OULU 2009
C 318

ACTA
UNIVERSITATIS OULUENSIS

Henri Puska

CODE ACQUISITION IN DIRECT SEQUENCE SPREAD SPECTRUM SYSTEMS USING SMART ANTENNAS

*FACULTY OF TECHNOLOGY,
DEPARTMENT OF ELECTRICAL AND INFORMATION ENGINEERING,
UNIVERSITY OF OULU*

ACTA UNIVERSITATIS OULUENSIS
C Technica 318

HENRI PUSKA

CODE ACQUISITION IN DIRECT SEQUENCE SPREAD SPECTRUM SYSTEMS USING SMART ANTENNAS

Academic dissertation to be presented, with the assent of the Faculty of Technology of the University of Oulu, for public defence in Raahensali (Auditorium L10), Linnanmaa, on April 3rd, 2009, at 12 noon

OULUN YLIOPISTO, OULU 2009

Acta Univ. Oul. C 318, 2009

Supervised by
Professor Jari Iinatti

Reviewed by
Doctor Marcos Katz
Professor Erik Ström

ISBN 978-951-42-9048-0 (Paperback)
ISBN 978-951-42-9049-7 (PDF)
http://herkules.oulu.fi/isbn9789514290497/
ISSN 0355-3213 (Printed)
ISSN 1796-2226 (Online)
http://herkules.oulu.fi/issn03553213/

Cover design
Raimo Ahonen

OULU UNIVERSITY PRESS
OULU 2009

Puska, Henri, Code acquisition in direct sequence spread spectrum systems using smart antennas
Faculty of Technology, Department of Electrical and Information Engineering, University of Oulu, P.O.Box 4500, FI-90014 University of Oulu, Finland
Acta Univ. Oul. C 318, 2009
Oulu, Finland

Abstract

In this doctoral thesis, initial code synchronization (i.e., code acquisition) of a direct sequence spread spectrum (DS/SS) system is studied when a smart antenna is used in a receiver. Code synchronization means time synchronization of the used spreading code in the receiver. After an introduction to the topic, a literature review of code acquisition is presented. In addition, a review of the results in the literature under fading, data modulation, Doppler, intentional interference, multiple-access interference, other system interference, and multiple antennas is given. After that, an overview of the smart antennas, especially focusing on digital beamforming and direction-of-arrival (DOA) estimation algorithms is presented.

The end part of the thesis concentrates on the author's own research of the topic. Original articles of this article dissertation have been classified according to their contents into two groups. The first group covers DS/SS code acquisition performance in intentional interference by exploiting how well different beamforming algorithms can eliminate narrowband and wideband interfering signals in the case, where the DOA of the desired signal is known. The obtained results show that most spatial beamforming algorithms are capable of cancelling multiple different types of interfering signals if they are not arriving from the same direction as the desired signal. If angle separation between desired and interfering signals is not sufficient, then more complex methods have to be used. The second group of articles focuses on a theoretical analysis of synchronization probabilities and mean acquisition times. If the DOA of the desired signal is unknown, the whole angular uncertainty region can be divided into small angular cells using beamforming techniques, as is proposed in the literature. Then there is a two-dimensional (delay-angle) acquisition problem. In this thesis, the research work of that area is expanded to cover also advanced beamforming techniques, since they offer increased interference suppression capability. It is shown that the code acquisition performance of the delay-angle method can be improved in some cases by adding a DOA estimator into the system, because it may reduce the number of required angular cells. In addition, such a minimum mean square error (MMSE) beamforming structure is proposed, where only one period of the known pseudo noise spreading code is used as a reference signal. The method was shown to have better acquisition performance than the delay-angle method has, since MMSE beamforming does not need DOA information. However, in this thesis, such a method was not found which outperforms the rest of the methods in all scenarios.

Keywords: adaptive antenna arrays, beamforming, DOA estimation, interference cancellation, smart antennas, spread-spectrum systems, synchronization

Puska, Henri, Koodivaiheen etsintä suorahajotushajaspektrijärjestelmissä käyttäen älyantenneja
Teknillinen tiedekunta, Sähkö- ja tietotekniikan osasto, Oulun yliopisto, PL 4500, 90014 Oulun yliopisto
Acta Univ. Oul. C 318, 2009
Oulu

Tiivistelmä

Tässä väitöstyössä tutkitaan suorahajotushajaspektrijärjestelmän (DS/SS, direct sequence spread spectrum) koodisynkronoinnin etsintävaihetta, kun vastaanottimessa käytetään älyantennia. Koodisynkronoinnilla tarkoitetaan järjestelmän käyttämän hajotuskoodin ajastuksen synkronointia vastaanottimessa. Johdannon jälkeen esitetään kirjallisuuskatsaus koodisynkronointiin sekä tuodaan esille kirjallisuudesta löytyviä tutkimustuloksia aihepiiristä seuraavissa tilanteissa: häipyvä kanava, Doppler-ilmiö, tahallinen häirintä, monikäyttöhäiriö, muiden järjestelmien aiheuttama häiriö sekä moniantennijärjestelmät. Tämän jälkeen esitetään yleiskatsaus älyantenneihin kohdistuen erityisesti digitaalisiin keilanmuodostus- sekä suuntaestimointialgoritmeihin.

Työn loppuosa keskittyy kirjoittajan omaan tutkimukseen aiheesta. Tämän nippuväitöskirjan alkuperäiset artikkelit on luokiteltu kahteen ryhmään niiden sisältöön perustuen. Ensimmäinen ryhmä käsittelee DS/SS-järjestelmän koodisynkronoinnin etsintävaiheen suorituskykyä tahallisessa häirinnässä tutkimalla, miten hyvin erilaiset keilanmuodostusalgoritmit kykenevät poistamaan kapea- ja leveäkaistaisia häirintäsignaaleja tilanteessa, jossa hyötysignaalin tulosuunta tiedetään. Tutkimustulokset osoittavat, että monet tilatason keilanmuodostusalgoritmit kykenevät poistamaan useita erityyppisiä häirintäsignaaleita, jos ne eivät saavu hyötysignaalin kanssa samasta suunnasta. Mikäli kulmaero hyöty- ja häirintäsignaalien välillä ei ole riittävä, joudutaan käyttämään rakenteeltaan monimutkaisempia menetelmiä. Toinen ryhmä artikkeleita keskittyy synkronointiin liittyvien todennäköisyyksien ja keskimääräisen etsintäajan teoreettiseen analyysiin. Jos hyötysignaalin tulosuunta on tuntematon, voidaan kulmaepävarmuusalue jakaa pieniin kulmasoluihin käyttäen keilanmuodostustekniikoita, kuten kirjallisuudessa esitetään. Tällöin kyseessä on kaksiulotteinen (viive-kulma) etsintäongelma. Tässä työssä kyseistä tutkimusaihetta laajennetaan koskemaan myös edistyneet keilanmuodostusmenetelmät, koska ne tarjoavat parantuneen häiriönvaimennuskyvyn. Työssä osoitetaan, että viive-kulma menetelmän suorituskykyä voidaan parantaa joissakin tilanteissa lisäämällä järjestelmään suuntaestimaattori, koska se saattaa vähentää tarvittavien kulmasolujen lukumäärää. Lisäksi tutkitaan sellaista pienimmän keskineliövirheen (MMSE, minimum mean square error) keilanmuodostusmenetelmää, jossa ainoastaan yhtä hajotuskoodin koodijaksoa käytetään opetukseen. Kyseisellä menetelmällä todettiin olevan parempi suorituskyky kuin viive-kulma etsinnällä, koska MMSE-menetelmä ei tarvitse suuntainformaatiota. Tässä työssä ei kuitenkaan löydetty yhtä sellaista menetelmää, jonka suorituskyky on muita parempi kaikissa tilanteissa.

Asiasanat: adaptiiviset antenniryhmät, hajaspektrijärjestelmät, häiriönvaimennus, keilanmuodostus, suuntaestimointi, synkronointi, älyantennit

Preface

Research work related to this thesis was carried out at the Centre for Wireless Communications (CWC) and Telecommunication laboratory, Department of Electrical and Information Engineering, University of Oulu, Oulu, Finland, during the years 2003-2009.

I am very grateful to my supervisor Prof. Jari Iinatti and Dr. Harri Saarnisaari for their support and guidance throughout the whole research project. Special thanks belongs also to my colleague Lic. Tech. Pekka Lilja for research co-operation. I would like to thank Dr. Ian Oppermann, Prof. Matti Latva-aho and Lic. Tech. Ari Pouttu, the directors of CWC during the course of this research work, and Prof. Pentti Leppänen, Head of the Telecommunication laboratory, for giving the possibility to do this work at the CWC.

I would like to thank the reviewers of this thesis, Prof. Erik Ström from the Chalmers University of Technology, Göteborg, Sweden, and Dr. Marcos Katz from VTT Technical Research Centre, Oulu, Finland, for their valuable work. Thanks belongs also to the whole CWC and Telecommunication laboratory staff equally for a comfortable working atmosphere.

The research funding provided by the Graduate School in Electronics, Telecommunication and Automation (GETA), the Finnish Defence Forces, the Finnish Funding Agency for Technology and Innovation (Tekes), Nokia, Elektrobit, and Instrumentointi are gratefully acknowledged. In addition, the following Finnish foundations have granted personal scholarships for my doctoral studies: Tekniikan edistämissäätiö, HPY:n tutkimussäätiö and Nokia Oyj:n säätiö. All these foundations earn the warmest thanks for their financial support.

I would like to express my deepest gratitude to my closest network, including my parents, brothers, parents-in-law, other relatives and friends. Finally, I want to express my loving thanks to my wife Hannele for all the care, patience, and understanding during all these years, and to our little son Lauri, for bringing joy to our lives.

Oulu, March 9, 2009 Henri Puska

Abbreviations

$\mathbf{a}(\theta)$	steering vector
$\mathbf{a}(\theta_0)$	steering vector toward desired signal
$\mathbf{a}(\theta_i)$	steering vector toward interfering signal
$\mathbf{a}_{ST}(\theta)$	space-time steering vector
$\mathbf{A}$	matrix consisting of steering vectors
B_{coh}	coherence bandwidth
$c(n)$	discrete time spreading code sequence
$c(t)$	continuous time spreading code sequence
$c(\zeta;t)$	time-variant impulse response of radio channel
$\mathbf{d}$	cross-correlation vector used in the MMSE algorithm
$\mathbf{e}$	constraint vector used in nullsteering algorithm
E_b/N_0	signal-to-noise ratio per bit
E_c/N_0	signal-to-noise ratio per chip
$f_{ACQ}(t)$	probability density function of acquisition time
f_c	carrier frequency
f_d	Doppler shift between the transmitter and receiver
$i(t)$	interfering signal
$i_m(t)$	interfering signal at *m*th antenna element
$\mathbf{i}(t)$	vector of interfering signals in all antennas
I/S	interference-to-signal ratio
L	code length
m	*m*th antenna element
M	number of antenna elements
n	discrete time variable
$n_m(t)$	additive white Gaussian noise at *m*th antenna element
$\mathbf{n}(t)$	vector of noise signals in all antennas
P	number of time taps in space-time beamforming
P_{ACQ}	probability of acquisition
$P_{Bartlett}(\theta)$	spatial spectrum using Bartlett's DOA estimation
$P_{Capon}(\theta)$	spatial spectrum using Capon's DOA estimation
P_D	probability of detection

P_D^{ov}	overall probability of detection
P_{FA}	probability of false alarm
P_{miss}	probability of miss
$P_{MUSIC}(\theta)$	spatial spectrum using the MUSIC algorithm
P_{miss}^{ov}	overall probability of miss
$\mathbf{R}$	array correlation matrix
$\hat{\mathbf{R}}$	estimate of correlation matrix
$\mathbf{R}_{IN}$	correlation matrix consisting of interference and noise.
$\mathbf{R}_{ST}$	space-time correlation matrix
$\hat{\mathbf{R}}_{ST}$	estimate of space-time correlation matrix
S	information signal power
t	continuous time variable
T_{ACQ}	acquisition time
T_c	chip time
T_{coh}	channel coherence time
T_d	dwell time
T_{FA}	false alarm penalty time
T_H	detection threshold
T_{MA}	mean acquisition time
T_{MA_max}	maximum expected acquisition time
T_{MA_min}	minimum expected acquisition time
T_s	symbol time
T_{stop}	stopping time
$\mathbf{V}_n$	noise subspace
w_m	adjustable weight coefficient at *m*th antenna element
$\mathbf{w}$	weight coefficient vector
$\mathbf{w}_{ST}$	space-time weight coefficient vector
W	transmitted signal bandwidth
$x(t)$	received signal
$x_m(n)$	received discrete time signal at *m*th antenna element
$x_m(t)$	received continuous time signal at *m*th antenna element
$\mathbf{x}(n)$	vector of received discrete time signals in all antennas, i.e., snapshot
$\mathbf{x}(t)$	vector of received continuous time signals in all antennas
$\mathbf{x}_{ST}(n)$	space-time sample vector
$y(n)$	array output signal

$y_m(n)$ discrete time MF output signal at mth antenna element
z decision variable at the detector output
$z(\tau_i)$ decision variable at the detector output as a function of delay
z_I decision variable at I-branch of the detector output
z_Q decision variable at Q-branch of the detector output

Δ is the maximum time delay from the first to last antenna element
ζ propagation delay
θ angle of arrival
θ_0 angle of arrival of desired signal
$\theta_1, \cdots, \theta_K$ angles of arrivals of interfering signals
$\sigma^2_{T_{ACQ}}$ variance of acquisition time
τ relative delay between received and local spreading codes
$\hat{\tau}$ estimate of τ
$\hat{\tau}_{ML}$ maximum likelihood estimate of τ
τ_i a code phase which is presently under investigation
ϕ_m carrier phase shift at the reference antenna
ϕ_m carrier phase shift at the mth antenna element

A/D analog-to-digital conversion
ADL adaptive diagonal loading
AIC Akaike information theoretic criteria
AWGN additive white Gaussian noise
BER bit error rate
BF beamforming
BF+MF single MF is located after BF unit
BPSK binary phase shift keying
CDMA code division multiple access
CFAR constant false alarm rate
CME consecutive mean excision
CW continuous wave
DOA direction-of-arrival
DC differentially coherent
DS direct sequence
DS/CDMA direct sequence code division multiple access

DS/SS	direct sequence spread spectrum
ESPRIT	estimation of signal parameters via rotational invariance techniques
FCME	forward consecutive mean excision
FDMA	frequency division multiple access
FFT	fast Fourier transform
FH	frequency hopping
FIR	finite impulse response
GLRT	generalized likelihood ratio test
GSC	generalized sidelobe canceller
GSM	global system for mobile communications
I	in-phase -branch
IC	interference cancellation
ICI	inter chip interference
IF	intermediate frequency
LMS	least mean square
LOS	line-of-sight
MAI	multiple-access interference
MaxSINR	Maximum SINR
MDL	minimum description length
MF	matched filter
MF+BF	MF is located in each antenna element before BF unit
ML	maximum likelihood
MSE	mean square error
MMSE	minimum mean square error
MUSIC	multiple signal classification
MVDR	minimum variance distortionless response
NLOS	non-line-of-sight
PDF	probability density function
PDI	post detection integration
PG	processing gain
PN	pseudo noise
Q	quadrature-branch
RF	radio frequency
RMSE	root mean square error
SDMA	space division multiple access

SINR	signal-to-interference-plus-noise ratio
SNR	signal-to-noise ratio
SS	spread spectrum
STAP	space-time adaptive processing
TDL	tapped delay line
TDMA	time division multiple access
UCA	uniform circular array
ULA	uniform linear array
2-D	two dimensional

$(\cdot)^*$	complex conjugate
$(\cdot)^{-1}$	inverse
$\lvert\cdot\rvert$	absolute value
$(\cdot)^H$	complex conjugate transpose
$(\cdot)^T$	transpose
$E\{\cdot\}$	expectation

List of original articles

This thesis is based on the following nine original articles (I–IX), which are referred to in the text by their Roman numerals:

I Puska H, Saarnisaari H & Iinatti J (2003) Utilizing beamformers as interference cancellers in code synchronization of DS/SS system. Proc of IEEE Finnish Signal Processing Symposium, Tampere, Finland, on CD: 5p.

