INVITED PAPER

Near-Capacity Wireless Transceivers and Cooperative Communications in the MIMO Era: Evolution of Standards, Waveform Design, and Future Perspectives

Multiple-input–multiple-output (MIMO) techniques said to promise to deliver speed volume and reliability needed by current wireless communication systems are discussed and the status of wireless baseband transceiver design is reviewed.

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ABSTRACT | Classic Shannon theory suggests that the achievable channel capacity increases logarithmically with the transmit power. By contrast, the MIMO capacity increases linearly with the number of transmit antennas, provided that the number of receive antennas is equal to the number of transmit antennas. With the further proviso that the total transmit power is increased proportionately to the number of transmit antennas, a linear capacity increase is achieved upon increasing the transmit power, which justifies the spectacular success of MIMOs. Hence we may argue that MIMO-aided transceivers and their cooperation-assisted distributed or virtual MIMO counterparts constitute power-efficient solutions. In a nutshell, since the conception of GSM in excess of three orders of magnitude bit-rate improvements were achieved in three decades, which corresponds to about a factor ten for each decade, because GSM had a data rate of 9.6 Kb/s, while HSDPA is capable of communicating at 13.7 Mb/s. However, the possible transmit power reductions remained more limited, even when using the most advanced multistage iterative detectors, since the required received signal power has not been reduced by as much as 30 dB. This plausible observation motivates the further research of advanced cooperation-aided wireless MIMO transceivers, as detailed in this treatise.

KEYWORDS | Author, please supply index terms/keywords for your paper. To download the IEEE Taxonomy go to http://www.ieee.org/documents/2009Taxonomy_v101.pdf **AQ1**

NOMENCLATURE

1G	First generation mobile system.
2G	Second generation mobile system.
3G	Third generation mobile system.
4G	Fourth generation mobile system.
AA	Antenna array.
ACS	Add–compare–select arithmetic operation.
AF	Amplify-and-forward.
AGM	Anti-Gray mapping.
AMPS	Advanced mobile phone system in the USA.
AMR-WB	Adaptive multirate wideband.
AWGN	Additive white Gaussian noise.
BCJR	Bahl–Cocke–Jelinek–Raviv.

Manuscript received November 12, 2009; revised April 28, 2010; accepted March 17, 2011.
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Digital Object Identifier: 10.1109/JPROC.2011.2148150

BER	Bit error ratio.
BICM	Bit-interleaved-coded modulation.
BPS	Bits per modulated symbol.
BPSK	Binary phase-shift keying.
BS	Base station.
CCMC	Continuous-input–continuous-output memoryless channel.
CDMA	Code-division multiple access.
CIR	Channel impulse response.
CRC	Cyclic redundancy check.
CSI	Channel state information.
CSNR	Chip signal-to-noise ratio.
D-AMPS	Digital advanced mobile phone system in the USA.
D-STTD	Double space-time transmit diversity.
DCMC	Discrete-input–continuous-output memoryless channel.
DF	Decode-and-forward.
DL	DownLink.
DOA	Direction of arrival.
DPSK	Differential phase-shift keying
DS-CDMA	Direct sequence code-division multiple access.
DSTBC	Differential space-time block codes.
DSTS	Differential space-time spreading.
DSTS-SP	Differential space-time spreading using sphere packing modulation.
DTC	Distributed turbo code.
EXIT	Extrinsic information transfer.
FD	Frequency domain.
FDMA	Frequency-division multiple access.
GM	Gray mapping.
GSM	Global system of mobile communication
HARQ	Hybrid Automatic-Repeat-reQuest.
HSDPA	High-speed downlink packet access.
HSUPA	High-speed uplink packet access.
HSPA	High-speed packet access.
i.i.d.	Independent and identically distributed.
IC	Interference cancellation.
IrCC	Irregular convolutional code.
IrVLC	Irregular variable length code.
ISCD	Iterative source and channel decoding.
ISI	Intersymbol interference.
IUC	Interuser channel.
LLR	Logarithmic likelihood ratio.
LM	Lloyd–Max.
LSSTC	Layered steered space-time codes.
LSSTS	Layered steered space-time spreading.
LST	Layered space time.
MAP	Maximum *a posteriori*.
MC CDMA	Multicarrier code-division multiple access.
MC DS-CDMA	Multicarrier direct sequence CDMA.
MED	Minimum Euclidean distance.
MI	Mutual information.
MIMO	Multiple-input–multiple-output.
ML	Maximum likelihood.
MS	Mobile station.
MUD	Multiuser detection.
MUI	Multiuser interference.
OFDM	Orthogonal frequency-division multiplexing.
P/S	Parallel-to-serial conversion.
PAM	Pulse amplitude modulation.
PDF	Probability density function.
PHS	Japanese handyphone system.
PSK	Phase-shift keying.
QAM	Quadrature amplitude modulation.
QoS	Quality of service.
QPSK	Quadrature phase-shift keying.
RCPC	Rate compatible punctured convolutional.
RSC	Recursive systematic convolutional.
S/P	Serial-to-parallel conversion.
SF	Spreading factor.
SIC	Successive interference cancellation.
SINR	Signal-to-interference-plus-noise ratio.
SNR	Signal-to-noise ratio.
SP	Sphere packing.
SP-SER	Sphere packing symbol error ratio.
ST	Space time.
STBC	Space-time block coding.
STC	Space-time coding.
STS	Space-time spreading.
STTC	Space-time trellis codes.
TCM	Trellis-coded modulation.
TD	Time domain.
TDD	Time-division duplex.
TDMA	Time-division multiple access.
UL	UpLink.
URC	Unity rate code.
V-BLAST	Vertical Bell Labs layered space time.
VAA	Virtual antenna array.
VSF	Variable spreading factor.
WCDMA	Wideband code-division multiple access
ZF	Zero forcing.

I. INTRODUCTION

Since Shannon quantified the maximum achievable capacity of wireless communication systems in 1948 [1], researchers have endeavored to devise high-speed, high-quality wireless communication systems exhibiting both a high bit rate and a low error rate, while requiring the lowest transmit power. The hostile wireless channel characteristics make it a challenging task to simultaneously accomplish all these objectives.

The demand for high-rate wireless communication systems driven by cellular mobile and wireless multimedia services has been rapidly increasing worldwide and at the time of writing a gradual transition may be observed towards the wireless Internet era. However, the available radio spectrum is limited and the associated bandwidth as well as power demands cannot be readily met without a significant increase in the achievable bandwidth efficiency [2], [3] expressed in bits/symbols/hertz. Furthermore, the wireless system capacity is often interference limited rather than noise limited, and hence cannot be readily increased by simply increasing the transmitted power because increasing the transmit power increases the interference and hence fails to improve the SINR. Therefore, against the explosive expansion of the Internet and the continued dramatic increase in demand for high-speed multimedia wireless services, there is an urging demand for flexible and bandwidth-efficient transceivers [3], [4]. Advances in forward error correction (FEC) coding made it feasible to approach Shannon's capacity limit in systems equipped with a single transmit and receive antennas [3], [5]–[7], but fortunately these capacity limits can be further extended with the aid of multiple antennas. Hence, they are likely to find employment in most future communication systems [8], [9]. Therefore, the family of wireless MIMO-aided communication systems has recently attracted considerable attention as one of the most significant technical breakthroughs in contemporary communications [4].

Recent advances in wireless communications have increased both the attainable throughput and reliability of systems communicating over wireless channels. The main driving force behind the advances in wireless communications is the promise of seamless global mobility and ubiquitous accessibility, while meeting a range of contradicting design challenges such as those that may be gleaned from the stylized illustration of Fig. 1. For example, it is possible to both increase the effective throughput and simultaneously to reduce the BER, if an increased implementational complexity and a higher power consumption may be tolerated to facilitate more sophisticated signal processing. The BER may also be further reduced, if a higher delay may be tolerated, for example, in non-real-time wireless Internet communications. A range of further plausible tradeoffs may be readily identified.

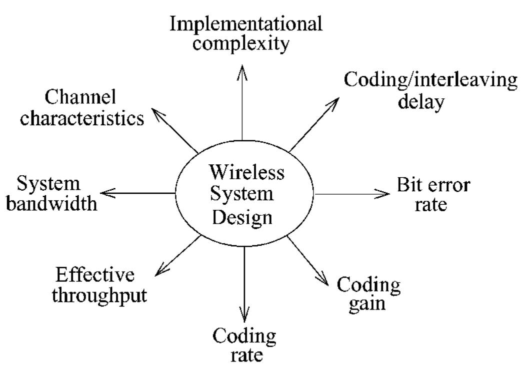

Fig. 1. ***Stylized relationship of the diverse constraints affecting the design of wireless systems.***

Therefore, in this paper, we review the state of the art in wireless baseband transceiver design and the associated overall performance expectations, when communicating over wireless channels. We first present a brief history of wireless standardization in Section II. In Section IV, an overview of different MIMO schemes is presented that can either achieve diversity gain in the interest of increasing the attainable transmission integrity or the multiplexing gain for the sake of increasing the throughput. Alternatively, a beamforming gain may be attained by forming an angular selective transmit/receive beam. We will also highlight that a combination of the abovementioned gains may be provided by multifunctional antenna arrays. These discussions are followed by an overview of FEC coding, while the corresponding iterative detection techniques are presented in Section V. A brief overview of the powerful design-tool of EXIT charts is also presented. Finally, we conclude inSection VI, where we offer some transceiver design guidelines and a range of future research options.

II. BRIEF HISTORY OF WIRELESS STANDARDIZATION

The electromagnetic theory of Maxwell and the pioneering contributions by Hertz assisted Marconi at the end of the 19th century in demonstrating the feasibility of wireless communications with the aid of his spark-gap antenna that was capable of radiating radio waves across the Atlantic. Morse-coded ON–OFF keying was used for mobile radio communications until the 1920s. Naturally, it was only the rich and famous who enjoyed the early privilege of tetherless communications. The first land mobile radio system designed for broadcasting messages to police vehicles was installed in 1928, while in 1933 a two-way mobile radio voice system was introduced by the Bayonne New Jersey Police Department. Naturally, these early mobile radio transceivers used power-hungry valves, since the transistor was not invented until 1947.

An early European development was the Swedish Mobile Telephone System A (MTA) introduced in 1957, which had a 40-kg "*mobile*" terminal and supported 125 users until 1967. In 1966, the Norwegian Offentling Landmobil Telefoni (OLT) system was launched, which operated until 1990.

The 1980s witnessed the development of numerous national mobile phone systems, most of which relied on analog frequency modulation and hence were unable to employ digital error correction codes. Consequently, their ability to exploit the radical advances in digital signal processing (DSP) theory and microelectronics, such as adaptive channel equalization and fading compensation techniques remained limited. Hence, the achievable speech quality was typically poor, especially when the MS roamed farther away from the BS, which provided radio coverage for the traffic cells.

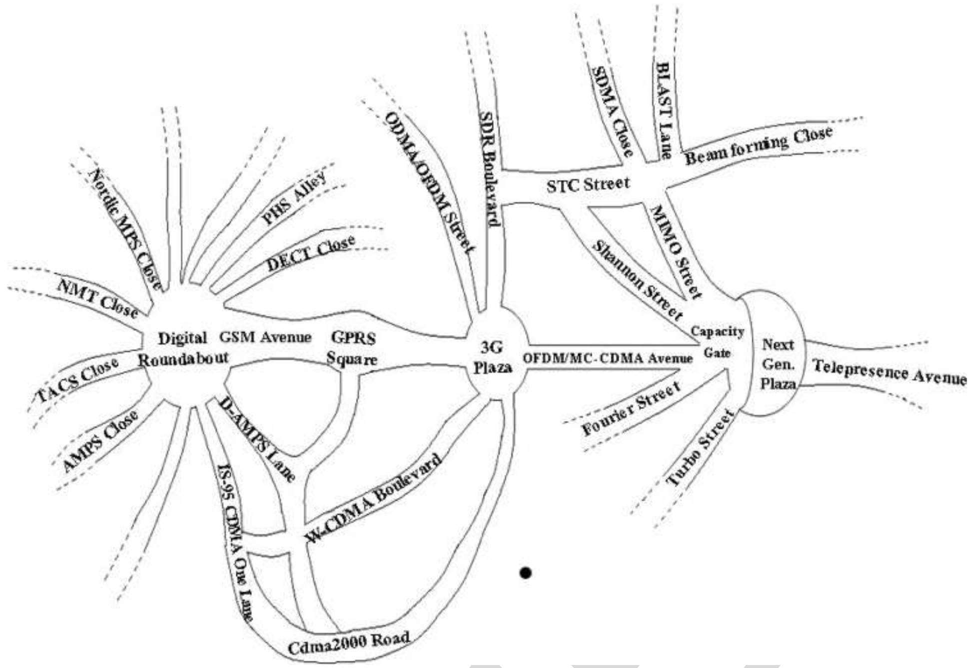

Fig. 2. ***"Anecdotal" evolution of science and its stylized impact on the generations of wireless standardization. The lose relationship and interpretation of the nontechnical terms "street, avenue, close, lane road, plaza, square, etc." as portrayed in the figure varies right across the English-speaking world and by no means should their hierarchical relationship indicate the objective preference of any of the technical solutions over others. It is worth mentioning nonetheless that the term "avenue" may be an exception, since we used it to imply that the related technology has enjoyed broad support.***

The historic developments of the past three decades in wireless communications and standardization are briefly portrayed in the stylized road map of wireless system evolution seen in Fig. 2, which shows more the general trends rather than the exact chronological order of standardization decisions. Suffice to say that the 1G systems were all based on analog frequency modulation, but predominantly used digital control-channel signaling. The Pan-American Advanced Mobile Phone Systems (AMPS), the Total Access Communications System (TACS) in the United Kingdom, the Nippon Mobile Telephone (NMT) system in Japan, and the Nordic Mobile Phone (NMP) system of Scandinavia all belong to the family of 1G systems.[1]

By contrast, the 2G systems briefly mentioned below opted for digital modulation techniques—hence the road map of Fig. 2 portrays that the family of 1G systems converge at "digital roundabout." The countries of the European Union (EU) developed the first digital cellular system during the 1980s, which was later adopted right across the globe. Hence, it is referred to as the GSM [10].

The success of GSM was so stunning—even daring futurists could not have predicted that it would be adopted right across the globe. At the time of writing GSM supports global roaming for more than 2 billion customers. The success of GSM shows the sheer power and attraction of global standardization, motivating competitors to line up behind a common worldwide solution, since GSM was the first digital mobile radio standard that supported international roaming.

Shortly after the ratification of GSM, a number of other digital standards emerged, such as the Pan-American D-AMPS and the ingenious DS-CDMA [5] based system known as IS-95, as also shown in Fig. 2. The PHS also turned out to be a successful system, but its employment remained limited to Japan. The European Digital Cordless Telephone known as DECT penetrated a large residential market, gradually replacing the analog frequency-modulation-based older domestic cordless phones, but it had no hand-over and roaming capabilities.

Diverging from the main "GSM avenue" of Fig. 2 at "digital roundabout," IS-95 had an evolved counterpart, namely the Pan-American cdma2000 system, which had three parallel CDMA carriers, leading to the first standardized MC-CDMA system [5]. In parallel, GSM evolved further by exploiting the dramatic advances in adaptive modulation and coding [11], which led to the standardization of the generic packet radio system (GPRS). A brief summary of the diverse 2G systems' parameters is provided at a glance in Table 1 for the astute reader, while further details of these systems may be found in [10].

[1] It is gratefully acknowledged by the authors that this was pointed out by the anonymous reviewers.

Table 1 Summary of 2G Mobile Systems

System	TACS	GSM	DCS-1800	Qualcomm IS-95 CDMA	IS-54 DAMPS	JDC	CT2	DECT	PHS	PACS
Origin	UK	Europe	Europe	USA	USA	Japan	UK.	Europe	Japan	USA
Forward Band (MHz)	935-950	935-960	1805-1880	869-894	869-894	810-826 1477-1489 1501-1513	864-868	1880-1900	1895-1918	1930-1990
Reverse Band (MHz)	890-905	890-915	1710-1785	824-849	824-849	940-956 1429-1441 1453-1465	(TDD)	(TDD)	(TDD)	1850-1910
Multiple Access	FDMA	TDMA	TDMA	CDMA	TDMA	TDMA	FDMA	TDMA	TDMA	TDMA
Duplex	FDD	FDD	FDD	FDD	FDD	FDD	TDD	TDD	TDD	FDD
Carrier Spacing	25	200	200	1250	30	25	100	1728	300	300
Channels/carrier	1/pair	8/pair	8/pair	55-62	3	3	1	12	4	8/pair
Bandwidth/channel (kHz)	50	50	50	21	20	16.66	100	144	75	75
Modulation	FM	GMSK	GMSK	DL:QPSK UL:64-ary	$\frac{\pi}{4}$-DQPSK	$\frac{\pi}{4}$-DQPSK	FSK	GMSK	$\frac{\pi}{4}$-DQPSK	$\frac{\pi}{4}$-QPSK
Modulation Rate (kBd)	N/A	271	271	1228	48.6	42	72	1152	192	192
Voice+FEC Rate(kbps)	N/A	22.8	22.8	8/Var.	11.2	13	32	32	32	32
Speech codec	N/A	RPE-LTP	RPE-LTP	CELP	VSELP	VSELP	ADPCM	ADPCM	ADPCM	ADPCM
Unprotected Voice Rate(kbps)	N/A	13	13	1.2-9.6	7.95	6.7	32	32	32	32
Control Chan. Name		SACCH	SACCH	SACCH	SACCH	SACCH	D	C	SACCH	
Control Chan. Rate (bps)		967	967	800	600		2000	6400		4000
Control Message Size (bits)		184	184	1	65		64	64		10/2.5ms
Control Delay (ms)		480	480	1.25	240		32	10		
Peak Power (Mobile) (W)	0.6-10	2-20	0.25-2	0.6-3	0.6-3	0.3-3	10mW	250mW	80mW	200mW
Mean Power (Mobile) (W)	0.6-10	0.25-2.5	0.03-0.25	0.2-1	0.6-3	0.1-1	5mW	10mW	10mW	
Power Control	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Opt.	
Voice Activity Detection	Yes	Yes	Yes	Yes	Opt.	Opt.	No	No		
Handover	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes
Dynamic Channel Allocation	No	No	No	N/A	No	Opt.	Yes	Yes	Yes	autonom.
Min. Cluster Size	7	3	3	1	7	4	N/A	N/A	N/A	N/A
Capacity(Dpx ch/cell/MHz)	2.8	6.7	6.7	16.5 †	7		N/A	N/A	N/A	N/A
Frame duration(ms)		4.615	4.615	20	40	40	2	10	5	2.5
Speech FEC	N/A	Conv. (2,1,5)	Conv. (2,1,5)	Conv. Fwd:(2,1,9) Rev: R=1/3	Conv. (2,1,5)	Conv. R=9/17	No	No	CRC	CRC
Channel Eq.	N/A	Yes	Yes	Yes	Opt.	Opt.	No	No	No	No
Half-rate Codec (kbps)	N/A	5.6	5.6	No	No	3.2	No	No	16	No
Half-rate+FEC (kbps)	N/A	11.4	11.4			5.6				
Enhanced Full-rate (kbps)	N/A	12.2	12.2	Yes	7.4	No	No	No	No	No

DCS-1800: GSM-like European system in the 1800 MHz band
IS-95: Pan-American CDMA system
PHS: Japanese Personal Handyphone System
TACS: Total Access Communications System
CDMA: Code Division Multiple Access
FDMA: Frequency Division Multiple Access
TDMA: Time Division Multiple Access
FM: Frequency Modulation
DQPSK: Differential Quadrature Phase Shift Keying
RPE-LTP: Regular Pulse Excited - Long Term Predicted
VSELP: Vector Sum Excited Linear Predictive
SACCH: Slow Associated Control Channel

IS-54: American Digital Advanced Mobile Phone System (DAMPS)
CT2: British Cordless Telephone System
PACS: Personal Access Communications System
GSM: Global System of Mobile Communications
DECT: Digital European Cordless Telephone
FDD: Frequency Division Duplex
TDD: Time Division Duplex
GMSK: Gaussian Minimum Shift Keying
GFSK: Gaussian Phase Shift Keying
CELP: Code Excited Linear Predicted
ADPCM: Adaptive Differential Pulse Code Modulation
JDC: Japanese Digital Cellular

†Assumes $\frac{2}{3}$ frequency re-use

N/A means not applicable.

The 2G systems of Table 1 were indeed based on substantial advances in DSP and microelectronics, which allowed the systems to support increased bit rates and improved voice qualities. These enhanced enabling techniques also facilitated the migration of the wireline-based high-rate multimedia services to wireless systems, although the achievable bit rates remained insufficiently high. In other words, the consumers' thirst for higher bit rates outstripped the bit-rate improvements attained. Hence, as observed in our road map of Fig. 2, during the early 1990s the research community turned its attention to developing the 3G systems and the march towards "3G Plaza" continued throughout the 1990s. Numerous candidates competed in order to become the *de facto* global 3G standard and the Universal Mobile Telecommunication System's Terrestrial Radio Access mode known as UTRA [12] found the widest global acceptance, which is based on wideband CDMA. Its basic system parameters are summarized in Table 2 for the initiated reader, while their detailed discussion and the performance characterization of 3G networks may be found in [12].

The 3G research started out with a much more ambitious bit-rate target than that of the 2G system and ended up with about 384 Kb/s, as the realistically achievable rate. The wideband-CDMA-based 3G solution [12] emerged partly from the experience gleaned from IS95, the Pan-American CDMA system. As mentioned above, in the interest of increasing the attainable throughput, a three-carrier version of IS-95, namely cdma2000 was also ratified, which had a commensurately higher throughput. The cdma2000 scheme is the first standardized terrestrial multicarrier wireless system and hence constitutes a historic milestone in paving the way towards a fully fledged OFDM-style multicarrier system, which was standardized for 4G wireless communications.

Over the years researchers realized that it is unrealistic to expect that any fixed-rate channel coding and modulation scheme could deliver a time-invariant QoS, which led to the intensive research of adaptive modulation and

Table 2 Basic 3G UTRA Parameters

Radio Access Technology	FDD : DS-CDMA TDD : TDMA/CDMA
Operating environments	Indoor/Outdoor to indoor/Vehicular
Chip rate (Mcps)	3.84
Channel bandwidth (MHz)	5
Nyquist rolloff factor	0.22
Duplex modes	FDD and TDD
Channel bit rates (kbps)	FDD (UL) : 15/30/60/120/240/480/960 FDD (DL) : 15/30/60/120/240/480/960/1920 TDD (UL)† : variable, from 366 to 6624 TDD (DL)† : 366/414/5856/6624
Frame length	10 ms
Spreading factor	FDD (UL) : variable, 4 to 256 FDD (DL) : variable, 4 to 512 TDD (UL) : variable, 1 to 16 TDD (DL) : 1, 16
Detection scheme	Coherent with time-multiplexed pilots Coherent with common pilot channel
Intercell operation	FDD : Asynchronous TDD : Synchronous
Power control	Inner-loop Open loop (TDD UL)
Tx. power dynamic range	80 dB (UL), 30 dB (DL)
Handover	Soft handover Inter-frequency handover

† Channel bit rate per time-slot.

coding (AMC)-aided [11] standardized systems, such as the 2G GPRS system of Table 1. In the ensuing era virtually all wireless systems were designed by using AMC, including the HSPA mode of the 3G systems detailed in [12]. Apart from the QAM [7] and channel coding modes, the number of superimposed DS-CDMA spreading codes can also be varied as a function of the near-instantaneous channel quality and user requirements. The user equipment (UE) terminology is used in the HSPA standard for the MS and there are 12 different UE categories depending on their grade of sophistication and achievable bit rate, as detailed in Table 3 for the HSDPA mode [12].

Despite the 40-year research history of OFDM [13], multicarrier cellular solutions only emerged during the 2000s as the dominant modulation technique in the context of the 3G Partnership Project's (3GPP) Long-Term Evolution (LTE) initiative. Clearly, during the 2000s multicarrier solutions have found their way into all the 802.11 wireless standards designed for wireless local area networks (WLANs), while using different-throughput modem and channel coding modes, depending on the near-instantaneous channel quality, as summarized in Table 4.

OFDM is also used in the wide area coverage fixed wireless access scheme known as WiMAX. The main characteristic of multicarrier solutions is the high degree of flexibility that they are capable of providing. They have a host of different parameters that allow us to appropriately configure them and program them, whatever the circumstances are—regardless of the propagation environment and regardless of the QoS requirements, as facilitated by

Table 3 HSDPA Enabled UE Categories [12]

UE class	Maximum transport block size	Max. No. of codes	Highest order modulation scheme	Total No. of soft channel bits	Bitrate (Mbps)
1	7298	5	16QAM	19200	3.649
2	7298	5	16QAM	28800	3.649
3	7298	5	16QAM	28800	3.649
4	7298	5	16QAM	38400	3.649
5	7298	5	16QAM	57600	3.649
6	7298	5	16QAM	67200	3.649
7	14411	10	16QAM	115200	7.206
8	14411	10	16QAM	134400	7.206
9	20251	15	16QAM	172800	10.126
10	27952	15	16QAM	172800	13.976
11	3630	5	QPSK	14400	1.815
12	3630	5	QPSK	28800	1.815

Table 4 802.11a Parameters

MBps	Modulation	Coderate R
6	BPSK	1/2
9	BPSK	3/4
12	QPSK	1/2
18	QPSK	3/4
24	16QAM	1/2
36	16QAM	3/4
48	64QAM	2/3
64	64QAM	3/4

the employment of AMC. Again, the various configurations of the OFDM-based 802.11 standard are shown in Table 4, while those of the 3GPP LTE standard in Table 5.

We are gradually approaching the "capacity gate" on our road map of Fig. 2—we are approaching the bit-rate limits upper-bounded by the channel capacity, but fortunately these are really only the limits of the classic single-input–single-output systems. There is a great deal of "headroom" further beyond that, when we consider MIMO systems. So "MIMO street," "capacity gate," and "turbo street" all join here, at "Next Generation Plaza" of Fig. 2. The sophisticated MIMOs to be reviewed are capable of combining the benefits of STCs designed for achieving a diversity gain, as well as attaining spatial bitstream multiplexing as in Bell Lab's layered space time (BLAST) architecture, while opting for beamforming-aided IC, as and when necessary.

Hence the goal of this treatise is to provide a succinct overview of the proven transmission techniques and to pave the way towards "telepresence avenue," constituted by the next generation systems, which are capable of providing all the proverbial "Swiss-army-knife-type" highly flexible wireless services of the near future.

In a nutshell, since the conception of GSM in excess of three orders of magnitude bit-rate improvements were achieved in three decades, which corresponds to a factor ten or so bit-rate improvement for each decade since the 1980s, because GSM had a data rate of 9.6 Kb/s, while HSDPA is capable of communicating at 13.7 Mb/s. However, the possible transmit power reductions remained more limited, even when using the most advanced multistage iterative detectors, since the required received signal power has not been reduced by as much as 30 dB. This plausible observation motivates the further research of advanced cooperation-aided wireless MIMO transceivers, as detailed in this treatise, which are capable of attaining substantial transmit power reductions.

III. WIRELESS SYSTEM COMPONENTS

The outer shell of boxes in Fig. 3 provides a glimpse of some of the available enabling techniques, while the inner core characterizes the conflicting design factors influencing the architecture of a wireless system.

A. Transceiver Techniques

The state-of-the-art wireless enabling techniques seen in the wireless communications "toolbox" of Fig. 3 are briefly highlighted first, following the outer shell of the figure. Then, we will briefly touch upon the inner core of this stylized illustration.

