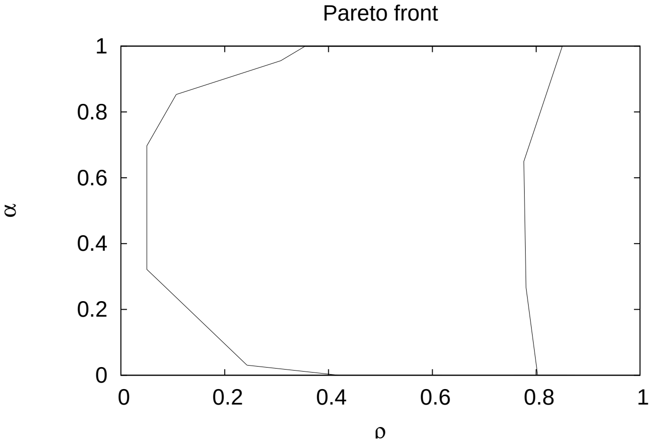

Fig 58. Pareto front. The area out of optimal region on the right tells that, with high load, opportunities for energy saving are reduced and delay starts to increase too much. The bottom left area tells that with light load it is not beneficial having only a few devices adapt to network conditions.

From Fig. 58, it can be seen that a practical limit corresponds to $\rho \approx 0.8$: beyond that value, although utilisation is good, delay starts to increase and possibilities for energy saving also decrease too much. Another interesting limit is the leftmost boundary which gives optimal design constraints when over-dimensioned capacity is allowed. In the region in the bottom-left corner, utilisation is too small, as it is the energy gain due to the small fraction of saving devices. Conversely, in the top-left region, the energy gain at larger values of α is paid with larger delay and low utilisation.

6.3.8 Discussion

The reference system with no collaboration (NCP) corresponds as seen to $\alpha = 0$. Fig. 57 suggests the energy gain provided by the proposed protocol. The transmit energy gain accounts for a fraction of the energy expenditure in transmission (see Fig. 32). The gains are surely larger for longer-range networks, where transmit energy is dominant, but also more generally for systems with transmit time dominant over receive time, regardless of the range. Nevertheless, as observed in Sect. 5.4.2, lower-rate modes may be associated to gains also in reception. In any case, any energy gain translates into a reduced impact on the environment and an extended device/network lifetime for battery operated devices.

On the other hand, when all energy consumption components are taken into account, the energy efficiency of higher rates (associated with shorter usage time) is further penalised due to the larger relative impact of transients, Sect. 5.2.3, or due to impact of protocol, see. Sect. 6.3.9.

A quantitative analysis of the overall energy expenditure requires detailed knowledge of a specific system and, being strongly implementation-dependent, has been left out of the scope of this study. Although arguments coming from realistic communication systems are used, the purpose of this study was to show the benefits of a collaborative protocol rather than to derive exact performance analysis of a particular system. To this end, the protocol has been analysed using queuing theory and the system model has been simplified to allow it, but approximations are discussed in Sect. 6.3.9.

Compared with a non-collaborative system, in presence of busy users, a network adopting the proposed collaborative protocol tends to occupy always the entire channel time. This implies towards neighbouring appliances a smoother interference, which may sometimes be better tolerated.

As for link-targeted rate adaptation, when for example due to fading and shadowing channel conditions are bad, the fastest feasible rate is instantaneously smaller. In our model, this translates in having the feasible rate k_s dynamically changing. It is intuitive that the energy gain will be smaller, thus the previous analysis provides an upper bound to the performance achieved with fading channel. This generalisation is left out of the scope of this study.

6.3.9 Example implementation

As an example target system, ECMA-368 (ECMA 2005), is considered. ECMA-368 is a multi-band orthogonal frequency-division multiplexing system and its channel time is divided into a BP for control and a DTP for data, together forming the SF, Fig. 59. The SF has fixed length of 256 medium access slots (MAS) of 256 μs each.

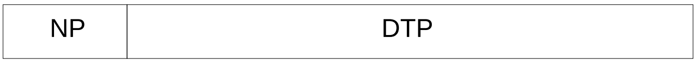

Fig 59. An example of time-division system. The shared channel time is divided into superframes (SF) and further divided into a network control part (NP) and a data transfer part (DTP). Sometimes, the duration of the NP depends more on the number of the associated devices than on the amount of information broadcast there.