II Puska H, Saarnisaari H & Iinatti J (2005) Comparison of antenna array algorithms in DS/SS code acquisition with jamming. Proc. of IEEE Military Communication Conference, Atlantic City, USA, 4: 2074–2080.

III Puska H & Saarnisaari H (2004) Performance comparison of robust array algorithms in delay estimation. Proc. of IEEE Sensor Array and Multichannel Signal Processing Workshop, Barcelona, Spain, 1: 332–336.

IV Puska H, Saarnisaari H & Iinatti J (2005) Comparison of matched filter acquisition using beamforming and CME algorithm in impulsive interference. Proc. of IEEE Vehicular Technology Conference (Spring), Stockholm, Sweden, 3: 1988–1992.

V Puska H, Saarnisaari H, Iinatti J & Lilja P (2007) Synchronization probabilities using conventional and MVDR beam forming with DOA errors. Proc. of IEEE Personal Indoor and Mobile Radio Communication, Athens, Greece, on CD: 5p.

VI Puska H, Saarnisaari H, Iinatti J & Lilja P (2008) Serial search code acquisition using smart antennas with single correlator or matched filter. IEEE Transactions on Communications 56(2): 299–308.

VII Puska H, Iinatti J & Saarnisaari H (2009) Serial search and maximum selection based code acquisition techniques for single and multi antenna systems. IEEE Transactions on Wireless Communications 8(3). In press.

VIII Puska H, Saarnisaari H & Iinatti J (2005) An iterative method for code acquisition using DOA estimation and beamforming. Proc. of IEEE Personal Indoor and Mobile Radio Communication, Berlin, Germany, 2: 1165–1169.

IX Puska H, Saarnisaari H, Iinatti J & Lilja P (2007) Performance comparison of DS/SS code acquisition using MMSE and MVDR beamforming in jamming. Proc. of IEEE Military Communication Conference, Orlando, USA, on CD: 7p.

Contents

Abstract

Preface 7

Abbreviations 9

List of original articles 15

Contents 17

1 Introduction 19

1.1 Background 19

1.2 Motivation 20

1.3 Author's contribution 22

1.4 Outline of the thesis 23

2 Literature review of code acquisition 25

2.1 Signal model 25

2.2 Basic methods for code acquisition 26

2.2.1 Search strategies 26

2.2.2 Detector structures 27

2.3 Performance measures 32

2.4 Performance results in various environments 34

2.4.1 Fading channels 35

2.4.2 Data modulation 38

2.4.3 Doppler effect 38

2.4.4 Intentional interference 39

2.4.5 Multiple-access interference 41

2.4.6 Other system interference 42

2.4.7 Multiple antennas 42

3 Smart antennas 47

3.1 Digital beamforming algorithms 47

3.1.1 Classical beamforming 48

3.1.2 Nullsteering 48

3.1.3 Minimum Variance Distortionless Response 49

3.1.4 MaxSINR 50

3.1.5 Whitening filter 50

3.1.6 Minimum Mean Square Error 51
3.1.7 Space-time beamforming 51
3.1.8 Beam-space techniques 53
3.2 DOA estimation algorithms 54
3.2.1 Conventional techniques 54
3.2.2 Subspace based techniques 55
3.2.3 Maximum likelihood techniques 56
3.2.4 Detection of number of signals 56
4 Summary of the original articles 59
4.1 General 59
4.2 Code acquisition performance under intentional interference 59
4.3 Analysis of synchronization probabilities and mean acquisition times with smart antennas 63
5 Conclusion and discussion 75
References 77
Original articles 89

1 Introduction

1.1 Background

The demand of wireless communications solutions has been increased during the last few decades. This demand has brought along a totally new business opportunities which have had positive effects on many economies. In order to fulfil more demanding communication requirements, a trend in the development of communication systems has taken place from analog to digital systems. Cellular systems have been digital since the 90's, when mobile phones started to use the second generation standard, Global System for Mobile Communications (GSM). Recently, the TV broadcasting system has also changed from analog to digital e.g., in Finland.

In a digital communication system, the original analog information, like speech, is first analog-to-digital (A/D) converted, then compressed and segmented into smaller blocks of data. In the transmitter, each data block proceeds through the protocol stack where each layer inserts its own layer information to the original end user data. Exactly the same protocol stack is sited also in the receiver, because the protocols define common rules for communication. The lowest level of the protocol stack is a physical layer whose task is to carry all information coming from upper layers to the receiver as reliably as possible. In wireless communication systems, the physical layer data which consists of the original end user data, protocol information, and possible control information is transmitted via electromagnetic radiation on a radio frequency (RF) carrier. Because there are multiple users and only one common transmission media, there must be some means (i.e., multiple access methods) to separate those users. Basically, there are four different multiple access methods: frequency division multiple access (FDMA), time division multiple access (TDMA), code division multiple access (CDMA), and space division multiple access (SDMA). Multiple access methods can also be combined (i.e., hybrid approach). This thesis concentrates mainly on CDMA systems, i.e., spread spectrum (SS) systems, where a spreading sequence is used to separate users and spread the spectrum of the transmitted signal. Also smart antennas are covered, which SDMA is based on. In SDMA, multiple users are separated in a spatial domain. Smart antennas (also known as adaptive antennas) are antenna arrays with smart signal processing algorithms used to identify spatial properties, such as the direction-of-arrival (DOA) of the signal. It uses this information for beamforming, i.e., for shaping the radiation pattern of the antenna array. However, the main contribution is in the code synchronization of spread spectrum signals using smart antennas. Code synchronization means time, i.e., delay synchronization and it consists of two phases: code acquisition (initial/coarse synchronization) and code tracking (fine synchronization) of which the initial process is considered in this thesis. The studied acquisition methods are applicable to the other multiple access methods too, if those methods have a separate spreading sequence for synchronization purposes. The most commonly used techniques in spread spectrum communications are direct-sequence (DS) and frequency hopping (FH) modulation schemes and their hybrids (DS/FH). In direct sequence spread spectrum (DS/SS) systems, which is investigated in this thesis, each information symbol in a physical layer is multiplied by a spreading code which consists of L chips. The spectrum spreads because one information symbol is divided into L chips, resulting in a pulse rate which is L times as high as without DS spreading. The receiver gets a benefit against interfering signals from DS spreading at the despreading (i.e., spectrum narrowing) phase. The amount of this benefit is equal to L and it is called the processing gain (PG) of the DS/SS system.

In order to recover the original end user information from the transmitted RF carrier, it is obvious that the communication system requires synchronization at many different levels. Because information is transmitted in a carrier, the receiver needs carrier synchronization where the frequency and phase of the received signal are estimated. In spread spectrum systems, code synchronization is needed to despread the received signal. In order to make symbol decisions, knowledge of the starting and ending time of the symbol is required which is called symbol synchronization. Because information symbols are transmitted in frames, the receiver needs also a knowledge of the starting and ending point of each frame. After frame synchronization, the receiver is able to remove protocol stack overhead from different layers so that the original transmitted end user information can be delivered to the recipient. Sometimes the communication system also needs network synchronization if the number of nodes in the network use a common timing reference.

1.2 Motivation

The high data rate, capacity, and coverage targets of future wireless communications systems require vast improvements in all the layers of wireless networks. It has been shown that the use of multiple antennas will improve communication system performance remarkably. Therefore, multiple antennas will be present in future wireless communication systems. Most of the multiple antenna research is concentrated in enhancing link- or network-level performance figures. It is worth investigating their potential also to improve the code synchronization performance of DS/SS systems. This topic has already been studied in some papers. Multiple antennas can be used either in a diversity mode or in a beamforming mode, depending on the interelement spacing in the antenna array. If antenna elements are widely spaced, then diversity techniques can be used (Rick & Milstein 1997, Park & Oh 1998, Ikai *et al.* 1999, Yang *et al.* 1999, Chang *et al.* 2000, Ryu *et al.* 2002, Je *et al.* 2003, Shin & Lee 2003, Kwon *et al.* 2006, Kwon *et al.* 2007). If antenna elements are closely spaced, then beamforming techniques can be applied. The approach based on beamforming is considered in this thesis.

One of the earliest papers dealing with code acquisition using beamforming has been published by Compton, who experimentally investigated the characteristics of an adaptive analog array in the presence of interference (Compton 1978). A code acquisition structure, where only a single correlator is needed after the beamforming unit, was proposed by Katz (Katz *et al.* 2001b). Therein, the authors investigated a beamforming structure that has as many fixed beams as there are antenna elements in the array. In particular, the basic idea was to divide the whole angular uncertainty (360°) into small angular cells using a simple beamforming technique like a Butler matrix. The result was a two dimensional (2-D) serial search strategy which provides both delay and direction-of-arrival (DOA) estimates. The study was expanded to cover also nonuniform spatial distributions of interference in (Katz *et al.* 2000, Katz *et al.* 2001a, Katz *et al.* 2004). The results showed that the acquisition performance was clearly degraded in this new scenario if a simple beamforming algorithm is used. This is because a simple beamformer offers only limited tolerance against interference. In those papers, the disturbance effects of interference were reduced using a different search strategy, adaptive integration time and adaptive threshold setting schemes, instead of applying interference resistant beamforming, i.e., advanced beamforming. Therefore, there is a need to expand the two-dimensional (delay – angle) code acquisition study to cover also advanced beamforming algorithms.

Even though there are many papers concerning interference cancellation using smart antennas (see Godara 1997, and references therein), there are not many papers which investigate code acquisition performance under interference when the advanced beamforming techniques are used. This thesis expands multi-antenna code acquisition research by introducing an approach where DOA estimation is used to reduce the number of angular cells in the hope of a reduced acquisition time. The investigated code acquisition methods (matched filter (MF) acquisition, serial search, maximum selection, verification) are well known in a single antenna case (e.g., Polydoros & Weber 1984a, Iinatti 2000a), but there is a lack of analysis in the multi-antenna case where DOA information is utilized.

The receiver structure where a correlator is used in each antenna branch was studied in (Wang & Kwon 2000a, Wang & Kwon 2000b, Wang & Kwon 2003b and Wang & Kwon 2003a). In those papers, the outputs of correlators are combined using beamforming and the weights of the beamformer are obtained via least mean square (LMS) adaptation using a pilot channel. Another code acquisition scheme which is based on minimum mean square error (MMSE) beamforming was presented in (Zhang *et al.* 2003 and Zhang *et al.* 2004). In those papers, beamforming weights are also obtained via a pilot channel, and code correlators instead of matched filters are used. MMSE beamforming is an attractive method, since it does not need DOA information. MMSE beamforming can be used in initial code acquisition without pilot symbols if only one period of the known pseudo noise (PN) spreading code is used as a reference signal. This particular scheme is studied in this thesis such that there is a MF in each antenna branch, since it is well known that MF-based acquisition is faster than correlator-based. Analysis of the mean acquisition time for MMSE beamforming is also derived in order to make performance comparisons between MMSE and the above-mentioned delay-angle search methods.

1.3 Author's contribution

The first main contribution of this thesis is to study how different beamforming techniques can be used for fighting against intentional interference during the code acquisition process (Articles I-IV). A radiation pattern can be shaped via beamforming so that maximum gain is directed toward the desired signal and minimum gains toward interfering signals. Because interference suppression is performed in a spatial domain, also wideband interfering signals can be suppressed. The root mean square error (RMSE) of the time delay estimate has been used as a performance measure. Results show that most spatial beamforming algorithms are capable of cancelling multiple different types of interfering signals. If interfering and desired signals are arriving from the same direction (i.e., mainlobe interference), then a more complex space-time processing must be applied. Also, the structures where a separate interference cancellation unit is located either before or after the beamformer are investigated as possible solutions against main-lobe interference.

The second main contribution of the thesis focuses on the theoretical analysis of synchronization probabilities and mean acquisition times (Articles V-IX). Therein, also the DOA of the desired signal is unknown, whereas it is assumed to be known in the first group of articles. The effects of DOA errors on the code synchronization probabilities and mean acquisition times are investigated. Research work of the delay-angle code acquisition (Katz *et al.* 2001b) is extended to cover also the advanced beamforming techniques, because they offer interference suppression capability. Also a method where the DOAs of arriving signals are estimated prior to the acquisition process is proposed. A model for code acquisition using DOA estimation and beamforming is presented and an expression for the mean acquisition time is derived, taking into account all the actions related to array signal processing. Also a MMSE beamforming structure, where only one period of the known PN spreading code is used as a training signal is proposed. This structure avoids a two-dimensional delay-angle search and it has, therefore, a smaller mean acquisition time.