- **OFDM** [13], [14] serial-to-parallel converts a single high-rate serial bitstream to a large number of parallel low-rate streams. The channel-induced dispersion leaves the resultant parallel low-rate streams largely unaffected and hence OFDM may be viewed as a technique of converting a dispersive frequency-selective channel to a multiplicity of parallel nondispersive flat-fading channels. Owing to its benefits, it has been employed in the 3GPP LTE initiative, in the IEEE 802.11 family of WLAN as well as in the Digital Audio Broadcast (DAB) and Digital Video Broadcast (DVB) standards. When assigning different subcarriers to different users, the OFDM scheme becomes an orthogonal frequency-division multiple access (OFDMA) arrangement.
- **PSK, QAM, and TCM** have a long history in wireless communications, as detailed in [7] and together with AMC they have found their way into numerous wireless standards such as HSPA [12]. The TCM scheme proposed by Ungerboeck [15] incorporates FEC coding by commensurately extending the modulated signal constellation. This is done for the sake of absorbing the redundant bits of the FEC encoder without any bandwidth expansion. Provided that the SNR is above a certain value—despite the reduced Euclidian distance of the QAM constellation points—an improved BER performance is achieved at the cost of an increased detection complexity.
- **Multidimensional sphere packing (SP) modulation** [3] constitutes an extension to the family of classic modulation schemes, such as QPSK and QAM. The SP modulation is designed to attain the maximum Euclidean distance among the signaling constellation points and hence it is capable of

Table 5 3GPP LTE DownLink OFDM Parameters

B_W [MHZ]	1.25	2.5	5	10	15	20
SubFr. Duration [ms]	0.5	0.5	0.5	0.5	0.5	0.5
SubC. Spacing [kHz]	15	15	15	15	15	.5
Sampling Fr. [MHz]	0.5 x 3.84	3.84	2 x 3.84	4x 3.84	6 x 3.84	8 x 3.84
FFT Size	128	256	512	1024	1536	2048

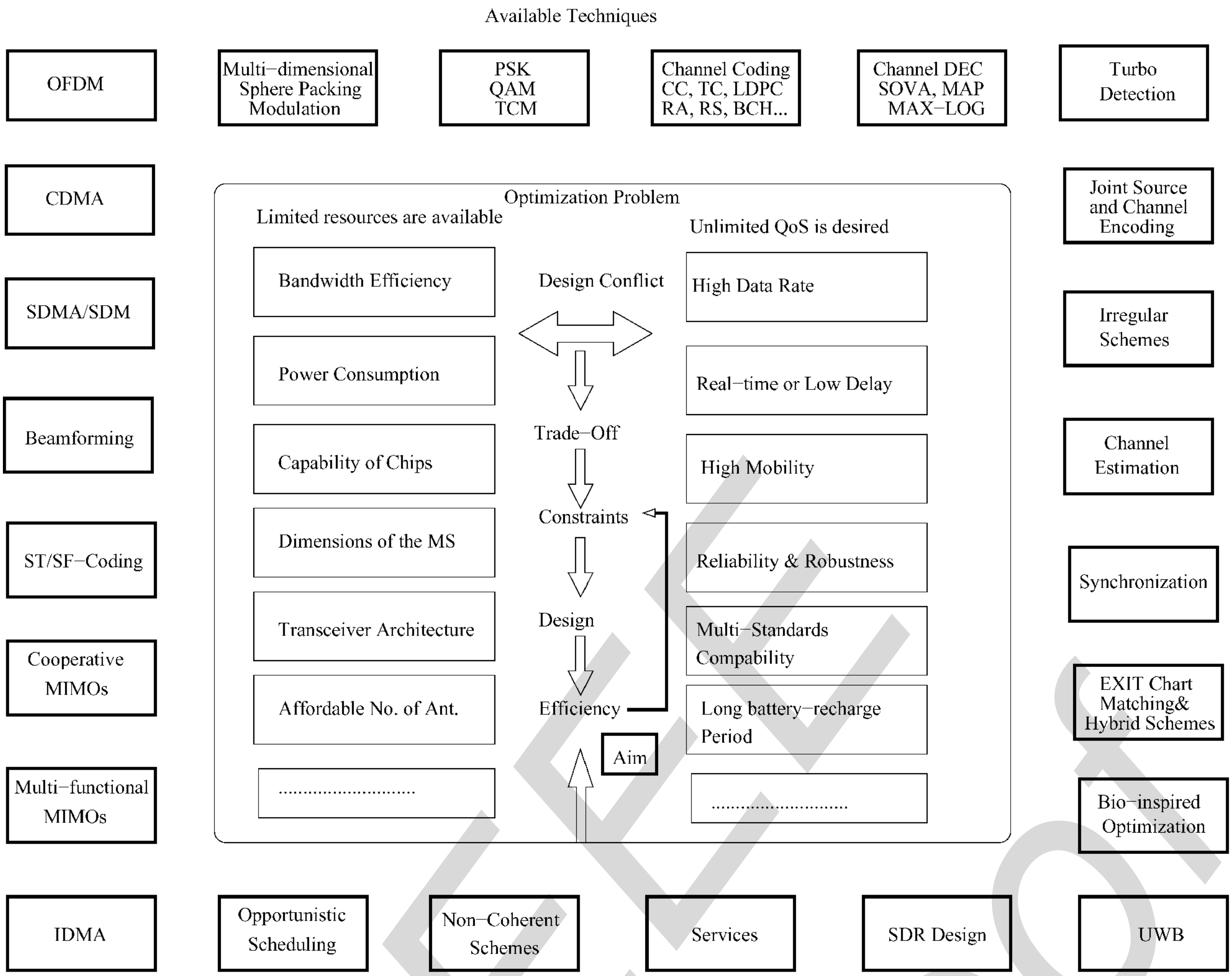

Fig. 3. ***Qualitative relationship of the diverse system components and factors affecting the design of wireless transceivers. This illustration may be viewed as a more detailed exposure of the relationships seen in Fig. 1 and defines the terminology used in Fig. 2 more explicitly.***

improving the achievable performance of conventional constellations. The SP modulation may be combined with temporal diversity, frequency diversity, and/or spatial diversity arrangements. In [3], the SP modulation was combined with STBCs in order to minimize the STBC symbol error probability. This was achieved by jointly designing several STBC time-slots' signal.

- **Channel coding** [6]—also termed as FEC coding—incorporates redundant bits or symbols into the original information stream, which are calculated from the original information symbols. The employment of FEC coding facilitated for the research community to approach Shannon's capacity limit by incorporating "just" the required amount of redundant information for protecting the primary information symbols, as we will discuss in Section V-A. A whole host of schemes having diverse attributes, such as complexity, delay, and coding gain, as briefly touched upon in Fig. 1, are available for the designers.
- **Channel decoders:** [6] In the spirit of Fig. 1, decoders of different complexity, delay and performance are available, such as the soft-output Viterbi algorithm (SOVA) [16], the MAP decoder [17], and its reduced-complexity version, namely the maximum-logarithmic MAP solution known as the Max-Log MAP decoder [18].
- **Turbo detection** as a principle was introduced by Berrou *et al.* [19] in the context of iteratively decoding two parallel concatenated convolutional codes combined with an interleaver. Their work has later found further applications in channel estimation [14], turbo equalization, and MUD [13], as further detailed in Section V.
- **Joint source and channel encoding** [20], [21] exploits the fact that most multimedia source signals are capable of tolerating "lossy," rather

than lossless delivery of multimedia signals to the human eye, ear, and other human sensors. This is achieved by exploiting the psycho-acoustic and psycho-visual coding-imperfection-masking properties of the human ear and eye, respectively. The bitstream produced by the corresponding low-rate and—preferably—low-delay multimedia source codecs however typically exhibits unequal error sensitivity. This requires stronger error protection for the more vulnerable bits and less strong higher rate FEC codes for the perceptually less important bits. A variety of such schemes designed for voice, audio and video signals may be found in [20] and [21]. The philosophy of joint source and channel coding does not contradict to Shannon's so-called source and channel coding separation theorem, which states that these coding operations may be carried out separately. That is due to the fact that this theorem was derived for lossless entropy-coding-based source coding, where a single bit error may result in failure to correctly decode the entire encoded sequence, because the decoder operates by simply reading and interpreting the consecutively received bits, until a legitimate codeword was found. Hence no legitimate entropy codeword is allowed to constitute a prefix of a longer codeword, but in the presence of transmission errors this condition may be violated.

- **EXIT chart matching** will be invoked in Section V-B as a powerful tool employed for designing near-capacity transceivers without the need for the time-consuming bit-by-bit Monte Carlo simulations.
- **Irregular codes** were proposed by Tuchler and Hagenauer [22] for the sake of approaching the channel's capacity using appropriately designed codes that are constructed from a range of different-rate constituent codes. More explicitly, appropriately selected fractions of the input bit stream are encoded with the different constituent code rates. The length of the input bit segments or fractions and the corresponding code rate may be designed with the aid of EXIT charts as proposed in [22].
- **Channel estimation** [11], [13] is necessary for all coherent-detection-aided transceivers and its accuracy has a grave impact on the achievable BER. This is normally carried out by incorporating the pilot symbols into the information stream, where the pilots are known at the receiver. However, the pilots transmitted result in a loss of the effective data throughput, which may be quite high for high-velocity vehicles and a high number of transmit antennas. More explicitly, the channel estimation complexity and the pilot overhead required for achieving accurate channel estimation may become particularly high in the context of MIMO systems, where $N_t \cdot N_r$ CIRs have to be estimated, resulting in 16 CIRs being estimated in a 4×4-element MIMO for example.
- **Synchronization** constitutes an essential part of all communications systems and it typically entails establishing coarse initial synchronization of both the symbol timing as well as of the carrier frequency of the transmitter and the receiver. The wireless channel as well as the oscillator's carrier phase offset induce undesirable phase rotation and hence loss of synchronization between the transmitter and the receiver, which hence requires accurate tracking.
- **Bioinspired optimization** using, for example, genetic algorithms (GAs) and ant colony optimization (ACO) has been shown to be a powerful reduced-complexity technique of finding near-optimum solutions both to challenging multiuser detection problems [5] as well as to joint channel and data estimation problems [14]. Their employment may be readily extended to other excessive-complexity optimization problems, such as those of identifying optimum routes in *ad hoc* networks, for example.
- **Ultrawideband (UWB)** systems [23] may operate in the baseband, i.e., without modulating a radio-frequency carrier and transmit high-bandwidth signals. Their loose definition requires that the bandwidth be at least 500 MHz or a third of their center frequency. Since most of the technologically accessible bands of frequencies are occupied by operational wireless systems, the somewhat unusual philosophy of UWB systems is that they overlay their transmissions to actively exploited frequency bands. However, this is carried out with extra care, using a sufficiently low power level, where they only impose "tolerable" interference on the comparatively narrowband systems communicating in the same spectral band. Their conceptual appeal is that they follow the Shannonian principle of making the extremely wideband transmitted signal noise-like, which renders the interference imposed appear as additional noise. The original UWB proposals by Win and Scholtz [23] advocated the transmission of appropriately shaped time-domain impulses, which signaled a binary one and zero with the aid of pulse position modulation (PPM). Since then, numerous solutions exhibiting diverse pros and cons have been proposed for UWB systems, including CDMA, OFDM, frequency hopping (FH), etc. Two beneficial features of UWB systems are as follows.
  1) Owing to their wide bandwidth, their receiver is capable of distinguishing a high number of multipath components.

2) Hence, even if some of the paths experienced a deep fade, the chances are that there is a sufficiently high number of nonfaded paths for recovering the signal at a high integrity, i.e., low BER.

As a result, UWB systems tend to achieve a high diversity order, which allows them to potentially operate close to the best possible Gaussian channel's performance. Second, it may be readily shown that the capacity increases linearly with the bandwidth, when the nadwidth tends to infinity. Similarly to MIMOs and multicode CDMA, these two features make UWB systems imminently applicable for "green" short-range communications, especially when combined with *ad hoc* routing and user-cooperation-aided hybrid wireless networks, which save power owing to their short-range line-of-sight cooperative transmissions.

- **Software-defined radio (SDR) design** techniques lend themselves to flexible HSPA-style reconfiguration in the interest of satisfying the abovementioned diverse system requirements, which were summarized in Figs. 1 and 3.
- **Services**: The proliferation of flawless wireless multimedia services [20], [21] imposes substantial demand on the available spectral resources, which motivates the exploration of new carrier frequency bands at frequencies beyond those used by the operational systems. These new frequency bands require careful propagation studies, because at increased carrier frequencies the path loss also tends to increase, which results in an increased transmit power requirement and/or reduced cell sizes. Naturally, having reduced cell sizes requires more BSs, although they may become low-power, low-cost radio ports, not unlike those that have recently become commercially available and are employed in residential femto-cells. The different multimedia services tend to have rather different integrity requirements and hence necessitate careful system optimization.
- **DS-CDMA** [5] assigns unique, user-specific K-chip spreading codes to each of the K system users. These unique codes allow the receiver to unambiguously separate their simultaneous transmissions, provided that the correlation of the K spreading codes remains sufficiently low even in the presence of channel-induced dispersion, which may increase the correlation of the spreading sequences. Wideband CDMA was adopted for the 3G systems and for its adaptive-modulation-aided version known as HSPA [5], [12].
- **Space-division multiple access (SDMA)** [13], [14] may be viewed as a close relative of CDMA, with the slight conceptual difference that we use the unique, user-specific CIRs instead of the CDMA spreading codes for differentiating the K users supported. The rationale behind this philosophy is that each user's transmitted spreading code is convolved with the CIR. In case of supporting users in close proximity of each other—who may have similar CIRs—the received spreading codes may become more correlated (i.e., similar) to each other. In this scenario, powerful MUDs may be required to jointly detect and yet to distinguish all the users' spreading codes. If the employment of a potentially complex MUD is affordable, then the employment of CDMA spreading codes for differentiating the users can be eliminated and we can simply rely on the unique CIRs, which leads to the concept of SDMA. It is also worth noting that instead of simultaneously detecting K users' signals, the same concept may be employed for jointly detecting the signals of N_t transmit antennas of a MIMO scheme, which results in an N_t-fold increased bit rate for a single user. In this scenario, the CIRs of the N_t antennas are likely to be more correlated than the carefully designed CDMA spreading codes owing to the antenna elements' proximity, which makes the SDMA MIMO multistream detector design more challenging than the classic MUD design. The related schemes will be further elaborated on in Section IV-A2.
- **Beamforming** [3], [12] constitutes an effective MIMO-aided transmission/reception technique, where the gain of the transmitter/receiver antenna is increased in the specific direction of the desired user, while reducing the gain towards the interfering users. Beamforming may be viewed as an "angularly selective" filter, where the filtering effect is achieved by positioning the MIMO elements half the wavelength apart. This geometric arrangement then launches the MIMO elements' transmitted signals with a specific phase difference of π from the adjacent elements after appropriately weighting and superimposing them. The family of beamformers will be further detailed in Section IV-A3.
- **Space-time or Space-frequency coding (ST/SF coding)** [6]. In a severely fading environment, the transmitted signal cannot be error-freely detected at the receiver, unless some unattenuated replicas of the transmitted signal are made available. Hence, diversity techniques, such as for example, temporal, frequency, and spatial diversity may be beneficially invoked. Explicitly, when different time slots are allocated for conveying the same information bits, we created temporal diversity. A typical example of utilizing temporal diversity is constituted by interleaved channel coding or DS-CDMA spreading. Similarly, frequency diversity may be achieved by assigning multiple signal replicas to independently fading carrier frequencies, as in the case of OFDM or when employing FH

techniques. Finally, a spatial diversity or antenna diversity gain can be attained by exploiting multiple spatially separated or differently polarized antennas, as in the case of STCs. Again, the underlying principle of diversity is that the redundant replicas carrying the same signal would be conveyed over independently fading propagation paths. However, the employment of multiple antennas may not be feasible or may have limited benefits for the transmitter of compact shirt-pocket-sized communicators. This is due to the fact that a sufficiently high physical separation has to be maintained between the different antennas for the sake of achieving spatial diversity, otherwise the correlation of fading erodes the achievable diversity gains.

- **Cooperative MIMOs** [3], [14] mitigate the above-mentioned problem of induced correlation among the diversity components with limited antenna spacing, which is particularly detrimental in the presence of correlated fading imposed by large-bodied vehicles and other obstructing objects in the path of the radio waves. This is achieved with the aid of cooperative or distributed MIMO techniques, where MSs equipped with a single antenna can cooperate by sharing their single antennas upon exchanging their information, as detailed further in Section IV-B. Provided that the cooperating MSs are sufficiently far apart, their antennas experience independent fading.
- **Multifunctional MIMO techniques** [3]: The above-mentioned MIMO schemes attain either diversity gain, multiplexing gain, or beamforming gain. By contrast, multifunctional MIMO schemes may attain a combination of these gains, as detailed in Section IV-A4.
- **Interleave division multiple access** (IDMA) also evolved from the above-mentioned philosophy of CDMA, when Frenger *et al.* combined CDMA with channel coding and interleaving [24], leading to the concept of *chip-interleaved* CDMA [25]. Hence, IDMA inherited all the attractive properties of CDMA. As an additional benefit of chip-interleaving relying on a sufficiently long interleaver, the originally adjacent chips of a spreading code are dispersed across the entire duration of the chip-interleaver and hence they may be deemed to fade independently. This typically results in an increased diversity gain and potentially allows us to differentiate the users based on their unique user-specific interleaver. The IDMA philosophy was then further developed by Ping and his team [26], [27] as well as by Höher and his group [28], [29]. In a nutshell, the system concept of [24] is essentially that of interleaving the chips right after DS spreading, rather than placing the classic interleaver after the channel encoder. It was demonstrated that the employment of chip-interleaving simplifies iterative detection.
- **Opportunistic scheduling** may also be interpreted as a diversity scheme, since the transmissions of users may be scheduled in unison with their channel quality fluctuations. When the channel quality happens to be high, a low transmit power is sufficient or a high throughput may be attained and *vice versa*. This opportunistic scheduling philosophy is intricately linked with HSPA-style adaptive modulation and coding [12].
- **Noncoherent schemes** [14] aim for avoiding both the high complexity channel estimation and the associated throughput loss imposed by the inclusion of pilot sequences used in channel estimation. However, noncoherent schemes typically suffer from a performance penalty and hence they require substantial further research for their adoption in low-complexity, low power-consumption standardized solutions, as detailed in Section IV-A1. Since the employment of channel estimation in the context of low-complexity cooperative systems is particularly undesirable, there is a natural synergy between cooperative and noncoherent systems, as detailed in [3] and [14].

B. Transceiver Optimization

To elaborate a little further on the message of Fig. 1 in the context of considering the optimization problems portrayed in the center core of Fig. 3, subscribers and service providers would like to aim for improving the achievable QoS quantified in terms of all quality metrics. These may include maintaining a high data rate, flawless real-time or low-delay multimedia "tele-presence" quality at high vehicular speeds, while guaranteeing a high integrity or low BER. Resilience against the interference imposed by other users as well as necessitating infrequent battery recharge, i.e., having a low power requirement, are also of paramount importance.

These ambitious objectives have to be achieved in the face of the limited resources listed in Fig. 3. For example, both the available bandwidth as well as the battery power are limited and so is the signal processing speed of the chips employed. Additionally, a lightweight shirt-pocket-sized MS is desired, which has limited space for accommodating MIMO elements. Hence, a flexible transceiver architecture is needed in order to accommodate the time-variant channel-quality encountered, while supporting multistandard operation.

IV. MIMO SYSTEMS

In digital communications, a specific feature of an analog carrier signal is modulated by a digital bit stream, where a modulator shapes and "prepares" the signal to be transmitted through the band-limited physical channel. The modulator maps each set of B bits into one of the $M = 2^B$ possible waveforms of the radio-frequency carrier, which may be in the range from 400 MHz to 3 GHz in contemporary wireless systems. On the other hand, in order to increase the achievable throughput of wireless communication systems, while maintaining a specific QoS and accommodating the channel-quality fluctuations, the concept of adaptive modulation was introduced by Hayes as early as in 1968 [30], which then led to a flurry of research activities, culminating in the definitions of the HSPA 3G standard and all its AMC-aided standardized successors.

In wireless communications, the quality of the received signal depends on several factors including the log-normal shadowing, fast-fading, and noise. On the other hand, different order modulation schemes allow the transmission of more bits per symbol, hence achieving increased spectral efficiencies. However, employing higher order constellations requires an increased SNR in order to maintain a certain BER performance. The employment of adaptive modulation allows a wireless system to choose the highest order modulation to achieve the required QoS, depending on the prevalent near-instantaneous channel conditions. An appealing benefit of AMC is that the power of the transmitted signal is held constant over a frame interval, while changing the modulation and coding format in order to match the current received signal quality or channel conditions. For example, in a system relying AMC, users close to the BS are typically assigned higher order modulation schemes combined with higher code rates, while users that are further from the BS can be assigned a lower modulation order and/or code rate in order to maintain a good BER performance and high throughput for all users.

Diverse adaptive modulation and coding arrangements have been proposed in [5], [31], and [32]. The fundamental goal of near-instantaneous adaptation is to ensure that the most efficient transceiver mode is used in the face of rapidly fluctuating time-variant channel conditions based on appropriate channel quality metrics [5], [11].

The fundamental limitation of wireless systems is constituted by the time- and frequency-domain fading of the channel's envelope, as exemplified in terms of the SINR fluctuations experienced by wireless modems [11], [33]. Furthermore, the continued increase in demand for all types of wireless services including voice, data, and multimedia increases the need for higher data rates. Hence, advanced MIMO techniques, coded modulation as well as adaptive modulation and coding arrangements have to be invoked, which are capable of near-instantaneous HSPA-style [12] reconfiguration. The above-mentioned advances in science have also found their way into the HSPA standard, which has the popular connotation of being a "3.5G" standard, because it is significantly more capable than the 3G standards, potentially reaching a bit rate of about 14 MBPS.

The limitation of the above-mentioned classic modems is that their capacity has to obey Shannon's classic capacity formula [1], [34], [35] of $C = B_W \cdot \log_2(1 + \mathrm{SNR})$, where B_W is the bandwidth and SNR is the signal-to-noise ratio. This implies that an exponentially increased transmit power is required for achieving a linearly increasing capacity, apart from using more sophisticated and hence more costly modems. Fortunately, this limitation may be overcome by the employment of MIMO systems, as we will demonstrate later in this section.

A MIMO system employs $N_t \geq 1$ transmit antennas and $N_r \geq 1$ receive antennas, as shown in Fig. 4. A wireless system employing a MIMO scheme transmits the signals $\mathbf{C}_{t,n}$, $n = 1, 2, \ldots, N_t$, simultaneously from the N_t transmit antennas at instant t. Each signal transmitted from each of the N_t antennas propagates through the wireless channel and arrives at each of the N_r receive antennas. In a wireless system equipped with N_r receive antennas, each received signal is constituted by a linear superposition of the faded versions of the transmitted signal, which is also perturbed by noise. Of particular interest is the specific propagation scenario, where the individual channels between given pairs of transmit and receive antennas may be accurately modeled by independent Rayleigh fading channels. As a result, the signal corresponding to every transmit antenna has a distinct spatial signature, namely its impulse response, at the receive antenna. Encountering independent Rayleigh fading can be assumed for each of the $(N_t \times N_r)$ MIMO links, provided that the antenna spacing is sufficiently higher than the carrier's wavelength. As a result, the signal corresponding to every transmit antenna has a distinct spatial signature at a receive antenna.

The information-theoretic aspects of MIMO systems were considered during their early development by

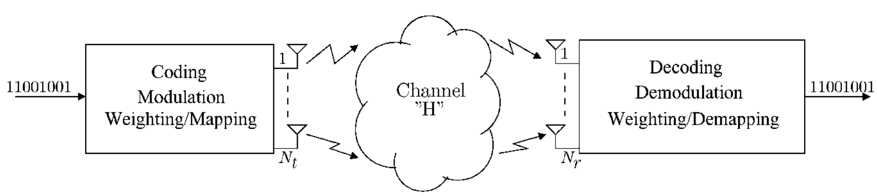

Fig. 4. *A generalized MIMO scheme block diagram.*

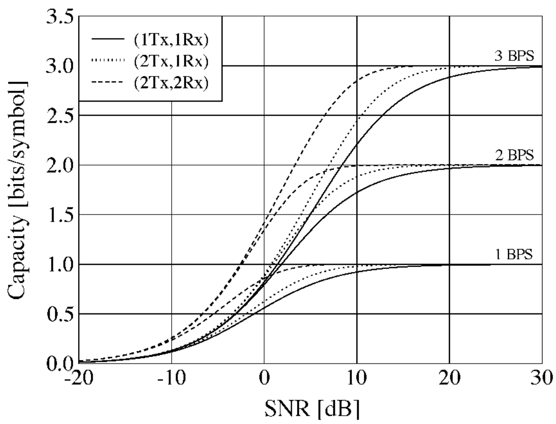

Fig. 5. ***Comparison of the capacity of a SISO scheme and two MIMO schemes associated with*** $(N_t, N_r) = (\mathbf{2}, \mathbf{1})$ ***and*** $(N_t, N_r) = (\mathbf{2}, \mathbf{2})$.

Winters [36], by Telatar [37] as well as by Foschini and Gans [38], for example. It was demonstrated that MIMO systems exhibit capacity gains in comparison to the employment of a single antenna at both the transmitter and the receiver. It was demonstrated in [37] and [38] that the capacity of a MIMO system may be portrayed as a linear function of the number of transmit antennas, when communicating over an i.i.d. flat Rayleigh fading channels, provided that the number of receive antennas is equal to or greater than the number of transmit antennas. Hence, it may be argued that in contrast to the logarithmic Shannon capacity of $C = B_W \cdot \log_2(1 + \mathrm{SNR})$ [39], MIMO schemes increase the systems' capacity linearly with the transmit power, provided that the increased power is assigned to a proportionately increased number of transmit antennas. Naturally, in practice it may not be feasible to substantially increase the number of antennas.

In all fairness, it should also be emphasized that based on Shannon's above-mentioned formula, *when we let the bandwidth B_W tend to infinity, the capacity does not tend to infinity! It becomes a constant times the transmit power. This implies that at a sufficiently high bandwidth the capacity of single-input–single-output (SISO) systems may also be deemed to increase near-linearly with the transmit power.* However, for a large bandwidth the noise power becomes high, which implies that potentially more sophisticated receivers may have to be implemented for maintaining reliable communications.[2]

Fig. 5 compares the capacity of a SISO system with that of two MIMO schemes associated with $(N_t, N_r) = (2, 1)$ and $(N_t, N_r) = (2, 2)$. Additionally, Fig. 5 compares the capacity for the systems employing BPSK, QPSK, and 8-PSK. The MIMO technique used in Fig. 5 is Alamouti's space-time block coding arrangement [40], which provides spatial diversity, as will be described in Section IV-A1. As shown in Fig. 5, the twin-antenna-aided MIMO scheme using a single receive antenna exhibits a higher capacity than the SISO scheme for all the modulation schemes considered. Similarly, the MIMO scheme employing $N_t = 2$ transmit and $N_r = 2$ receive antennas exhibits a higher capacity than its counterpart employing a single receive antenna. For example, consider the QPSK modulated system associated with the curves labeled as 2 BPS in Fig. 5, which exhibits a capacity of 1.72 BPS at $\mathrm{SNR} = 10$ dB in a SISO scheme. By contrast, the (2,1) MIMO scheme attains a capacity of 1.88 BPS and the (2,2) MIMO scheme has a capacity of 2 BPS. On the other hand, the SISO requires 6.7 dB for achieving a capacity of 1.5 BPS, while the (2,1) MIMO scheme requires 5 dB and the (2,2) MIMO scheme necessitates 1.2 dB.

In addition to the fact that MIMO systems attain a higher capacity than the SISO scheme, MIMOs can be used to attain a better BER performance and/or a higher throughput than the SISO schemes, depending on whether the MIMO is used for attaining diversity or multiplexing gains. The classification of different MIMO systems is summarized in Fig. 6, which can be classified as colocated MIMOs and distributed MIMOs. The colocated MIMOs

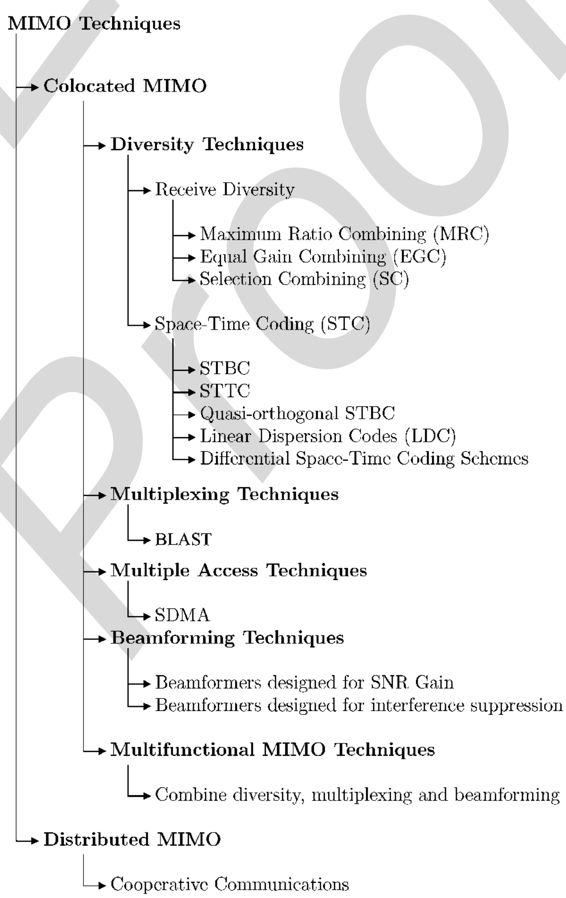

Fig. 6. ***Classification of MIMO Techniques.***

[2]The authors are grateful to the anonymous reviewer for his suggestion to include these important insights on the capacity of SISO systems.

can be categorized as diversity techniques [40], [41], multiplexing techniques [42], multiple-access methods [13], beamforming [12] as well as multifunctional MIMO techniques [3] as shown in Fig. 6. The concept of distributed MIMOs is also often viewed as an ingredient of cooperative communications [43], [44] recently advocated by Sendonaris *et al.*

A. Colocated MIMO Techniques

As argued above, MIMO systems exhibit a higher capacity than SISO systems. Multiple antennas can be used to provide either diversity gains and hence a commensurately improved BER performance or an increased throughput translating into multiplexing gains.[3] As a third design alternative, multiple antennas can be used at the transmitter or the receiver in order to attain a beamforming gain. Finally, sophisticated multifunctional antenna arrays (MFAAs) may be employed in order to combine all of the above-mentioned MIMO functions and hence simultaneously attain diversity gains, multiplexing gains as well as beamforming gains as shown in Fig. 6.