ECMA-368 devices implement up to eight PHY modes. Rate adaptation is performed in DTP only, since in BP a predefined rate is needed for interoperability and backwards compatibility. We assume that rate adaptation is performed in the entire channel time and that the DTP capacity is given by the datarate. As we will shortly see, in the above performance analysis we can neglect the impact of the control part and assume that only data traffic is present. The latter assumption of negligible protocol overhead is also discussed below.

Approximations

The BP duration depends on the network population. With $2n_m$ devices, the BP length is $T_{\mathrm{BP}} = \lceil (2n_m + 10)/3 \rceil$ MAS. In some practical scenarios, the BP has a limited impact on the total DTP availability, hence $T_{\mathrm{DTP}} = T_{\mathrm{SF}} - T_{\mathrm{BP}} \approx T_{\mathrm{SF}}$ can be assumed (for $n_m < 33$ the approximation is within the order of 10^{-2}). The BP can therefore be neglected for *busy* devices. (Clearly, the BP cannot be neglected in general, as for example for *idle* devices, but this is not relevant here since we focus on data transmission. We focused on the network control part in Chapt. 5.)

Taking into account the physical layer convergence protocol (PLCP) preamble and header length L_s, the PHY service data unit (PSDU) frame check sequence (FCS) and tail lengths L_c and L_t, neglecting the pad bits in the PSDU added to align to the interleaver boundary, and using the values in Table 17 and 18, the PLCP protocol data unit (PPDU) efficiency can be approximated as:

$$\eta_{\text{PPDU}} = \frac{\frac{L_i}{rT_s}}{\frac{L_i+L_c+L_t}{rT_s}+L_s} \approx \frac{\frac{L_i}{rT_s}}{\frac{L_i}{rT_s}+L_s} = \frac{L_i}{L_i+rT_sL_s} \tag{30}$$

The assumption done in the analysis of Sect. 6.3.6, i.e., the approximation of the DTP capacity with the datarate, reasonable at lower rates ($\eta_{\text{PPDU}} \approx 0.98$), becomes looser at higher rates ($\eta_{\text{PPDU}} \approx 0.84$), due to a PSDU faster than the rest of PPDU. Incidentally, this observation signifies that the lower rates are even more energy-efficient than the faster ones.

Table 17. Some PHY and MAC parameters of ECMA-368. Values from ECMA (2005).

Parameter	Symbol	Value	Unit
maximum frame payload	L_i	4095	octect
PSDU FCS	L_c	4	octect
PSDU tail	L_t	6	bit
PLCP header + preamble	L_s	42	symbol
FFT size	N_{FFT}	128	
zero-padded suffix length	N_z	37	
number of data sub-carriers	N_c	100	
symbol duration	T_s	312.5	ns

For a multi-band OFDM system, the bandwidth utilisation η_B can be rewritten as

$$\eta_B = \frac{1}{B}\frac{B}{N_{\text{FFT}}+N_z}\frac{N_c}{k_fk_t}\frac{\eta_m\eta_c}{k_m} = \frac{N_c}{N_{\text{FFT}}+N_z}\frac{\eta_m\eta_c}{k_fk_tk_m} \tag{31}$$

where N_{FFT} is the fast Fourier transform (FFT) size, N_z is the zero-padded suffix length, N_c the number of data sub-carriers, k_f and k_t the frequency-domain and time-domain spreading factors, k_m the carrier repetition factor, η_m the modulation efficiency and η_c the channel coding rate. In (31), the first factor is constant with the modes, whereas the last factor incorporates all mode-dependent terms.

The quantitative values for the example system ECMA-368 are given in Table 18, which shows also the values for the required information bit energy to noise-power-density ratio (23) increasing with datarate r.

Table 18. ECMA-368 PHY modes: mode ID, frequency-domain and time-domain spreading factors, modulation scheme and bits per symbol, carrier repetition factor, forward error correction (FEC) code rate, resulting datarate, bandwidth utilisation, and required information bit energy to noise power density ratio.

	k_f	k_t	mod	η_m	k_m	η_c	r Mbit/s	η_B	γ
0	2	2	QPSK	2	1	1/3	53.3	0.1010	0.7180
1	2	2	QPSK	2	1	1/2	80	0.1515	0.7309
2	1	2	QPSK	2	1	1/3	106.7	0.2020	0.7440
3	1	2	QPSK	2	1	1/2	160	0.3030	0.7713
4	1	2	QPSK	2	1	5/8	200	0.3788	0.7927
5	1	1	DCM	4	2	1/2	320	0.6061	0.8615
6	1	1	DCM	4	2	5/8	400	0.7576	0.9117
7	1	1	DCM	4	2	3/4	480	0.9091	0.9656

DCM = dual-carrier modulation.