This thesis is based on nine original articles included as Appendices. The basic idea of using beamforming as an aiding device was given by Dr. Harri Saarnisaari who has done a lot of research work in the interference suppression area. Prof. Jari Iinatti introduced the author to the theory of code acquisition. All the papers have been done as team work where, however, the author of this thesis contributed as the main author. The author developed the theoretical models, derived the performance expressions, performed numerical analysis and analyzed the results in all published papers.

1.4 Outline of the thesis

The thesis is organized as follows. Chapter 2 gives an overview of code acquisition literature. It describes commonly used code acquisition methods and gives the basics of the different performance measures used in code acquisition. In addition, the performance results of code acquisition under various environments are reviewed. Chapter 3 gives an introduction to smart antennas, in which especially digital beamforming and DOA estimation algorithms are covered. Chapter 4 concentrates on the author's own research and therefore, a summary of the original papers is presented therein. Finally, conclusions of the main results of the thesis are given in Chapter 5, where also some possible directions for further research are presented.

2 Literature review of code acquisition

2.1 Signal model

The code acquisition problem can be defined using the following signal model. The received signal at the mth antenna element ($m \in [1,\ldots,M]$) is

$$x_m(t) = \sqrt{2S}c(t-\tau)cos(2\pi f_c t + 2\pi f_d t + \phi_m) + i_m(t) + n_m(t), \tag{1}$$

where M is the number of antenna elements, S the received signal power, τ the relative delay between received and reference spreading codes, $c(t)$ the PN spreading code sequence, f_c the carrier frequency, f_d the Doppler shift between the transmitter and receiver, ϕ_m the carrier phase shift, $i_m(t)$ the interfering signal, and $n_m(t)$ the additive white Gaussian noise (AWGN) process. τ is not typically the actual propagation delay since there are multiple code periods between transmitter and receiver. Using the narrowband signal assumption, all signals in different antennas can be expressed in a vector form as

$$\mathbf{x}(t) = \sqrt{2S}c(t-\tau)cos(2\pi f_c t + 2\pi f_d t + \phi)\mathbf{a}(\theta_0) + i(t)\mathbf{a}(\theta_i) + \mathbf{n}(t), \tag{2}$$

where $\mathbf{a}(\theta_0)$ is the array steering vector, which consists of carrier amplitude and phase shifts in different antenna elements when the DS/SS signal is arriving from direction θ_0, ϕ the carrier phase shift of the DS/SS signal at the reference antenna, $i(t)$ the interfering signal, $\mathbf{a}(\theta_i)$ the steering vector of the interfering signal, θ_i the DOA of the interfering signal, and $\mathbf{n}(t)$ the vector of noise signals in all antennas, respectively. The array steering vector depends on the array geometry, calibration, etc., and is assumed to be known in the receiver. Narrowband assumption is usually valid in array signal processing, because the carrier frequency is normally much higher than the bandwidth (W) of the desired signal. Under narrowband assumption, $c(t) \approx c(t-\Delta)$, where Δ is the maximum time delay from the first to last antenna element. The DS/SS signal is usually narrowband from the array signal processing point of view, although it is wideband compared to the data symbol rate.

In DS/SS-systems, the spectrum of the transmitted data signal is spread by multiplying it with a *spreading* code sequence. The receiver has to remove the effects of carrier and DS spreading modulations, so that the transmitted data symbols can be demodulated successfully. This thesis concentrates on an estimation of τ, where the temporal position of the received code phase is estimated. After code synchronization, the receiver is able to remove DS spreading by multiplying the received signal with the local synchronized reference spreading code $c(t-\hat{\tau})$, where $\hat{\tau}$ is an estimate of τ. This procedure is denominated as *despreading* in spread spectrum communication literature. The code synchronization process is typically split into two stages: *code acquisition* where an integer part of τ/T_c (coarse synchronization) and *code tracking* where a fractional part of τ/T_c is estimated (fine adjustment). Normalization factor T_c is the chip time. Since this thesis concentrates on code acquisition, the next section will describe how a coarse estimate of τ/T_c can be found.

2.2 Basic methods for code acquisition

2.2.1 Search strategies

The term search strategy is used when we are talking about the strategy to find the correct code phase. If there is not *a priori* information about τ, the timing uncertainty is the whole spreading code period. Thus, if a spreading code consists of L chips, then the timing uncertainty is LT_c, depicted in Fig. 1. In code acquisition, the whole timing uncertainty area is divided into finite number of small delay cells, and the quantized timing uncertainty region is defined as the total number of those delay cells to be searched. Therefore, the size of the quantized timing uncertainty region depends on the quantizing interval, which may be selected to be equal to the T_c but it can be also smaller.

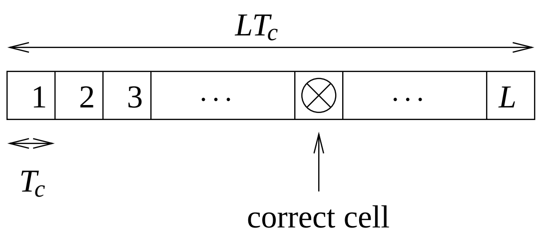

Fig 1. Time uncertainty region.

The most typically used search strategies for code acquisition are the *serial search* and *parallel search* schemes. Classification into parallel and serial search can be made according to how many cells are investigated in parallel. If the number of simultaneously investigated cells is higher than one, then the strategy used is refered to as a parallel search and otherwise a serial search. In an extreme parallel search scheme, all the cells inside an uncertainty region are investigated simultaneously. This method has been studied in (Milstein *et al.* 1985, Davisson & Flikkema 1988, Cheng 1988). It will largely reduce the acquisition time at the expense of an increased implementation complexity of the receiver, because there must be one correlating element per each uncertainty cell. However, it is optimal in the sense that it finds a correct delay cell as fast as possible. The number of parallel correlating elements can also be smaller than was used in the previous method. Such a scheme has been studied in (Sourour & Gupta 1989, Sourour & Gupta 1992, Chawla & Sarwate 1994, Srinivasan & Sarwate 1996).

The serial search scheme is a very commonly used acquisition strategy, because only a single correlating element is needed there. In the serial search scheme cells inside an uncertainty region are investigated serially in a predetermined order until a correct one is found. The decision of the correct cell is made using a detector, where the decision variable is compared to a detection threshold. If the threshold is exceeded, then the investigated cell is considered as a correct one. The cells inside the uncertainty region are searched in an order which depends on the amount of *a priori* information about the correct code phase. If there is no *a priori* information, then the simplest straight-line serial search scheme is typically utilized. If there is some *a priori* information, then more sophisticated search strategies, like Z-search or expanding window, could be used to improve synchronization performance (Polydoros 1982, Polydoros & Weber 1984a, Polydoros & Weber 1984b). The serial search acquisition scheme was originally presented in (Sage 1964). Hybrid serial-parallel search schemes have been proposed in (Milstein *et al.* 1985, Zhuang 1996, Baum & Veeravalli 1994).

2.2.2 Detector structures

The detector is another very important element in the acquisition circuit. The search strategy tells which cell will be investigated next and the detector makes a decision whether this cell corresponds to the synchro position or not. The detector can be divided further into two operational blocks: *decision variable calculation* and *threshold comparison*, as depicted in the block diagram of Fig. 2.

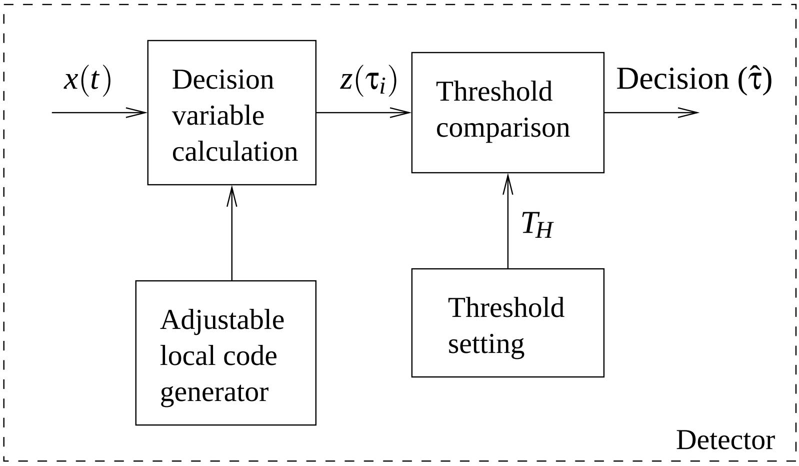

Fig 2. Detector structure.

Decision variable calculation

In the decision variable calculation process, such a decision variable $z(\tau_i)$ is determined from which the decision about synchro or nonsynchro position can be made as reliably as possible. It has been shown in (Polydoros 1982) that in the AWGN channel, and without data modulation, the optimal method to calculate a decision variable is to correlate the received signal $x(t)$ with the local reference signal as

$$z(\tau_i) = \int_0^{T_d} x(t)c(t-\tau_i)cos(2\pi f_c t + 2\pi f_d t + \phi)\, dt, \tag{3}$$

where τ_i is a delay cell which is presently under investigation, and T_d is known as the *integration time*, *dwell time* or *observation time*. Dwell time can be fixed or variable, where the latter is also known as sequential detection (Polydoros 1982). Most of the studies dealing with code acquisition are based on fixed-dwell time detectors, but some approaches based on variable-dwell time detectors are studied in (Gumacos 1963, Davidovici *et al.* 1984, Su & Weber 1990, Ravi & Ormondroyd 1991, Wang & Sheen 2000, Lin 2002). It can be observed from (3) that f_c, f_d and ϕ must be known before correlation. This is known as *coherent detection*. Usually, coherent detection is not used, because estimation of the carrier phase is difficult from the DS/SS-signal which has a low signal-to-noise ratio (SNR). However, it has been studied in some references (Davidovici *et al.* 1984, Jianlin & Tantaratana 1995, Madhow & Pursley 1995, Salih

& Tantaratana 1996, Iinatti 1997, Salih & Tantaratana 1999, Delva & Howitt 2001) due to simplified analysis. Therefore, code synchronization is normally carried out before carrier synchronization using *noncoherent detection*. In the noncoherent receiver, a decision variable is calculated either via an *envelope detector*

$$z(\tau_i) = \sqrt{z_I^2(\tau_i) + z_Q^2(\tau_i)} \text{ or a } \textit{square-law detector } z(\tau_i) = z_I^2(\tau_i) + z_Q^2(\tau_i), \tag{4}$$

where the in-phase (z_I) and quadrature (z_Q) correlations are defined as (Polydoros 1982)

$$z_I(\tau_i) = \frac{\sqrt{2}}{T_d} \int_0^{T_d} x(t)c(t-\tau_i)cos(2\pi f_c t + 2\pi f_d t)\, dt \tag{5}$$

and

$$z_Q(\tau_i) = \frac{\sqrt{2}}{T_d} \int_0^{T_d} x(t)c(t-\tau_i)sin(2\pi f_c t + 2\pi f_d t)\, dt. \tag{6}$$

The third type is the *differentially coherent* (DC) detector structure, which is studied in (Chung 1995, Zarrabizadeh & Sousa 1997, Iinatti & Pouttu 1999). Decision variable in the DC detector is obtained by multiplying the present and delayed samples among themselves. It has been shown in (Zarrabizadeh & Sousa 1997) that the DC detection offers about 4-5 dB improvement in performance compared to the noncoherent detection. Coherent detection has the best performance, but unfortunately it cannot be used in practice.

The correlation between the received and local codes can be performed using an *active* or *passive* correlation method depicted in Fig. 3. In the active correlation method, the conventional *correlator* structure is used. Therein, the received and local codes are multiplied on a chip-by-chip basis and then integrated over T_d. Therefore, decision variables are generated at a rate of $1/T_d$. The term active refers to the fact that a code phase under investigation must be actively set during the code acquisition process. The second alternative is to use a passive correlating unit, where correlation is performed using the code *matched filter* instead of the correlator. Therefore, this method is known as MF acquisition, where the impulse response of the MF is time-reversed and a delayed version of the spreading code in some predetermined code phase. With these settings, a MF performs exactly the same correlation operation as was calculated in active correlation. The only difference is the rate at which decision variables are generated. In MF acquisition, integration time is typically the whole spreading code, i.e., over L chips. Chips are correlated simultaneously in MF operation and, thus, decision variables from MF output are achieved at rate $1/T_c$. So, if the integration time is the same in both cases, then passive MF acquisition produces decision variables L times as fast as in the active correlator. The term passive refers to the fact that the receiver waits until the received code phase matches with a predetermined code phase. The active correlator and passive MF approaches are studied in more detail in (Polydoros & Weber 1984a, Polydoros & Weber 1984b, Rappaport & Grieco 1984). The output signal of an active or passive correlation unit is proportional to the autocorrelation function of the spreading code. Since the used spreading codes have been especially designed to have good autocorrelation properties, in an AWGN channel there occurs a clear spike at a time instant when the received and local codes are synchronized.

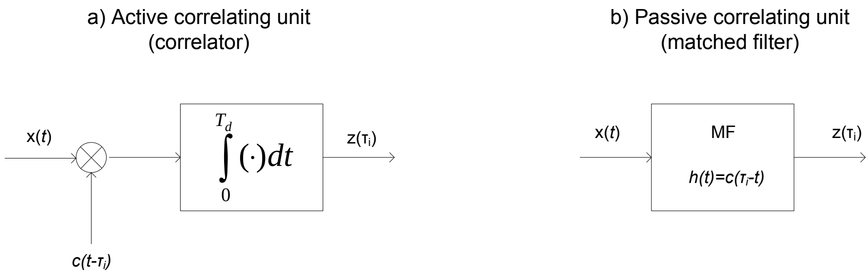

Fig 3. Active and passive correlation units (Katz 2002).