For a general MIMO system having $N_t > 1$ transmit antennas and $N_r \geq 1$ receive antennas, there is a theoretical tradeoff between the achievable diversity and multiplexing. Zheng and Tse [45] showed that for a MIMO channel there is a fundamental tradeoff between the achievable diversity gain and the attainable multiplexing gain. Explicitly, in order to achieve an increased spatial multiplexing gain, the attainable diversity gain has to be sacrificed. In other words, the diversity-multiplexing tradeoff quantifies how rapidly the throughput of STCs may increase with the SNR, while maintaining a certain diversity order.

The terminology of colocated MIMOs refers to the family of systems where the multiple antennas are located at the same transmitter or receiver station. Again, the immunity of these colocated MIMOs to shadow-fading-induced correlation may be mitigated, for example, by invoking the concept of distributed MIMO elements constituted by single-antenna-aided cooperating mobiles at the cost of reducing the attainable throughput, as detailed
AQ2 during our further discourse [3]. In the sequel, we will provide an overview of the family of MIMOs designed for achieving diversity, multiplexing, or beamforming gains.

1) Diversity Techniques: Maintaining reliable communication over fading channels has been one of the grand research challenges in recent times. In a fading channel, the associated severe attenuation often results in decoding errors. A natural way of overcoming this problem is to provide the receiver with several replicas of the same transmitted signal, while assuming that at least some of them are not severely attenuated. This technique is referred to as diversity, where *it is possible to attain diversity gains by creating independently fading signal replicas in the time, frequency, or spatial domain and both at the transmitter and the receiver*. This paper advocates the employment of both transmit and receive diversity.

To elaborate a little further, classic FEC coding [6] is also often referred to as a time diversity technique, since it assigns redundant bits to the original information bits and the redundant bits are transmitted at different instants, hence are subjected to independent fading. Similarly, frequency diversity may be achieved, for example, by employing FH [5], where different transmit frequencies are activated at different symbol instants. Typically, the activated frequencies are outside the coherence bandwidth, which is defined as the minimum frequency separation beyond which independent fading is experienced. Finally, spatial diversity is achieved, for example, by employing multiple antennas. The signal energy extracted from the multiple signal replicas may then be combined using one of the numerous established diversity combining techniques [5], such as, for example, switched diversity, which detects the largest of several signal replicas, equal-gain combining, or maximum ratio combining, where the latter weights the more reliable diversity paths more highly than the less reliable, more faded paths.

More specifically, spatial diversity can be attained by employing multiple antennas at the transmitter and/or the receiver, as shown in Fig. 7, where the multiple antennas can be used to transmit and receive the several replicas of the same information sequence in order to achieve a diversity gain and hence to obtain an improved BER performance. A simple spatial diversity technique, which does not involve any loss of bandwidth, is constituted by the employment of multiple antennas at the receiver. In case of narrowband frequency flat fading, the optimum combining strategy in terms of maximizing the SNR at the combiner's output is maximum ratio combining (MRC) [6], [46], [47]. Additionally, other combining techniques have been proposed in the literature, as shown in Fig. 6, including Brennan's equal gain combining (EGC) [47] and

[3]The authors are grateful to the anonymous reviewer for his suggestion to include the following notes on the potentially detrimental effects of correlated fading on the achievable MIMO-aided performance. Explicitly, when shadow fading is imposed, for example, by large-bodied vehicles, the signals received by the different antenna elements fade together and hence the performance becomes no better than that of a single antenna. The correlation experienced by the signals received by MIMOs subjected to shadow fading may be mitigated, for example, by invoking the concept of distributed MIMO elements constituted by single-antenna-aided cooperating mobiles at the cost of reducing the attainable throughput, as detailed during our further discourse [3].

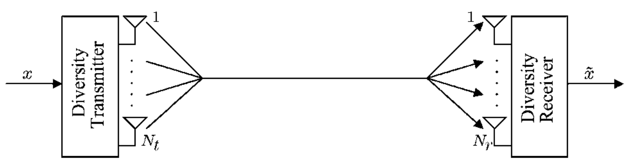

Fig. 7. ***Stylized diagram of a spatial diversity technique.***

selection combining (SC) [5]. All the above-mentioned combining techniques are said to achieve full diversity order, which is equal to the number of receive antennas [48].

In an $N_t \times N_r$-element MIMO system, at the receiver side there are N_r copies of the same transmitted symbol. In selection diversity, the receiver selects the specific antenna with the highest received signal power, since each antenna experiences independent fading. In this case, the receiver ignores the signals received at the other antennas. This is not the optimal solution, since $(N_r - 1)$ antennas' signals are ignored. The MRC uses the received signals of all the receive antennas and uses different weights for the different antennas in order to maximize the output SNR. The best a diversity combiner can do is to choose the weights commensurately with the channel quality estimates at each receiver. However, the technique requires the weights to be estimated for the fading signals, whose magnitude may fluctuate rapidly. The equal-gain combiner circumvents this problem by assigning a unity gain to each antenna.

On the other hand, the concept of transmit diversity corresponds to the transmission of replicas of the same signal over multiple transmit antennas. One of the early bandwidth-efficient transmit diversity schemes was proposed by Wittneben [49], who demonstrated that the diversity advantage of his scheme was proportional to the number of transmit antennas, which was also confirmed in [4], [50], and [51]. The criterion that has to be met for achieving the maximum attainable transmit diversity order was derived in [52], which is the so-called *rank criterion* proposed for the design of STCs that will be briefly highlighted below. Furthermore, the "approximate" equivalent of the so-called *determinant criterion* to be highlighted below and employed for designing STCs was also derived in [52]. An indepth study on achieving the maximum attainable diversity gain, while also providing a beneficial coding gains was offered in [53], where the concept of space-time trellis codes was also introduced.

To expound a little further, some design criteria aim at maximizing the attainable mutual information between the transmitted and received signals in a MIMO system. The *rank criterion* [52], [54] suggests that for two space-time codewords $\mathbf{C}$ and $\mathbf{C}'$, the error matrix $\mathbf{C} - \mathbf{C}'$ has to have full rank in order to achieve the maximum attainable diversity gain, which is also often termed in parlance as having "full-diversity." On the other hand, the *determinant criterion* [4] implies that the minimum determinant of the matrix $(\mathbf{C} - \mathbf{C}')^H \times (\mathbf{C} - \mathbf{C}')$ has to be sufficiently high in order to attain a high coding gain.

In [40], Alamouti proposed an appealingly simple, yet potent transmit diversity technique using two transmit antennas. Its key advantage was the employment of low-complexity single-antenna detection at the receiver. The decoding algorithm of [40] may be generalized to an arbitrary number of receive antennas using MRC, EGC, or SC. Alamouti's proposition inspired Tarokh *et al.* [41], [55] to generalize the transmit diversity concept to more than two antennas, leading to the general concept of STBCs. Motivated by the benefits of STBCs, Hochwald *et al.* [56] proposed the transmit diversity concept known as STS for the downlink of WCDMA [5] that is also capable of achieving the highest possible transmit diversity gain in a CDMA context.

Alamouti's design was proposed for a system with two transmit as well as one receive antennas and was shown to achieve the full diversity gain of 2, while having a transmission rate or—synonymously—throughput of 1 bit per space-time MIMO symbol or per "channel-use." It was shown in [4] that orthogonal STBC designs are characterized by a full diversity gain of $N_t \cdot N_r$, which is the maximum attainable diversity gain. On the other hand, full-rate orthogonal designs transmitting complex-valued modulated symbols are not possible for more than two transmit antennas. More explicitly, orthogonal STBC designs for $N_t > 2$ transmit antennas result in a reduction of the transmission rate per channel use or per MIMO symbol. Again, the main benefits of orthogonal designs are their low-complexity decoding associated with the independent decoding of all the streams, since they do not interfere with each other and their full diversity gain. An alternative idea for constructing full-rate STBCs for complex-valued modulation schemes and more than two antennas was pursued by Jafarkhani [4], [57]. He relaxed the strict requirement of perfect orthogonality for the diversity components and hence sacrificed the decoding simplicity in favor of achieving a higher throughput. The resultant STBCs were referred to as quasi-orthogonal STBCs [57].

The family of STBCs may be deemed capable of attaining the same diversity gain as STTCs [54], [58] at a typically lower decoding complexity, when employing the same number of transmit antennas. However, a disadvantage of STBCs when compared to STTCs is that they provide no coding gain and are less tolerant against ISI [6], [59]. STTCs intricately combine modulation and trellis-coding-based FEC for reliably transmitting information over multiple antennas. The main motivation behind combining modulation with coding is that of intentionally incorporating specifically constructed redundancy in order to reduce the effects of all types of channel impairments and hence to improve the attainable system performance. An STTC having N_t transmit antennas is designed by assigning N_t constellation points to every trellis transition and then using, for example, the Viterbi algorithm [6] for selecting the most likely trellis path associated with the most likely transmitted symbol in order to FEC-decode the received signal. Again, STTCs are capable of attaining full diversity and high coding gains at the expense of a potentially higher decoding complexity than orthogonal STBCs while also better tolerating the effects of ISI than STBCs [6].

The STBC and STS designs offer at best the same data rate as an uncoded single-antenna-aided system, but they provide a better BER performance than the family of SISO systems by attaining diversity gains. It was shown in [68] that Alamouti's scheme [40] using two transmit and one receive antennas is the only unity-rate orthogonal STBC that is capable of approaching the channel's capacity. In other words, for all remaining orthogonal STBCs, there is a loss in the maximum attainable mutual information compared to the MIMO capacity. In contrast to this, several high-rate space-time transmission schemes having a normalized rate or throughput higher than one have been proposed in the literature. For example, high-rate STCs such as the so-called linear dispersion codes (LDC), were proposed by Hassibi and Hochwald [68]. LDCs strike a flexible tradeoff between achieving space-time coding and spatial multiplexing gains and may be interpreted as a general class, subsuming all STBC solutions, as detailed in [3].

Additionally, the concept of combining orthogonal transmit diversity designs with the principle of SP was introduced by Su *et al.* [69] in order to maximize the achievable coding advantage, where it was demonstrated that the proposed SP-aided STBC scheme was capable of outperforming the conventional-orthogonal-design-based STBC schemes of [40] and [41]. A further advance was proposed in [3], where the SP demapper of [69] was modified for the sake of accepting the *a priori* information passed to it from the channel decoder as extrinsic information.

A common feature of all the above-mentioned schemes is that they use coherent detection, which assumes the availability of accurate CSI at the receiver.[4] In practice, the CSI of each of the $(N_t \times N_r)$ links between each transmit and each receive antenna pair has to be estimated at the receiver either blindly or using training symbols. However, channel estimation invoked for all the $(N_t \times N_r)$ antennas substantially increases both the cost and complexity of the transceiver. For example, given a 4-by-4-element MIMO, 16 channels have to be estimated. Furthermore, when the CSI fluctuates dramatically, the channel's complex-valued envelope has to be sampled at an increased rate and hence an increased number of training symbols has to be transmitted, potentially resulting in an undesirably high transmission overhead and wastage of transmission power. Sophisticated decision-directed CSI estimation techniques were detailed in substantial depth, for example, in [13, Ch. 16]. Here we focus our attention on the family of lower complexity transceiver techniques that do not require any CSI and thus are capable of mitigating the complexity of MIMO-channel estimation.

A detection algorithm designed for Alamouti's scheme [40] was proposed by Tarokh *et al.* [62], where the channel encountered at instant$t$ was estimated using the pair of symbols detected at instant $(t-1)$. The algorithm, nonetheless, has to estimate the channel during the very first instant using training symbols and hence it does not use a truly differential detector. Tarokh and Jafarkhani [63], [70] proposed a differential encoding and decoding algorithm for Alamouti's scheme [40] using real-valued phasor constellations and hence the transmitted signal can be demodulated both with or without CSI at the receiver. The resultant differential decoding aided noncoherent receiver performs within 3 dB from the coherent receiver relying on the idealized simplifying assumption of perfect channel knowledge at the receiver. The differential scheme of [63] was restricted to complex-valued PSK modulation. The twin-antenna-aided differential STBC scheme of [63] was extended to QAM constellations in [71] and [72].

DSTBC schemes designed for multiple antennas were proposed in [67] for real-valued modulation constellations. As a further advance, Hwang *et al.* and Nam *et al.* [71], [76] developed a DSTBC scheme that supports nonconstant modulus constellations combined with four transmit antennas. This extension, however, requires the knowledge of the received power in order to appropriately normalize the received signal. The received power was estimated blindly using the received differentially encoded signals without invoking any channel estimation techniques or without transmitting any pilot symbols. A further differential modulation scheme was proposed by Hochwald and Sweldens [64] for the sake of attaining transmit diversity based on unitary STCs [81]. The proposed scheme may be employed in conjunction with an arbitrary number of transmit antennas. Around the same time, a similar differential scheme was also proposed by Hughes [65] based on the employment of group codes.

Zhu *et al.* [78] proposed a differentially encoded modulation scheme based on quasi-orthogonal STBCs, which were compared to the scheme of [67] and resulted in an improved BER as a benefit of providing full diversity. Furthermore, in [3] and [82], a differential encoder and decoder pair has been designed for space-time spreading, which was referred to as DSTS. Additionally, an appealing quasi-orthogonal STBC was proposed by Song and Burr [79], which had a low-complexity differential decoding scheme that avoided any signal constellation expansion. In [79], a general differential modulation scheme was presented for both partial-diversity quasi-orthogonal space-time block codes and for full-diversity quasi-orthogonal space-time block codes. The differential encoding and decoding philosophy was simplified to differential Alamouti codes by appropriately grouping the signals in the transmit matrix and then decoupling the detection of data symbols. The major contributions on the family of spatial diversity techniques are summarized in Tables 6 and 7.

The DSTS scheme of [3] and [82] was proposed as a noncoherent scheme for eliminating the potentially excessive complexity of MIMO channel estimation required by the coherent STS scheme of [56]. In order to study the effects of channel estimation errors on the performance of the coherently detected STS signals, the channel information at the receiver side was contaminated

[4] The authors are grateful to the anonymous reviewer for his suggestion to include further discussions on the role of CSI in the context of MIMOs.

Table 6 Major Spatial Diversity Techniques (Part 1)

Year	Author(s)	Contribution
1959	Brennan [47]	introduced and provided analysis for the three combining techniques: selection combining, maximum ratio combining and equal gain combining.
1991	Wittneben [49]	proposed a bandwidth-efficient transmit diversity technique, where different base stations transmit the same signal.
1993	Wittneben [60]	proposed a modulation diversity scheme in a system equipped with multiple transmit antennas.
	Seshadri *et al.* [61]	proposed a transmit diversity scheme that was inspired by the delay diversity design of Wittneben [60].
1994	Winters [50]	proved that the diversity advantage of the scheme proposed in [49] is equal to the number of transmit antennas.
1996	Eng *et al.* [48]	Compared several diversity combining techniques in a Rayleigh fading transmission with coherent detection.
1998	Alamouti [40]	discovered a transmit diversity scheme using two transmit antennas with simple linear processing at the receiver.
	Tarokh *et al.* [58]	proposed a complete study of design criteria for maximum diversity and coding gains in addition to the design of space-time trellis codes.
	Tarokh *et al.* [62]	proposed a detection algorithm for the Alamouti scheme [40] dispensing with channel estimation.
1999	Tarokh *et al.* [41], [55]	generalized Alamouti's diversity scheme [40] to more than two transmit antennas.
	Guey [52]	derived the criterion for designing the maximum transmit diversity gain.
	Tarokh *et al.* [63]	proposed a differential encoding/decoding of Alamouti's scheme [40] with PSK constellations.
2000	Hochwald *et al.* [64]	proposed a differential modulation scheme for transmit diversity based on unitary space-time codes.
	Hughes [65]	proposed a differential modulation scheme that is based on group codes.
2001	Hochwald *et al.* [56]	proposed the twin-antenna-aided space-time spreading scheme.
	Jafarkhani *et al.* [57]	designed rate-one STBC codes which are quasi-orthogonal and provide partial diversity gain.
	Ganesan *et al.* [66]	showed that STBC can achieve the maximum SNR gain and that they correspond to a generalized maximum ratio combiner.
	Jafarkhani *et al.* [67]	proposed a differential detection scheme for the multiple antenna STBC [41].

with noise. AWGN was imposed on the channel information at the receiver side to model the effect of errors that may occur due to the channel estimation. Although the channel estimation error typically does not obey a Gaussian distribution, this simplified investigation gives an insight concerning the effects of channel estimation errors on the system performance degradation of coherent systems. Fig. 8 compares the BER performance of the DSTS and STS schemes, while using two transmit antennas, one receive antenna, BPSK modulation, a

Table 7 Major Spatial Diversity Techniques (Part 2)

Year	Author(s)	Contribution
2002	Hassibi *et al.* [68]	proposed the LDCs that provide a flexible trade-off between space-time coding and spatial multiplexing.
	Stoica *et al.* [73]	compared the performance of STBC when employing different estimation/detection techniques and proposed a blind detection scheme dispensing with the pilot symbols transmission for channel estimation.
	Schober *et al.* [74]	proposed non-coherent receivers for differential space-time modulation (DSTM) that can provide satisfactory performance in fast fading unlike the conventional differential schemes that perform poorly in fast fading.
2003	Wang *et al.* [75]	derived upper bounds for the rates of complex orthogonal STBCs.
	Su *et al.* [69]	introduced the concept of combining orthogonal STBC designs with the principle of sphere packing.
	Hwang *et al.* [71], [72]	extended the scheme of [67] to QAM constellations.
2004	Nam *et al.* [76]	extended the scheme of [71], [72] to four transmit antennas and QAM constellations.
2005	Zhang *et al.* [77]	derived the capacity and probability of error expressions for PSK/PAM/QAM modulation with STBC for transmission over Rayleigh-, Ricean- and Nakagami-fading channels.
	Zhu *et al.* [78]	proposed a differential modulation scheme based on quasi-orthogonal STBCs, which when compared with that of [67] results in a lower BER and provides full diversity.
2006	Liew *et al.* [59]	studied the performance of STTC and STBC in the context of wideband channels using adaptive orthogonal frequency division multiplex modulation.
	El-Hajjar *et al.* [3]	proposed a non-coherent transceiver for the space-time spreading of [56] and combined the proposed scheme with sphere packing modulation in order to attain a better symbol error rate.
2007	Alamri *et al.* [3]	modified the SP demapper of [69] for the sake of accepting the *a priori* information passed to it from the channel decoder as extrinsic information.
	Song *et al.* [79]	proposed a new class of quasi-orthogonal STBCs and presented a simple differential decoding scheme for the proposed structures that avoids signal constellation expansion.
2008	Luo *et al.* [80]	combined orthogonal STBCs with delay diversity and designed special symbol mappings for maximizing the coding advantage.

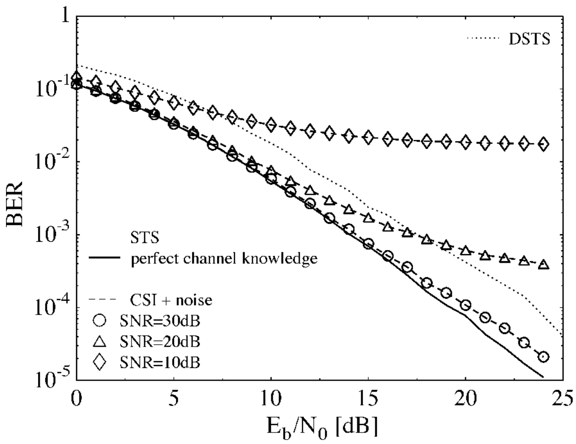

Fig. 8. ***Comparison of the BER performance of coherent and differentially encoded noncoherent space-time spreading, while using a BPSK modulated signal, two transmit antennas, one receive antenna, a spreading factor of four for supporting a single user. The CSI in the coherent STS is contaminated with AWGN in order to compare the performance, when there is a channel estimation error.***

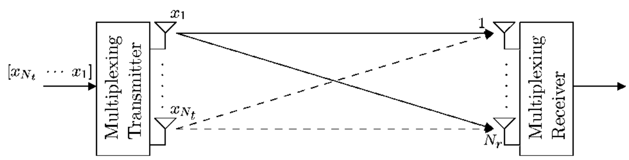

Fig. 9. ***Block diagram of a multiplexing MIMO scheme.***

spreading factor of four, and a single user. Coherent systems assuming perfect channel knowledge at the receiver outperform their differentially encoded, noncoherently detected counterpart by about 3 dB. However, when the CSI used by the coherent STS scheme is contaminated, the STS scheme's BER performance degrades, as shown in Fig. 8. More quantitatively, Fig. 8 shows that when the power of the modeled channel estimation error imposed on the CSI is increased and hence the corresponding CSI SNR is 20 dB or less, the performance of the coherent STS scheme tends to exhibit an error floor and as a result, its BER curve crosses the BER curve of the DSTS scheme. Beyond this crossover point the DSTS outperforms the STS despite its substantially lower complexity. Therefore, the differential MIMO schemes constitute a convenient and low-complexity design alternative to the coherent MIMO schemes, since the differential schemes eliminate the complexity of channel estimation and also result in a better performance when the channel estimation error is high.

2) Multiplexing Techniques: STBCs and STTCs are capable of providing diversity gains for the sake of improving the achievable system performance. However, this BER performance improvement is often achieved at the expense of an effective throughput loss compared to SISO systems. As a design alternative, a specific class of MIMO systems was designed for improving the attainable bandwidth efficiency or throughput of the system by transmitting the signals independently from each of the transmit antennas, hence resulting in a multiplexing gain.

The basic principle of spatial multiplexing can be summarized as follows. As shown in Fig. 9, the source symbol sequence at the transmitter side is split into N_t sequences, which are transmitted simultaneously from the N_t transmit antennas using the same carrier frequency. At the receiver side, IC is employed in order to separate the different transmitted signals. In the case of narrowband frequency flat fading, there are several decoding algorithms designed for IC at the receiver side of spatial multiplexing aided systems. The different receivers can be characterized by a tradeoff between the achievable performance and the complexity imposed. A low-complexity receiver is constituted by the ZF or the minimum mean square error (MMSE) technique [83], [84]. However, when we employ the ZF receiver, the attainable BER performance is typically poor in addition to imposing the condition that the number of receive antennas should be at least equal to the number of transmit antennas. The optimum ML receiver [39] is capable of achieving full diversity gain, i.e., the same diversity order as the number of receive antennas. However, a major drawback of the ML receiver is that its complexity increases exponentially with the number of transmit antennas and the number of bits per symbol employed by the modulation scheme. Fortunately, the complexity of the ML decoders can be reduced by employing sphere decoders proposed by Viterbo and Boutros [85], Damen *et al.* [86], and Agrell *et al.* [87] that are capable of achieving a similar performance to the ML decoders at a fraction of their complexity.

Foschini [42] proposed a multilayer MIMO structure known as the diagonal Bell Labs layered space-time (D-BLAST) scheme,[5] which is in principle capable of approaching the capacity of MIMO systems. As a potentially lower complexity solution, Wolniansky *et al.* proposed the so-called vertical BLAST (V-BLAST) scheme [88], where—again—each transmit antenna simultaneously transmits independent data over the same carrier frequency band. At the receiver side, provided that the number of receive antennas is higher than or equal to the number of transmit antennas, a low complexity single-stream decoding algorithm may be applied to detect the transmitted data rather than having to detect the combined multistream symbols jointly. These spatial multiplexing-oriented BLAST transceivers are capable of providing a substantial increase in a specific user's effective

[5]The diagonal approach implies that the signal mapped to the consecutive antenna elements is delayed in time, which has the potential of subjecting the delayed signal components of a space-time symbol to less correlated fading, hence leading to an increased diversity gain.

Table 8 Major Spatial Multiplexing Techniques

Year	Author(s)	Contribution
1996	Foschini *et al.* [42]	studied the encoding and decoding of the diagonal BLAST structure.
1998	Wolniansky *et al.* [88]	introduced the vertical BLAST architecture for reducing the implementation complexity of the diagonal approach.
1999	Golden *et al.* [89]	provided the first real-time BLAST demonstrations.
2001	Benjebbour *et al.* [90]	introduced the minimum mean square error receiver for V-BLAST and introduced an ordering scheme for improving the attainable performance.
2002	Sellathurai *et al.* [91]	studied the combination of BLAST architecture with that of a turbo code to improve its performance.
2003	Wubben *et al.* [92]	proposed a detector for improving the attainable performance of V-BLAST.
2004	Zhu *et al.* [93]	proposed a complexity-reduction algorithm for BLAST detectors.
2005	Huang *et al.* [94]	proposed a new detection algorithm for BLAST based on the concept of particle filtering and provided a near ML performance at a reasonable complexity.

bit rate without increasing either their transmit power or transmission bandwidth. However, a limitation of BLAST is that it was not designed for exploiting transmit diversity.

Diverse multistream detectors having various pros and cons may be employed for detecting the BLAST signal [13], some of which will be further detailed below. The conceptually simple, but implementationally complex ML detector of an M-ary modulation scheme has to evaluate all the M^{N_t} legitimate decision candidates and hence its complexity increases exponentially with N_t [13]. As reduced-complexity detectors, both the family of successive and parallel IC schemes to be detailed further below may be employed. However, the decision errors of a particular antenna's single-stream IC-aided detector may propagate to other bits of the multiple-antenna symbol, when erroneously canceling the effects of the sliced and remodulated bits from the composite multistream signal. In order to circumvent this potential error propagation, the successive IC-based V-BLAST detector first aims for selecting that particular layer[6] which has the highest SNR and estimates the transmitted bits of this highest quality layer while treating the other layers as interference. The detected symbol is then remodulated and its contribution is subtracted from the received multistream signal. Then the layer having the second-highest SNR is selected for decoding. The procedure is repeated for all the layers. The BER performance of each layer is different and it depends on the received SNR of each layer. The first decoded layer has the highest SNR and it is also immune to error propagation, while the layers detected later potentially benefit from a higher diversity gain as well as from a reduced interantenna interference.

The BLAST detection algorithm is based on SIC [13], [95], which was originally proposed for multiuser detection in CDMA systems [96]. Several BLAST detectors have been proposed in the literature for either reducing the complexity [97]–[102] or for improving the attainable BER performance [92], [103]–[107]. An alternative design approach contrived for spatial multiplexing using less receive antennas than transmit antennas was proposed by Elkhazin *et al.* [108] based on group MAP detection. In [91] and [109], a spatial multiplexing scheme referred to as Turbo-BLAST was proposed by Sellathurai and Haykin, which uses quasi-random interleaving in conjunction with an iterative receiver structure in order to separate the individual layers. The major spatial multiplexing techniques are summarized in Table 8.

3) Beamforming Techniques: According to Sections IV-A1 and IV-A2, it becomes clear that multiple antennas can be used for the sake of attaining either spatial diversity or spatial multiplexing gains. However, multiple antennas can also be used in order to improve the SNR achieved at the receiver or the SINR in a multiuser scenario. This can be achieved by employing beamforming techniques [110], [111]. Beamforming constitutes an effective technique of reducing the multiple-access interference where the antenna gain is increased in the direction of the desired user while reducing the gain towards the interfering users, as shown in Fig. 10.

In a wireless communications scenario the transmitted signals propagate via several paths and hence are received from different directions/phases at the receiver. If the directions of arrival for the different propagation paths are known at the transmitter or the receiver, then beamforming techniques can be employed in order to focus the received beam pattern in the direction of the specified antenna or user [112], [113]. Hence, significant SNR gains

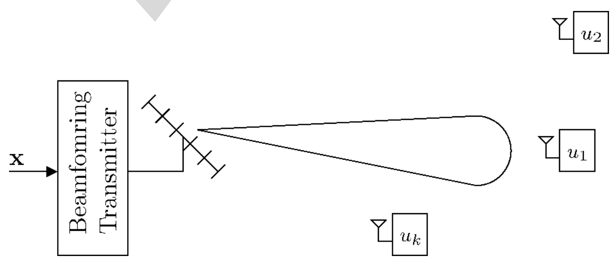

Fig. 10. ***Beamforming system model.***

[6] A "layer" in the case of the V-BLAST transceiver corresponds to each of the stream of a specific transmit antenna.

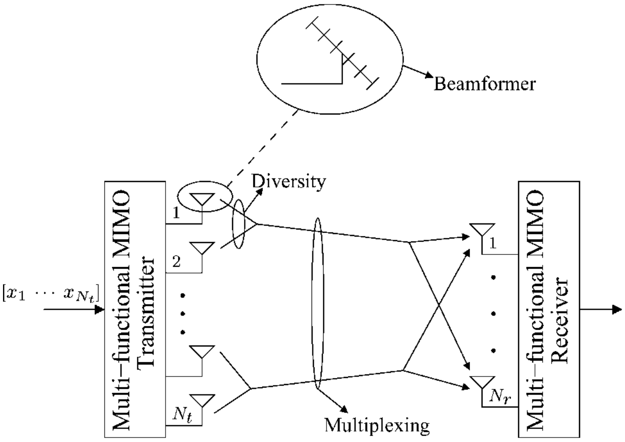

Fig. 11. ***Block diagram of a multifunctional MIMO scheme benefiting from diversity, multiplexing as well as beamforming gains.***

can be achieved in comparison to a SISO. At the transmitter side, when the DOA of the dominant paths at the receiver is known for the transmitter, then the transmit power is concentrated in the direction of the target user, where less power is wasted in the other directions.