6.4 On the source-destination distance

In Chapt. 5 some issues related to node clustering have been discussed. Here are considered the *natural clusters* made of nodes related by some function, like in the case of devices belonging to a person, members of a group, etc.

Consider network nodes deployed in an planar, infinite area according to a planar, stationary, isotropic, Poisson point process (Stoyan *et al.* 1995, e.g.) with intensity λ_p. Consider a destination probability $p(r)$ decreasing with the distance r, namely following the Gaussian distribution:

$$p(r) = \frac{1}{\sigma_D\sqrt{2\pi}} \exp\left(-r^2/2\sigma_D^2\right) \tag{32}$$

In this case, the typical source-destination distance is found[61] to be

$$\bar{d}_\infty = \int_0^\infty 2\pi\lambda_p r^2 \frac{1}{\sigma_D\sqrt{2\pi}} \exp\left(-r^2/2\sigma_D^2\right) \mathrm{d}r = 16\sqrt{\pi}\lambda\sigma_D^2 \tag{33}$$

---

[61] Averaging over the infinitesimal annuli dR, $\bar{d} = \int_0^\infty Rp(R)\mathrm{d}R$, substituing (32), replacing $\rho \leftarrow r/\sigma_D\sqrt{2}$, and integrating by parts, (33) is obtained. Note that with equiprobable destination, the typical source-destination distance grows cubically: $\bar{d}_\infty = \int_0^\infty r2\pi r\lambda_p \mathrm{d}r \propto \infty^3$.

which does not depend on the size of the network area. The typical source-destination distance, even in infinite crowds, only grows linearly with the intensity of the point process and with the variance of the destination probability.

6.5 Discussion

This chapter presented selected problems in link and network adaptation. For the former, a probabilistic model of imperfections and a model for the goodput of adaptive links gave a model for the effective capacity of imperfect adaptive links. The effective capacity has been derived in compact form and its sensitivity to estimation errors, estimation delay, acquisition error, as well as the sensitivity to the hysteresis region width has been discussed. Again for this former case, a PHY-mode signalling method with reduced overhead, allowing efficient fast adaptation, has been presented. The learning method exploits classification of the channel conditions and selection of the active mode sub-set, and various options have been presented and discussed.

Collaborative datarate adaptation has been presented in the second part. Network devices are allowed to reduce their datarate to save energy but collaborative measures, both proactive and reactive, allow sharing the energy gain among more nodes. The delay-energy trade-off has been discussed making use of the results obtained by queuing theory. The analysis in this part gave further insight into the energy costs in transceivers. Finally, an expression for the source-destination distance in infinite clusters has been discussed.

This chapter concludes the overview of concurrent and cognitive networks. The discussion on the entire dissertation continues in the following, concluding chapter.

7 Conclusions

Voimat vaipuvat uneen, mutta mielikuvitus saa siivet, kuin kultaperhot leijailevat sen häilyvät kuvat edessäni yksinäisellä salopolulla.	Strength drifts off to sleep, but imagination gets its wings, like golden butterflies hover its vacillating images in front of me on a solitary backwoods trail.

– Into Konrad Inha (Konrad Into Nyström) (1909) *Suomen maisemia. Näkemänsä kuvaillut I. K. Inha.* WSOY, Porvoo.

In this final and concluding chapter, Sect. 7.2 identifies the paths that may possibly stem out of the contributions, introduced in Sect. 1.2 and Sect. 1.3, and summarised in the following Sect. 7.1, together with a speculation on their possible exploitation.

7.1 Summary and exploitation of contributions

Stemming from an historical outlook of the development of cognitive networks, in Chapt. 1 challenges of various nature are highlighted. They range from the lack of available radio spectrum to environmental and other dependability issues. Consequent trends concerning design targets are further reviewed in Sect. 2.1 and Sect. 5.1. The derived objectives are an improved use of spectrum resources and of energy, together with an increased flexibility and dependability needed in the resulting systems. These goals can be achieved by cognitive functionalities enabled by awareness of the context and exploiting the available reconfiguration capabilities. In its five central chapters, this dissertation covers, at different levels and from different perspectives, various aspects of cognitive systems.

Concurrent networks are networks operating in relative vicinity and simultaneously with some form of interaction. One particular case of concurrent networks, concurrent spectrum use, is addressed in Chapt. 2, where various access models are rationalised. The obvious related challenge is to conciliate incumbent protection and adequate quality of service in the opportunistic (sub)system, and architectural issues for supporting the necessary gathering and exchange of information are addressed in Chapt. 2.