Threshold comparison

In threshold comparison, a decision variable $z(\tau_i)$ is compared to a threshold T_H (Fig. 2) in order to make a decision about a cell which is presently under investigation. The threshold is set above the noise level but below the main peak of the autocorrelation function. If the threshold is exceeded, then the detector makes a decision that a synchro cell has been found and synchronization process enters to the code tracking mode. If the threshold is not exceeded, then the detector decides that a nonsynchro cell has been found and acquisition process will continue to a next code phase, which is determined by the search strategy. A decision made by a detector can be either correct or wrong because $z(\tau_i)$ is a random variable. If an actual synchro cell is under investigation, then it is detected correctly (i.e., the threshold is exceeded) with probability of detection P_D or missed (i.e., the threshold is not exceeded) with probability of miss $P_{miss} = 1 - P_D$. Correspondingly, if a nonsynchro cell is under investigation, then it is wrongly detected (i.e., a threshold is exceeded) with a probability of false alarm P_{FA} and correctly (i.e., a threshold is not exceeded) with probability $1 - P_{FA}$.

The threshold setting is a critical phase in a detector, because it affects P_D, P_{FA} and, thus, to the overall performance of the acquisition system. The threshold value can be based on the Neyman-Pearson decision criterion if all the cells have the same threshold value (Polydoros 1982). This criterion leads to a detector, which has a fixed P_{FA} in each cell. When *a priori* information on the synchro cell is available, the Bayesian type of detector can be used where the threshold can be different for each cell (Polydoros 1982). Then, lower thresholds are used for probably correct cells. However, some parameters like noise variance are typically unknown in the receiver. If estimated parameter values instead of actual ones are used in detection, then the detector is called as a generalized likelihood ratio test (GLRT) or a constant false alarm rate (CFAR) detector (Kay 1998).

Fixed thresholds can be used in stable channel conditions, but in dynamic channel conditions, where interference is present, adaptive threshold schemes are used. Since the threshold should be set above the noise level, the detector has to estimate noise power that prevails just before threshold comparator. After noise power estimation, the threshold value can be solved theoretically from the probability density function (PDF) of the signal coming into the comparator, as in (Rappaport 1969), to obtain a CFAR threshold. There are also threshold setting schemes where SNR or interference-to-signal ratio (I/S) estimators are used to control the threshold (Siess & Weber 1986). Instead of estimating noise power, SNR or I/S, methods exploiting a reference filter for threshold setting are also investigated. In those methods, an impulse response of the reference filter is orthogonal to the original PN sequence (Ziemer & Peterson 1985, Ibrahim & Aghvami 1994). An adaptive threshold setting based on a calculated number of crossings during a given amount of code periods is proposed in (Glisic 1988a). After that, the threshold can be adjusted by a small increment toward the target crossing-rate. Instantaneous threshold setting and CFAR algorithms are analyzed in (Glisic 1988b). A rank filter based threshold setting is considered in (Iinatti 1996), and a median filter based scheme in (Stojanovic & Jovanovic 1992). Wide comparisons between the different threshold setting methods and the maximum-selection method is studied in (Iinatti 2000a). An adaptive threshold setting, which is based on the output power estimation of an adaptive antenna array is considered in (Wang & Kwon 2000b). It is shown in (Lee & Kim 2001, Lee & Kim 2002) that the use of multiple thresholds improves the acquisition performance compared to the single threshold approaches.

The methods considered so far make a cell decision based on a single-dwell. This is not effective from the acquisition time point of view, because the same dwell-time is spent on testing the nonsynchro cells than the synchro cell. Therefore, multiple-dwell approaches have been developed to reduce the acquisition time (DiCarlo & Weber 1983). In multiple-dwell acquisition, the first test level is followed by one or more observations of the same cell, if the first threshold is exceeded. This allows the checking of nonsynchro cells rapidly, because a shorter integration time is used in the first test. If the first threshold is exceeded, then the correctness of the first decision is verified by equal length or longer observation, thus avoiding false alarms. The synchro cell is declared only after all the stages indicate a synchro cell position. Multiple-dwell acquisition is classified as the immediate rejection scheme if the acquisition process immediately moves on to the next cell only after one failure in synchro cell detection at any dwell stages. There are also more advanced multiple-dwell approaches, like the two-step rejection and the up-down counter method, where past behavior of the cell is taken into account before rejecting it (Simsa & Triska 1994, Triska & Simsa 1994, Eynon & Tozer 1995).

2.3 Performance measures

The ultimate task of the code acquisition subsystem is to coarsely phase-align the received and local spreading codes. Success of this task can be measured in many different ways, as can be seen from the wide literature on the topic. This section will give an overview of different performance measures used in code acquisition. First of all, a code tracking loop requires that the error between received and local PN codes does not exceed half of a chip duration after the code acquisition process has concluded. Therefore, one alternative is to perform a delay estimation for the received signal and then evaluate an amount of error of this estimate. According to Polydoros (1982) in a noncoherent receiver, the maximum likelihood (ML) method for delay estimation in a AWGN channel is the structure shown in Fig. 4.

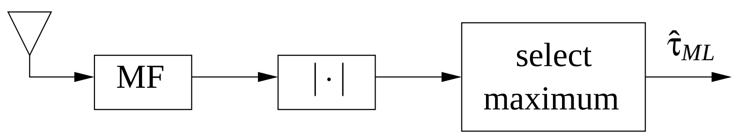

Fig 4. ML receiver for delay estimation in AWGN channel.

More precisely, the ML receiver correlates the received signal with the spreading code, then performs envelope detection and finally makes such a decision that the ML delay estimate $\hat{\tau}_{ML}$ is a time instant which corresponds to the maximum of the envelope detector output within a given time frame. The ML estimate is defined as the value of the unknown parameter for which the likelihood function is maximized. RMSE of delay estimate is an often used performance measure in delay estimation literature and it can be calculated in chips as

$$\mathrm{RMSE}\left(\frac{\hat{\tau}_{ML}}{T_c}\right) = \sqrt{\mathrm{MSE}\left(\frac{\hat{\tau}_{ML}}{T_c}\right)} = \sqrt{E\left\{\frac{\tau - \hat{\tau}_{ML}}{T_c}\right\}^2}. \tag{7}$$

If the RMSE of delay estimate is smaller than half of a chip time, it can be concluded that code acquisition succeeds, but it does not tell that how much time this takes. In delay estimation, we either have to take multiple samples from one chip or use interpolation in order to get more accurate estimates. In an extreme case, the receiver should have an infinite number of values within the uncertainty region and perform the impossible task of correlating the received data with the infinite number of code shifts and choose the maximum. Therefore, the uncertainty region is quantized into small fragments or "cells" in order to simplify the implementation of the receiver. Thus, the estimation problem is transformed into a multiple-hypothesis testing problem (Polydoros 1982). Therefore, the papers which are dealing with estimation are interested about the question of how well a parameter can be estimated under an assumption that the uncertainty region is not divided into cells and all decision variables can be calculated simultaneously. They are not dealing with the question of how much time it takes to find the parameter.

When a suboptimal but implementable receiver structure is used, where the uncertainty region is quantized into small cells, then new performance measures are introduced. The goal of the code acquisition unit is now to decide which one of all the possible discrete code phases is within a cell's distance from the phase of the received code. Therefore, synchronization probabilities (P_D, P_{FA} and P_{miss}) can be considered as performance measures. Most often in code acquisition literature we are interested about the total acquisition time T_{ACQ} which is consumed during the acquisition process. This is a widely used performance measure, because it includes the effects of multiple design parameters (threshold setting, correlation time, number of cells, search strategy, verification, code length, penalty time of false alarm, SNR, etc.). When T_{ACQ} is used as a performance measure, then two basic scenarios can be distinguished based on the existence of the stopping time T_{stop} (Polydoros 1982). If the radio link operates continuously, then the time limit T_{stop} does not exist, which defines when the synchronization must be finished. In this case the most important parameter is the mean acquisition time $T_{MA} = E\{T_{ACQ}\}$ and sometimes also the variance of acquisition time $\sigma^2_{T_{ACQ}}$ (Polydoros 1982). The mean acquisition time should be as short as possible. In burst or packet like communications, initial synchronization should take place before data reception starts, i.e., before the time limit T_{stop}. Then the better performance measure is the probability of acquisition $P_{ACQ} = P\{T_{ACQ} \leq T_{stop}\}$, which should be as high as possible. P_{ACQ} is also called the overall probability of detection P_D^{ov} and its complement as the overall probability of missing the code $P_{miss}^{ov} = 1 - P_D^{ov}$ (Polydoros 1982).

Because the acquisition time is a random variable, it has PDF $f_{ACQ}(t)$ which can be used in derivation of aforementioned performance measures. This method is also known as the direct approach and it is based on the algebraic characterization of the search strategy (DiCarlo & Weber 1980, Braun 1982, Weinberg 1983, Meyr & Polzer 1983, Jovanovic 1988, Jovanovic 1992, Corazza 1996, Pan *et al.* 1995, Simsa 1996). However, a closed-form expression for $f_{ACQ}(t)$ is often difficult to obtain. Performance measures T_{MA}, $\sigma^2_{T_{ACQ}}$ and P_{ACQ} can also be obtained without knowledge of the $f_{ACQ}(t)$ using signal flow graph techniques in the transform domain (Holmes & Chen 1977, Polydoros 1982, DiCarlo & Weber 1983, Polydoros 1984). Therefore, the former method is known as the time domain technique and the latter as the transform domain technique.

Because the T_{MA} is the total time expected to be consumed from the start to the end of the acquisition process, the two most important issues which affect it are the search strategy and the detector structure which were discussed in Section 2.2. The detector brings along a set of parameters T_H, P_D, P_{FA}, T_d, and the false alarm penalty time T_{FA}, which all have an impact on the T_{MA}.

2.4 Performance results in various environments

A review of code acquisition performance results in various environments are presented in this section. Most of the code acquisition literature considers the situation where only AWGN is disturbing reception (e.g., Holmes & Chen 1977, Polydoros & Weber 1984a, Polydoros & Weber 1984b). In addition to AWGN, there may be also other sources of disturbance which are considered separately in the following subsections.

2.4.1 Fading channels

When a signal is transmitted through a radio channel, the received signal consists of multiple copies of the transmitted signal due to multipath propagation. The impulse response of the radio channel is time-variant, because the propagation delay, attenuation factor and phase shift of each path are changing with time. Therefore, the impulse response of the typical radio channel fluctuates and it is modeled as a stochastic process $c(\zeta;t)$, where ζ is the propagation delay, and t denotes that impulse response is changing with time. In a non-line-of-sight (NLOS) environment, $c(\zeta;t)$ is modeled as a zero-mean complex valued Gaussian process and its envelope $|c(\zeta;t)|$ is Rayleigh distributed. Such a channel is said to be a *Rayleigh fading channel*. If there is a line-of-sight (LOS) component, then $|c(\zeta;t)|$ is Ricean distributed and the channel is said to be a *Ricean fading channel*. (Proakis 1995)

Coherence bandwidth (B_{coh}) of the channel is inversely proportional to the *multipath spread*, so it is related to the spread of time parameter ζ. If the bandwidth of the transmitted signal ($W \approx 1/T_c$) is much smaller than B_{coh}, then all of the frequency components in the transmitted signal undergo the same attenuation and phase shift, and the channel is called *frequency-nonselective* or *flat fading*. In this case, the multipath components in the received signal are not resolvable. If the multipath spread of the channel is greater than the chip length of the spreading code (i.e., $W \gg B_{coh}$), the multipath components can be resolved into a discrete number of paths and the channel is called *frequency-selective* since frequency response is not flat within the transmitted signal's bandwidth. The bandwidth of a DS/SS signal is typically designed to be larger than B_{coh}, because it allows frequency diversity to be utilized via the Rake receiver. This is one advantage of spread spectrum systems. (Proakis 1995)

Another way of characterizing a radio channel is by the time variation t in $c(\zeta;t)$. *Coherence time* (T_{coh}) is inversely proportional to the *Doppler spread*. When a transmitter, a receiver, or a reflector in the environment is moving, then the received frequency is different than the transmitted frequency and the amount of this frequency difference is called the Doppler shift. Since each multipath component has its own Doppler shift, the spread of these Doppler shifts is known as the Doppler spread. The radio channel can be classified as *slow-fading* if the symbol time (T_s) is much smaller than T_{coh}. In this case, the channel remains fixed during the symbol interval. If $T_s \gg T_{coh}$, then the channel is called *fast-fading*. (Proakis 1995)

Typically, fading channels are categorized according to their fading rate by comparing the channel coherence time to the duration of a symbol, as was described above. However, from the code acquisition point of view, it is more reasonable to compare T_{coh} against the duration of the acquisition process itself. Therefore, in the slow fading channels $T_{coh} \gg T_{MA\_max}$, where T_{MA_max} is the maximum expected acquisition time. This condition means that the channel remains unchanged during the entire code acquisition process. When a new code acquisition process starts, there is also a new realization of the channel. In the fast fading channels $T_{coh} \ll T_{MA\_min}$, where T_{MA_min} is the minimum expected acquisition time. The above condition means that the channel will pass through all the states every time the cell is searched. (Katz *et al.* 2002b)

Code acquisition in a frequency-nonselective Rayleigh fading channel is studied in (Sourour & Gupta 1990), where the receiver includes parallel MFs. It is found that frequency-nonselective Rayleigh fading causes a severe degradation in acquisition performance. That is because the fading channel causes amplitude fluctuations, which deteriorates P_D performance. Another result is that in the nonfading channel it is advantageous to increase the MF length, i.e., decrease the number of parallel MF's, while in the fading channel, the opposite is true. Thus, the parallelism improves performance more in a fading channel than in a static channel if compared to the serial search approach. Acquisition performance in frequency-nonselective and frequency-selective Ricean fading channels is studied in (Sourour & Gupta 1992), where the parallel MF acquisition scheme is investigated. It is concluded that frequency-selective fading is causing more degradation to the acquisition time performance than the nonselective channel. The degradation increases when the specular component becomes weaker. Analysis of MF code acquisition with a reference filter in frequency-nonselective and frequency-selective Rayleigh fading channels is presented in (Ibrahim & Aghvami 1994). It is again concluded that frequency-selective fading causes more degradation in performance compared to the frequency-nonselective channels. Code acquisition in a frequency-selective Rayleigh fading channel using a least mean square (LMS) adaptive filter is studied in (El-Tarhuni & Sheikh 1998b). Therein, both slow- and fast-fading cases are investigated. The results show that flat fading degrades the performance by about 3 dB while frequency selective fading has only a 0.5 - 2 dB degradation, compared to the AWGN case. The degradation using this adaptive filter structure is much less than which was reported in (Sourour & Gupta 1990), where parallel MFs were utilized. Thus, the paper presented by (El-Tarhuni & Sheikh 1998b) concludes that frequency selective fading produces less degradation than flat fading since the system can exploit the inherent multipath diversity when acquiring the strongest available path. This is a different result than that which was presented before.