On the other hand, beamforming can also be used in order to reduce the cochannel interference or multiuser interference. When using beamforming, each user adjusts his/her beam pattern to ensure that there are nulls in the directions of the other users, while there is a high directivity in the direction of the desired receiver [110], [114]. Hence, the system attains an SINR gain.

4) Multifunctional MIMO Techniques: The MIMO schemes discussed in the previous sections are "unifunctional," in other words they can attain either diversity gain, multiplexing gain or beamforming gain. By contrast, a multifunctional MIMO scheme may attain a combination of the three gains, as shown in Fig. 11. V-BLAST is capable of achieving full multiplexing gain, while STBC may achieve full antenna diversity gain. Hence, it was proposed by Tarokh *et al.* [115] to combine these two techniques to provide both antenna diversity and spectral efficiency gains. More specifically, it was proposed that the antennas at the transmitter be partitioned into layers, where each layer uses STBC. At the receiver side, successive group IC was applied to each layer before decoding the signals using the STBC decoder of [40]. Therefore, by combining V-BLAST and STBC, an improved transmit diversity gain can be achieved as compared to pure V-BLAST, while ensuring that the overall bandwidth efficiency is higher than that of pure STBC due to the independence of the signals transmitted by the different STBC layers. Furthermore, the combined array processing proposed in [115] was improved in [116] by Tao and Cheng by optimizing the decoding order of the different antenna layers. An iterative decoding algorithm was also proposed in [116] that results in a full receive diversity gain for the combined STBC-aided V-BLAST system.

In [120], Onggosanusi *et al.* presented a transmission scheme referred to as D-STTD, which consists of two STBC layers at the transmitter that is equipped with four transmit antennas, while the receiver is equipped with two antennas. The decoding of D-STTD presented in [120] is based on the linear decoding scheme presented by Naguib *et al.* [131], where the authors provided a broad overview of space-time coding and signal processing designed for high data rate wireless communications. Additionally, a two-user scheme was presented in [131], where each user is equipped with a twin-antenna-aided STBC arrangement, transmitting at the same carrier frequency and in the same time slot. A two-antenna-aided receiver was implemented for the sake of decoding the two users' data, while eliminating the interference imposed by the users on each others' data. An extension to the idea of combining IC with STBC techniques was presented by Huang *et al.* [118], [122], where the STBC and IC arrangements were combined with CDMA for the sake of increasing the number of users supported by the system. A ZF decoder designed for the D-STTD scheme was presented by Lee *et al.* [127] for the sake of reducing the decoding complexity. Finally, Stamoulis *et al.* [119] and Al-Dhahir *et al.* [132] presented further results that compare the performance of STBC versus D-STTD while extending the applicability of the D-STTD scheme to more than two STBC layers.

Furthermore, in order to achieve additional performance gains, beamforming has been combined both with spatial diversity as well as spatial multiplexing techniques. STBC has been combined with beamforming in order to attain an angular selectivity-induced SNR gain in addition to diversity gain [121], [124], [125], [133]–[135]. In [121], Jongren *et al.* combined classic transmit beamforming with STBC assuming that the transmitter has knowledge of the channel's envelope and derived a performance criterion for a frequency-flat independently fading channel. Furthermore, in [125], the performance of combined beamforming and STBC has been analyzed by Zhu and Lim when using either a single or a pair of beamforming antenna arrays and studied the effect of the DOA on the attainable system performance. Finally, spatial multiplexing techniques have been combined with beamforming techniques by Nabar *et al.* [136], Hong *et al.* [137] as well as Kim and Chun [138]. The major contributions on multifunctional MIMO techniques are summarized in Tables 9 and 10.

In [130], a tri-functional MIMO scheme referred to as LSSTC was proposed that combines the benefits of STBC, V-BLAST, and beamforming. Thus, the LSSTC system benefits from the multiplexing gain of V-BLAST, from the diversity gain of STBCs, and from the angular selectivity-related SNR gain of the beamformer.

A block diagram of the proposed LSSTC scheme is illustrated in Fig. 12. The system's architecture is portrayed

Table 9 Major Multifunctional MIMO Techniques (Part 1)

Year	Author(s)	Contribution
1998	Naguib *et al.* [117]	presented a multiuser scenario where each user employs STBC and the receiver applies interference cancellation for eliminating the co-channel interference and then uses ML decoding for the STBC of each user.
1999	Tarokh *et al.* [115]	proposed to combine STBC with V-BLAST in order to provide both antenna diversity and spectral efficiency gains.
2000	Huang *et al.* [118]	extended the idea of combining interference cancellation with STBC to multiuser scenarios using CDMA.
2001	Stamoulis *et al.* [119]	proposed a simple decoder for the two-user system, where each user employs STBC and showed how the decoder can be extended to more users and then extended the results for frequency-selective channels.
2002	Onggosanusi *et al.* [120]	presented the Double Space-Time Transmit Diversity scheme, which consists of two STBC blocks at the transmitter that is equipped with four antennas, while the receiver is equipped with two antennas.
	Jongren *et al.* [121]	combined conventional transmit beamforming with STBC assuming that the transmitter has partial knowledge of the channel and derived a performance criteria for improving the system performance.
	Huang *et al.* [122]	introduced a transmission scheme that can achieve transmit diversity and spatial separation and proposed a generalization of the V-BLAST detector for CDMA signals.
	Soni *et al.* [123]	designed a hybrid downlink technique for achieving both transmit diversity and transmit beamforming combined with DS-CDMA.
2003	Liu *et al.* [124]	combined the twin-antenna-aided Alamouti STBC with ideal beamforming in order to show that the system can attain a better performance while keeping full diversity and unity rate.
2004	Tao *et al.* [116]	improved the design of [115] by optimizing the decoding order of the different antenna layers. Also proposed an iterative decoder than can achieve full diversity.
	Zhu *et al.* [125]	compared the performance of two systems combining beamforming with STBC, while using a single or two antenna arrays and studied the effect of the DOA on the performance of the two schemes.

in Fig. 12, which hasN_t transmit antenna arrays (AAs) spaced sufficiently far apart in order to experience independent fading and hence to achieve transmit diversity. The L_{AA} number of elements of each of the AAs are spaced at a distance of $\lambda/2$ for the sake of achieving a beamforming gain. Furthermore, the receiver is equipped with $N_r \geqslant N_t$ antennas. According to Fig. 12, a block of B input information symbols is serial-to-parallel converted to K groups of symbol streams of length $B_1, B_2, \cdots, B_K$, where $B_1 + B_2 + \cdots + B_K = B$. Each group of B_k symbols, $k \in [1, K]$, is then encoded by a constituent STC_k associated with m_k transmit AAs, where we have $m_1 + m_2 + \cdots + m_K = N_t$.

The L_{AA}-dimensional spatio-temporal vector of CIRs spanning from the mth transmitter AA, $m \in [1, \cdots, N_t]$, to the nth receiver antenna, $n \in [1, \cdots, N_r]$, can be expressed as $\mathbf{h}_{nm}(t) = \mathbf{a}_{nm}(t)\delta(t - \tau_k)$, where τ_k is the signal's delay and $\mathbf{a}_{nm}(t)$ is the CIR of the mnth link between the mth AA and the nth receive antenna. Based on the assumption that the array elements are separated by half a wavelength, we have $\mathbf{a}_{nm}(t) = \alpha_{nm}(t) \cdot \mathbf{d}_{nm}$, where $\alpha_{nm}(t)$ is a Rayleigh faded envelope and $\mathbf{d}_{nm}$ is an L_{AA}-dimensional vector, whose elements are based on the received signal's DOA. As for the AA-specific DOA, we consider a scenario where the distance between the transmitter and the receiver is significantly higher than that between the AAs and thus we can assume that the signals arrive at the different AAs in parallel, i.e., that the DOA at the different AAs is the same. In this scenario, the MRC-criterion-based transmit

Table 10 Major Multifunctional MIMO Techniques (Part 2)

Year	Author(s)	Contribution
2005	Zhao *et al.* [126]	compared the performance of the combined diversity and multiplexing systems while employing ZF, QR and MMSE group interference cancellation techniques.
	Lee *et al.* [127]	proposed a computationally efficient ZF decoder for the double space-time transmit diversity scheme [120] that achieves similar performance to the conventional ZF decoder but with less complexity.
2007	Sellathurai *et al.* [128]	investigated the performance of multi-rate layered space-time coded MIMO systems and proposed a framework where each of the layers is encoded independently with different rates subject to equal per-layer outage probabilities.
2008	Ekbatani *et al.* [129]	combined STBC and transmit beamforming while using limited-rate channel state information at the transmitter. Also proposed a combined coding, beamforming and spatial multiplexing scheme over multiple-antenna multiuser channels that enables a low-complexity joint interference cancellation.
	Luo *et al.* [80]	considered a new class of full-diversity STCs that consist of a combination of delay transmit diversity with orthogonal STBCs and specially designed symbol mappings.
	El-Hajjar *et al.* [130]	proposed the LSSTC scheme that combines the benefits of STC, V-BLAST and beamforming.

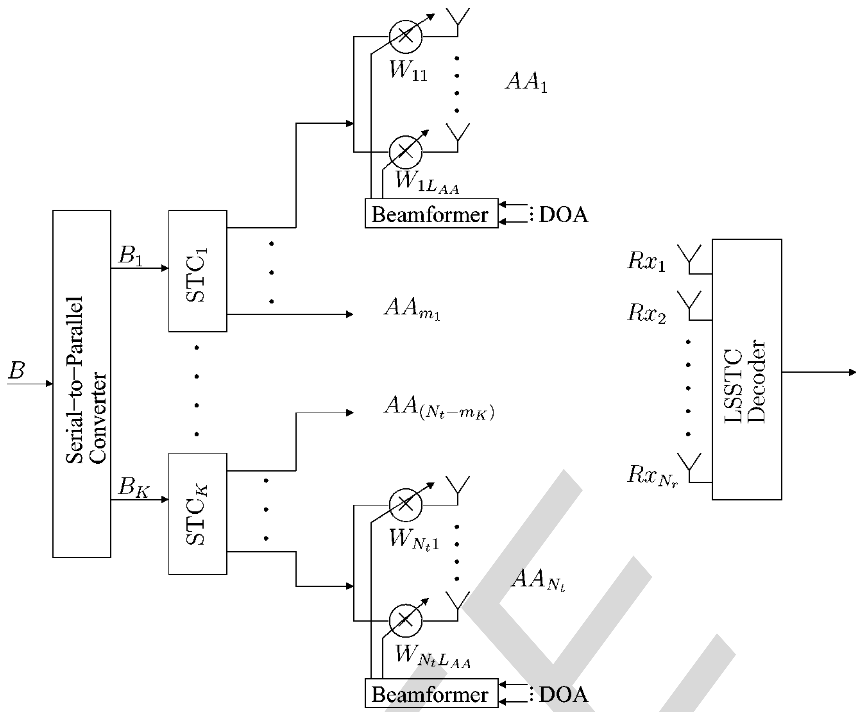

Fig. 12. ***Layered steered STC system block diagram.***

beamformer, which constitutes an effective solution for maximizing the angular-selectivity-induced antenna gain is the optimum beamformer.

The receiver may invoke a variety of detection techniques [12], such as for example the group successive interference cancellation (GSIC) based on the ZF algorithm [115]. Tarokh *et al.* suggested that the most beneficial decoding order of the STC layers is determined on the basis of detecting the highest power layer first for the sake of a high correct detection probability. For simplicity, let us highlight the operation of the GSIC for the simple case of $K = 2$ STBC layers, where the highest power layer 1 is detected first. This allows us to eliminate the interference caused by the signal of layer 2. However, the proposed concept is applicable to arbitrary STCs and to an arbitrary number of layers K. For this reason, the decoder of layer 1 has to compute a matrix $\mathbf{Q}$, so that we have $\mathbf{Q} \cdot \widehat{\mathbf{H}}_2 = 0$, where $\widehat{\mathbf{H}}_2$ represents the channel matrix of the second STBC layer whose nmth element is α_{nm}. Therefore, the decoder computes an orthonormal basis for the left null space of $\widehat{\mathbf{H}}_2$ and assigns the vectors of the basis to the rows of $\mathbf{Q}$. Multiplying $\mathbf{Q}$ by the received signal matrix $\mathbf{Y}$ suppresses the interference of layer 2 originally imposed on layer 1 and generates a signal, which can be detected using the STBC decoding of [40]. Then, the decoder subtracts the remodulated contribution of the decoded symbols of layer 1 from the composite twin-layer received signal $\mathbf{Y}$. Finally, the decoder applies direct STBC decoding to the second layer, since the interference imposed by the first layer has been eliminated. This group-IC procedure can be generalized to arbitrary N_t and K values.

The LSSTC scheme combines the benefits of V-BLAST, STBC and beamforming and hence is characterized by a diversity gain, a multiplexing gain as well as a beamforming gain. However, a drawback of the LSSTC scheme is the fact that the number of receive antennas N_r should be at least equal to the number of transmit antennas N_t. This condition is not very practical for employment in shirt-pocket sized MSs that are limited in size and complexity, but it may be readily applied in a scenario where two BSs cooperate or a BS is communicating with a MIMO-aided laptop. Therefore, in order to facilitate communications between a BS and a MS accommodating less antennas than the transmitting BS, powerful nonlinear receivers such as radial basis function (RBF)-aided detectors [11], GA-assisted schemes [5] or SD [95] can be employed in order to allow rank-deficient systems employing less receive antennas than transmit antennas. Nonetheless, the intelligent linear receiver proposed by Onggosanusi [120] can also be used for a DL system employing four transmit and two receive antennas. Additionally, in order to allow the multifunctional MIMO to accommodate multiple users, STS can be employed in the different antenna layers. Furthermore, frequency diversity can be achieved by the LSSTC scheme by employing the generalized Multicarrier direct sequence code-division multiple-access (MC DS-CDMA) scheme of [139]. The resultant multifunctional MIMO is referred to as LSSTS.

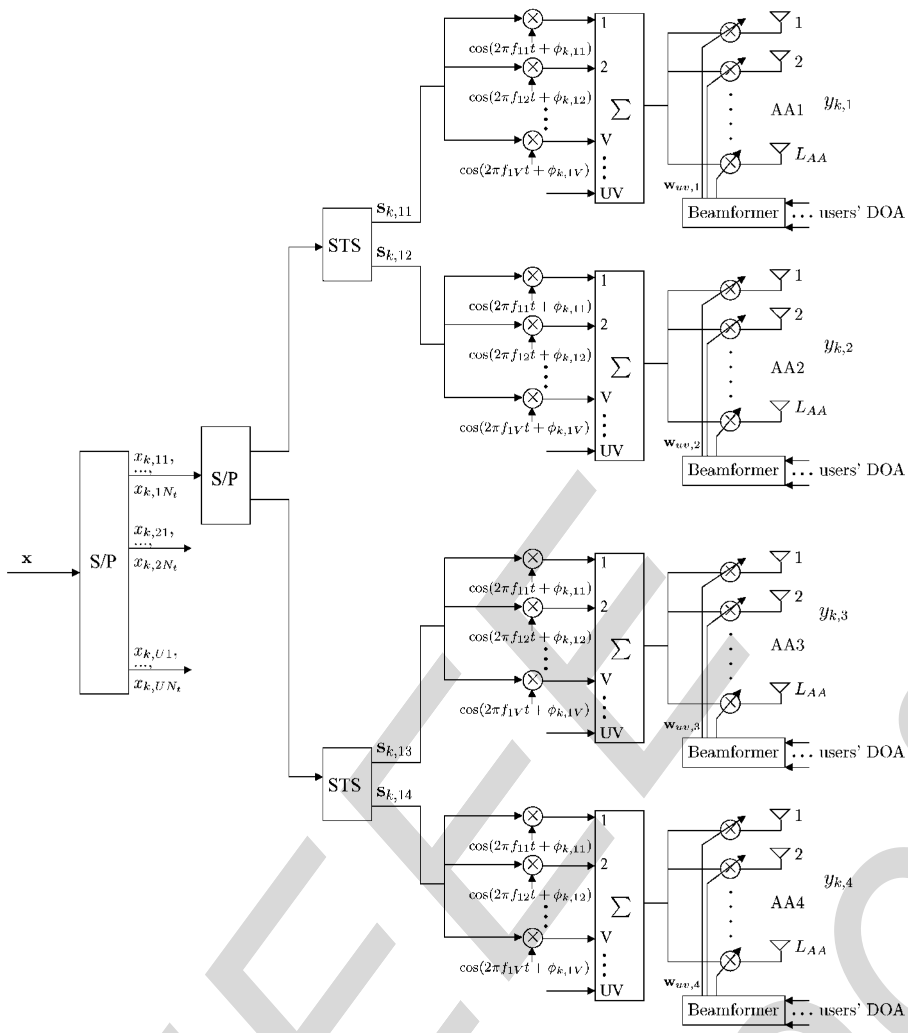

Fig. 13. *The kth user's LSSTS-aided generalized MC DS-CDMA transmitter model.*

A block diagram of the LSSTS scheme is shown in Fig. 13, which combines the benefits of V-BLAST, STS, and beamforming with generalized MC DS-CDMA [139] for the sake of achieving a multiplexing gain, a spatial and frequency diversity gain as well as a beamforming gain. The LSSTS scheme described in this section is capable of supporting K users differentiated by the user-specific spreading codes $\bar{\mathbf{c}}_k$, where $k \in [1, K]$. We consider the scenario of $K = 32$ users, $N_t = 4$ transmit antennas and $N_r = 2$ receive antennas and employs a linear receiver to decode the received signal.

The system architecture portrayed in Fig. 13 for the LSSTS scheme is equipped with $N_t = 4$ transmit AAs spaced sufficiently far apart in order to experience independent fading. The L_{AA} number of elements of each of the AAs are spaced at a distance of $\lambda/2$ for the sake of achieving beamforming. Additionally, in the generalized MC DS-CDMA system considered, the subcarrier frequencies are appropriately arranged to guarantee that the same STS signal is spread to and hence transmitted by the specific V number of subcarriers having the maximum possible frequency separation, so that they experience independent fading and hence achieve the maximum attainable frequency diversity order.

The LSSTS system considered here employs the generalized MC DS-CDMA scheme of [139] using UV number of subcarriers. The transmitter schematic of the kth user is shown in Fig. 13, where a block of UN_t data symbols $\mathbf{x}$ is S/P converted to U parallel subblocks. Afterwards, each set of N_t symbols is S/P converted to $G = 2$ groups, where each group is encoded using the $N_{tg} = 2$ antenna-aided STS procedure of [56], where the transmitted signal is spread to N_{tg} transmit antennas with the aid of the orthogonal spreading codes of $\{\bar{\mathbf{c}}_{k,1}, \bar{\mathbf{c}}_{k,2}, \cdots, \bar{\mathbf{c}}_{k,N_{tg}}\}$, $k = 1, 2, \ldots, K$. The spreading codes $\bar{\mathbf{c}}_{k,1}$ and $\bar{\mathbf{c}}_{k,2}$ are generated from the same user-specific spreading code $\bar{\mathbf{c}}_k$ as in [56]. The discrete symbol duration of the orthogonal STS codes is $N_{tg}N_e$, where N_e represents the kth user's TD spreading factor.

The UN_t outputs of the UG number of STS blocks modulate a group of subcarrier frequencies $\{f_{u,1}, f_{u,2}, \ldots, f_{u,V}\}$. Since each of the$U$ subblocks is spread to and hence conveyed with the aid of V subcarriers, a total of UV number of subcarriers are required in the MC DS-CDMA system considered. The UV number of subcarrier signals are superimposed on each other in order to form the complex-valued modulated signal for transmission. Finally, according to the kth user's channel information, the UVN_t signals of the kth user are weighted by the transmit weight vector $\mathbf{w}_{uv,n}^{(k)}$ determined for the uvth subcarrier of the kth user, which is generated for the nth AA. Assuming that the system employs a modulation scheme transmitting D bits per symbol, then the bandwidth efficiency of the LSSTS-aided generalized MC DS-CDMA system is given by $2UD$ bits per channel use.

The uvth CIR considered in the case of LSSTS is the same as that considered in the previous section for LSSTC. Assuming that the K users' data are transmitted synchronously over a dispersive Rayleigh fading channel, decoding is carried out in two steps—first SIC is performed according to [120], followed by the STS decoding procedure of [56].

Finally, after combining the $k = 1$st user's identical replicas of the same signal transmitted by spreading over V number of subcarriers, the decision variables corresponding to the symbols transmitted in the$u$th subblock can be expressed as $\widetilde{x}_{1,u} = \sum_{v=1}^{V} \widetilde{x}_{1,uv}$. Therefore, the decoded signal has a diversity order of $2V$. More explicitly, second-order spatial diversity is attained from the STS operation and a diversity order of V is achieved as a benefit of spreading by the generalized MC DS-CDMA scheme, where again the subcarrier frequencies are appropriately arranged to ensure that the same STS signal is spread to and hence transmitted by the specific V number of subcarriers having the maximum possible frequency separation, so that they experience as independent fading as possible.

Fig. 14 compares the attainable BER performance of LSSTS assisted generalized MC DS-CDMA to that of the LSSTC scheme, noting that the former is capable of supporting multiple users. The figure also shows the BER performance of both the twin-antenna-aided STS and of the SISO benchmark systems. The LSSTS scheme employs four transmit AAs and two receive antennas, while the LSSTC scheme of Fig. 14 employs four transmit AAs and four receive antennas. Observe in Fig. 14 that the BER performance of the LSSTS scheme is identical to that of the twin-antenna-aided STS scheme, when a single subcarrier is used. This means that the LSSTS scheme attains a spatial diversity order of 2, while achieving a multiplexing gain that is twice that of a twin-antenna-aided STS scheme. Additionally, as shown in Fig. 14, increasing the number of subcarriers V improves the attainable BER performance for the LSSTS scheme. Hence, the LSSTS scheme is also capable of attaining frequency diversity gain. On the other hand, comparing the BER performance of the LSSTS scheme employing $V = 1$ subcarrier to that of the LSSTC scheme shows that the LSSTC scheme attains a better BER performance. This is due to the fact that the LSSTC scheme employs more receive antennas than the LSSTS scheme and hence the former is capable of attaining a higher spatial diversity gain. Finally, Fig. 14 shows the beamforming gain attained by the LSSTC scheme when the number of elements L_{AA} per AA is increased from $V = 1$ to 4.

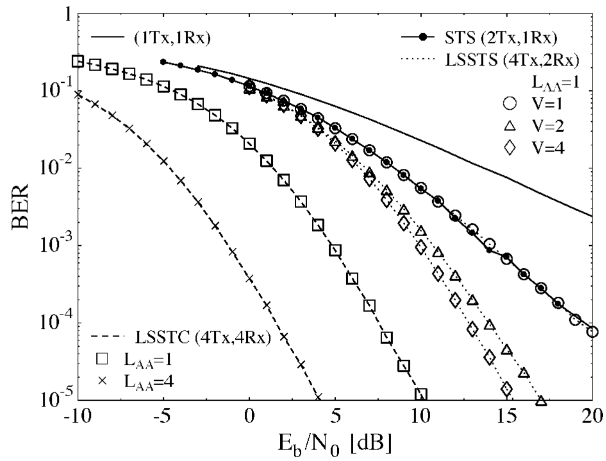

Fig. 14. ***BER performance comparison of the SISO, STBC, LSSTC, and LSSTS schemes, while communicating over a correlated Rayleigh fading channel associated with a normalized Doppler frequency of $f_d = 0.01$.***

B. Distributed MIMO Techniques

Wireless channels suffer from multipath propagation of the signals that results in channel fading. Employing multiple transmit antennas is a beneficial method that can be used for counteracting the effects of the channel fading by providing diversity gains, provided that the different antennas experience independent fading. Transmit diversity results in a significantly improved BER performance when the different transmit antennas are spatially separated to ensure that the paths arriving from each transmit antenna to the destination experience independent fading. This can be achieved by having a sufficiently high distance between the different antennas. This antenna separation has to be significantly higher than the carrier's wavelength. However, considering a handheld mobile phone, it is not a feasible option to position the transmit antennas far enough in order to achieve independent fading. On the other hand, the spatial fading correlation imposed by the insufficiently high antenna spacing at the transmitter or receiver of a MIMO system results in a degradation of both the achievable capacity and the BER performance of MIMO systems. The problem of receiving correlated signals can be circumvented by introducing a new class of MIMOs also referred to as distributed MIMOs, which are

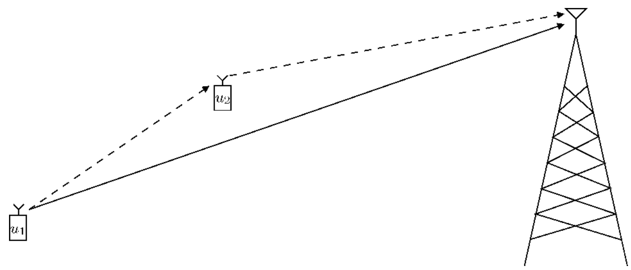

Fig. 15. ***System model of a two-user distributed MIMO scheme.***

applied in the context of cooperative communications [43], [44], as shown in Fig. 15.

The basic philosophy of cooperative communications can be traced back to the idea of the classic relay channel, which was introduced in 1971 by Van der Meulen [140]. Cover and El Gamal characterized the relay channel from an information theoretic point of view in [141]. The relay model is composed of three components: a source transmitting data, a destination directly receiving the data from the source, and a relay receiving the data from the source, which is then either amplified or decoded and re-encoded before its retransmission to the destination. Cooperative communications may be interpreted as a generalization of the now classic concept of the relay channel, where the source and the relay transmit their own data as well as other subscribers' data, which results in receiving multiple copies of the same data—both directly from the source as well as indirectly from the relays. Hence, the system benefits from a spatial diversity gain and eventually from an improved BER performance for both of the cooperating users. Cooperative techniques exploit the fact that the signal transmitted from a specific user to a specific destination can be "overheard" by neighboring users. These users can process the signal they happen to have overheard without compromising the security of the data and then transmit the processed data to the destination.

In [143], Sendonaris *et al.* generalized the relay model to multiple nodes that transmit their own data as well as serve as relays for each other. The scheme proposed in [143] was referred to as "user cooperation diversity," where the authors examined the achievable rate/throughput regions and outage probabilities for this particular scheme. In [43] and [44], Sendonaris *et al.* presented a simple user-cooperation methodology based on a DF signaling scheme using CDMA. The orthogonality of the different spreading codes of the different users makes it possible for the intended receiver to distinguish between the information transmitted from different cooperating users. In [144], Laneman *et al.* reported the gains achieved in terms of an improved data rate and reduced sensitivity to channel variations, where it was concluded that cooperation effectively mimics a multiple-antenna-aided distributed MIMO scenario with the aid of single-antenna terminals. Dohler *et al.* [146] introduced the concept of VAA that emulates Alamouti's STBC for single-antenna-aided cooperating users. Space-time-coded cooperative diversity protocols designed for exploiting spatial diversity in a cooperative scenario were proposed by Laneman and Wornell in [147]. In [147], a space-time-coded cooperative diversity design was proposed, where a source transmits its signal to its destination and many relays receive the transmission. Those terminals that can fully decode the transmission utilize an STC to cooperatively relay the data to the destination.

Cooperative communications has been shown to offer significant performance gains in terms of various performance metrics including diversity gains [147], [150], [170] as well as multiplexing gains, as advocated by Azarian *et al.* [154]. Again, diverse techniques have been proposed in the literature for achieving a cooperation-aided diversity gain including the compress-and-forward (CF) [141], DF [141], [171], AF [144] as well as coded cooperation schemes [145], [158]. These techniques may employ different algorithms for relaying the data, but the following general two-phase procedure is used in all practical cases. More explicitly, during the first phase of cooperation each user transmits his/her own data both to the destination as well as to the cooperating users. Then during the second phase of cooperation, the users cooperate by relaying the signal received during the first phase of cooperation. The convenience of this two-phase cooperative procedure is that the relays do not have to transmit and receive simultaneously, which has to be avoided in the interest of circumventing the contamination of the low-power signal (say -100 dBm) received from the remote source by the high-power (say $+10$ dBm) transmitted signal's leakage into the receiver. This potential leakage could readily desensitize the receiver's automatic gain control (AGC) and hence the desired signal might be deemed to be noise/interference, which would preclude its detection. Furthermore, the destination receives from the source during the broadcast phase and from the relays during the cooperative phase, i.e., in different time slots, hence the two replicas of the source signal do not interfere with each other at the destination and may be efficiently combined in the interest of maximizing the attainable diversity gain. However, we emphasize that this two-phase philosophy is reminiscent of the two-slot transmission regime of an STBC and hence it halves the achievable throughput. Hence, it is an attractive research topic to design powerful so-called echo cancelers, which are capable of canceling the effects of the above-mentioned high-power transmitted signals contaminating the low-power received signals—hence potentially eliminating the factor-two throughput reduction.