Chapt. 3 covers, under the unifying concept of concurrent networks, different kinds of interaction with their dynamics and considers for those the quality of service management by looking at the entire ecosystem. As outlined above, cognition comes in help in concurrent networks and decision-making in opportunistic spectrum access is modelled here. In addition to the above contributions, Chapt. 3 starts broadening the treatment of cognitive networks, commencing with the definition of cognitive entity and network adopted in this monograph. Flexibility is brought up to the network design level and topological domains are defined to aid the allocation of functionalities, cognitive and not, by domain, to be assigned to network elements only when detailing the specific case. The result of this contribution is an easier reuse of protocol specifications across a larger range or application cases.

Chapt. 4 stays into the core topic of cognitive networks and studies the peculiarities of a generic cognitive entity, looking at both humans and machines. Three major categories of cognitive entities – memoryless adaptive, learning and developing – are identified, depending on how the information is used and how the knowledge impacts on the structure of the entity. By observing the important role that social interaction has in humans and reminding that co-operation and collaboration of artificial cognitive entities bring their improvements, interaction and shared knowledge are brought explicitly into the proposed model for networked cognitive entities. Functions are divided into four categories (observation, consolidation, interworking and operation) as well as split into a cognitive frontier and a metacognitive hub, also with a look at the practical realisation of those entities. This contribution permits to model cognitive processes at the entity level, which in turn allows considering interaction aspects, guiding the design of system architecture and of the cognitive entity. Such an approach is applicable to any case of interacting cognitive entities.

Chapt. 5 moves the focus on example solutions that cognitive features making use of context awareness bring, addressing selected dependability challenges. As reminded above, among our goals is energy efficiency. After the presentation of a conjecture on power consumption, the chapter presents an energy-efficient transmission method, which also may allow privacy protection against simple overhearing. Another contribution realises fair use of energy in a network, to extend the lifetime of its entirety. The solutions presented in this chapter are thought for short-range communications systems. For a technology using distributed control, a flexible beaconing structure is proposed. Among the benefits of this contribution is to relieve from some burdens or constraints imposed by the standard, such as network size, beaconing periodicity or transmission method, thus improving flexibility. Chapt. 3 outlined dynamics in concurrent networks. Chapt. 5 concludes presenting solutions concerning mobility and dynamics. As for physical mobility, a contribution enforces protection of sensitive sites, such as health care centres. Finally, a contribution shows how to cope with efficient energy and resource use for networks with dynamic population or activity by using a collaborative protocol. The contributions of this chapter give special attention to the actual feasibility and also show that existing technologies can be compatibly augmented by advanced features.

Cognitive functionalities control reconfiguration capabilities and adaptation is a form cognitive networks manifest themselves in. This is the subject of Chapt. 6, which addresses link and network adaptation. A contribution on the first topic is a model for the effective capacity of adaptive links in presence of imperfections. Imperfections and implementation constraints are incorporated with a probabilistic analysis into a compact-form expression used to study the sensitivity to hysteresis region width, estimation errors, estimation delay and acquisition errors. This characterisation is exploitable in both analysis and simulators. A second contribution in this topic presents an efficient environment-aware link adaptation method that makes use of learning to achieve overhead reduction. On network adaptation, the above collaborative protocol is studied by a queuing model, whose analysis shows the optimal protocol parameter settings to fairly maximise energy gain. The approximations used in the theoretical model are discussed with the use of real system parameters.

7.2 Future work

The direct exploitation of the contributions presented in this monograph is described above. This dissertation tries to give insight into system-level as well as narrow-scoped aspects related to cognitive wireless networks and some of the contributions summarised in the previous Sect. 7.1 can be intended as a set of tools or guidelines for selected design problems.

Additional future work stemming from here may try to further combine the above system-level and narrow-scoped views together, thus bringing the attention to the study of complex systems, see Sect. 4.5. Complex systems have been studied in diverse branches, such as biology, sociology and economics. However, the research for *engineered* complex adaptive systems is not as broad (Haghnevis & Askin 2012) and this is just the case relevant to the examples outlined right at the beginning of Chapt. 4. Since the study of complex systems is intrinsically trans-disciplinary and because different systems may possess commonalities, a cross-disciplinary approach is natural and possibly a way to progress in this area (San Miguel *et al.* 2012).

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ISBN 978-952-62-0418-5 (Paperback)
ISBN 978-952-62-0419-2 (PDF)
ISSN 0355-3213 (Print)
ISSN 1796-2226 (Online)

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