A differentially coherent detection technique for acquisition in a frequency-nonselective fast Rayleigh fading channel is proposed in (Chung 1995). It outperforms the conventional noncoherent method. In (Tantaratana *et al.* 1995), a noncoherent sequential acquisition is investigated for AWGN and slowly Rayleigh fading channels. Results indicate that fading does not affect the false alarm probabilities, but it can drastically reduce the probability of detecting the alignment of the two PN sequences. Optimal decision strategies for code acquisition in frequency-selective fading channels are analyzed in (Rick & Milstein 1998) when full parallel search is utilized. Code acquisition is studied in static multipath and fading multipath channels in (Iinatti 2000b), where equations for the mean acquisition time in the multipath environment are derived. Results indicate that the T_{MA} performance in the static channel is better than in the slow-fading channel. On the other hand, the T_{MA} performance in the static channel is worse than in the fast-fading channel. Code acquisition based on multiple-dwell or sequential linear tests are investigated for Rayleigh fading channels in (Wang & Sheen 2000, Lee & Kim 2002). Novel methods to analyze code acquisition over correlated fading channels are proposed in (Sheen & Wang 2001, Corazza *et al.* 2004, Caini *et al.* 2004), where the channel memory incurred by fading between different cell detections is taken into account. An interesting proposal for a serial-search strategy exploiting the possible knowledge of the multipath delay spread is reported in (Shin & Lee 2001), where consecutive tests are performed on cells which are separated by the number of resolvable paths. The proposed acquisition scheme significantly outperforms the conventional schemes over frequency-selective Rayleigh fading channels. The method where the energy of all the multipath components are utilized already at the acquisition stage is proposed in (Iinatti & Latva-aho 1998, Iinatti & Latva-aho 2001). Acquisition with a Rake receiver is studied in (Garrett & Noneaker 1998, Glisic & Katz 2001). Delay estimation in a direct sequence code division multiple access (DS/CDMA) system operating over fading channels is studied e.g., in (Ström & Parkvall 1995, Ström *et al.* 1996a, Ström & Malmsten 1998).

2.4.2 Data modulation

Acquisition of the DS/SS signal is often accomplished in the absence of data modulation to speed up the acquisition process. However, there are cases when it becomes necessary to acquire the incoming code in the presence of data modulation, e.g., re-acquisition. It is shown in (Siess & Weber 1986) that the detection probability of an active noncoherent I-Q detector degrades considerably when the DS/SS is binary phase shift keying (BPSK) modulated. This degradation can be partially overcome by using multiple receivers to make the decision such that each receiver is tuned to expect a data bit transition in a different position within the correlation period. In so doing, one is able to attain a high P_D in at least one of the receivers. Another approach to avoid data degradation is to divide the integration interval into several subintervals which are then noncoherently combined for decision making (Cheng 1988, Cheng *et al.* 1990, Davisson & Flikkema 1988).

The optimal ML code acquisition scheme with data modulation is presented in (Li & Tantaratana 1995). However, the ML scheme is not practical for implementation, so the authors presented several suboptimal schemes. The results show that these suboptimal schemes have almost the same performance as conventional schemes when there is no data modulation and significantly better in the presence of data modulation. Correspondingly, optimal and suboptimal noncoherent code acquisition methods with data modulation are considered in (Su *et al.* 1998, Kwon & Tarafder 1996). Maximum likelihood code acquisition in the presence of multipath propagation, Doppler shift and data modulation is considered in (Wetzker *et al.* 1998). Differentially coherent code acquisition in the presence of data modulation is studied in (Iinatti & Pouttu 1999) and differentially noncoherent in (Pirhonen & Ristaniemi 2002). The results show that differentially coherent scheme with data removal unit offers about 4 dB improvement in performance compared to the noncoherent acquisition. A fast code acquisition scheme based on fast Fourier transform (FFT) and noncoherent integration is proposed in (Chen *et al.* 2007).

2.4.3 Doppler effect

The Doppler effect is caused by the relative movement between transmitter and receiver. It shifts the received carrier frequency and code rate, so the Doppler effect can be divided into the carrier Doppler and code Doppler, respectively. The carrier Doppler causes a significant reduction of the correlation peak and SNR (Polydoros 1982, Mauss *et al.* 1993). The code Doppler has to be taken into account only if the carrier Doppler is large (Cheng *et al.* 1990), and hence the carrier Doppler is the most commonly investigated Doppler effect in code acquisition literature. If the code Doppler can be considered as insignificant, then we have a two-dimensional (time – frequency) uncertainty region from which the correct delay and carrier frequency must be found (Holmes & Chen 1977, Peterson *et al.* 1995). Two-dimensional search can be performed by changing both the center frequency and code phase of the receiver. However, the actual carrier Doppler is usually not an integer multiple of the cell spacing, a fractional carrier Doppler still remains after the searching process is completed. The article (Yoon *et al.* 2008) introduces a new method which can be used for fighting against fractional carrier Doppler.

If the code Doppler cannot be considered as insignificant, then time varying timing offset causes problems and a two-dimensional time-frequency search cannot be directly applied. A highly parallel scheme is proposed in (Cheng *et al.* 1990), where the local reference signal of each parallel unit is adjusted such that the corresponding carrier and the code Doppler offsets are compensated. This requires a large number of parallel units, but it caused only 3 dB SNR loss compared to the case when there are no carrier and code Doppler offsets. The code Doppler problem is investigated also in (Fuxjaeger & Iltis 1994), where a short duration correlation is used to acquire timing information and a subsequent longer correlation to acquire the Doppler velocity. Code Doppler has an effect on the probability of detection and on the search rate of the acquisition process, and thus on the mean acquisition time (Holmes & Chen 1977, Simon *et al.* 1994, Bezueha 2002). The code acquisition in the presence of both carrier and code Doppler is investigated in (Su *et al.* 1995).

2.4.4 Intentional interference

The receiver may encounter also intentional interfering signals, which are especially designed to hinder the receiver's operation. These signals are also known as jamming signals. In order to ensure successful synchronization and data detection under interference, it has been necessary to develop different types of interference cancellers. In single antenna systems, interference cancellation methods are based on either a time or frequency domain analyzing and processing of signals. An overview of these methods is presented in (Milstein 1988a). Examples of frequency domain interference cancellers are the notch filter (Davidovici & Kanterakis 1989), the phase interference extractor (Kanterakis 1994), the consecutive mean excision (CME) (Henttu & Aromaa 2002), and the forward consecutive mean excision (FCME) (Saarnisaari & Henttu 2003) algorithms. Time domain interference cancellation can be realized using adaptive filtering (Gardner 1993, Zhang *et al.* 1999), constant modulus algorithm (Mendoza *et al.* 1989), and singular value decomposition (Henttu 2000). The combined time-frequency interference cancellation is studied in (Tazebay & Akansu 1995). Many of those methods are capable of suppressing only narrowband interfering signals, but some wideband interference cancellation methods are proposed in (Gardner 1993, Henttu 2000). Jamming signals can also be suppressed using smart antennas, in which case interference cancellation is accomplished in a spatial domain. This is one of the main topics of this thesis, thus it is studied in more detail in Chapters 3 and 4.

The effects of interference on the code acquisition performance is studied in some papers. It is shown in (Siess & Weber 1986) that the performance of initial code acquisition is very sensitive to sinusoidal and pulsed interference. Authors also concluded that the sinusoidal interference is an optimal interference in some situations causing the highest damage. Sinusoidal interference is also known as tone or continuous wave (CW) interference. The study of sinusoidal interference is extended to sequential detectors in (Ravi & Ormondroyd 1992). Interference suppression or rejection techniques are also studied in context of code acquisition. A transform domain notch filter is proposed in (Milstein 1988b) to suppress strong sinusoidal interference. The notch filter was designed to null-out 10% of the spread-spectrum bandwidth. The results show that the notch filter can significantly improve acquisition performance under sinusoidal interference. The linear prediction filter as an interference suppressor is studied in (Gottesman & Milstein 1990). The results indicate that at small interference bandwidths, the linear prediction filter system outperforms the transform domain notch filter system. On the other hand, at larger interference bandwidths, the transform domain notch filter system outperforms the linear prediction filter system. The strategy where the median filter is placed after the matched filter is proposed in (Iinatti 1997). Therein, the effects of sinusoidal and pulsed interference on code acquisition are investigated. The results show that the combination of matched filter and median filter is robust against investigated interference types, and its performance is better or equal than that of the transversal filter approach.

It can be concluded that sinusoidal interference is not a good choice for jamming, since its cancellation is relatively easy. Narrowband interfering signals can also be cancelled using a phase interference extractor (Saarnisaari 2000) and a whitening filter (Saarnisaari 2001). Performance of differentially coherent code acquisition under sinusoidal interference is studied in (Ristaniemi & Pirhonen 2002). Differentially coherent and differentially noncoherent acquisition schemes under narrowband interference are considered in (Iinatti & Pouttu 1999) and the study is extended to cover also wideband interference in (Iinatti & Pouttu 2000). The results show that both schemes outperform conventional noncoherent MF code acquisition. In the wideband interference study, bandwidths of interfering signals were 20% and 100% of the DS/SS signal bandwidth. The results indicate that the differentially coherent approach is robust against low-powered wideband interference.

2.4.5 Multiple-access interference

The other users of the same CDMA system cause so called multiple-access interference (MAI) for each other, because the spreading codes of different users are not fully orthogonal. If there is a large number of users, then the central limit theorem can be applied to model the MAI as a Gaussian process, which increases the total noise power (Corazza 1996, Zhuang 1996). Noise enhancement naturally reduces P_D and deteriorates T_{MA} performance. It has been shown in (Madhow & Pursley 1993) that the acquisition based capacity of a CDMA system may be smaller than the bit error rate (BER) based capacity, if a coherent detector without verification is used. However, the verification mode makes the acquisition process more robust against the MAI (Corazza & Degli-Esposti 1994). Multiple-access interference cannot be necessarily modeled as a Gaussian process if there are only a few users or they have different data rates. Then, the effect of MAI can be analyzed by mapping it to the search process as a source of disturbing signal (Katz & Glisic 1998, Katz & Glisic 2000).

Different kinds of acquisition structures have been proposed to be applied in the presence of MAI. A two-stage hybrid acquisition method based on passive and active correlation can achieve rapid acquisition in the absence of a near-far problem (Madhow & Pursley 1995). If there is a near-far problem, it has a considerable degrading effect on the acquisition based capacity (Corazza & Degli-Esposti 1994). In that case such receiver structures must be developed which take the MAI into account. Typically these structures contain a separate MAI cancellation unit just before an acquisition circuit like in (Madhow 1997, El-Tarhuni & Sheikh 1998a, Smith & Miller 1999, Lee & Kim 2001, Bharadwaj & Buehrer 2004). A code acquisition method where two cascaded matched filters are employed is proposed in (Kim *et al.* 2001). Code acquisition algorithms which utilize differential correlations are investigated for CDMA systems in (Ristaniemi & Joutsensalo 2001). It was shown that the receiver can efficiently filter noise and interference when a constant preamble or an unmodulated pilot channel is available for the desired user. Pilot-aided synchronization is studied also in (Ristaniemi 1999b, Ristaniemi 1999a). The propagation delay estimation problem under a near-far effect is studied in (Ström *et al.* 1996b). The code acquisition performance of CDMA systems with antenna array is studied in (Kim 2004, Kim 2005). The results show that antenna arrays significantly improve the acquisition performance over the case of a single antenna. Code acquisition under severe MAI conditions with multiple antennas is studied in (Reed 2004, Reed *et al.* 2008).

2.4.6 Other system interference

Other communication systems which utilize the same frequency band can disturb the reception of DS/SS signals. This kind of situation is denominated as a CDMA overlay system. In (Gottesman & Milstein 1996) a linear prediction filter is used to suppress narrowband users. The results show that narrowband overlay interference can be effectively eliminated using the proposed scheme. When the bandwidth is larger, the performance deteriorates due to a wider notch. The performance of a linear prediction filter structure is also very dependent on the interference power. An interference suppression filter is employed also in (Kim 2001) to suppress narrowband overlay interference. The performance of the subspace and MMSE based code acquisition techniques under overlay interference are compared in (Miller 1995). The results show that both of these techniques are robust towards narrowband interference and near far cochannel interference. Code acquisition for a DS/CDMA overlay system with imperfect power control is analyzed in (Kim & Lee 1997). Generally, the same kind of interference cancellation methods can be applied as in the case of intentional interference.

2.4.7 Multiple antennas

When multiple antennas are utilized, then two basic techniques can be distinguished depending on the distance between antenna elements. If the antenna elements are widely spaced (i.e., the distance between antenna elements is at least few wavelengths), then antenna diversity techniques can be exploited. If antenna elements are closely spaced (i.e., the distance between antenna elements is at most half a wavelength), then beamforming techniques can be exploited.

Widely spaced antenna elements ensure that signals in different antennas undergo independent fading processes. This property is used in antenna diversity techniques to improve SNR in fading channels. However, the signals of different diversity branches cannot be combined coherently during initial code acquisition, because channel coefficients are unknown at this stage. Hence, noncoherent combining is typically utilized. Parallel code acquisition with antenna diversity is studied in (Rick & Milstein 1997) for both frequency-nonselective and frequency-selective fading channels. The authors found that antenna diversity substantially improves acquisition performance when more diversity branches are used. Two schemes for code acquisition using antenna array are proposed in (Park & Oh 1998). In the studied receiver, there is a correlator in each antenna branch. In the first scheme, the output signals from correlators are not combined, but acquisition is declared only if the multiple of those outputs signals exceed the threshold. In the second scheme, the output signals from correlators are combined. The results show that the acquisition performance of the proposed schemes becomes improved continually as the number of antennas increases. This study is extended to cover also parallel search in (Ryu *et al.* 2002), where multiple MFs are located in each antenna branch. The outputs of MFs are added noncoherently, and the result is compared to a threshold. The results indicate that acquisition performance becomes improved continually as the number of antennas increases, and the performance improvement depends on the degree of spatial fading correlation. A generalized code acquisition scheme, where antennas and correlators are divided into groups, and the signals are combined noncoherently afterwards is proposed in (Je *et al.* 2003, Shin & Lee 2003). Such a code acquisition scheme, where multiple receive and transmit diversity antennas are exploited is studied in (Ikai *et al.* 1999). The authors found that the receive antenna diversity is more effective than transmit antenna diversity. However, transmit diversity is important since it helps to reduce miss-acquisition probability. An interesting approach of code acquisition with multiple diversity antennas is studied in (Yang *et al.* 1999). Therein, a MF is located in each antenna branch and two different cases are studied based on the initial code phases of these MFs. In the first case, all MFs use the same code phase and output signals of MFs are then combined to improve SNR. In the second case, different code phases are used in each MF to increase the parallelism of the search. The results indicate that in low SNR scenarios, antenna combining is more effective while the parallel scheme is better in high SNR scenarios. Therefore, a combination of both approaches is shown to provide the best performance for a particular SNR value. Based on these results, (Chang *et al.* 2000) proposed an adaptive scheme that adjusts the degree of combining without the explicit knowledge of the SNR. Adaptive code acquisition schemes have also been studied in (Kwon *et al.* 2006, Kwon *et al.* 2007).