Again, both the DF as well as the CF principles were proposed in [141]. The fundamental difference between these two strategies is whether the relay decodes the relayed signal, before it is forwarded to the destination. In the CF relaying strategy, the relay sends a Wyner–Ziv compressed version of the signal received during the first phase of cooperation to the receiver. This technique strikes a balance between the regenerative and nonregenerative methods, where the received signal may be demodulated to regenerate the transmitted nonbinary symbols instead of being also channel decoded to bits and then the symbols may be subjected to lossless data compression.

In the DF signaling scheme the relay decodes the cooperating partners' signals and then re-encodes the detected bits before their retransmission [171]. The destination combines the signal received from both the source as well as from the relay, hence creating spatial diversity. An ingenious low-complexity DF signaling strategy can be found in [43] and [44], where two users were paired to cooperate with each other using CDMA. Each signaling period is divided into three time slots, where in the first and second time slots each user transmits his/her own data. Each user's data are broadcast and hence can be detected by the other user. In the second time slot, each user detects the other user's data. In the third time slot, both users transmit a linear combination of their own second-time-slot data and the partners' second-time-slot data, each multiplied by the appropriate spreading code. Additionally, a prerequisite for this regaim's operation is that the destination has acquired the knowledge of the CIR of the IUC for the sake of optimal decoding [171].

In order to circumvent the notorious problem of error propagation, a channel-quality-based relay-activation DF technique was proposed by Laneman *et al.* [150], where the relay detects the signal received from the source and only forwards it to the destination when the instantaneous SNR of the IUC guarantees its reliable exploitation. Otherwise, the source continues its direct transmission to the destination in the form of repetition coding or automatic repeat request techniques potentially combined with more powerful FEC codes [171]. If the IUC's SNR falls below a given channel-quality threshold, the relay may transmit the signal it received from the source using either AF or DF, in order to attain a diversity gain.

Another signaling strategy is referred to as incremental relaying [150], which may be viewed as an extended form of transmitting incremental redundancy or that of invoking HARQ. In this scenario, the relay retransmits its contribution, if the destination provides a negative acknowledgment in an attempt to attain a diversity gain.

As a further advance, it was shown in [172] that DF relaying is more beneficial when the relay roams close to the source, because the probability of avalanche-like error propagation is reduced. By contrast, Kramer *et al.* also argue that the employment of CF relaying is beneficial when the relay roams close to the destination. It is also plausible that AF relaying does not inflict error propagation since no decisions are invoked at the relay. However, it is unable to improve the SNR, since the signal and noise are inseparable and hence they are jointly amplified. Nonetheless, the employment of AF relaying is realistic for industry-wide rollout at the time of writing owing to its low complexity, while DF relaying has numerous open problems that have to be solved before its widespread employment.

In [173], the attainable capacity gains of both transmitter and receiver cooperation were compared in a relay-aided network relying on cooperating nodes in each other's vicinity. When all nodes have the same average transmit power and perfect CSI, Ng and Goldsmith demonstrated that transmitter cooperation outperforms receiver cooperation. By contrast, when the total transmit power was assumed to be optimally shared across the cooperating nodes and only the received signal's phase but not its magnitude was deemed to be known at the receiver, then receiver cooperation was shown to be more beneficial. Ng and Goldsmith also emphasized the plausible fact that access to accurate CSI was essential in transmitter cooperation, while optimal power allocation was vital for reliable receiver cooperation.

Again, in the context of the AF signaling strategy [144], the relay simply amplifies the noise-contaminated received signal without improving its SNR and retransmits it to the destination. The destination then combines the information directly received from the source as well as from the relay and makes a final decision on the transmitted bits [171]. The benefit of this is that although the relay amplifies the noise in addition to amplifying the desired signal, the destination still observes two independently faded versions of the signal, thus benefiting from a diversity gain as compared to noncooperative schemes.

AF was first proposed and analyzed by Laneman *et al.* in [144], where the authors have shown that in the case of two-user cooperation, AF is capable of achieving a diversity order of two. In the scheme of [144], it was assumed that the destination has perfect knowledge of the IUC so that optimal decoding can be performed, where the IUC knowledge was assumed to be acquired by exchanging this IUC information between the nodes with the aid of side-information signaling or by invoking blind IUC estimation [171]. More elaborate AF algorithms and more general linear relaying schemes have been considered in [151] and [174].

On the other hand, coded cooperation [145], [158] combines the concept of cooperative communications with channel coding. Coded cooperation maintains the same information rate, code rate, bandwidth as well as transmit power as a comparable noncooperative system. The basic idea is that each user attempts to transmit incremental redundancy for his/her partner. Whenever the IUC is not favorable, the users automatically revert to a noncooperative mode [171]. The key to the efficiency of coded cooperation is that all this is managed automatically with the aid of sophisticated code design with no feedback between the users [171].

Each user encodes his/her data bits using a CRC followed by a specific code FEC from the family of RCPC codes [145]. Each user's encoded codeword is divided into two segments containing N_1 and N_2 bits, where $N_1 + N_2 = N$ and N is the total codeword length of the encoded sequence. In the first time slot, each user transmits his/her own first set of N_1 bits, where the encoded codeword is punctured to N_1 bits and hence the N_1 bits transmitted constitute a legitimate codeword. The remaining N_2 bits are the punctured bits. Each user then attempts to decode the transmission of the other user. If this attempt is deemed to be successful based on the CRC code, the user computes and transmits the N_2 bits of the other user in the second time slot. Otherwise, the user transmits his/her own N_2 bits. Thus, each user always transmits a total of $N = N_1 + N_2$ bits per source block over the two time slots [145], [171].

The users act independently in the second time slot, with no knowledge of whether their own first frame was correctly decoded. As a result, there are four possible cases for the transmission of the second frame: both users cooperate, neither user cooperates, user 1 cooperates, and user 2 does not or *vice versa*. It was suggested in [152] that the destination successively decodes according to all possibilities and checks the CRC code's success for each case. If the CRC fails for all possibilities, then the destination will select the specific codeword having the lowest path metric from the Viterbi algorithm.

Additionally, it was proposed in [147] to use distributed STCs for the relay channel, demonstrating its benefits from an information theoretic point of view. In [152], Janani *et al.* proposed space-time cooperation in addition to implementing turbo coding by exchanging extrinsic information between the data received from the source and the relay. Furthermore, a method designed for achieving cooperative diversity using rate compatible punctured codes was proposed in [145] and [158]. In [148] and [149], it was proposed to employ distributed turbo codes by exchanging extrinsic information between the data received from the source and that received from the relay, where the relay applies interleaving for the data received from the source and then uses an appropriate channel code before retransmission.

Recently, substantial research efforts have been devoted to the idea of soft relaying, where the relay passes soft information to the destination. Sneessens and Vandendorpe [155] argued that the DF signaling loses soft information and hence it was proposed to use soft DF signaling, where all operations are performed using the LLR-based representation of soft information. It was shown in [155] that the soft DF philosophy outperforms the DF and the AF signaling strategies. In [163], soft DF was used by Bui and Yuan, where the soft information was quantized and encoded using the superposition encoder of [175] before transmission to the destination. In [160], soft-information-based relaying was employed by Li *et al.* in a turbo coding scheme, where the relay derives parity-checking-based BPSK symbol estimates for the received source information and forwards the symbols to the destination. In short, it could be concluded from [155], [160], and [163] that soft DF attains a better performance than hard DF. Furthermore, in [156] and [161], distributed source coding techniques have been adopted by Hu and Li for employment in wireless cooperative communications in order to improve the attainable performance. The major contributions to distributed MIMO techniques are summarized in Tables 11 and 12.

V. NEAR-CAPACITY PERFORMANCE FOR MIMO SCHEMES

Again, recall from Shannon's theory [1] that it is possible to reliably transmit information over any unreliable error-infested channel, provided that the information transmission rate is lower than the channel's capacity. This is facilitated by the employment of FEC codes. The basic idea is that of generating redundant bits from the original information bits, where the channel capacity determines the exact amount of redundancy that has to be incorporated by the encoder in order for the decoder to be able to correct the errors imposed by the channel.

A. Concatenated Schemes and Iterative Detection

The family of concatenated codes pioneered by Forney in 1966 [176] failed to generate as much research interest as it deserves, largely owing to its complexity. Nonetheless, the consultative committee for space data systems (CCSDSs) standardized an attractive combination of powerful inner convolutional coding and outer Reed–Solomon codes in [177], which refrained from iterative detection.

Convolutional codes were used in the GSM standard, which were combined with block interleaving. Similarly, FEC coding was employed in GPRS using conventional convolutional codes with no iterative detection. On the other hand, the digital audio broadcasting (DAB) standard in Europe employs punctured convolutional codes as the channel codec. Additionally, digital video broadcasting for terrestrial TV (DVB-T) standard adopted punctured convolutional codes as the channel codec. More recent standards, such as the improved version of DAB known as DAB+ uses convolutional codes as the inner code combined with Reed–Solomon codes as its outer code for eliminating any potential BER floor.

Upon the discovery of turbo codes by Berrou *et al.* [19], it was shown that efficient iterative decoding of concatenated codes can be carried out at a low complexity by employing simple constituent codes. Since then, the appealing iterative decoding of concatenated codes has inspired numerous authors to extend the technique to other transmission schemes consisting of a concatenation of two or more constituent detection/decoding stages [178]–[194]. The turbo principle was extended to multiple parallel concatenated codes in 1995 by Divsalar and Pollara [178], to serially concatenated block codes and

Table 11 Major Distributed MIMO Techniques (Part 1)

Year	Author(s)	Contribution
1971	Meulen [140]	investigated a simple 3-node relay channel incorporating a transmitter, a relay and a receiver using a time-sharing approach.
1979	Cover *et al.* [141]	characterized the relay channel from an information theoretic point of view.
1983	Willems [142]	introduced a partially cooperative communications scenario where the encoders are connected by communication links with finite capacities, which permit both encoders to communicate with each other. The paper also established the capacity region of the multiple access channel with partially cooperating encoders.
1998	Sendonaris *et al.* [143]	generalized the relay model to multiple nodes that transmit their own data as well as serve as relays for each other.
2001	Laneman *et al.* [144]	built upon the classical relay channel and exploited space diversity available at distributed antennas through coordinated transmission and processing by cooperating radios.
2002	Hunter *et al.* [145]	proposed a user cooperation scheme for wireless communications in which the idea of cooperation was combined with the existing channel coding methods.
	Dohler *et al.* [146]	introduced the concept of virtual antenna arrays that emulates Alamouti's STBC for single-antenna-aided cooperating users.
2003	Sendonaris *et al.* [43], [44]	presented a simple user-cooperation methodology based on a DF signalling scheme using CDMA.
	Laneman *et al.* [147]	developed space-time coded cooperative diversity protocols for exploiting spatial diversity in a cooperation scenario, which can also be used for higher spectral efficiencies than repetition-based schemes.
	Valenti and Zhao [148], [149]	proposed a turbo coding scheme in a relay network.
2004	Laneman *et al.* [150]	developed and analyzed cooperative diversity protocols and compared the DF, AF, selection relaying and incremental relaying.
	Nabar *et al.* [151]	analyzed the spatial diversity performance of various signalling protocols.
	Janani *et al.* [152]	presented two extensions to the coded cooperation framework [145]: increased the diversity of coded cooperation via ideas borrowed from space-time codes and applied turbo codes in the proposed relay framework.

convolutional codes by Benedetto and Montorsi in 1996 [179] as well as to multiple serially concatenated codes by Benedetto *et al.* in 1998 [180]. The stunning success of the "turbo principle" resulted in the adoption of turbo codes in several standards, including the UMTS, HSPA, and LTE standards of mobile communications. In the context of broadcasting standards, turbo codes were also used in the integrated services digital broadcasting for terrestrial transmission (ISDB-T) set of recommendations.

In [185], a turbo equalization scheme was proposed by Douillard *et al.*, where iterative decoding was invoked for exchanging extrinsic information between a soft-output

Table 12 Major Distributed MIMO Techniques (Part 2)

Year	Author(s)	Contribution
2004	Stefanov *et al.* [153]	analyzed the performance of channel codes that are capable of achieving the full diversity provided by user cooperation in the presence of noisy interuser channels.
2005	Azarian *et al.* [154]	proposed cooperative signalling protocols that can achieve the diversity-multiplexing trade off.
	Sneessens *et al.* [155]	proposed a soft decode-and-forward signalling strategy that can outperform the conventional DF and AF.
	Hu *et al.* [156]	proposed Slepian-Wolf cooperation that exploits distributed source coding technologies in wireless cooperative communication.
	Yu[157]	compared the AF and DF signalling schemes in practical scenarios.
2006	Hunter *et al.* [158], [159]	developed the idea of coded cooperation [145] by computing BER and FER bounds as well as the outage probability of coded cooperation.
	Li *et al.* [160]	employed soft information relaying in a BPSK modulated relay system employing turbo coding.
	Hu *et al.* [161]	proposed Wyner-Ziv cooperation as a generalization of the Slepian-Wolf cooperation [156] with a compress-and-forward signalling strategy.
	Hϕst-Madsen [162]	derived upper and lower bounds for the capacity of four-node ad hoc networks with two transmitters and two receivers using cooperative diversity.
2007	Bui *et al.* [163]	proposed soft information relaying where the relay LLR values are quantized, encoded and superimposedly modulated before being forwarded to the destination.
	Khormuji *et al.* [164]	improved the performance of the conventional DF strategy by employing constellation rearrangement in the source and the relay.
	Bao *et al.* [165]	combined the benefits of AF and DF and proposed a new signalling strategy referred to as decode-amplify-forward.
	Xiao *et al.* [166]	introduced the concept of network coding in cooperative communications.
2008	Yue *et al.* [167]	compared the multiplexed coding and superposition coding in the coded cooperation system.
	Zhang *et al.* [168]	proposed a distributed space-frequency coded cooperation scheme for communication over frequency-selective channels.
	Wang *et al.* [169]	introduced the complex field network coding approach that can mitigate the throughput loss in the conventional signalling schemes and attain full diversity gain.

symbol detector and an outer channel decoder in order to combat the deleterious effects of ISI. A serially concatenated scheme was proposed in [218] by Benedetto *et al.*, where iterative decoding was carried out by exchanging information between an outer convolutional decoder and an inner TCM decoder, which was originally devised by Ungerboeck in 1982 [15]. The Advanced Television Systems Committee (ATSC) of the digital television research community incorporated TCM in the terrestrial TV standard.

Caire *et al.* [187], [188] presented a unified theory of BICM, which was originally introduced in [197] and [198] by Zehavi and provided tools for its performance analysis as well as guidelines for its design. In [189], the employment of the turbo principle was considered for iterative soft demapping in the context of BICM by ten Brink *et al.*, where a soft demapper was used between the multilevel demodulator and the channel decoder. The resultant scheme is referred to as BICM using iterative decoding (BICM-ID), which was further studied by Li and Ritcey [190]–[192]. Iterative multiuser detection and channel decoding was proposed by Wang and Poor [193] for CDMA schemes. In [194], a turbo coding scheme was proposed by Sezgin *et al.* for the MIMO Rayleigh fading channel, where an additional block code was employed as an outer channel code, while an orthogonal STBC scheme was considered as the inner code.

Surprisingly, the family of low-density parity-check (LDPC) codes originally devised by Gallager as early as 1963 [203] remained more or less unexploited until after the discovery of turbo codes by Berrou *et al.* in 1993 [19]. Since then, however, LDPC codes have experienced a renaissance largely stimulated by Richardson and Urbanke [219] and attracted substantial research interests. MacKay and Neal demonstrated in [202] that despite their simple decoding structure, LDPC codes are also capable of operating near the channel capacity. In 1998, Davey and MacKay proposed a nonbinary version of LDPC codes [220], which is potentially capable of outperforming binary LDPC codes. Most LDPC designs, both binary and nonbinary, are based on randomly generated parity check matrices. However, it was shown recently that equally powerful codes may be generated on the basis of systematic parity check design, for example, using the techniques outlined in [221]–[223] by Ammar *et al.* As a further advance in the field, both Lentmaier [224] as well as Hirst and Honary [225], [226] designed generalized LDPC (GLDPC) codes, which replaced the classic parity check codes by more powerful constituent codes, such as binary or nonbinary BCH codes [227]. In [228], a coding and modulation technique was studied where the coded bits of an irregular LDPC code are passed directly to a modulator. EXIT charts were used to optimize the irregular LDPC code design. In [228], ten Brink *et al.* presented LDPC design examples for both SISO systems operating in AWGN channels as well as for MIMO systems communicating over fading channels. Recently, LDPC codes have also been adopted as the inner code in all the 2G DVB standards, including the terrestrial (DVB-T2), cable (DVB-C2), and satellite (DVB-S2) standards.

It was shown in [204] that a recursive inner code having an infinite impulse response is needed in order to maximize the interleaver gain and to avoid having a BER floor, when employing iterative decoding. This principle has been adopted by several authors designing serially concatenated schemes, where rate-1 inner codes were employed for designing low-complexity turbo codes suitable for bandwidth and power-limited systems having stringent BER requirements [186], [210], [211], [229]–[231].

It is widely recognized that the choice of a specific bit-to-symbol mapping scheme or a beneficial constellation labeling is an influential factor when designing BICM-ID schemes exhibiting a high iteration gain [134], [209], [212], [213], [216], [232]–[234]. In [209], ten Brink advocated the construction and comparison of different bit-to-symbol mapping schemes based on the bitwise mutual information. On the other hand, the mapping optimization scheme of Schreckenbach *et al.* [212], [213] was based on the so-called binary switching algorithm (BSA), which was previously employed for index optimization in vector quantization by Zeger and Gersho [235]. Recently, it was shown in [216] by Huang and Ritcey that the constellation design problem may be viewed as quadratic assignment problem (QAP) [217].

Generally, a larger constellation size of a higher dimensional space renders the bit-to-symbol mapping design more flexible. Multidimensional constellations were shown to be beneficial in the design of TCM schemes as early as 1987 [196], [236]–[238]. Additionally, multidimensional labeling was also proposed by Tran and Nguyen for QPSK-based BICM employing iterative decoding for transmission over a single antenna [214], [215]. Further improvements of multidimensional constellation labeling were proposed by Bäro [239], Simoens *et al.* [240], [241] and Wymeersch *et al.* [242]. More recently, multidimensional constellation labeling was also proposed for bit-interleaved space-time-coded modulation using iterative decoding by Mohammed *et al.* [243], where the labeling of the two 16-QAM symbols transmitted over two antennas in two consecutive time slots was designed jointly and was optimized using the so-called reactive tabu search (RTS) technique of Battiti and Tecchiolli [244].

For the reader's convenience, we have summarized the major contributions on the design of concatenated schemes and iterative decoding in Tables 13 and 14.

B. EXIT Charts

Semi-analytical tools devised for analyzing the convergence behavior of iteratively decoded systems have attracted considerable research attention [22], [209], [229], [245]–[250]. In [209], ten Brink proposed the employment of the so-called EXIT characteristics for describing

Table 13 Major Contributions on Concatenated Schemes and Iterative Decoding (Part 1)

Year	Author(s)	Contribution
1966	Forney [176]	promoted concatenated codes.
1967	Viterbi [195]	invented the Viterbi algorithm, a maximum-likelihood sequence estimation algorithm for convolutional codes.
1974	Bahl *et al.* [17]	invented the Maximum A-Posteriori (MAP) algorithm, which is a forward-backward algorithm for the computation of the per-symbol a posteriori probabilities in a trellis.
1987	Wei [196]	multi-dimensional constellations was shown to be beneficial in the design of TCM.
1989	Zehavi [197], [198]	introduced bit-interleaved coded modulation.
1990	Koch and Baier [16]	proposed the MAX-Log-MAP for reducing the complexity the MAP algorithm by transferring the computation to the logarithmic domain and invoke an approximation in order to reduce the decoding complexity.
1993	Berrou *et al.* [19]	invented turbo codes and showed that efficient decoding of concatenated codes can be carried out with low complexity by employing iterative decoding.
1995	Robertson *et al.* [18]	proposed Log-Map algorithm, which partially corrected the approximation in the Max-Log-MAP algorithm resulting in a performance to that of the MAP algorithm but at a significantly lower complexity.
	Douillard *et al.* [185]	a turbo equalization scheme was proposed, where iterative decoding was considered between a soft-output symbol detector and an outer channel decoder in order to combat ISI.
	Wiberg *et al.* [199], [200], [201]	iterative decoding of concatenated codes is generalized to message-passing on graphs.
	Wiberg *et al.* [199], [200], [201]	the min-sum algorithm, a generalized version of the Viterbi algorithm, was proposed to allow for decoding with Tanner graphs. The iterative algorithm converges to a maximum-likelihood decision for cycle-free Tanner graphs.
	Divsalar and Pollara [178]	extended the turbo principle to multiple parallel concatenated codes.
1996	Benedetto and Montorsi [179]	the turbo principle was extended to serially concatenated block and convolutional codes.
	MacKay and Neal [202]	LDPC codes, originally invented by Gallager [203], were re-discovered and near-Shannon limit performance was reported.
1997	Benedetto *et al.* [204]	iterative decoding was carried out between an outer convolutional decoder and an inner TCM decoder, originally devised by Ungerboeck in 1982 [15].
	Caire *et al.* [187], [188]	presented a unified theory of BICM, provided tools for performance analysis and gave guidelines for its design.

Table 14 Major Contributions on Concatenated Schemes and Iterative Decoding (Part 2)

Year	Author(s)	Contribution
1998	ten Brink *et al.* [189]	the employment of the turbo principle was considered for iterative soft demapping in the context of BICM, where a soft demapper was used between the multilevel demodulator and the channel decoder.
	Divsalar *et al.* [205]	repeat-accumulate (RA) codes were invented and turbo-like performance with low complexity was reported.
	McEliece *et al.* [206]	discovered that the turbo-decoding algorithm was an instance of Pearl's belief propagation algorithm [207].
	Benedetto *et al.* [180]	extended the turbo principle to multiple serially concatenated codes.
1999	Wang and Poor [193]	iterative multiuser detection and channel decoding was proposed for coded CDMA schemes.
	Bauch [208]	proposed a symbol-by-symbol MAP algorithm for decoding STBC.
2000	Divsalar *et al.* [186]	rate-1 inner codes were employed for designing low complexity turbo codes suitable for bandwidth and power limited systems having stringent BER requirements.
	ten Brink [209]	the mutual information was used for the construction and comparison of different mapping schemes for BICM.
2001	Narayanan [210]	the effect of precoding on the convergence of turbo equalization for partial response channels was studied.
	Lee [211]	the effect of precoding on serially concatenated systems was studied when communicating over an ISI channel.
2003	Sezgin *et al.* [194]	a turbo coding scheme was proposed for the MIMO Rayleigh fading channel, where an additional block code was employed as an outer channel code, while an orthogonal STBC scheme was considered as the inner code.
	Schreckenbach *et al.* [212], [213]	a mapping optimization scheme based on the binary switching algorithm was proposed.
2004	Tran and Nguyen [214], [215]	multi-dimensional labeling was used for QPSK based BICM-ID for transmission over a single antenna.
2005	Huang and Ritcey [216]	it was shown that the constellation design problem could be viewed as quadratic assignment problem (QAP) [217].

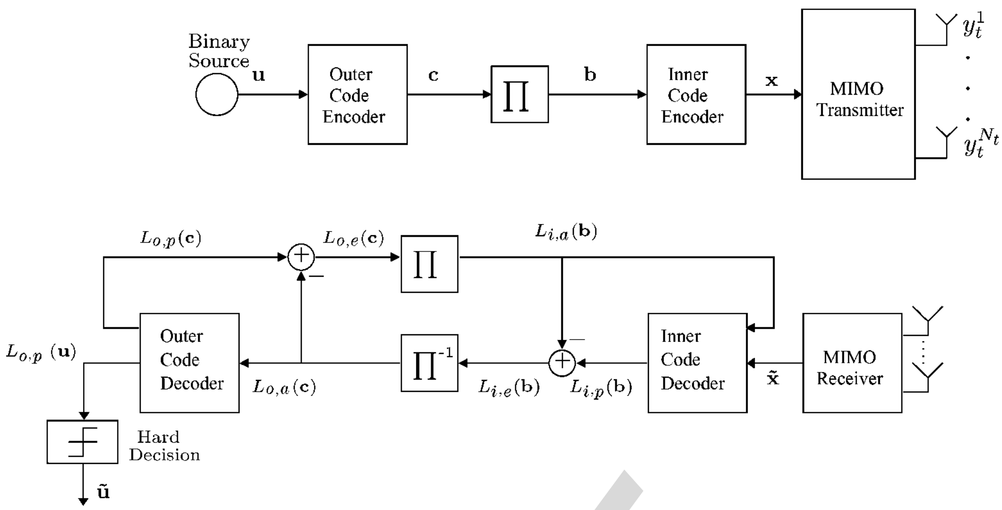

Fig. 16. ***Iterative-detection-aided MIMO system block diagram.***

the flow of extrinsic information between the soft-in–soft-out constituent decoders. The computation of EXIT charts was further simplified by Tüchler and Hagenauer [22] to a time averaging, when the PDFs of the information communicated between the input and output of the constituent decoders are both symmetric and consistent.[7] A tutorial introduction to EXIT charts was provided by Hagenauer [247]. The concept of EXIT chart analysis has been extended to three-stage concatenated systems by ten Brink [251], Tüchler [252], and Brännström *et al.* [250].

The main objective of employing EXIT charts is to predict the convergence behavior of the iterative decoder by examining the evolution of the input/output mutual information exchange between the inner and outer decoders in consecutive iterations. The application of EXIT charts is based on two assumptions, namely that upon assuming large interleaver lengths, which ensures that

- the *a priori* LLR values are fairly uncorrelated;
- the PDF of the *a priori* LLR values is Gaussian.

In what follows we will show how the EXIT charts may be used to analyze the expected performance of iteratively detected systems. For this reason, we consider the iteratively detected MIMO assisted system shown in Fig. 16. According to Fig. 16, the transmitted source bit stream $\mathbf{u}$ is encoded by the outer channel code and then interleaved by a random bit interleaver Π. After bit interleaving, the bit sequence $\mathbf{b}$ of Fig. 16 is encoded by the inner encoder, where the output sequence $\mathbf{x}$ is transmitted using the MIMO scheme.

In the receiver, the soft-in–soft-out outer code's decoder iteratively exchanges extrinsic LLR information with the soft inner code's decoder, as shown in Fig. 16, for the sake of assisting each other's operation, as detailed by Benedetto and Montorsi [253]. In Fig. 16, $L(\cdot)$ denotes the LLRs of the bits concerned, where the subscript i indicates the inner decoder, while o corresponds to outer decoder. Additionally, the subscripts a, p, and e denote the dedicated role of the LLRs with a, p, and e indicating *a priori*, *a posteriori*, and extrinsic information, respectively.

As shown in Fig. 16, the decoded complex-valued MIMO symbols $\tilde{\mathbf{x}}$ are demapped to their LLR representation for each of the outer channel-coded bits per symbol. The *a priori* LLR values $L_{i,a}(\mathbf{b})$ of the inner decoder are subtracted from the *a posteriori* LLR values $L_{i,p}(\mathbf{b})$ for the sake of generating the so-called extrinsic LLR values $L_{i,e}(\mathbf{b})$ because it is only possible to achieve an improved error probability if we ensure by this subtraction that the already exploited *a priori* information is removed from the output of the inner decoder, as detailed in [6]. More explicitly, this provides independent extra information for the outer decoder. Then, the LLRs $L_{i,e}(\mathbf{b})$ are deinterleaved by the soft-bit deinterleaver Π^{-1}, as seen in Fig. 16. Next, the soft bit LLRs $L_{o,a}(\mathbf{c})$ are passed to the outer decoder in order to compute the *a posteriori* LLR values $L_{o,p}(\mathbf{c})$ provided by the log-MAP algorithm [18] for all the outer channel-coded bits. This way the decoder components improved each others' estimates. During the last iteration, only the LLR values $L_{o,p}(\mathbf{u})$ of the original uncoded systematic information bits are required, which are passed to the hard decision decoder of Fig. 16 in order to determine the estimated transmitted source bits. As seen in Fig. 16, the extrinsic information $L_{o,e}(\mathbf{c})$ is generated by subtracting the *a priori* information from the *a posteriori* information according to $[L_{o,p}(\mathbf{c}) - L_{o,a}(\mathbf{c})]$, which is then fed back to the inner decoder as the *a priori* information $L_{i,a}(\mathbf{b})$ after appropriately reordering them using the interleaver Π of Fig. 16. The inner decoder of Fig. 16 exploits the *a priori* information

[7]The LLR values are symmetric if their PDF is symmetric $p(-\zeta|X=+1) = p(\zeta|X=-1)$. Additionally, all LLR values with symmetric distributions satisfy the consistency condition [22]

$$p(-\zeta|X=x) = e^{-x\zeta}p(\zeta|X=x).$$

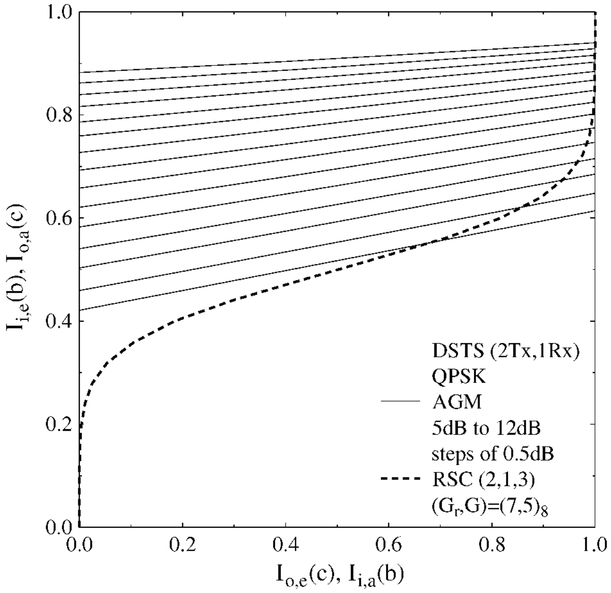

Fig. 17. ***EXIT chart of an iteratively detected RSC-coded DSTS-QPSK scheme employing two transmit antennas and AGM in combination with the outer RSC(2,1,3) code, while communicating over a temporally correlated Rayleigh fading channel associated with $f_D = 0.01$.***

for the sake of providing improved *a posteriori* LLR values, which are then passed to the outer decoder and then back to the inner decoder for further iterations.