Code acquisition structures which utilize beamforming have been studied in some papers. One of the earliest papers dealing with this subject has been published by Compton, who experimentally investigated the characteristics of an adaptive analog array in the presence of sinusoidal interference while receiving a DS/SS signal (Compton 1978). He presents performance results in terms of the amount of interference rejection and output SNR. The maximum likelihood delay estimator of a receiver using an antenna array is derived in (Dlugos & Scholtz 1989). A serial search code acquisition in the delay domain is extended also to include the angular domain in (Katz *et al.* 2001b, Katz 2002). The result is a two dimensional (delay – angle) serial search strategy where only a single correlator is needed. The receiver in (Katz *et al.* 2001b) generates orthogonal fixed beams using a Butler matrix and evaluates these beams using a serial search technique that results in joint delay and DOA estimates. The study is extended to cover also nonuniform spatial distributions of interference (Katz *et al.* 2000, Katz *et al.* 2001a, Katz *et al.* 2004). Authors show that the acquisition performance is clearly degraded in this new scenario, but this degradation can be effectively reduced using a different type of search strategy, adaptive integration time, and adaptive threshold setting. Acquisition procedures where a correlator is used in each antenna are studied in (Wang & Kwon 2000a, Wang & Kwon 2000b, Wang & Kwon 2003b and Wang & Kwon 2003a). The outputs of the correlators are combined using beamforming. The weights of the beamformer are obtained via LMS adaptation using a pilot channel, i.e., the DOA information is not needed. The principle of utilizing MMSE beamforming during code acquisition is published in (Zhang *et al.* 2003 and Zhang *et al.* 2004). A code acquisition scheme employing an adaptive beamformer and an adaptive temporal filter is proposed in (Yang & Wu 2005, Yang & Wu 2007). A technique that combines temporal filtering and spatial beamforming for joint PN code acquisition and DOA estimation is proposed in (Chuang *et al.* 2003). The results show that the proposed solution is resistant to the near-far effect and robust against the change of the fading environment.

A performance comparison of code acquisition using antenna diversity and beamforming is studied in (Katz *et al.* 2002a). The authors found that in low SNR scenarios, the diversity scheme provides the best performance. As SNR increases, both beamforming and diversity schemes will attain similar performance. There are also papers (e.g., van der Veen *et al.* 1998, Raleigh & Boros 1998, Gu *et al.* 2001, Khalaj *et al.* 1994, Kataoka *et al.* 2004, Rui & Ristaniemi 2005) which consider joint angle and delay estimation. Based on this literature review, it can be concluded that the research problems which are covered in this thesis have not been published previously.

3 Smart antennas

A smart antenna (i.e., adaptive antenna) is an electronically controllable antenna array, whose radiation pattern can be adjusted. This feature will increase overall system capacity because different users can be separated in the spatial domain (i.e., SDMA), although they would use the same time, frequency and spreading code (Saunders 1999). In addition to capacity improvement, smart antennas improve also the peak data rate, average throughput, coverage and spectral efficiency of cellular systems (Liberti & Rappaport 1999). Smart antennas can be used for interference cancellation purposes by placing the maximum gain of the radiation pattern toward the desired signal and minimum gains (i.e., nulls) toward interfering signals. By means of an appropriate adaptive algorithm, the radiation pattern can follow sources of interfering signals although they are moving. In conclusion, significant improvements both in link and network level can be attained by employing smart antennas.

Beamforming can be analog or digital. Analog beamforming is performed either in RF or in intermediate frequency (IF) using e.g., a Butler-matrix (Litva & Lo 1996, Hansen 1998, Liberti & Rappaport 1999). Digital beamforming is performed either in the baseband or in IF, but not until analog-to-digital conversion (A/D) (Litva & Lo 1996, Liberti & Rappaport 1999). The use of digital beamforming has been generalized lately due to the development of powerful signal processing systems. Therefore, only digital beamforming is covered in this thesis. Beamforming can be carried out in both the transmit and receive direction. Only the receiving aspect of beamforming is covered in this work, since the focus is on synchronization.

3.1 Digital beamforming algorithms

Smart antennas can be used for interference cancellation by using different beamforming algorithms. The principle of spatial beamforming is illustrated in Fig. 5. The term spatial beamforming means that there is only one weight coefficient after each antenna element. Then the array output signal can be written as

$$y(n) = \sum_{m=1}^{M} w_m^* x_m(n), \tag{8}$$

where $x_1(n), \cdots, x_M(n)$ are discrete time signals obtained after downconversion from (1), $w_1, \cdots, w_M$ are adjustable complex valued weight coefficients of the beamformer, and $(\cdot)^*$ denotes complex conjugate. The array output signal can be presented in vector form as

$$y(n) = \mathbf{w}^H \mathbf{x}(n), \tag{9}$$

where $\mathbf{w} = [w_1\ w_2\ \cdots\ w_M]^T$, $\mathbf{x}(n) = [x_1(n)\ x_2(n)\ \cdots\ x_M(n)]^T$, and $(\cdot)^H$ denotes complex conjugate transpose.

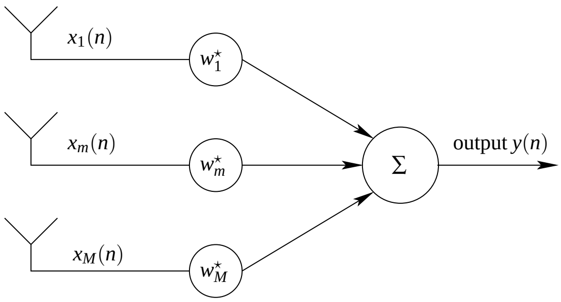

Fig 5. Principle of spatial beamforming (Godara 1997).

3.1.1 *Classical beamforming*

In the classical beamforming, which is also known as the Bartlett's or conventional beamforming, the maximum gain of a radiation pattern is directed toward the desired signal, but minimum gains toward interfering signals are not attempted. Therefore, the DOA of the desired signal must be known. Maximum gain is achieved by using the steering vector of the desired signal as the weight coefficient vector i.e., $\mathbf{w} = \mathbf{a}(\theta_0)$. Then a signal arriving from direction θ_0 becomes combined coherently. This means that the antenna array gain, which is defined as SNR improvement, is equal to the number of antenna elements in the array. (Godara 1997)

3.1.2 *Nullsteering*

Nullsteering is another simple beamforming algorithm. Its purpose is to shape the radiation pattern so that maximum gain is directed toward the desired signal and minimum points toward interfering signals. Maximum gain is obtained by selecting

$$\mathbf{w}^H \mathbf{a}(\theta_0) = 1, \tag{10}$$

as in classical beamforming. Minimum gains toward interfering signals are obtained from the following constraints

$$\mathbf{w}^H \mathbf{a}(\theta_i) = 0, \quad i = 1, \cdots, K, \tag{11}$$

where $\theta_1 \cdots \theta_K$ are DOAs of interfering signals and K is their number. Thus, the nullsteering method has a disadvantage that it requires DOA information from all signals. The weight coefficient vector of the nullsteering beamformer can be obtained from

$$\mathbf{w}^H = \mathbf{e}^T \mathbf{A}^{-1}, \tag{12}$$

where $\mathbf{A} = [\mathbf{a}(\theta_0)\ \mathbf{a}(\theta_1)\ \cdots\ \mathbf{a}(\theta_K)]$ contains steering vectors on its columns and $\mathbf{e} = [1\ 0\ \cdots\ 0]^T$ contains the constraints from (10) and (11). Equation (12) requires $\mathbf{A}$ to be invertible. If A is not a square matrix, we can use the estimate

$$\mathbf{w}^H = \mathbf{e}^T \mathbf{A}^H (\mathbf{A}\mathbf{A}^H)^{-1}, \tag{13}$$

where $\mathbf{A}^H (\mathbf{A}\mathbf{A}^H)^{-1}$ is a so called pseudoinverse. (Godara 1997)

Although nullsteering beamforming produces nulls toward interfering signals, it is not designed to minimize uncorrelated noise at the output of the array. Thus, it is a suboptimal method because it does not maximize the signal-to-interference-plus-noise ratio (SINR) at the output of the beamformer. (Godara 1997)

3.1.3 Minimum Variance Distortionless Response

In minimum variance distortionless response (MVDR) beamforming, the basic principle is to minimize the output power of the array. This minimization is done conditionally so that the gain in the direction of the desired signal is kept constant, meaning that the desired signal is passed without distortion. The weight coefficient vector of the MVDR method can be solved using Lagrange multipliers and its derivation is presented in (Haykin 1996). The weight coefficients can be solved from

$$\mathbf{w} = \frac{\mathbf{R}^{-1}\mathbf{a}(\theta_0)}{\mathbf{a}^H(\theta_0)\mathbf{R}^{-1}\mathbf{a}(\theta_0)}, \tag{14}$$

where $\mathbf{R} = E\{\mathbf{x}(n)\mathbf{x}^H(n)\}$ is the array correlation matrix, and $\mathbf{R}^{-1}$ is its inverse. $E\{\cdot\}$ denotes expectation. Elements of the array correlation matrix describe correlations between signals in different antennas. An array correlation matrix can be estimated from data using a simple averaging as

$$\hat{\mathbf{R}} = \frac{1}{N}\sum_{i=1}^{N}\mathbf{x}(i)\mathbf{x}^H(i). \tag{15}$$

It can be noticed from (14) that only the DOA of the desired signal must be known. Interfering signals appear in $\mathbf{R}$ with large correlation values, and they are removed in MVDR beamforming although their DOAs would be unknown.

3.1.4 MaxSINR

A commonly used optimization criteria is to maximize SINR at the output of the antenna array. This method has such a disadvantage that the correlation matrix estimation has to be done at the time when the desired signal is absent. Due to this restriction, the maxSINR algorithm can be used mainly in radar applications. If this kind of correlation matrix estimation is possible, the weight coefficient vector can be written as (Godara 1997)

$$\mathbf{w} = \frac{\mathbf{R}_{IN}^{-1}\mathbf{a}(\theta_0)}{\mathbf{a}^H(\theta_0)\mathbf{R}_{IN}^{-1}\mathbf{a}(\theta_0)}, \tag{16}$$

where ($\mathbf{R}_{IN}$) is the correlation matrix of noise and interference. The correlation matrix $\mathbf{R}$ can be written as $\mathbf{R} = \mathbf{R}_S + \mathbf{R}_{IN}$, where $\mathbf{R}_S$ is the correlation matrix of the desired signal. If strong interfering signals are disturbing the DS/SS system, the term $\mathbf{R}_{IN}$ dominates since $\mathbf{R}_S$ consists of small values due to the low power spectrum density of a DS/SS signal. This means that $\mathbf{R} \approx \mathbf{R}_{IN}$. Therefore, the MVDR and maxSINR algorithms have almost the same weight coefficients in this case.

3.1.5 Whitening filter

A whitening filter tries to enforce a white spectrum in its output. It has been used as a time domain interference suppressor in (Proakis 1996). It can be applied for DS/SS signals because their spectrum is like white noise. Therefore, a whitening filter cannot estimate a DS/SS signal, but narrowband interfering signals can be estimated and removed. The restriction on interference cancellation in the time domain is that the bandwidth of the interfering signal must be less than 50 % of the bandwidth of the DS/SS-signal (Saarnisaari 2001). The idea of a whitening filtering can be applied in antenna arrays too, but then we are not restricted to eliminating narrowband interfering signals due to spatial processing. Beamforming based on a whitening filter does not need DOA information, but it has also two disadvantages compared to many other beamforming algorithms. Firstly, an acquisition decision will be based on the output of one antenna, i.e., antenna combining gain is not attained. This means that higher transmission power is needed, or sensitivity is lost if compared to the other beamforming techniques. Secondly, the desired DS/SS signal will also be removed if its SNR is too high.

3.1.6 Minimum Mean Square Error

In adaptive filter theory, one of the most general optimization criteria is the minimum mean square error (MMSE), where the filter's weight coefficients are defined by minimizing the mean squared error between training and filter output signals (Haykin 1996). The MMSE algorithm can be applied also in beamforming, because it is just filtering in the spatial domain. However, in initial code acquisition, such a training sequence cannot be used which will be based on the detected data symbols, because the receiver is unable to detect symbols before code synchronization. Instead, the receiver can utilize the known PN spreading code as a training signal. The weight coefficient vector of MMSE beamforming can be obtained from the Wiener filter theory as (Haykin 1996)

$$\mathbf{w} = \mathbf{R}^{-1}\mathbf{d}, \tag{17}$$

where $\mathbf{d} = E\{\mathbf{x}(n)c^*(n)\}$ is a cross-correlation vector between the training and array input signals. The MMSE beamformer has the advantage that it does not need DOA information at all. Therefore, the MMSE beamforming and whitening filter are unsensitive to nonidealities like calibration errors. If these algorithms are used in code acquisition, then a two-dimensional (delay – angle) search is not required.

3.1.7 Space-time beamforming

In spatial or narrowband beamforming, there is only one weight coefficient after each antenna element, whereas in space-time or wideband beamforming there are multiple weight coefficients as is illustrated in Fig. 6. A narrowband beamformer is able to form nulls exactly only at a single frequency, because the steering vector is function of frequency and antenna spacing (Rodgers & R. T. Compton 1979, Compton 1988). In space-time processing, each of M antennas is followed by a P-tap finite impulse response (FIR) filter, i.e., a tapped delay line (TDL). This structure allows each antenna element to have a phase response which can be adjusted as a function of frequency. This makes it possible to compensate different phase shifts of different frequencies (Liberti & Rappaport 1999). Bandwidth performance of adaptive arrays with tapped delay-line processing is studied in (Vook & R. T. Compton 1992, and references therein).