The exchange of extrinsic information in the system of Fig. 16 can be visualized by plotting the extrinsic information characteristics of both the inner decoder and of the outer decoder in EXIT chart [209], [246]. The outer decoder's extrinsic output mutual information $I_{o,e}(\mathbf{c})$ becomes the inner decoder's *a priori* input information $I_{i,a}(\mathbf{b})$, which is represented on the x-axis of the EXIT chart. Similarly, on the y-axis, we plot the inner decoder's extrinsic output information $I_{i,e}(\mathbf{b})$, which becomes the outer decoder's *a priori* input information $I_{o,a}(\mathbf{c})$.

Fig. 17 depicts the EXIT chart of the iteratively detected twin-antenna-aided DSTS scheme employing an RSC code as an outer code and an anti-gray mapping (AGM)[8]-aided QPSK modulator as the inner code. The outer RSC code is a 1/2-rate RSC code having a constraint length of $K = 3$, denoted as RSC(2,1,3), in conjunction with an octally represented generator polynomial $(G_r, G) = (7, 5)$, where G_r denoted the feedback generator polynomial and G represents the feedforward generator polynomial. Ideally, in order for the exchange of extrinsic information between the QPSK demapper and the outer RSC decoder to converge at a specific E_b/N_0 value, the EXIT curve of the QPSK demapper at the E_b/N_0 value of interest and the extrinsic transfer characteristics curve of the outer RSC decoder should only intersect at the (1.0, 1.0) point [209], [246]. If this condition is satisfied, then a so-called *convergence tunnel* [209], [246] appears on the EXIT chart. The narrower the tunnel, the more iterations are required for reaching the (1.0,1.0) point and the closer the performance is to the channel capacity. If however the two extrinsic transfer characteristics intersect at a point close to the line at $I_{o,e}(\mathbf{c}) = 1.0$ rather than at the (1.0,1.0) point, then a moderately low BER may be still achieved, although it will remain higher than the schemes where the intersection is at the (1.0,1.0) point. These types of tunnels are referred to here as *semi-convergent tunnels*. Observe in Fig. 17 that a semi-convergent tunnel exists at $E_b/N_0 =$ 5.0 dB. This implies that according to the predictions of the EXIT chart seen in Fig. 17, the iterative decoding process is expected to converge at an E_b/N_0 value between 5.0 and 5.5 dB.

Observe in the EXIT chart of Fig. 17 that once a semi-convergent tunnel is formed, the intersection point of the extrinsic transfer characteristic curves of the QPSK demapper and the outer RSC decoder slides gradually towards the (1.0,1.0) point upon increasing the SNR. In order to investigate how the specific position of the intersection point affects the BER performance, Fig. 18 shows the achievable BER as a function of the mutual information $I_{o,e}(c)$ at the output of the RSC decoder for different constraint lengths. According to Fig. 18, the intersection point should be at least at $I_{o,e}(c) = 0.985$ in order to achieve a BER of 10^{-3}, which is independent of the RSC code's constraint length. This is true because Fig. 18 relates the mutual information at the *output* of the RSC decoder to the achievable BER. Fig. 19, however, relates the mutual information at the *input* of the RSC decoder to the achievable BER. The effect of the code's constraint length becomes evident in Fig. 19, since RSC codes having higher constraint lengths require lower $I_{o,a}(c)$ values in order to

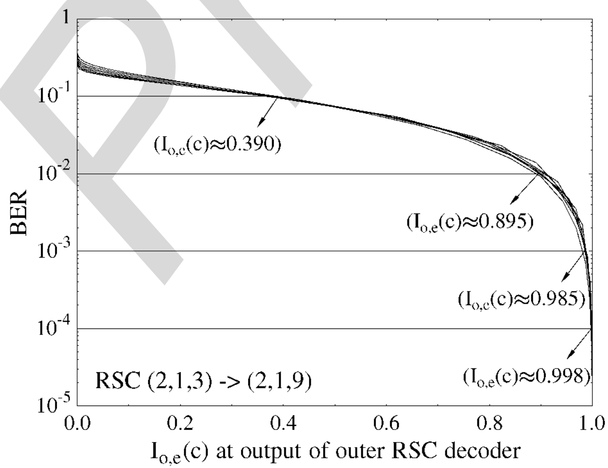

Fig. 18. ***BER of different 1/2-rate RSC decoders versus their extrinsic output $I_{o,e}(c)$, when increasing the code's constraint length from $K = 3$ to $K = 9$.***

[8]The AGM is any non-Gray mapping, which maps the bits to symbols differently from classic Gray mapping.

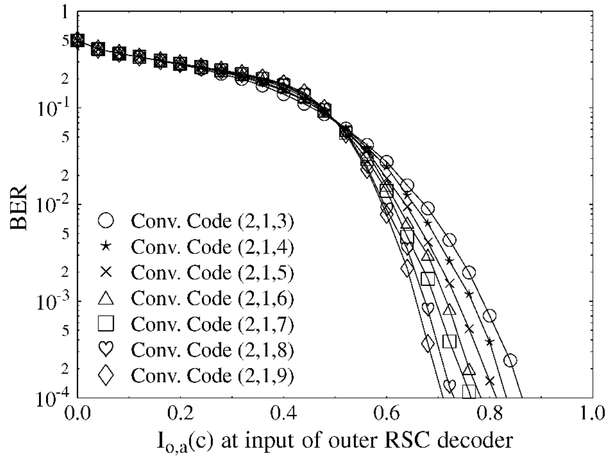

Fig. 19. ***BER of different 1/2-rate RSC decoders versus their a priori input $I_{o,a}(c)$.***

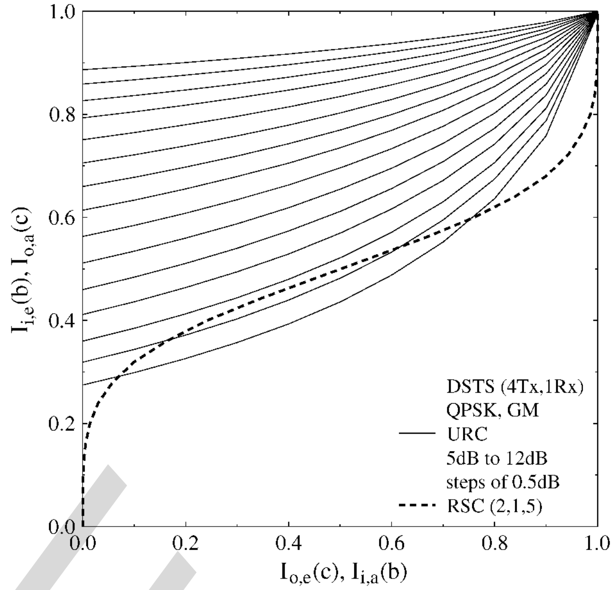

Fig. 20. ***EXIT chart of an RSC-coded and URC-precoded DSTS-QPSK scheme employing GM, while using an interleaver depth of $D_{\mathrm{int}} = 1\,000\,000$ bits.***

achieve a similar BER. Table 15 summarizes the $I_{o,a}(c)$ values required for achieving BER of 10^{-4} at the input of the RSC decoders of Table 16.

According to the previous discussion it becomes clear that the closer to the (1.0,1.0) point the intersection between the EXIT curves of the inner and outer codes is, the lower the BER is. Therefore, in order to allow the inner EXIT curve to reach the (1.0,1.0) point, the inner code's encoder should have a recursive i.e., IIR structure, because it was shown by Benedetto *et al.* [204] that a recursive inner code is needed in order to maximize the interleaver gain and to avoid the formation of a BER floor when employing iterative decoding. In [186], unity-rate inner codes were employed for designing low-complexity iterative-detection-aided schemes suitable for bandwidth and power-limited systems having stringent BER requirements. Hence, in the following we show the effect of employing a recursive unity-rate inner code on the EXIT chart and consequently on the achievable performance of the system. Thus, an iteratively detected RSC-coded and unity-rate precoded DSTS scheme is considered, where iterative detection is carried out between the outer RSC decoder and the inner URC decoder.

Table 15 Required $I_{o,a}(c)$ at the Input of the RSC Decoders of Table 16 for Achieving BER of 10^{-4}

Constraint length	Required $I_{o,a}(c)$
3	0.863
4	0.832
5	0.813
6	0.783
7	0.764
8	0.731
9	0.710

Table 16 1/2-Rate RSC Code Parameters

Constraint Length K	Generator Polynomials in Octals	
	G_r	G
3	05	07
4	15	17
5	35	23
6	53	75
7	133	171
8	247	371
9	561	753

Fig. 20 depicts the EXIT chart of the iterative-detection-aided channel-coded DSTS system employing Gray mapped QPSK in conjunction with the 1/2-rate RSC outer code and the URC inner code for different E_b/N_0 values. Observe from Fig. 20 that an open convergence tunnel is formed at an E_b/N_0 of 6.5 dB. This implies that according to the predictions of the EXIT chart seen in Fig. 20, the iterative decoding process is expected to converge to an infinitesimally low BER at $E_b/N_0 \in [6.0, 6.5]$ dB. The EXIT-chart-based convergence predictions can be verified by the actual iterative decoding trajectory of Fig. 21, where the trajectory at $E_b/N_0 = 6.5$ dB was recorded, while using an interleaver depth of $D_{\mathrm{int}} = 1\,000\,000$ bits. The "staircase-like" steps seen in the figure represent the actual EXIT between the URC decoder and the outer RSC channel decoder.

Fig. 22 compares the attainable performance of the iteratively detected DSTS scheme employing URC precoding for different number of iterations, which are also contrasted to that of the system dispensing with URC for $I = 7$

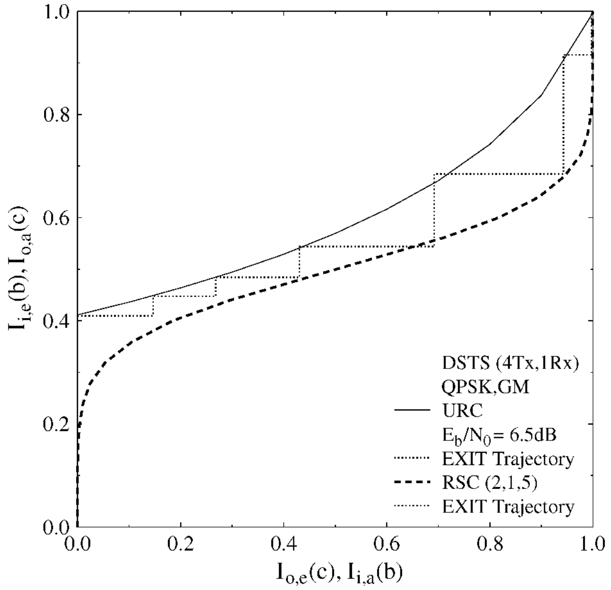

Fig. 21. ***Decoding trajectory of the iteratively detected RSC-coded and URC-precoded DSTS-QPSK scheme employing GM, while operating at $E_b/N_0 = 6.5$ dB.***

iterations between the outer RSC code and the inner QPSK demapper. In Fig. 22, an interleaver depth of $D_{\text{int}} = 1\,000\,000$ bits was employed and a normalized Doppler frequency of $f_D = 0.01$ was used. Observe in Fig. 22 that the BER performance of the URC-coded system is better than that of the nonprecoded system. This result matches with the EXIT-chart-based performance predictions of Figs. 17 and 20. In other words, the URC precoded system attains a lower BER, since the point of intersection between the EXIT curves of the outer RSC code and the inner

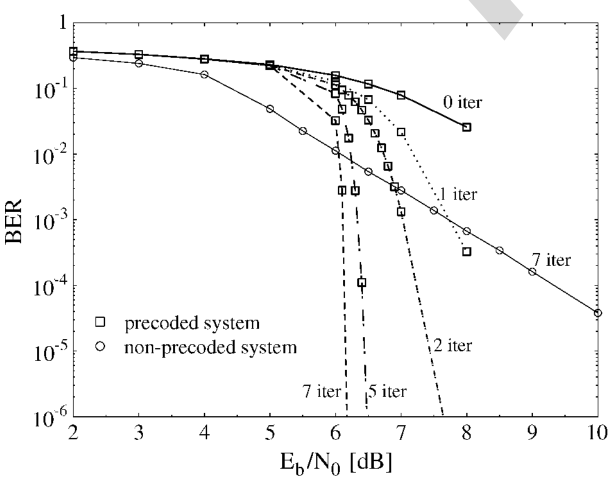

Fig. 22. ***Performance comparison of URC-precoded GM-based RSC-coded DSTS-QPSK scheme when using an interleaver depth of $D_{\text{int}} = 1\,000\,000$ bits for a variable number of iterations.***

Table 17 Mapping the Mutual Information Values From the Trajectory in Fig. 21 to the Corresponding BER Values in Fig. 22 at E_b/N_0 of 6.5 dB

$I_{o,a}(c)$	$I_{o,e}(c)$	BER
0.4099	0.1464	6.749466×10^{-2}
0.4474	0.2681	3.283040×10^{-2}
0.4840	0.4306	8.401655×10^{-3}
0.5438	0.6922	3.952832×10^{-4}
0.6848	0.9425	2.937515×10^{-7}
0.9157	0.9966	1.125006×10^{-7}
0.9939	1.0000	1.918760×10^{-8}

URC code is at the (1.0,1.0) point, while the intersection between the EXIT curves of the RSC code and the QPSK demapper is different from the (1.0,1.0) point, which results in the error floor for the nonprecoded system characterized in Fig. 22. Observe furthermore in Fig. 22 that the BER performance of the URC-coded system improves as the number of iterations increases from 1 to 7.

Table 17 shows how the BER curves seen in Fig. 22 are related to the decoding trajectory of Fig. 21. The trajectory of Fig. 21 is plotted for the system at $E_b/N_0 = 6.5$ dB and hence the results seen in Table 17 are shown for the same E_b/N_0. For example, for the first iteration, which corresponds to the first step in the decoding trajectory of Fig. 21, the outer decoder's *a priori* MI is 0.4099 in the absence of any inner decoder's *a priori* information, i.e., at $I_{i,a}(b) = 0$, and the corresponding extrinsic MI measured along the x-axis becomes 0.1464, which results in a BER of 6.749466×10^{-2} in Fig. 22. However, if we consider the sixth iteration, where the outer decoder's *a priori* MI is 0.9157, the resultant extrinsic MI of 0.9966 measured along the x-axis and hence in a vastly improved BER of 1.125006×10^{-7} in Fig. 22. This result also matches with what is presented in Fig. 18.

Additionally, the EXIT chart can be used to compute the maximum achievable rate of the system. More explicitly, it was argued by Tüchler [254] and Ashikhmin *et al.* [255] that the maximum achievable bandwidth efficiency of the system is equal to the area under the EXIT curve of the inner code, provided that the bit stream $\mathbf{b}$ of Fig. 16 has independently and uniformly distributed bits as well as assuming that the channel is an erasure channel, the inner code is of unity rate, and the MAP algorithms is used for decoding. Assuming that the area under the EXIT curve of the inner decoder is represented by $\mathcal{A}_i$, then the *maximum* achievable rate for the outer code is given by $R_{\max} = \mathcal{A}_i(E_b/N_0)$ [254] at a specific E_b/N_0 value. In other words, if $\mathcal{A}_i$ is calculated for different E_b/N_0 values, the maximum achievable bandwidth efficiency may be formulated as a function of the E_b/N_0 value as follows:

$$\begin{aligned}\eta_{\max}(E_b/N_0) &= D \cdot R_{\text{MIMO}} \cdot R_{\max}\\ &\approx D \cdot R_{\text{MIMO}} \cdot \mathcal{A}_i(E_b/N_0) \quad [\text{bit/s/Hz}] \qquad (1)\end{aligned}$$

where D is the number of bits per symbol, R_{MIMO} is the achievable transmission rate of the MIMO scheme employed, for example, $R_{\mathrm{DSTS}} = 1$ for the $N_t = 2$ transmit antenna case, and $R_{\mathrm{DSTS}} = 1/2$ for the $N_t = 4$ transmit antenna scenario. Additionally, $\underline{E_b/N_0}$ and E_b/N_0 are related as follows:

$$\underline{E_b/N_0} = E_b/N_0 + 10\log\left(\frac{R_o}{\mathcal{A}_i(E_b/N_0)}\right) \qquad [\mathrm{dB}] \qquad (2)$$

where R_o is the original outer code's rate used for generating the EXIT curve of the inner decoder corresponding to the different $\mathcal{A}_i$ values. A simple procedure may be used to calculate the maximum achievable bandwidth efficiency of (1) for $E_b/N_0 \in [\rho_{\min}, \rho_{\max}]$, assuming that $R_{\mathrm{arbitrary}}$ is an arbitrary rate andϵ is a small constant. Below we formulate the knowledge available at the time of writing about the bandwidth efficiency of wireless systems as follows.

Algorithm 1: Maximum Achievable Bandwidth Efficiency using EXIT Charts

Step 1: Let $R_o = R_{\mathrm{arbitrary}}$.
Step 2: Let $E_b/N_0 = \rho_{\min}$ dB.
Step 3: Calculate N_0.
Step 4: Let $I_{i,a}(\mathbf{b}) = 0$.
Step 5: Activate the demapper.
Step 6: Save $I_{i,e}(\mathbf{b}) = T_i(I_{i,a}(\mathbf{b}), E_b/N_0)$.
Step 7: Let $I_{i,a}(\mathbf{b}) = I_{i,a}(\mathbf{b}) + \epsilon$.
  If $I_{i,a}(\mathbf{b}) \leq 1.0$, go to Step 5.
Step 8: Calculate $\mathcal{A}_i(E_b/N_0) = \int_0^1 T_i(i, E_b/N_0)\ \mathrm{d}i$.
Step 9: Calculate $\underline{E_b/N_0}$ using (2).
Step 10: Save $\eta_{\max}(\underline{E_b/N_0})$ of (1).
Step 11: Let $E_b/N_0 = E_b/N_0 + \epsilon$.
  If $E_b/N_0 \leq \rho_{\max}$ dB, go to Step 3.
Step 12: Output $\eta_{\max}(\underline{E_b/N_0})$ from Step 10.

The MIMO channel's capacity curves for the DSTS scheme considered are shown in Fig. 23 for four transmit antennas. The figure portrays both the DCMC bandwidth efficiency curve [82] as well as the maximum achievable rate of the system derived from the EXIT curves according to Algorithm 1. Observe in Fig. 23 that the maximum achievable rate of the system derived from the EXIT curves is quite close to the DCMC bandwidth efficiency. Note that the maximum achievable rate obtained from the EXIT charts and the bandwidth efficiency limit were only shown to be equal for the family of binary erasure channels [255]. Nonetheless, similar experimentally verified trends have been observed for both AWGN and ISI contaminated channels [22], [254], when ML decoders are used for all decoder blocks [255]. However, the DSTS decoder used in our design example employs a simple decoding algorithm that utilizes only two or four consecutively received symbols, despite the fact that all the symbols are interdependent. Therefore, the decoder employed is suboptimum hence its rate may not be expected to approach the DCMC capacity. By contrast, if a trellis-based DSTS decoder—such as the MAP algorithm [17]—is employed, then the maximum achievable rate obtained from the EXIT chart may be able to more accurately match the capacity limit computed. Nevertheless, the complexity of the MAP algorithm may be deemed excessive in return for the modest gain of 0.2 dB observed in Fig. 23.

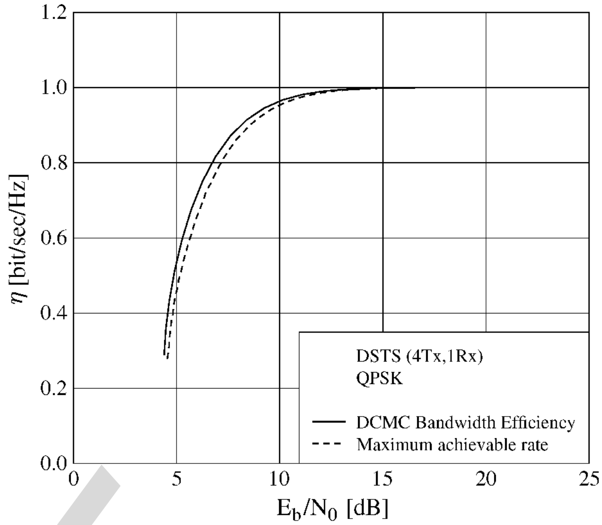

Fig. 23. ***Comparison of the DCMC bandwidth efficiency and the maximum achievable rate obtained using EXIT charts of the four-antenna-aided DSTS-QPSK system.***

VI. CONCLUSIONS AND POTENTIAL FUTURE RESEARCH

A. Conclusions

We demonstrated a number of significant benefits of both colocated as well as of distributed MIMOs employing iterative detection. The main driving force behind the advances in wireless communications is the promise of seamless global mobility and ubiquitous accessibility, while meeting a range of contradicting design challenges such as those shown in the stylized illustration of Fig. 1. In simple terms, the ultimate goal is to devise high-speed, high-quality yet power-efficient wireless communication systems exhibiting both a high bit rate and a low error rate. Unfortunately, the hostile wireless channel characteristics make it a challenging task to simultaneously accomplish all these objectives. Another challenging factor is the fact that the available radio spectrum is limited and the associated bandwidth as well as power demands cannot be readily met without a significant increase in the achievable bandwidth efficiency expressed in bits/symbols/hertz. Furthermore, the wireless system capacity is often interference limited rather than noise limited, and hence cannot be readily increased by simply increasing the transmitted power because increasing the transmit power increases the interference and hence fails to improve the SINR. Against the above-mentioned requirements and challenges, there is an urging demand for flexible, bandwidth-efficient as well as power-efficient transceivers. In this section, we offer a few general design guidelines for next generation wireless transceivers based on the solutions discussed throughout this paper.

- The adverse effects of channel fading may be significantly reduced by providing the receiver with several independently fading transmitted signal replicas in the time, frequency, or spatial domain, assuming that at least some of these replicas are not severely attenuated. Spatial diversity, for example, can be attained without any bandwidth penalty by employing multiple antennas at the transmitter and/or the receiver.
- MIMO systems may be used to attain a better BER performance or a higher throughput than SISO systems, depending on whether the MIMO scheme is designed for attaining spatial diversity or spatial multiplexing gains. Nevertheless, striking the most appropriate diversity-versus-multiplexing tradeoff constitutes a feasible design option in the context of MIMO systems.
- The multiple antennas of a MIMO system may be employed for the sake of improving the SNR or the SINR of a multiuser scenario at the receiver.
- Multifunctional MIMO techniques may be used to design MIMO systems that combine the benefits of diversity, multiplexing, and beamforming gains.
- Carrying out accurate channel estimation increases both the cost and complexity of the transceiver, especially in the context of MIMO systems, since the CSI of all links between each transmit and each receive antenna pair has to be estimated at the receiver. Furthermore, when the CSI fluctuates dramatically, it has to be sampled at an increased rate and hence an increased number of training symbols has to be transmitted, potentially resulting in an undesirably high transmission overhead and wastage of transmission power. However, mitigating the complexity of MIMO channel estimation may be achieved by invoking differential MIMO detection techniques that eliminate the complexity of channel estimation and may potentially outperform coherent detection when the associated channel estimation error is not negligible.[9]
- MIMO systems that employ the turbo principle in the context of concatenated schemes may achieve near-capacity performance, when using a recursive inner code having an IIR. The recursive inner code hence spreads the extrinsic information as efficiently as possible and maximizes the achievable interleaver gain and avoids having a BER floor when employing iterative decoding. Furthermore, the joint design of channel coding and modulation plays a crucial role in achieving a near-capacity MIMO performance. This may be conveniently accomplished by using EXIT charts as our tool, which provide useful insights into, for example, choosing appropriate bits-to-symbol mapping schemes that complement the EXIT characteristics of specific channel codes. The employment of EXIT charts is also essential when designing irregular codes that facilitate near-capacity performance and an infinitesimally low BER.
- The benefits of the above-mentioned colocated MIMO systems are subject to the assumption of having an independent propagation path between each transmit and receive antennas pair. This is not, however, always guaranteed because of the potential spatial correlation imposed by shadow fading and/or insufficient antenna separation resulting from size limitations, especially in handheld mobile units. The existence of spatial fading correlation at the transmitter or receiver of a MIMO system results in a degradation of both the achievable capacity and the BER performance of MIMO systems. The problem of receiving correlated signals may be circumvented by adopting the recently introduced class of distributed MIMOs, applied in the context of cooperative communications.

B. Future Research

It is worth pointing out that the solutions presented in the paper may be further developed in several different ways, as detailed below.

- The MIMO channel estimation complexity increases with the product of the number of transmit and receive antennas and the channel estimation errors substantially degrade the attainable performance of MIMO systems, when coherent detection is employed. A solution for eliminating the complexity of MIMO channel estimation is to employ noncoherent detection dispensing with channel estimation, provided that the channel is nondispersive. For dispersive channels, noncoherently detected OFDM systems may be recommended. At the time of writing, noncoherent wireless communications has not found its way into wireless standards due to the performance degradation of noncoherent systems, when any

[9]It is also worth noting that despite substantial recent advances in noncoherent wireless systems, they are not sufficiently mature at the time of writing to replace the coherent systems requiring explicit CSI estimation. Hence, further research has to be invested in the area of noncoherent systems that are capable of performing well in rapidly fluctuating frequency-selective channels, while dispensing with channel estimation.

frequency/time offset is encountered. This motivates further research in the area of noncoherent wireless communications in order to design efficient systems dispensing with channel estimation. This potentially allows us to eliminate the complexity of channel estimation at the receiver as well as eliminating the wastage of bandwidth due to the transmission of pilot symbols in coherent systems.

- While most of the MIMO gain is based on the assumption that the MIMO channels are i.i.d., in many applications there may not be sufficient space available to accommodate multiple antennas, which are sufficiently far apart in order to experience independent fading. This problem becomes specifically accurate for shirt-pocket-sized communicators. MIMO systems using dual-polarized antennas may solve the problem of size, since a single antenna having two different polarizations can be used for attaining MIMO gains. The idea of dual-polarization-aided MIMO techniques is not well studied in the literature and while it has the potential to provide a real solution for future wireless communication standards using MIMO techniques, further research has to be carried out in order to study the dual-polarization MIMO channel and hence to design efficient dual-polarization-aided MIMO techniques.
- Cooperative communications was also briefly highlighted in this paper as a promising technology for future wireless systems. Both transmitter cooperation and receiver cooperation have a substantial promise with different pros and cons. When the cooperating transmitters are close to each other, the DF strategy is beneficial since it avoids error propagation, while for larger distances AF relaying is less prone to error propagation. It is also readily feasible to construct a hybrid DF/AF/CF cooperative regime, activating the most appropriate mode depending on the position of the relays. Future research is needed on combining the turbo principle with receiver cooperation invoking multiple-round iterative cooperation.
- Cooperative system research invariably assumes at the time of writing that perfect synchronization was established, which is a strong idealized assumption. New research has to focus on the design of asynchronous systems as well as on radical new synchronization techniques, which do not have to rely on the central BS controller. An attractive potential solution is to mimic the bio-inspired behavior of fire flies in the design of radically new synchronization techniques for cooperative systems.
- Further research efforts should also be dedicated to the design of noncoherent cooperative systems, which are capable of closing the performance gap with respect to their coherently detected counterparts. A range of solutions may be found in [14], where the joint detection of multiple consecutive symbols is employed for closing this performance gap. Naturally, the detection complexity is exponentially increased with the detection window length. Hence, the complexity was substantially reduced with the aid of sphere decoding, as detailed in [14]. In the presence of dispersive channels, multiple-symbol differential detection techniques suffer substantial performance degradation and hence blind joint channel and data estimators have to be conceived.
- As mentioned above, the two-phase cooperative regime results in halving the effective throughput, since we need a broadcast and a cooperative phase/slot for avoiding simultaneous transmission and reception by the cooperating mobiles. This 100% throughput loss may however be avoided by designing powerful echo cancelers.
- A range of near-capacity variable-length codes were proposed in [256], which conveniently lend themselves to employment in high-performance CF cooperative schemes.

Given that near-capacity operation has become feasible, in the spirit of Fig. 1, the research community is turning to more balanced system design principles, where bandwidth efficiency may have to be sacrificed in the interest of creating reduced-complexity, reduced-delay, power-efficient "green" transceivers. We expect a linear throughput increase upon increasing the transmit power, as facilitated by MIMOs, multicode CDMA and UWB systems combined with ad hoc networking and user-cooperation-aided hybrid networking. A challenging future for wireless researchers... ■

REFERENCES

[1] C. E. Shannon, "A mathematical theory of communication," *Bell Syst. Tech. J.*, vol. 27, pp. 623–656, Oct. 1948.

[2] B. Vucetic and J. Yuan, *Space-Time Coding.* New York: Wiley, 2003.

[3] L. Hanzo, O. Alamri, M. El-Hajjar, and N. Wu, *Near-Capacity Multi-Functional MIMO Systems: Sphere-Packing, Iterative Detection and Cooperation.* Chichester, U.K.: Wiley/IEEE Press, May 2009.

[4] H. Jafarkhani, *Space-Time Coding: Theory and Practice.* Cambridge, U.K.: Cambridge Univ. Press, 2005.

[5] L. Hanzo, L.-L. Yang, E.-L. Kuan, and K. Yen, *Single and Multi-Carrier DS-CDMA: Multi-User Detection, Space-Time Spreading, Synchronisation, Networking and Standards.* Chichester, U.K.: Wiley/IEEE Press, 2003.

[6] L. Hanzo, T. H. Liew, and B. L. Yeap, *Turbo Coding, Turbo Equalisation and Space Time Coding for Transmission Over Fading Channels.* Chichester, U.K.: Wiley/IEEE Press, 2002.

[7] L. Hanzo, S. X. Ng, T. Keller, and W. Webb, *Quadrature Amplitude Modulation: From Basics to Adaptive Trellis-Coded, Turbo Equalised and Space-Time Coded OFDM, CDMA and MC-CDMA Systems,* 2nd ed. Chichester, U.K.: Wiley/IEEE Press, 2004.

[8] G. J. Foschini, D. Chizhik, M. J. Gans, C. Papadias, and R. A. Valenzuela, "Analysis and performance of some basic space-time

architectures," *IEEE J. Sel. Areas Commun.*, vol. 21, no. 3, pp. 303–320, Apr. 2003.

[9] S. Siwamogsatham and M. Fitz, "Robust space-time coding for correlated Rayleigh fading channels," *IEEE Trans. Signal Process.*, vol. 50, no. 10, pp. 2408–2416, Oct. 2002.

[10] R. Steele and L. Hanzo, *Mobile Radio Communications: Second and Third Generation Cellular and WATM Systems*, 2nd ed. Chichester, U.K.: Wiley, 1999.

[11] L. Hanzo, C. H. Wong, and M. S. Yee, *Adaptive Wireless Transceivers: Turbo-Coded, Turbo-Equalized and Space-Time Coded TDMA, CDMA and OFDM Systems*. Chichester, U.K.: Wiley/IEEE Press, 2002.

[12] L. Hanzo, J. Blogh, and S. Ni, *3G, HSPA and FDD versus TDD Networking: Smart Antennas and Adaptive Modulation*, Wiley/IEEE Press, 2008.

[13] L. Hanzo, M. Münster, B. J. Choi, and T. Keller, *OFDM and MC-CDMA for Broadband Multi-User Communications, WLANs and Broadcasting*. Chichester, U.K.: Wiley/IEEE Press, 2003.

[14] L. Hanzo, J. Akhtman, L. Wang, and M. Jiang, *MIMO-OFDM for LTE, WiFi and WiMax: Coherent versus Non-Coherent and Cooperative Turbo-Transceivers*. Chichester, U.K.: Wiley/IEEE Press, 2010.

[15] G. Ungerboeck, "Channel coding with multilevel/phase signals," *IEEE Trans. Inf. Theory*, vol. IT-28, no. 1, pp. 55–67, Jan. 1982.

[16] W. Koch and A. Baier, "Optimum and sub-optimum detection of coded data disturbed by time-varying intersymbol interference," in *Proc. IEEE Global Telecommun. Conf.*, San Diego, CA, Dec. 1990, vol. 3, pp. 1679–1684.

[17] L. Bahl, J. Cocke, F. Jelinek, and J. Raviv, "Optimal decoding of linear codes for minimizing symbol error rate," *IEEE Trans. Inf. Theory*, vol. IT-20, no. 2, pp. 284–287, Mar. 1974.

[18] P. Robertson, E. Villebrun, and P. Hoeher, "A comparison of optimal and sub-optimal MAP decoding algorithms operating in the Log domain," in *Proc. Int. Conf. Commun.*, Seattle, WA, Jun. 1995, pp. 1009–1013.

[19] C. Berrou, A. Glavieux, and P. Thitimajshima, "Near Shannon limit error-correcting coding and decoding: Turbo-codes. 1," in *Proc. IEEE Int. Conf. Commun.*, Geneva, May 1993, vol. 2, pp. 1064–1070.

[20] L. Hanzo, F. C. Somerville, and J. P. Woodard, *Voice and Audio Compression for Wireless Communications*. New York: IEEE Press/Wiley, 2008.

[21] L. Hanzo, P. J. Cherriman, and J. Streit, *Video Compression and Communications*. New York: IEEE Press/Wiley, 2008.

[22] M. Tüchler and J. Hagenauer, "EXIT charts of irregular codes," in *Proc. Conf. Inf. Sci. Syst.*, Princeton, NJ, Mar. 2002, pp. 748–753.

[23] M. Z. Win and R. A. Scholtz, "Ultra-wide bandwidth time-hopping spread-spectrum impulse radio for wireless multiple-access communications," *IEEE Trans. Commun.*, vol. 48, no. 4, pp. 679–689, Apr. 2000.

[24] P. Frenger, P. Orten, and T. Ottosson, "Code-spread CDMA using maximum free distance low-rate convolutional codes," *IEEE Trans. Wireless Commun.*, vol. 48, no. 1, pp. 135–144, Jan. 2000.

[25] R. H. Mahadevappa and J. G. Proakis, "Mitigating multiple access interference and intersymbol interference in uncoded CDMA systems with chip-level interleaving," *IEEE Trans. Wireless Commun.*, vol. 1, no. 4, pp. 781–792, Oct. 2002.

[26] L. Ping, L. Liu, K. Wu, and L. W. K., "Interleave-division multiple-access," *IEEE Trans. Wireless Commun.*, vol. 5, no. 4, pp. 938–947, Apr. 2006.

[27] L. Liu, J. Tong, and L. Ping, "Analysis and optimization of CDMA systems with chip-level interleavers," *IEEE J. Sel. Areas Commun.*, vol. 24, no. 1, pp. 141–150, Jan. 2006.

[28] H. Schoeneich and P. A. Hoeher, "Adaptive interleave-division multiple access—A potential air interference for 4G bearer services and wireless LANs," in *Proc. Wireless Opt. Commun. Netw.*, Muscat, Oman, Jun. 7–9, 2004, pp. 179–182.

[29] P. A. Hoeher and H. Schoeneich, "Interleave-division multiple access from a multiuser point of view," in *Proc. 4th Int. Symp. Turbo Codes Related Topics/6th Int. ITG Conf. Source Channel Coding*, Munich, Germany, Sep. 3–7, 2006, pp. 140–144.

[30] J. Hayes, "Adaptive feedback communications," *IEEE Trans. Commun.*, vol. 16, no. 1, pp. 29–34, Jan. 1968.

[31] W. T. Webb and R. Steele, "Variable rate QAM for mobile radio," *IEEE Trans. Commun.*, vol. 43, no. 7, pp. 2223–2230, Jul. 1995.

[32] A. J. Goldsmith and S.-G. Chua, "Variable-rate variable-power MQAM for fading channels," *IEEE Trans. Commun.*, vol. 45, no. 10, pp. 1218–1230, Oct. 1997.

[33] L.-L. Yang and L. Hanzo, "Adaptive space-time-spreading-assisted wideband CDMA systems communicating over dispersive Nakagami-m fading channels," *EURASIP J. Wireless Commun. Netw.*, vol. 2, pp. 216–230, Apr. 2005.

[34] C. E. Shannon, "Communication in the presence of noise," *Proc. IRE*, vol. 37, no. 1, pp. 10–21, Jan. 1949.

[35] B. Sklar, *Digital Communications: Fundamentals and Applications*, 2nd ed. Upper Saddle River, NJ: Prentice-Hall, 2001.

[36] J. Winters, "On the capacity of radio communication systems with diversity in a Rayleigh fading environment," *IEEE J. Sel. Areas Commun.*, vol. 5, no. 5, pp. 871–878, Jun. 1987.

[37] E. Telatar, "Capacity of multi-antenna Gaussian channels," *Eur. Trans. Telecommun.*, vol. 10, pp. 585–595, Nov./Dec. 1999.

[38] G. J. Foschini and M. J. Gans, *On Limits of Wireless Communications in a Fading Environment When Using Multiple Antennas*. Norwell, MA: Kluwer, 1998, pp. 311–335.

[39] J. G. Proakis, *Digital Communications*. New York: McGraw-Hill, 2001.

[40] S. M. Alamouti, "A simple transmit diversity technique for wireless communications," *IEEE J. Sel. Areas Commun.*, vol. 16, no. 8, pp. 1451–1458, Oct. 1998.

[41] V. Tarokh, H. Jafarkhani, and A. R. Calderbank, "Space-time block codes from orthogonal designs," *IEEE Trans. Inf. Theory*, vol. 45, no. 5, pp. 1456–1467, Jul. 1999.

[42] G. J. Foschini, "Layered space-time architecture for wireless communication in a fading environment when using multiple antennas," *Bell Lab. Tech. J.*, vol. 1, pp. 41–59, Autumn 1996.

[43] A. Sendonaris, E. Erkip, and B. Aazhang, "User cooperation diversity Part I: System description," *IEEE Trans. Commun.*, vol. 51, no. 11, pp. 1927–1938, Nov. 2003.

[44] A. Sendonaris, E. Erkip, and B. Aazhang, "User cooperation diversity Part II: Implementation aspects and performance analysis," *IEEE Trans. Commun.*, vol. 51, no. 11, pp. 1939–1948, Nov. 2003.

[45] L. Zheng and D. N. C. Tse, "Communication on the Grassmann manifold: A geometric approach to the noncoherent multiple-antenna channel," *IEEE Trans. Inf. Theory*, vol. 48, no. 2, pp. 359–383, Feb. 2002.

[46] D. G. Brennan, "Linear diversity combining techniques," *Proc. IEEE*, vol. 91, no. 2, pp. 331–356, Feb. 2003.

[47] D. G. Brennan, "Linear diversity combining techniques," *Proc. IRE*, vol. 47, no. 6, pp. 1075–1102, Jun. 1959.

[48] T. Eng, N. Kong, and L. B. Milstein, "Comparison of diversity combining techniques for Rayleigh-fading channels," *IEEE Trans. Commun.*, vol. 44, no. 9, pp. 1117–1129, Sep. 1996.

[49] A. Wittneben, "Base station modulation diversity for digital simulcast," in *Proc. 41st IEEE Veh. Technol. Conf. Gateway to the Future Technol. in Motion*, St. Louis, MO, May 1991, pp. 848–853.

[50] J. H. Winters, "The diversity gain of transmit diversity in wireless systems with Rayleigh fading," in *Proc. IEEE Int. Conf. Commun.*, New Orleans, LA, May 1994, pp. 1121–1125.

[51] J. H. Winters, "The diversity gain of transmit diversity in wireless systems with Rayleigh fading," *IEEE Trans. Veh. Technol.*, vol. 47, no. 1, pp. 119–123, Feb. 1998.

[52] J.-C. Guey, M. P. Fitz, M. R. Bell, and W.-Y. Kuo, "Signal design for transmitter diversity wireless communication systems over Rayleigh fading channels," *IEEE Trans. Commun.*, vol. 47, no. 4, pp. 527–537, Apr. 1999.

[53] N. Seshadri, V. Tarokh, and A. R. Calderbank, "Space-time codes for wireless communication: Code construction," in *Proc. IEEE Veh. Technol. Conf.*, Phoenix, AZ, 1997, vol. 2, pp. 637–641.

[54] V. Tarokh, A. Naguib, N. Seshadri, and A. R. Calderbank, "Space-time codes for high data rate wireless communication: Performance criteria in the presence of channel estimation errors, mobility and multiple paths," *IEEE Trans. Commun.*, vol. 47, no. 2, pp. 199–207, Feb. 1999.

[55] V. Tarokh, H. Jafarkhani, and A. R. Calderbank, "Space-time block coding for wireless communications: Performance results," *IEEE J. Sel. Areas Commun.*, vol. 17, no. 3, pp. 451–460, Mar. 1999.

[56] B. Hochwald, T. L. Marzetta, and C. B. Papadias, "A transmitter diversity scheme for wideband CDMA systems based on space-time spreading," *IEEE J. Sel. Areas Commun.*, vol. 19, no. 1, pp. 48–60, Jan. 2001.

[57] H. Jafarkhani, "A quasi-orthogonal space-time block code," *IEEE Trans. Commun.*, vol. 49, no. 1, pp. 1–4, Jan. 2001.

[58] V. Tarokh, N. Seshadri, and A. R. Calderbank, "Space-time codes for high data rate wireless communication:

Performance criterion and code construction," *IEEE Trans. Inf. Theory*, vol. 44, no. 2, pp. 744–765, Mar. 1998.

[59] T.-H. Liew and L. Hanzo, "Space-time trellis and space-time block coding versus adaptive modulation and coding aided OFDM for wideband channels," *IEEE Trans. Veh. Technol.*, vol. 55, no. 1, pp. 173–187, Jan. 2006.

[60] A. Wittneben, "A new bandwidth efficient transmit antenna modulation diversity scheme for linear digital modulation," in *Proc. IEEE Int. Conf. Commun.*, Geneva, May 1993, vol. 3, pp. 1630–1634.

[61] N. Seshadri and J. H. Winters, "Two signaling schemes for improving the error performance of frequency-division-duplex transmission systems using transmitter antenna diversity," in *Proc. IEEE Veh. Technol. Conf.*, Secaucus, NJ, May 1993, pp. 508–511.

[62] V. Tarokh, S. M. Alamouti, and P. Poon, "New detection schemes for transmit diversity with no channel estimation," in *Proc. IEEE Int. Conf. Universal Personal Commun.*, Oct. 1998, vol. 2, pp. 917–920.

[63] V. Tarokh and H. Jafarkhani, "A differential detection scheme for transmit diversity," in *Proc. IEEE Wireless Commun. Netw. Conf.*, Sep. 1999, vol. 3, pp. 1043–1047.

[64] B. M. Hochwald and W. Sweldens, "Differential unitary space-time modulation," *IEEE Trans. Commun.*, vol. 48, no. 12, pp. 2041–2052, Dec. 2000.

[65] B. L. Hughes, "Differential space-time modulation," *IEEE Trans. Inf. Theory*, vol. 46, no. 7, pp. 2567–2578, Nov. 2000.

[66] G. Ganesan and P. Stoica, "Space-time block codes: A maximum SNR approach," *IEEE Trans. Inf. Theory*, vol. 47, no. 4, pp. 1650–1656, May 2001.

[67] H. Jafarkhani and V. Tarokh, "Multiple transmit antenna differential detection from generalized orthogonal designs," *IEEE Trans. Inf. Theory*, vol. 47, no. 6, pp. 2626–2631, Sep. 2001.

[68] B. Hassibi and B. M. Hochwald, "High-rate codes that are linear in space and time," *IEEE Trans. Inf. Theory*, vol. 48, no. 7, pp. 1804–1824, Jul. 2002.

[69] W. Su, Z. Safar, and K. J. R. Liu, "Space-time signal design for time-correlated Rayleigh fading channels," in *Proc. IEEE Int. Conf. Commun.*, 2003, vol. 5, pp. 3175–3179.

[70] V. Tarokh and H. Jafarkhani, "A differential detection scheme for transmit diversity," *IEEE J. Sel. Areas Commun.*, vol. 18, no. 7, pp. 1169–1174, Jul. 2000.

[71] C.-S. Hwang, S. H. Nam, J. Chung, and V. Tarokh, "Differential space time block codes using QAM constellations," in *Proc. 14th IEEE Proc. Personal Indoor Mobile Radio Commun.*, 2003, vol. 2, pp. 1693–1697.

[72] C.-S. Hwang, S. H. Nam, J. Chung, and V. Tarokh, "Differential space time block codes using nonconstant modulus constellations," *IEEE Trans. Signal Process.*, vol. 51, no. 11, pp. 2955–2964, Nov. 2003.

[73] P. Stoica and G. Ganesan, "Space-time block codes: Trained, blind and semi-blind detection," in *Proc. IEEE Int. Conf. Acoust. Speech Signal Process.*, Orlando, FL, 2002, vol. 2, pp. 1609–1612.

[74] R. Schober and L. Lampe, "Noncoherent receivers for differential space-time modulation," *IEEE Trans. Commun.*, vol. 50, no. 5, pp. 768–777, May 2002.

[75] H. Wang and X.-G. Xia, "Upper bounds of rates of complex orthogonal space-time block codes," *IEEE Trans. Inf. Theory*, vol. 49, no. 10, pp. 2788–2796, Oct. 2003.

[76] S. H. Nam, C.-S. Hwang, J. Chung, and V. Tarokh, "Differential space time block codes using QAM for four transmit antennas," in *Proc. IEEE Int. Conf. Commun.*, 2004, vol. 2, pp. 952–956.

[77] H. Zhang and T. A. Gulliver, "Capacity and error probability analysis for orthogonal space-time block codes over fading channels," *IEEE Trans. Wireless Commun.*, vol. 4, no. 2, pp. 808–819, Mar. 2005.

[78] Y. Zhu and H. Jafarkhani, "Differential modulation based on quasi-orthogonal codes," *IEEE Trans. Wireless Commun.*, vol. 4, no. 6, pp. 3005–3017, Nov. 2005.

[79] L.-Y. Song and A. G. Burr, "General differential modulation scheme for quasi-orthogonal space-time block codes with partial or full transmit diversity," *IET Commun.*, vol. 1, pp. 256–266, Apr. 2007.

[80] P. Luo and H. Leib, "Class of full-rank space-time codes combining orthogonal designs with delay diversity," *IEEE Trans. Veh. Technol.*, vol. 57, no. 1, pp. 260–272, Jan. 2008.

[81] B. M. Hochwald and T. L. Marzetta, "Unitary space-time modulation for multiple-antenna communications in Rayleigh flat fading," *IEEE Trans. Inf. Theory*, vol. 46, no. 2, pp. 543–564, Mar. 2000.

[82] M. El-Hajjar, O. Alamri, S. X. Ng, and L. Hanzo, "Turbo detection of precoded sphere packing modulation using four transmit antennas for differential space-time spreading," *IEEE Trans. Wireless Commun.*, vol. 7, no. 3, pp. 943–952, Mar. 2008.

[83] E. Biglieri, G. Taricco, and A. Tulino, "Performance of space-time codes for a large number of antennas," *IEEE Trans. Inf. Theory*, vol. 48, no. 7, pp. 1794–1803, Jul. 2002.

[84] A. J. Paulraj, D. A. Gore, R. U. Nabar, and H. Bolcskei, "An overview of MIMO communications—A key to gigabit wireless," *Proc. IEEE*, vol. 92, no. 2, pp. 198–218, Feb. 2004.

[85] E. Viterbo and J. Boutros, "A universal lattice code decoder for fading channels," *IEEE Trans. Inf. Theory*, vol. 45, no. 5, pp. 1639–1642, Jul. 1999.

[86] O. Damen, A. Chkeif, and J.-C. Belfiore, "Lattice code decoder for space-time codes," *IEEE Commun. Lett.*, vol. 4, no. 5, pp. 161–163, May 2000.

[87] E. Agrell, T. Eriksson, A. Vardy, and K. Zeger, "Closest point search in lattices," *IEEE Trans. Inf. Theory*, vol. 48, no. 8, pp. 2201–2214, Aug. 2002.

[88] P. W. Wolniansky, G. J. Foschini, G. D. Golden, and R. A. Valenzuela, "V-BLAST: An architecture for realizing very high data rates over the rich-scattering wireless channel," in *Proc. Int. Symp. Signals Syst. Electron.*, Sep. 1998, pp. 295–300.

[89] G. D. Golden, C. J. Foschini, R. A. Valenzuela, and P. W. Wolniansky, "Detection algorithm and initial laboratory results using V-BLAST space-time communication architecture," *Electron. Lett.*, vol. 35, pp. 14–16, Jan. 1999.

[90] A. Benjebbour, H. Murata, and S. Yoshida, "Comparison of ordered successive receivers for space-time transmission," in *Proc. IEEE Veh. Technol. Conf.*, Atlantic City, NJ, Oct. 2001, vol. 4, pp. 2053–2057.

[91] M. Sellathurai and S. Haykin, "Turbo-BLAST for wireless communications: Theory and experiments," *IEEE Trans. Signal Process.*, vol. 50, no. 10, pp. 2538–2546, Oct. 2002.

[92] D. Wubben, R. Bohnke, V. Kuhn, and K.-D. Kammeyer, "MMSE extension of V-BLAST based on sorted QR decomposition," in *Proc. IEEE Veh. Technol. Conf.*, Oct. 2003, vol. 1, pp. 508–512.

[93] H. Zhu, Z. Lei, and F. P. S. Chin, "An improved square-root algorithm for BLAST," *IEEE Signal Process. Lett.*, vol. 11, no. 9, pp. 772–775, Sep. 2004.

[94] Y. Huang, J. Zhang, and P. M. Djuric, "Bayesian detection for BLAST," *IEEE Trans. Signal Process.*, vol. 53, no. 3, pp. 1086–1096, Mar. 2005.

[95] L. Hanzo and T. Keller, *OFDM and MC-CDMA: A Primer*. New York: IEEE Press/Wiley, Apr. 2006.

[96] S. Verdu, *Multiuser Detection*. Cambridge, U.K.: Cambridge Univ. Press, 2003.

[97] B. Hassibi, "An efficient square-root algorithm for BLAST," in *Proc. IEEE Int. Conf. Acoust. Speech Signal Process.*, Istanbul, Jun. 2000, vol. 2, pp. 737–740.

[98] D. Wubben, R. Bohnke, J. Rinas, V. Kuhn, and K. D. Kammeyer, "Efficient algorithm for decoding layered space-time codes," *Electron. Lett.*, vol. 37, pp. 1348–1350, Oct. 2001.

[99] W. Zha and S. D. Blostein, "Modified decorrelating decision-feedback detection of BLAST space-time system," in *Proc. IEEE Int. Conf. Commun.*, New York, Apr./May 2002, vol. 1, pp. 335–339.

[100] T. Xiaofeng, Y. Zhuizhuan, Q. Haiyan, Z. Ping, H. Haas, and E. Costa, "New sub-optimal detection algorithm of layered space-time code," in *Proc. IEEE Veh. Technol. Conf.*, May 2002, vol. 4, pp. 1791–1794.

[101] J. Choi, "A bi-directional zero-forcing BLAST receiver," *IEEE Trans. Signal Process.*, vol. 52, no. 9, pp. 2670–2673, Sep. 2004.

[102] H. Zhu, Z. Lei, and F. P. S. Chin, "An improved square-root algorithm for BLAST," *IEEE Signal Process. Lett.*, vol. 11, no. 9, pp. 772–775, Sep. 2004.

[103] S. Baro, G. Bauch, A. Pavlic, and A. Semmler, "Improving BLAST performance using space-time block codes and turbo decoding," in *Proc. IEEE Global Telecommun. Conf.*, San Francisco, CA, 2000, vol. 2, pp. 1067–1071.

[104] X. Jing, H. Wang, C. Ming, and S. Cheng, "A novel BLAST detection algorithm based instantaneous error ordering," in *Proc. IEEE Int. Conf. Commun.*, May 2003, vol. 5, pp. 3056–3060.

[105] C. Shen, H. Zhuang, L. Dai, and S. Zhou, "Detection algorithm improving V-BLAST performance over error propagation," *Electron. Lett.*, vol. 39, pp. 1007–1008, Jun. 2003.

[106] H. Yao and G. W. Wornell, "Lattice-reduction-aided detectors for MIMO communication systems," in *Proc. IEEE Global Telecommun. Conf.*, Nov. 2002, vol. 1, pp. 424–428.

[107] D. Wubben, R. Bohnke, V. Kuhn, and K.-D. Kammeyer, "Near-maximum-likelihood detection of MIMO systems using MMSE-based lattice reduction," in *Proc. IEEE Int. Conf. Commun.*, Jun. 2004, vol. 2, pp. 798–802.

[108] A. Elkhazin, K. Plataniotis, and S. Pasupathy, "Group MAP BLAST detector," in *Proc.*

IEEE Int. Conf. Acoust. Speech Signal Process., May 2004, vol. 4, pp. 785–788.

[109] M. Sellathurai and S. Haykin, "T-BLAST for wireless communications: First experimental results," *IEEE Trans. Veh. Technol.*, vol. 52, no. 5, pp. 530–535, May 2003.

[110] J. Blogh and L. Hanzo, *Third-Generation Systems and Intelligent Wireless Networking: Smart Antennas and Adaptive Modulation*. New York: Wiley/IEEE Press, 2002.

[111] R. T. Compton, *Adaptive Antennas: Concepts and Performance*. Englewood Cliffs, NJ: Prentice-Hall, 1988.

[112] L. C. Godara, "Applications of antenna arrays to mobile communications I: Performance improvement, feasibility and system considerations," *Proc. IEEE*, vol. 85, no. 7, pp. 1031–1060, Jul. 1997.

[113] L. C. Godara, "Application of antenna arrays to mobile communications II: Beam-forming and direction-of-arrival considerations," *Proc. IEEE*, vol. 85, no. 8, pp. 1195–1245, Aug. 1997.

[114] M. Chryssomallis, "Smart antennas," *IEEE Antennas Propag. Mag.*, vol. 42, pp. 129–136, Jun. 2000.

[115] V. Tarokh, A. Naguib, N. Seshadri, and A. R. Calderbank, "Combined array processing and space-time coding," *IEEE Trans. Inf. Theory*, vol. 45, no. 4, pp. 1121–1128, May 1999.

[116] M. Tao and R. S. Cheng, "Generalized layered space-time codes for high data rate wireless communications," *IEEE Trans. Wireless Commun.*, vol. 3, no. 4, pp. 1067–1075, Jul. 2004.

[117] A. F. Naguib, N. Seshadri, and A. R. Calderbank, "Applications of space-time block codes and interference suppression for high capacity and high data rate wireless systems," in *Proc. Conf. 32nd Asilomar Conf. Signals Syst. Comput.*, Pacific Grove, CA, 1998, vol. 2, pp. 1803–1810.

[118] H. Huang and H. Viswanathan, "Multiple antennas and multiuser detection in high data rate CDMA systems," in *Proc. IEEE 51st Veh. Technol. Conf. Proc.*, Tokyo, May 2000, vol. 1, pp. 556–560.

[119] A. Stamoulis, N. Al-Dhahir, and A. Calderbank, "Further results on interference cancellation and space-time block codes," in *Proc. Conf. 35th Asilomar Conf. Signals Syst. Comput.*, Pacific Grove, CA, Nov. 2001, vol. 1, pp. 257–261.

[120] E. N. Onggosanusi, A. G. Dabak, and T. A. Schmidl, "High rate space-time block coded scheme: Performance and improvement in correlated fading channels," in *Proc. IEEE Wireless Commun. Netw. Conf.*, Mar. 2002, vol. 1, pp. 194–199.

[121] G. Jongren, M. Skoglund, and B. Ottersten, "Combining beamforming and orthogonal space-time block coding," *IEEE Trans. Inf. Theory*, vol. 48, no. 3, pp. 611–627, Mar. 2002.

[122] H. Huang, H. Viswanathan, and G. J. Foschini, "Multiple antennas in cellular CDMA systems: Transmission, detection and spectral efficiency," *IEEE Trans. Wireless Commun.*, vol. 1, no. 3, pp. 383–392, Jul. 2002.

[123] R. A. Soni, R. M. Buehrer, and R. D. Benning, "Intelligent antenna system for CDMA2000," *IEEE Signal Process. Mag.*, vol. 19, no. 4, pp. 54–67, Jul. 2002.

[124] J. Liu and E. Gunawan, "Combining ideal beamforming and Alamouti space-time block codes," *Electron. Lett.*, vol. 39, pp. 1258–1259, Aug. 2003.

[125] F. Zhu and M. S. Lim, "Combined beamforming with space-time block coding using double antenna array group," *Electron. Lett.*, vol. 40, pp. 811–813, Jun. 2004.

[126] L. Zhao and V. K. Dubey, "Detection schemes for space-time block code and spatial multiplexing combined system," *IEEE Commun. Lett.*, vol. 9, no. 1, pp. 49–51, Jan. 2005.

[127] H. Lee, E. J. Powers, and J. Kang, "Low-complexity ZF detector for D-STTD systems in time-selective fading channels," in *Proc. IEEE 62nd Veh. Technol. Conf.*, Sep. 2005, vol. 3, pp. 2043–2047.