Another advantage of space-time processing is that it allows interference cancellation in the frequency or time domain, as well as in the spatial domain, by optimizing all MP taps. In space-time adaptive processing (STAP), P sample vectors (i.e., snapshots $\mathbf{x}(n)$) are included into a space-time sample vector as

$$\mathbf{x}_{ST}(n) = [\mathbf{x}^T(n) \cdots \mathbf{x}^T(n-P+1)]^T. \tag{18}$$

A space-time steering vector can be constructed as (Saarnisaari *et al.* 2005)

$$\mathbf{a}_{ST}(\theta_0) = [0 \cdots \mathbf{a}(\theta_0)^T \cdots 0]^T, \tag{19}$$

which contains a spatial steering vector at the center and zeros elsewhere. If a space-time steering vector is constructed in this way, it avoids inter chip interference (ICI). An estimate of space-time correlation matrix ($\hat{\mathbf{R}}_{ST}$) can be achieved from (15) when $\mathbf{x}_{ST}(n)$ instead of $\mathbf{x}(n)$ is used there. The same beamforming algorithms that were just described in the context of spatial beamforming can also be applied in space-time beamforming. This means that the spatial domain steering vector, the sample vector, and the correlation matrix must be replaced with their space-time counterparts.

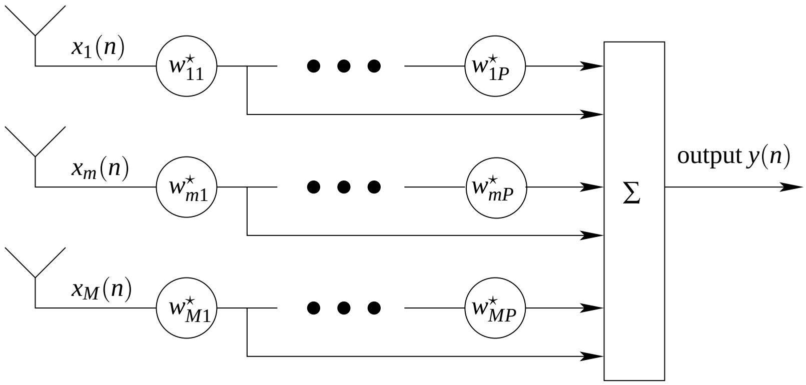

Fig 6. Principle of space-time beamforming.

3.1.8 *Beam-space techniques*

In beam-space processing, the signals in different antennas are not weighted directly as in the aforementioned element-space processing. Instead, the set of orthogonal beams are generated and outputs of these beams are weighted. The number of beams utilized in the beam-space processing is smaller or equal to the number of antenna elements. If the number of beams is smaller than the number of antenna elements, the number of required weight coefficients is also smaller than in element-space processing. This is one advantage of the beam-space processing, since it reduces computational load. Another advantage is its robustness against non-idealities of implementation. Beam-space processing has been studied in (Godara 1997, and references therein). The beam-space versions of different DOA estimation methods are studied in (Zoltowski *et al.* 1991, Zoltowski *et al.* 1993, Mathews & Zoltowski 1994, Trees 2002). The generalized sidelobe canceller (GSC) is an example of beam-space beamforming and its exact description can be found from (Haykin 1996). The basic idea is to construct a mainbeam by using the information that is on hand in advance. Then auxiliary beams orthogonal to the mainbeam are produced. By weighting these auxiliary beams appropriately, those interfering signals which are located in the sidelobes can be cancelled.

3.2 DOA estimation algorithms

In this section, a short overview of different DOA estimation algorithms will be presented. These algorithms can be broadly divided into three different categories: conventional techniques, subspace based techniques and maximum likelihood techniques. Next, the algorithms inside those categories are briefly described.

3.2.1 Conventional techniques

The conventional DOA estimation techniques are based on the digital beamforming algorithms, and they require a large number of antenna elements to achieve high resolution. These techniques electronically steer beams in all possible directions and look for peaks in the output power. (Liberti & Rappaport 1999)

Bartlett's method

One of the simplest DOA estimation techniques is Bartlett's method, where the spatial uncertainty region is scanned with power measurement purposes for all directions using Bartlett's (i.e., classical) beamforming. After scanning, the so-called Bartlett's spatial spectrum can be expressed as

$$P_{Bartlett}(\theta) = \mathbf{w}^H\mathbf{R}\mathbf{w} = \mathbf{a}^H(\theta)\mathbf{R}\mathbf{a}(\theta). \tag{20}$$

Because the spatial spectrum represents received power as a function of DOA, those DOAs which correspond to maximum points are considered as the actual DOAs of arriving signals. This technique has poor spatial resolution due to large beamwidth and high sidelobes, if there are multiple signals. Resolution can be increased by adding more antenna elements. (Liberti & Rappaport 1999)

Capon's method

Capon's minimum variance technique (Capon 1969) is based on Capon's or MVDR beamforming, which was described in Section 3.1.3. Capon's DOA estimator has better spatial resolution than Bartlett's method has, and its spatial spectrum can be written to form

$$P_{Capon}(\theta) = \frac{1}{\mathbf{a}^H(\theta)\mathbf{R}^{-1}\mathbf{a}(\theta)}. \tag{21}$$

The DOAs can be estimated by locating the peaks of the spectrum, as was done in Bartlett's method. (Liberti & Rappaport 1999)

3.2.2 Subspace based techniques

Most of the resolution limitations of the conventional DOA estimation techniques arise because they do not exploit the eigen structure of the input data matrix. Subspace based techniques exploit this structure, which makes it possible to find out high resolution algorithms.

MUSIC algorithm

Schmidt proposed the multiple signal classification (MUSIC) algorithm (Schmidt 1979), which provides information about the number of incident signals, DOAs, strengths, cross correlations, noise power, etc. The MUSIC algorithm is based on the eigenvalue decomposition of correlation matrix $\mathbf{R}$. Eigenvectors of $\mathbf{R}$ are separated into two orthogonal subspaces, called the signal subspace and noise subspace. If those eigenvectors which belongs to the noise subspace are included in matrix $\mathbf{V}_n$, then DOAs of arriving signals can be estimated by locating peaks from a MUSIC spatial spectrum given by

$$P_{MUSIC}(\theta) = \frac{1}{\mathbf{a}^H(\theta)\mathbf{V}_n\mathbf{V}_n^H\mathbf{a}(\theta)}. \tag{22}$$

The results shown in (Liberti & Rappaport 1999) indicate that the MUSIC algorithm can resolve also closely spaced signals which cannot be detected by Capon's method. When arriving signals are highly correlated, then MUSIC algorithm fails. Spatial smoothing techniques have been proposed to handle also highly correlated signals (Shan *et al.* 1985, Takao & Kikuma 1987). Various modifications to the MUSIC algorithm have been proposed to increase its resolution performance and to decrease its computational complexity. One such modification is the Root-MUSIC algorithm (Barabell 1983), which is based on polynomial rooting and it provides higher resolution. The Root-MUSIC algorithm has an advantage that it does not require scanning through all directions, because unknown DOAs can be solved mathematically from polynomial roots. One disadvantage is its applicability only for a uniform linear array (ULA), where antenna elements have been spaced at regular intervals along a line. Another modification is the Cyclic MUSIC algorithm (Schell *et al.* 1989), which exploits the spectral coherence properties of signals. Fast subspace decomposition techniques have been studied in (Xu & Kailath 1994) to decrease the computational complexity of the MUSIC algorithm.

ESPRIT algorithm

Estimation of signal parameters via rotational invariance techniques (ESPRIT) is another subspace-based DOA estimation technique introduced in (Roy & Kailath 1989). The ESPRIT algorithm notably reduces the computational and storage requirements of the MUSIC algorithm and it does not require scanning through all directions to estimate DOAs. The ESPRIT algorithm requires that an antenna array be decomposed into two equal-sized identical subarrays. The exact description of the ESPRIT algorithm is presented in (Liberti & Rappaport 1999).

3.2.3 Maximum likelihood techniques

The maximum likelihood DOA estimation techniques (Schweppe 1968, Li & Compton 1993) are optimal techniques in the sense that they produce the most accurate DOA estimates, but they are computationally very intensive. Therefore, the ML techniques have been less popular than the suboptimal subspace techniques. However, the ML techniques have a superior performance compared to the subspace techniques, especially in low SNR conditions or when the number of signal samples is small (Ziskind & Wax 1988). In addition, the ML techniques can also perform well in correlated signal conditions, whereas the subspace based methods fail in this situation.

3.2.4 Detection of number of signals

Many DOA estimation algorithms require information about the number of arriving signals. Therefore, estimation of the number of sources is an important issue. The methods which are based on eigen decomposition are the most commonly used. In these methods, an estimate of the number of signals is obtained from the number of repeated smallest eigenvalues (Liberti & Rappaport 1999). One of the earliest methods is an eigen-threshold method (Chen *et al.* 1991), which is based on threshold setting and hypothesis testing. This method is computationally attractive, but the need for threshold setting is a major disadvantage. Two other detection schemes are based on the Akaike information theoretic criteria (AIC) and the minimum descriptive length (MDL) criteria

(Wax & Kailath 1985). The latter methods do not require threshold setting. It is shown in (Wax & Kailath 1985) that the MDL method provides a consistent estimate of the number of signals, whereas the AIC method tends to overestimate the number of signals. However, the eigen-threshold method has better performance than the AIC and MDL methods have (Chen *et al.* 1991). An alternative scheme for estimating the number of signals uses eigenvectors instead of eigenvalues (Lee & Li 1994).

4 Summary of the original articles

4.1 General

The contents of the nine original articles are divided into two groups. Articles I-IV consider code acquisition in intentional interference by exploring how different beamforming algorithms can cope with narrowband and wideband interfering signals, when the DOA of the desired DS/SS signal is assumed to be known. All interfering signals are highly directional, because each of them is arriving from a certain direction in the spatial domain. Moreover, they are located at the center frequency of the DS/SS signal. This part of the study is based on computer simulations and such a receiver structure is investigated where a single MF is located after the beamforming (BF) unit (i.e., BF+MF structure). The second group of Articles (V-IX) focuses on a theoretical analysis of synchronization probabilities and mean acquisition times when the DOA of the desired signal is unknown. In this part of the study, a BF+MF structure, as well as a structure where MF is located in each antenna branch before beamforming (i.e., MF+BF structure) are investigated.

4.2 Code acquisition performance under intentional interference

Article I deals with the interference cancellation performance of different spatial domain beamforming algorithms, which were discussed in Section 3.1. The used BF+MF receiver structure is shown in Fig. 7. The investigated spatial beamforming algorithms are: classical, nullsteering, MVDR, maxSINR, GSC and whitening filter. A ULA with 8 antenna elements and half wavelength antenna separation is used. The interference scenario in the paper is such that there exists both narrowband and wideband interfering signals and I/S is 30 dB for each interfering signal. Narrowband interference is a sinusoidal wave and wideband interfering signals have as large of a bandwidth as the DS/SS signal has. However, wideband interfering signals are assumed to be narrowband from the array signal processing point of view, i.e., their fractional bandwidth $W/f_c \ll 1$. Otherwise space-time beamforming would be needed as was described in Section 3.1.7. This narrowband assumption is valid throughout the thesis. A Gold code of a length of

127 chips is used as the spreading code and the performance measure is the RMSE of the delay estimate. Article I compares the performances of different spatial beamforming algorithms and concludes that all the methods, except for classical beamforming, are able to cancel multiple strong interfering signals if they are not arriving from the same direction as the desired signal. If interfering and desired signal are arriving from the same direction (i.e., a case of mainlobe interference), then spatial processing is not a sufficient interference cancellation method.

Which one of the investigated beamforming algorithms should be used in practice depends on the available *a priori* information. When there are strong interfering signals, then classical beamforming is not suitable for interference cancellation. If DOAs of desired and interfering signals are all known, then the nullsteering method is a good choice due to its simplicity. However, if only the DOA of the desired signal is known, then a more advanced MVDR or maxSINR method must be used. MMSE beamforming is not investigated in Article I, but Article IX shows that it is a good choice when all DOAs are unknown.

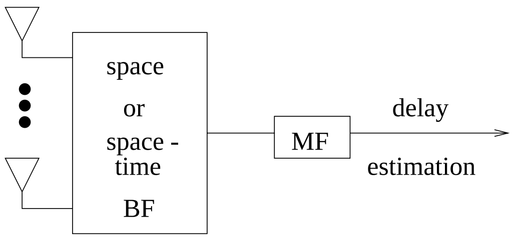

Fig 7. The BF+MF receiver structure. Modified from [II], © 2005 IEEE.

The purpose of Article II is to investigate the interference suppression capabilities of the following three structures. The first structure is the spatial MVDR beamforming, which was used also in Article I. The second structure is a combination of a spatial MVDR beamformer and a separate interference cancellation (IC) unit depicted in Fig. 8. In this study, the used IC method is the FCME algorithm (Saarnisaari & Henttu 2003). It operates herein in the frequency domain, because the aim is to eliminate narrowband interfering signal arriving from the mainlobe. The FCME algorithm operates iteratively and in each iteration it eliminates those frequency components whose power is somewhat larger than the average power. The third strategy is the space-time MVDR beamformer (Fig. 7), which utilizes multiple weight coefficients after each antenna element as was described in Section 3.1.7. The weight coefficient vector of the space-time MVDR algorithm can be written into the form (Saarnisaari *et al.* 2005)

$$\mathbf{w}_{ST} = \frac{\mathbf{R}_{ST}^{-1}\mathbf{a}_{ST}(\theta_0)}{\mathbf{a}_{ST}^{H}(\theta_0)\mathbf{R}_{ST}^{-1}\mathbf{a}_{ST}(\theta_0)}, \tag{23}$$

which is a very similar solution as that found in spatial domain MVDR processing (14). Herein, $\mathbf{R}_{ST}$ is a space-time correlation matrix and $\mathbf{a}_{ST}(\theta_0)$ is a space-time steering vector.