[128] M. Sellathurai, T. Ratnarajah, and P. Guinand, "Multirate layered space-time coding and successive interference cancellation receivers in quasi-static fading channels," *IEEE Trans. Wireless Commun.*, vol. 6, no. 12, pp. 4524–4533, Dec. 2007.

[129] S. Ekbatani and H. Jafarkhani, "Combining beamforming and space-time coding using quantized feedback," *IEEE Trans. Wireless Commun.*, vol. 7, no. 3, pp. 898–908, Mar. 2008.

[130] M. El-Hajjar, O. Alamri, J. Wang, S. Zummo, and L. Hanzo, "Layered steered space-time codes using multi-dimensional sphere-packing modulation," *IEEE Trans. Wireless Commun.*, vol. 8, no. 7, pp. 3335–3340, Jul. 2009.

[131] A. F. Naguib, N. Seshadri, and A. R. Calderbank, "Increasing data rate over wireless channels," *IEEE Signal Process. Mag.*, vol. 17, no. 3, pp. 76–92, May 2000.

[132] N. Al-Dhahir, C. Fragouli, A. Stamoulis, W. Younis, and R. Calderbank, "Space-time processing for broadband wireless access," *IEEE Commun. Mag.*, vol. 40, no. 9, pp. 136–142, Sep. 2002.

[133] W. Meng, L. Gu, and C. Li, "The combined beamforming and space-time block coding technique for downlink transmission," in *Proc. Int. Conf. Wireless Netw. Commun. Mobile Comput.*, Jun. 2005, vol. 1, pp. 481–486.

[134] K.-H. Li and M. A. Ingram, "Space-time block-coded OFDM systems with RF beamformers for high-speed indoor wireless communications," *IEEE Trans. Commun.*, vol. 50, no. 12, pp. 1899–1901, Dec. 2002.

[135] R. Negi, A. M. Tehrani, and J. M. Cioffi, "Adaptive antennas for space-time codes in outdoor channels," *IEEE Trans. Commun.*, vol. 50, no. 12, pp. 1918–1925, Dec. 2002.

[136] R. Nabar, H. Bolcskei, and A. J. Paulraj, "Transmit optimization for spatial multiplexing in the presence of spatial fading correlation," in *Proc. IEEE Global Telecommun. Conf.*, San Antonio, TX, Nov. 2001, vol. 1, pp. 131–135.

[137] Z. Hong, K. Liu, R. W. Heath, Jr., and A. M. Sayeed, "Spatial multiplexing in correlated fading via the virtual channel representation," *IEEE J. Sel. Areas Commun.*, vol. 21, no. 5, pp. 856–866, Jun. 2003.

[138] H. Kim and J. Chun, "MIMO structure which combines the spatial multiplexing and beamforming *Proc. IEEE Veh. Technol. Conf.*, May 2004, vol. 1, pp. 108–112.

[139] L.-L. Yang and L. Hanzo, "Performance of generalized multicarrier DS-CDMA over Nakagami-m fading channels," *IEEE Trans. Commun.*, vol. 50, no. 6, pp. 956–966, Jun. 2002.

[140] E. C. Van der Meulen, "Three-terminal communication channels," *Adv. Appl. Probab.*, vol. 3, no. 1, pp. 120–154, 1971.

[141] T. Cover and A. El Gamal, "Capacity theorems for the relay channel," *IEEE Trans. Inf. Theory*, vol. IT-25, no. 5, pp. 572–584, Sep. 1979.

[142] F. Willems, "The discrete memoryless multiple access channel with partially cooperating encoders," *IEEE Trans. Inf. Theory*, vol. IT-29, no. 3, pp. 441–445, May 1983.

[143] A. Sendonaris, E. Erkip, and B. Aazhang, "Increasing uplink capacity via user cooperation diversity," in *Proc. IEEE Int. Symp. Inf. Theory*, Cambridge, MA, Aug. 1998, DOI: 10.1109/ISIT.1998.708750.

[144] J. N. Laneman, G. W. Wornell, and D. N. C. Tse, "An efficient protocol for realizing cooperative diversity in wireless networks," in *Proc. IEEE Int. Symp. Inf. Theory*, Washington, DC, 2001, DOI: 10.1109/ISIT.2001.936157.

[145] T. E. Hunter and A. Nosratinia, "Cooperation diversity through coding," in *Proc. IEEE Int. Symp. Inf. Theory*, 2002, DOI: 10.1109/ISIT.2002.1023492.

[146] M. Dohler, E. Lefranc, and H. Aghvami, "Space-time block codes for virtual antenna arrays," in *Proc. 13th IEEE Int. Symp. Personal Indoor Mobile Radio Commun.*, Sep. 2002, vol. 1, pp. 414–417.

[147] J. N. Laneman and G. W. Wornell, "Distributed space-time-coded protocols for exploiting cooperative diversity in wireless networks," *IEEE Trans. Inf. Theory*, vol. 49, no. 10, pp. 2415–2425, Oct. 2003.

[148] M. C. Valenti and B. Zhao, "Distributed turbo codes: Towards the capacity of the relay channel," in *Proc. IEEE Veh. Technol. Conf.*, Oct. 2003, vol. 1, pp. 322–326.

[149] B. Zhao and M. C. Valenti, "Distributed turbo coded diversity for relay channel," *Electron. Lett.*, vol. 39, pp. 786–787, May 2003.

[150] J. N. Laneman, D. N. Tse, and G. W. Wornell, "Cooperative diversity in wireless networks: Efficient protocols and outage behavior," *IEEE Trans. Inf. Theory*, vol. 50, no. 12, pp. 3062–3080, Dec. 2004.

[151] R. U. Nabar, H. Bolcskei, and F. W. Kneubuhler, "Fading relay channels: Performance limits and space-time signal design," *IEEE J. Sel. Areas Commun.*, vol. 22, no. 6, pp. 1099–1109, Aug. 2004.

[152] M. Janani, A. Hedayat, T. Hunter, and A. Nosratinia, "Coded cooperation in wireless communications: Space-time transmission and iterative decoding," *IEEE Trans. Signal Process.*, vol. 52, no. 2, pp. 362–371, Feb. 2004.

[153] A. Stefanov and E. Erkip, "Cooperative coding for wireless networks," *IEEE Trans. Commun.*, vol. 52, no. 9, pp. 1470–1476, Sep. 2004.

[154] K. Azarian, H. El Gamal, and P. Schniter, "On the achievable diversity-multiplexing tradeoff in half-duplex cooperative channels," *IEEE Trans. Inf. Theory*, vol. 51, no. 12, pp. 4152–4172, Dec. 2005.

[155] H. Sneessens and L. Vandendorpe, "Soft decode and forward improves cooperative communications," in *Proc. 6th IEE Int. Conf. 3G Beyond*, Washington, DC, Nov. 2005, pp. 1–4.

[156] R. Hu and J. Li, "Exploiting Slepian-Wolf codes in wireless user cooperation," in *Proc.*

IEEE 6th Workshop Signal Process. Adv. Wireless Commun., Jun. 2005, pp. 275–279.

[157] M. Yu and J. Li, "Is amplify-and-forward practically better than decode-and-forward or vice versa?" in *Proc. IEEE Int. Conf. Acoust. Speech Signal Process.*, Mar. 2005, vol. 3, pp. 365–368.

[158] T. E. Hunter and A. Nosratinia, "Diversity through coded cooperation," *IEEE Trans. Wireless Commun.*, vol. 5, no. 2, pp. 283–289, Feb. 2006.

[159] T. E. Hunter, S. Sanayei, and A. Nosratinia, "Outage analysis of coded cooperation," *IEEE Trans. Inf. Theory*, vol. 52, no. 2, pp. 375–391, Feb. 2006.

[160] Y. Li, B. Vucetic, T. F. Wong, and M. Dohler, "Distributed turbo coding with soft information relaying in multihop relay networks," *IEEE J. Sel. Areas Commun.*, vol. 24, no. 11, pp. 2040–2050, Nov. 2006.

[161] R. Hu and J. Li, "Practical compress-forward in user cooperation: Wyner-Ziv cooperation," in *Proc. IEEE Int. Symp. Inf. Theory*, Seattle, WA, Jul. 2006, pp. 489–493.

[162] A. Host-Madsen, "Capacity bounds for cooperative diversity," *IEEE Trans. Inf. Theory*, vol. 52, no. 4, pp. 1522–1544, Apr. 2006.

[163] T. Bui and J. Yuan, "A decode and forward cooperation scheme with soft relaying in wireless communication," in *Proc. IEEE 8th Workshop Signal Process. Adv. Wireless Commun.*, Helsinki, Finland, Jun. 2007, pp. 1–5.

[164] M. N. Khormuji and E. G. Larsson, "Improving collaborative transmit diversity by using constellation rearrangement," in *Proc. IEEE Wireless Commun. Netw. Conf.*, Kowloon, Hong Kong, Mar. 2007, pp. 803–807.

AQ3 [165] X. Bao and J. Li, "Efficient message relaying for wireless user cooperation: Decode-amplify-forward (DAF) and hybrid DAF and coded-cooperation," *IEEE Trans. Wireless Communi.*, vol. 6, no. 11, pp. 3975–3984, Nov. 2007.

AQ4 [166] L. Xiao, T. Fuja, J. Kliewer, and D. Costello, "A network coding approach to cooperative diversity," *IEEE Trans. Inf. Theory*, vol. 53, no. 10, pp. 3714–3722, Oct. 2007.

[167] G. Yue, X. Wang, Z. Yang, and A. Host-Madsen, "Coding schemes for user cooperation in low-power regimes," *IEEE Trans. Signal Process.*, vol. 56, no. 5, pp. 2035–2049, May 2008.

[168] W. Zhang, Y. Li, X.-G. Xia, P. C. Ching, and K. B. Letaief, "Distributed space-frequency coding for cooperative diversity in broadband wireless Ad Hoc networks," *IEEE Trans. Wireless Commun.*, vol. 7, no. 3, pp. 995–1003, Mar. 2008.

[169] T. Wang and G. B. Giannakis, "Complex field network coding for multiuser cooperative communications," *IEEE J. Sel. Areas Commun.*, vol. 26, no. 3, pp. 561–571, Apr. 2008.

[170] P. Mitran, H. Ochiai, and V. Tarokh, "Space-time diversity enhancements using collaborative communications," *IEEE Trans. Inf. Theory*, vol. 51, no. 6, pp. 2041–2057, Jun. 2005.

[171] A. Nosratinia, T. E. Hunter, and A. Hedayat, "Cooperative communication in wireless networks," *IEEE Commun. Mag.*, vol. 42, no. 10, pp. 74–80, Oct. 2004.

[172] G. Kramer, M. Gastpar, and P. Gupta, "Cooperative strategies and capacity theorems for relay networks," *IEEE Trans. Inf. Theory*, vol. 51, no. 9, pp. 3037–3063, Sep. 2005.

[173] C. T. K. Ng and A. Goldsmith, "Capacity gain from transmitter and receiver cooperation," in *Proc. IEEE Int. Symp. Inf. Theory*, 2005, pp. 397–401.

[174] Y. Jing and B. Hassibi, "Wireless networks, diversity and space-time codes," in *Proc. IEEE Inf. Theory Workshop*, Oct. 2004, pp. 463–468.

[175] X. Ma and L. Ping, "Coded modulation using superimposed binary codes," *IEEE Trans. Inf. Theory*, vol. 50, no. 12, pp. 3331–3343, Dec. 2004.

[176] G. Forney, *Concatenated Codes*. Cambridge, MA: MIT Press, 1966.

[177] Consultative Committee for Space Data Systems, *Recommendations for Space Data System Standards: Telemetry Channel Coding*, 1984.

[178] D. Divsalar and F. Pollara, "Multiple turbo codes for deep-space communications Jet Propulsion Laboratory, Pasadena, CA, Telecommunications and Data Acquisition Progress Rep. 42-121, May 1995.

[179] S. Benedetto and G. Montorsi, "Iterative decoding of serially concatenated convolutional codes," *Electron. Lett.*, vol. 32, pp. 1186–1188, Jun. 1996.

[180] S. Benedetto, D. Divsalar, G. Montorsi, and F. Pollara, "Analysis, design and iterative decoding of double serially concatenated codes with interleavers," *IEEE J. Sel. Areas Commun.*, vol. 16, no. 2, pp. 231–244, Feb. 1998.

[181] D. Raphaeli and Y. Zarai, "Combined turbo equalization and turbo decoding," in *Proc. IEEE Global Telecommun. Conf.*, Phoenix, AZ, Nov. 1997, vol. 2, pp. 639–643.

[182] D. Raphaeli and Y. Zarai, "Combined turbo equalization and turbo decoding," *IEEE Commun. Lett.*, vol. 2, no. 4, pp. 107–109, Apr. 1998.

[183] M. Toegel, W. Pusch, and H. Weinrichter, "Combined serially concatenated codes and turbo-equalization," in *Proc. 2nd Int. Symp. Turbo Codes*, Brest, France, Sep. 2000, pp. 375–378.

[184] R. Ramamurthy and W. E. Ryan, "Convolutional double accumulate codes (or double turbo DPSK)," *IEEE Commun. Lett.*, vol. 5, no. 4, pp. 157–159, Apr. 2001.

[185] C. Douillard, M. Jezequel, C. Berrou, A. Picart, P. Didier, and A. Glavieux, "Iterative correction of intersymbol interference: Turbo equalization," *Eur. Trans. Telecommun.*, vol. 6, pp. 507–511, Sep./Oct. 1995.

[186] D. Divsalar, S. Dolinar, and F. Pollara, "Serial concatenated trellis coded modulation with rate-1 inner code," in *Proc. IEEE Global Telecommun. Conf.*, San Francisco, CA, 2000, vol. 2, pp. 777–782.

[187] G. Caire, G. Taricco, and E. Biglieri, "Bit-interleaved coded modulation," in *Proc. IEEE Int. Symp. Inf. Theory*, Ulm, Germany, Jun./Jul. 1997, p. 96.

[188] G. Caire, G. Taricco, and E. Biglieri, "Bit-interleaved coded modulation," *IEEE Trans. Inf. Theory*, vol. 44, no. 3, pp. 927–946, May 1998.

[189] S. ten Brink, J. Speidel, and R.-H. Yan, "Iterative demapping and decoding for multilevel modulation," in *Proc. IEEE Global Telecommun. Conf.*, Sydney, NSW, Australia, 1998, vol. 1, pp. 579–584.

[190] X. Li and J. A. Ritcey, "Bit-interleaved coded modulation with iterative decoding," *IEEE Commun. Lett.*, vol. 1, no. 11, pp. 169–171, Nov. 1997.

[191] X. Li and J. A. Ritcey, "Bit-interleaved coded modulation with iterative decoding using soft feedback," *IEE Electron. Lett.*, vol. 34, pp. 942–943, May 1998.

[192] X. Li and J. A. Ritcey, "Trellis-coded modulation with bit interleaving and iterative decoding," *IEEE J. Sel. Areas Commun.*, vol. 17, no. 4, pp. 715–724, Apr. 1999.

[193] X. Wang and H. V. Poor, "Iterative (turbo) soft interference cancellation and decoding for coded CDMA," *IEEE Trans. Commun.*, vol. 47, no. 7, pp. 1046–1061, Jul. 1999.

[194] A. Sezgin, D. Wuebben, and V. Kuehn, "Analysis of mapping strategies for turbo-coded space-time block codes," in *Proc. IEEE Inf. Theory Workshop*, Paris, France, Mar./Apr. 2003, pp. 103–106.

[195] A. Viterbi, "Error bounds for convolutional codes and an asymptotically optimum decoding algorithm," *IEEE Trans. Inf. Theory*, vol. IT-13, no. 2, pp. 260–269, Apr. 1967.

[196] L.-F. Wei, "Trellis-coded modulation with multidimensional constellations," *IEEE Trans. Inf. Theory*, vol. IT-33, no. 4, pp. 483–501, Jul. 1987.

[197] E. Zehavi, "8-PSK trellis codes on Rayleigh channel," in *Proc. IEEE Military Commun. Conf.*, Boston, MA, Oct. 1989, pp. 536–540.

[198] E. Zehavi, "8-PSK trellis codes for a Rayleigh channel," *IEEE Trans. Commun.*, vol. 40, no. 5, pp. 873–884, May 1992.

[199] N. Wiberg, H.-A. Loeliger, and R. Kotter, "Codes and iterative decoding on general graphs," *Eur. Trans. Telecommun.*, vol. 6, pp. 513–526, 1995.

[200] N. Wiberg, H.-A. Loeliger, and R. Kotter, "Codes and iterative decoding on general graphs," in *Proc. IEEE Int. Symp. Inf. Theory*, Whistler, BC, Canada, Sep. 1995, p. 468.

[201] N. Wiberg, "Codes and decoding on general graphs," Ph.D. dissertation, Linköping University, Linköping, Sweden, 1996.

[202] D. J. MacKay and R. M. Neal, "Near Shannon limit performance of low density parity check codes," *IEE Electron. Lett.*, vol. 32, Aug. 1996.

[203] R. Gallager, "Low density parity check codes," *IEEE Trans. Inf. Theory*, vol. IT-8, no. 1, pp. 21–28, Jan. 1962.

[204] S. Benedetto, D. Divsalar, G. Montorsi, and F. Pollara, "Serial concatenation of interleaved codes: Performance analysis, design and iterative decoding," *IEEE Trans. Inf. Theory*, vol. 44, no. 3, pp. 909–926, May 1998.

[205] D. Divsalar, H. Jin, and R. J. McEliece, "Coding theorems for turbo-like codes," in *Proc. 36th Allerton Conf. Commun. Control Comput.*, Sep. 1998, pp. 201–210.

[206] R. J. McEliece, D. J. MacKay, and J.-F. Cheng, "Turbo decoding as an instance of Pearl's "belief propagation" algorithm," *IEEE J. Sel. Areas Commun.*, vol. 16, no. 2, pp. 140–152, Feb. 1998.

[207] J. Pearl, *Probabilistic Reasoning in Intelligent Systems: Networks of Plausible Inference*. San Mateo, CA: Morgan Kaufmann, 1988.

[208] G. Bauch, "Concatenation of space-time block codes and Turbo-TCM," in *Proc. IEEE Int. Conf. Commun.*, Vancouver, BC, Canada, Jun. 1999, pp. 1202–1206.

[209] S. ten Brink, "Designing iterative decoding schemes with the extrinsic information transfer chart," *AEÜ Int. J. Electron. Commun.*, vol. 54, pp. 389–398, Nov. 2000.

[210] K. R. Narayanan, "Effect of precoding on the convergence of turbo equalization for partial response channels," *IEEE J. Sel. Areas Commun.*, vol. 19, no. 4, pp. 686–698, Apr. 2001.

[211] I. Lee, "The effect of a precoder on serially concatenated coding systems with an ISI channel," *IEEE Trans. Commun.*, vol. 49, no. 7, pp. 1168–1175, Jul. 2001.

[212] F. Schreckenbach, N. Geortz, J. Hagenauer, and G. Bauch, "Optimized symbol mappings for bit-interleaved coded modulation with iterative decoding," in *Proc. IEEE Global Telecommun. Conf.*, Dec. 2003, vol. 6, pp. 3316–3320.

[213] F. Schreckenbach, N. Geortz, J. Hagenauer, and G. Bauch, "Optimization of symbol mappings for bit-interleaved coded modulation with iterative decoding," *IEEE Commun. Lett.*, vol. 7, no. 12, pp. 593–595, Dec. 2003.

[214] N. H. Tran and H. H. Nguyen, "Improving the performance of QPSK BICM-ID by mapping on the hypercube," in *Proc. IEEE 60th Veh. Technol. Conf.*, Sep. 2004, vol. 2, pp. 1299–1303.

[215] N. H. Tran and H. H. Nguyen, "Design and performance of BICM-ID systems with hypercube constellations," *IEEE Trans. Wireless Commun.*, vol. 5, no. 5, pp. 1169–1179, May 2006.

[216] Y. Huang and J. A. Ritcey, "Improved 16-QAM constellation labeling for BI-STCM-ID with the Alamouti scheme," *IEEE Commun. Lett.*, vol. 9, no. 2, pp. 157–159, Feb. 2005.

[217] E. Cela, *The Quadratic Assignment Problem: Theory and Algorithms.* Norwell, MA: Kluwer, 1998.

[218] S. Benedetto, D. Divsalar, G. Montorsi, and F. Pollara, "A soft-input soft-output APP module for iterative decoding of concatenated codes," *IEEE Commun. Lett.*, vol. 1, no. 1, pp. 22–24, Jan. 1997.

[219] T. Richardson and R. Urbanke, "The renaissance of Gallager's low-density parity-check codes," *IEEE Commun. Mag.*, vol. 41, no. 8, pp. 126–131, Aug. 2003.

[220] M. C. Davey and D. J. MacKay, "Low density parity check codes over GF(q)," *IEEE Commun. Lett.*, vol. 2, no. 6, pp. 165–167, Jun. 1998.

[221] B. Ammar, B. Honary, Y. Kou, and S. Lin, "Construction of low density parity check codes: A combinatoric design approach," in *Proc. IEEE Int. Symp. Inf. Theory (ISIT)*, Lausanne, Switzerland, Jun.–Jul. 2002, p. 311.

[222] B. Ammar, B. Honary, Y. Kou, J. Xu, and S. Lin, "Construction of low-density parity-check codes based on balanced incomplete block designs," *IEEE Trans. Inf. Theory*, vol. 50, no. 6, pp. 1257–1269, Jun. 2004.

[223] B. Honary, A. Moinian, and B. Ammar, "Construction of well-structured quasi-cyclic low-density parity check codes," *Inst. Electr. Eng. Proc.—Commun.*, vol. 152, pp. 1081–1085, Dec. 2005.

AQ5

[224] M. Lentmaier and K. S. Zigangirov, "On generalized low-density parity-check codes based on Hamming component codes," *IEEE Commun. Lett.*, vol. 3, no. 8, pp. 248–250, Aug. 1999.

[225] S. Hirst and B. Honary, "Application of efficient Chase algorithm in decoding of generalized low-density parity-check codes," *IEEE Commun. Lett.*, vol. 6, no. 9, pp. 385–387, Sep. 2002.

[226] S. Hirst and B. Honary, "Decoding of generalised low-density parity-check codes using weighted bit-flip voting," *Inst. Electr. Eng. Proc.—Commun.*, vol. 149, pp. 1–5, Feb. 2002.

[227] S. Honary, N. Pandya, G. Markarian, and B. Honary, "Migration to capacity approaching codes for digital video broadcasting," *Inst. Electr. Eng. Proc.—Commun.*, vol. 152, pp. 1103–1107, Dec. 2005.

[228] S. ten Brink, G. Kramer, and A. Ashikhmin, "Design of low-density parity-check codes for modulation and detection," *IEEE Trans. Commun.*, vol. 52, no. 4, pp. 670–678, Apr. 2004.

[229] D. Divsalar, S. Dolinar, and F. Pollara, "Low complexity turbo-like codes," in *Proc. 2nd Int. Symp. Turbo Codes Related Topics*, Brest, France, Sep. 2000, pp. 73–80.

[230] H. M. Tullberg and P. H. Siegel, "Serial concatenated trellis coded modulation with inner rate-1 accumulate code," in *Proc. IEEE Global Telecommun. Conf.*, San Antonio, TX, Nov. 2001, vol. 2, pp. 936–940.

[231] L. Lifang, D. Divsalar, and S. Dolinar, "Iterative demodulation, demapping and decoding of coded non-square QAM," *IEEE Trans. Commun.*, vol. 53, no. 1, pp. 16–19, Jan. 2005.

[232] A. Chindapol and J. A. Ritcey, "Design, analysis and performance evaluation for BICM-ID with square QAM constellations in Rayleigh fading channels," *IEEE J. Sel. Areas Commun.*, vol. 19, no. 5, pp. 944–957, May 2001.

[233] J. Tan and G. L. Stuber, "Analysis and design of interleaver mappings for iteratively decoded BICM," in *Proc. IEEE Int. Conf. Commun.*, Apr./May 2002, vol. 3, pp. 1403–1407.

[234] J. Tan and G. L. Stuber, "Analysis and design of symbol mappers for iteratively decoded BICM," *IEEE Trans. Wireless Commun.*, vol. 4, no. 2, pp. 662–672, Mar. 2005.

[235] K. Zeger and A. Gersho, "Pseudo-Gray coding," *IEEE Trans. Commun.*, vol. 38, no. 12, pp. 2147–2158, Dec. 1990.

[236] L.-F. Wei, "Rotationally invariant trellis-coded modulations with multidimensional M-PSK," *IEEE J. Sel. Areas Commun.*, vol. 7, no. 9, pp. 1281–1295, Dec. 1989.

[237] R. H. Deng and D. J. Costello, Jr., "High rate concatenated coding systems using multidimensional bandwidth-efficient trellis inner codes," *IEEE Trans. Commun.*, vol. 37, no. 10, pp. 1091–1096, Oct. 1989.

[238] S. S. Pietrobon, R. H. Deng, A. Lafanechere, G. Ungerboeck, and D. J. Costello, Jr., "Trellis-coded multidimensional phase modulation," *IEEE Trans. Inf. Theory*, vol. 36, no. 1, pp. 63–89, Jan. 1990.

[239] S. Bäro, "turbo-detection in MIMO systems: Bit labeling and pre-coding," in *Proc. 5th Int. ITG Conf. Source Channel Coding*, Erlangen, Germany, Jan. 2004.

[240] F. Simoens, H. Wymeersch, and M. Moeneclaey, "Spatial mapping for MIMO systems *Proc. IEEE Inf. Theory Workshop*, Oct. 2004, pp. 187–192.

[241] F. Simoens, H. Wymeersch, H. Bruneel, and M. Moeneclaey, "Multidimensional mapping for bit-interleaved coded modulation with BPSK/QPSK signaling," *IEEE Commun. Lett.*, vol. 9, no. 5, pp. 453–455, May 2005.

[242] H. Wymeersch, F. Simoens, H. Bruneel, and M. Moeneclaey, "Multi-dimensional modulation for UWB communications," in *Proc. IEEE 6th Workshop Signal Process. Adv. Wireless Commun.*, Jun. 2005, pp. 42–46.

[243] A. S. Mohammed, W. Hidayat, and M. Bossert, "Multidimensional 16-QAM constellation labeling of BI-STCM-ID with the Alamouti scheme," in *Proc. IEEE Wireless Commun. Netw. Conf.*, Las Vegas, NV, Apr. 2006, vol. 3, pp. 1217–1220.

[244] R. Battiti and G. Tecchiolli, "Reactive search: Toward self-tuning heuristics," *ORSA J. Comput.*, vol. 6, no. 2, pp. 126–140, 1994.

[245] H. El Gamal and A. R. Hammons, "Analyzing the turbo decoder using the Gaussian approximation," *IEEE Trans. Inf. Theory*, vol. 47, no. 2, pp. 671–686, Feb. 2001.

[246] S. ten Brink, "Convergence behavior of iteratively decoded parallel concatenated codes," *IEEE Trans. Commun.*, vol. 49, no. 10, pp. 1727–1737, Oct. 2001.

[247] J. Hagenauer, "The EXIT chart—Introduction to extrinsic information transfer in iterative processing," in *Proc. Eur. Signal Process. Conf.*, Vienna, Austria, Sep. 2004, pp. 1541–1548.

[248] M. Tüchler, S. ten Brink, and J. Hagenauer, "Measures for tracing convergence of iterative decoding algorithms," in *Proc. 4th Int. ITG Conf. Source Channel Coding*, Berlin, Germany, Jan. 2002, pp. 53–60.

[249] J. Kliewer, S. X. Ng, and L. Hanzo, "Efficient computation of EXIT functions for non-binary iterative decoding," *IEEE Trans. Commun.*, vol. 54, no. 12, pp. 2133–2136, Dec. 2006.

[250] F. Brännström, L. K. Rasmussen, and A. J. Grant, "Convergence analysis and optimal scheduling for multiple concatenated codes," *IEEE Trans. Inf. Theory*, vol. 51, no. 9, pp. 3354–3364, Sep. 2005.

[251] S. ten Brink, "Convergence of multidimensional iterative decoding schemes," in *Proc. Conf. 35th Asilomar Conf. Signals Syst. Comput.*, Pacific Grove, CA, 2001, vol. 1, pp. 270–274.

[252] M. Tüchler, "Convergence prediction for iterative decoding of threefold concatenated systems," in *Proc. IEEE Global Telecommun. Conf.*, Nov. 2002, vol. 2, pp. 1358–1362.

[253] S. Benedetto and G. Montorsi, "Serial concatenation of block and convolutional codes," *Electron. Lett.*, vol. 32, pp. 887–888, May 1996.

[254] M. Tüchler, "Design of serially concatenated systems depending on the block length," *IEEE Trans. Commun.*, vol. 52, no. 2, pp. 209–218, Feb. 2004.

[255] A. Ashikhmin, G. Kramer, and S. ten Brink, "Extrinsic information transfer functions: Model and erasure channel properties," *IEEE Trans. Inf. Theory*, vol. 50, no. 11, pp. 2657–2673, Nov. 2004.

[256] L. Hanzo, R. Maunder, J. Wang, and L.-L. Yang, *Near-Capacity Variable-Length Coding: Regular and Exit-Chart Aided Irregular Designs.* Chichester, U.K.: Wiley/IEEE Press, 2010.

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