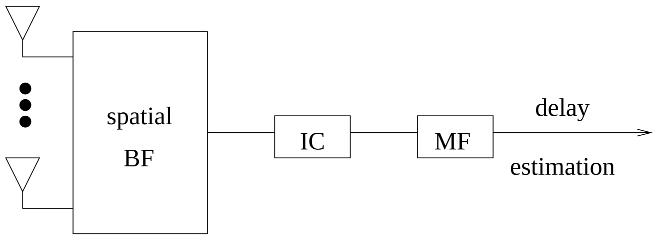

Fig 8. The BF+IC+MF receiver structure. Reprinted from [II], © 2005 IEEE.

In simulations of Article II, antenna array structure, spreading code and performance measure are the same as in Article I. The number of time taps after each antenna element is 5 in space-time beamforming. Performances of algorithms are compared in four different interference scenarios. Research is started from sinusoidal interference, then follows the cases where either 10 %, 20 %, or 40 % of the bandwidth of DS/SS signal is interfered. The results again show that all the investigated interference cancellation methods can suppress those interfering signals which are not arriving from the same direction as the desired signal. It is shown that the ability to suppress an interfering signal, in closeness of a DS/SS signal, depends on the prevailing SNR and I/S level. If SNR is high or I/S is low, then angle separation can be smaller. Naturally, this depends on the antenna array structure used also. If it is desired that code acquisition succeeds also in the scenario where interference arrives from the same direction as the desired signal, then the best alternative is to use space-time MVDR beamforming. It gives a very good protection against all kinds of interference types. The use of the FCME interference canceller after the spatial MVDR algorithm gives additional interference tolerance against mainlobe interference, when compared to the spatial MVDR processing alone, but it does not have as good of a performance as the space-time MVDR algorithm has.

Article III deals with the cancellation of impulsive interfering signals using smart antennas. The receiver structure is depicted in Fig. 9, where the same space-time MVDR algorithm is used as in Article II. There is also an additional interference cancellation unit (pre-processing algorithm), which is now located before beamforming. That is because the space-time MVDR beamforming cannot eliminate impulses if they are arriving from the mainlobe. Four different pre-processing algorithms which manipulate snapshots before beamforming are investigated. Two of them are algorithms where each snapshot is normalized either by its norm (Visuri *et al.* 2001) or norm squared. The other two methods are the CME and FCME algorithms. The original work of the CME algorithm (Henttu & Aromaa 2002) concentrated on excising narrowband interference in the frequency domain. This study investigates how well the CME algorithm can eliminate impulses in the time domain. The CME algorithm is an iterative interference cancellation method like the FCME. Impulse suppression capability is demonstrated through simulations. In the fixed DOA case, impulses are arriving 30° distance from the desired signal, and in the random DOAs case, they are randomly generated between ±60° from the desired signal. Antenna array, spreading code and performance measure are the same as in Articles I and II. The results show that space-time MVDR beamforming alone can suppress impulses when they are arriving from a fixed DOA which, however, is different than the DOA of a desired signal. In the random DOAs case, a pre-processing algorithm is required. The results indicate that all investigated pre-processing algorithms are powerful methods against impulsive interferences. In Article IV, a study of impulsive interference cancellation is extended to cover also synchronization probabilities and mean acquisition times.

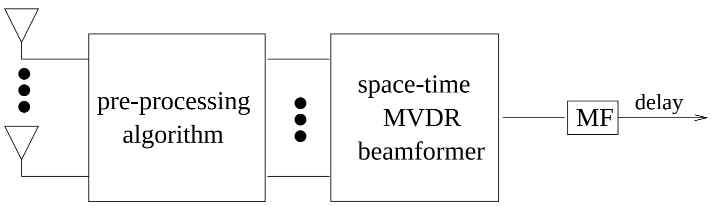

Fig 9. The IC+BF+MF receiver structure. Modified from [III], © 2004 IEEE.

As a conclusion of the research in these interference scenarios, it is clear that the proper interference cancellation method depends on the type of interference, if the interfering signal is arriving from the same direction as the desired signal. Otherwise, the type of interference is not a critical issue. Therefore, the number of signals, DOAs and strengths of signals among other things are important factors, if interference cancellation is based on the use of adaptive antennas. Therefore, the selected interference cancellation method depends on *a priori* information obtained from the signal environment.

4.3 Analysis of synchronization probabilities and mean acquisition times with smart antennas

So far in this thesis, consideration of smart antennas in code acquisition has mainly been based on computer simulations, and the performance measure used has been the RMSE of the time delay estimate. It can be concluded from those results that code acquisition succeeds using the beamforming and interference cancellation structures studied in Articles I-III. However, in those articles we are not interested about the question of how much time it takes to perform acquisition. This section, and Articles IV-IX, focus on the acquisition time. Therefore, the used performance measure is changed to the T_{MA}, which was described in Section 2.3. As it was discussed, T_{MA} is amongst other things a function of the synchronization probabilities P_D and P_{FA}. The uniform circular array (UCA) is used instead of ULA in Articles V-IX, because DOA of the desired signal is also unknown there. An angular uncertainty of 360° is more easily covered using a single UCA, whereas three ULAs placed in a triangular form are typically needed to do the same task. It is possible to use other array structures too. However, the array structure and the number of antennas in the array have an influence, for instance, on DOA estimation accuracy and interference cancellation capability.

It was assumed in Articles I-IV, that the DOA of the desired signal is exactly known in advance. This is not necessarily the situation in practise and thus, the effects of steering vector errors (i.e., DOA errors) into code synchronization probabilities are investigated in Article V. DOA error is the error between actual and estimated DOA. It has an impact on the amount of achieved antenna array gain, because the mainlobe of radiation pattern is not steered exactly toward the actual DOA of the desired signal. In Article V, beamforming is performed using either the classical or MVDR algorithm and a block diagram of the used receiver structure is depicted in Fig. 10. Probability density functions at the output of squaring operation $Z_1(n)$ are analyzed and then, probabilities P_D and P_{FA} are derived. A loss of antenna array gain affects the probability density functions and thus, the probabilities P_D and P_{FA} also. Moreover, advanced beamforming algorithms like the MVDR start to suppress the desired signal also, if DOA error is too large. Analyzed synchronization probabilities are verified by simulations.

The following conclusions can be made from the results. As expected, the MVDR is more sensitive to DOA errors than the classical beamformer, especially at large DOA errors and high SNR values. If DOA error is relatively small and SNR per chip (E_c/N_0) < -5 dB, then there is no considerable difference between these two beamformers. If DOA error is large, then the robustness of the MVDR against DOA errors may be improved by using, for example, the adaptive diagonal loading (ADL) algorithm, which was used in this study. In the ADL algorithm, a main diagonal of correlation matrix $\mathbf{R}$ is weighted by an adaptive load, which reduces the effects of DOA errors (Lilja & Saarnisaari 2005). However, this loading happens at the expense of decreased interference suppression capability.

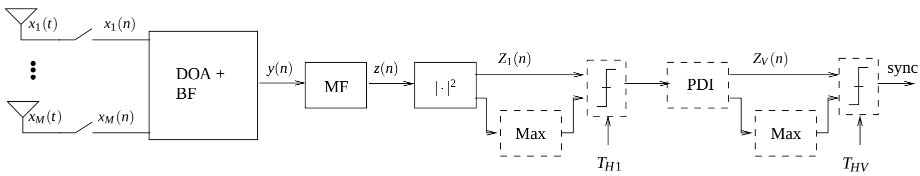

Fig 10. A block diagram of the BF+MF receiver structure used in Article V. Reprinted from [VII], © 2009 IEEE.

In Article VI, a receiver structure is investigated which consists of a smart antenna followed by a single correlator or a MF. A block diagram of the investigated structure is depicted in Fig. 11. When this kind of receiver structure is used and the DOA of the desired signal is unknown, there is a two-dimensional acquisition problem because both the angle and delay must be found. In this case, the whole angular uncertainty region (360°) can be divided into small angular cells using the fixed beam techniques, like the Butler matrix. The strategy where the receiver searches through all angular and delay cells via a serial search procedure was originally proposed in (Katz *et al.* 2001b). Division of the uncertainty region into angular and delay cells is illustrated in Fig. 12. In the Butler matrix case, the number of angular cells is equal to the number of antennas in the array.

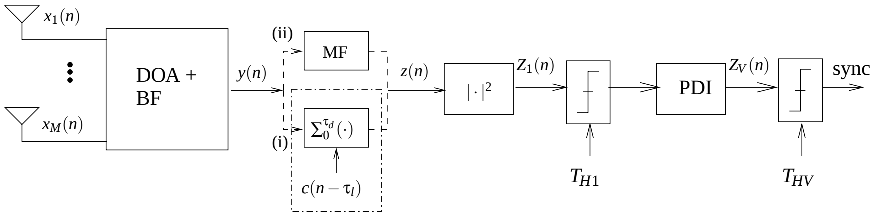

Fig 11. A block diagram of the receiver structure used in Article VI. Reprinted from [VI], © 2008 IEEE.

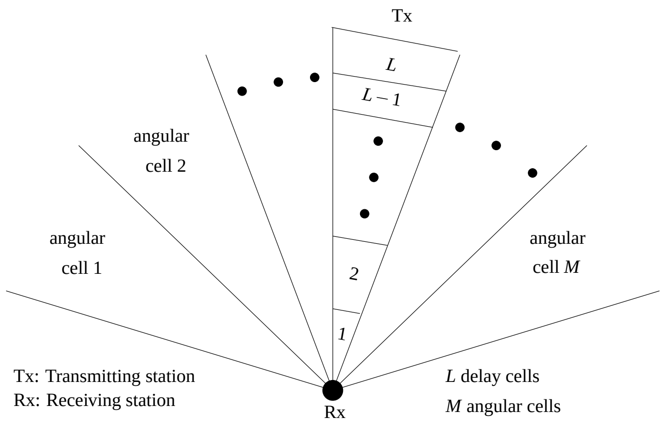

Fig 12. Principle of two-dimensional code acquisition with fixed beams (Katz *et al.* 2001b).

In Article VI, research work is expanded from fixed beams to cover also the advanced beamforming techniques which require more computation, but they offer significantly better interference suppression capability. Also, such a method is proposed where the DOAs of arriving signals are estimated prior to the acquisition process. This may reduce angular uncertainty because the number of needed angular cells is equal to the number of arriving signals as is illustrated in Fig. 13. All these acquisition strategies are compared in serial search acquisition using either a correlator or a MF acquisition. A model for code acquisition using DOA estimation and beamforming in the MF acquisition case is presented, and an expression for the mean acquisition time is derived, when also the actions related to array signal processing are taken into account. In this particular T_{MA} analysis, it is assumed that there is no overlapping between adjacent beams. If overlapping is taken into account, then a directional signal arriving precisely in the direction that beams overlap, will appear in both of the adjacent angular cells. This will have a positive effect on the overall acquisition time performance. The obtained analytical results indicate that in the AWGN channel, a single antenna receiver has the best T_{MA} performance if SNR per bit (E_b/N_0) is high. This is because the slightly time consuming array signal processing operations are not needed in the single antenna receiver. However, single antenna methods without any interference cancellation are sensitive to interference, whereas smart antennas are not. Moreover, a single antenna receiver is easily obtained from a multi-antenna receiver by ignoring all but one of the antenna outputs. If E_b/N_0 is low, then multi-antenna receivers typically outperform single antenna receivers. SNR per bit in the dB-scale is obtained by adding the processing gain of DS combining (PG = $10\log_{10}(L)$) up to the SNR per chip (i.e., $E_b/N_0 = E_c/N_0$ + PG). Results indicate also that the DOA estimation-based methods outperform the fixed beam methods, if the number of arriving signals is low. However, DOA estimation from the chip level may be difficult and time consuming if E_c/N_0 is very low, as is illustrated in Fig. 14. DOA estimation accuracy depends among other things on the used DOA estimation algorithm, array structure, number of antennas, E_c/N_0 and the number of sample vectors used for correlation matrix estimation. Estimation of the DOA of DS/SS signal becomes more difficult when the spreading code length L increases, because SNR in the channel (E_c/N_0) typically decreases. If L is large, more averaging (i.e., more sample vectors) or higher transmission power must be used in the synchronization phase. If DOA estimation is not possible at all, either a whitening filter, MMSE or scanning through the whole angular uncertainty region must be used. One solution to this DOA estimation problem is to utilize the structure where MFs are located in each antenna element. This structure will be described in more detail when Article IX is summarized. It makes it possible to perform DOA estimation after despreading when SNR is higher.

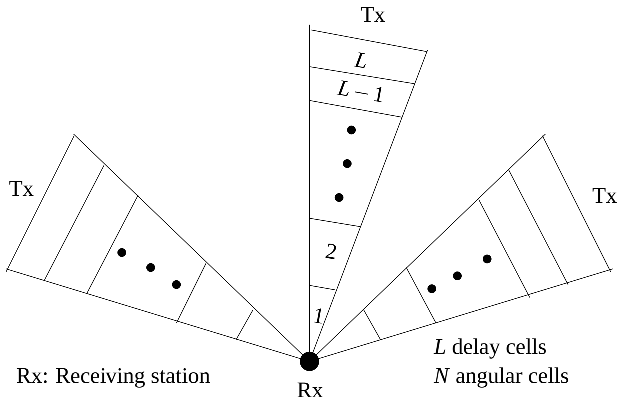

Fig 13. Principle of two-dimensional code acquisition with DOA estimation (Puska *et al.* 2005).

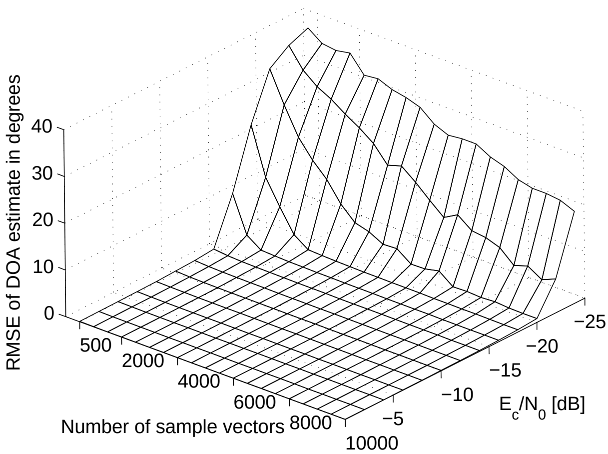

Fig 14. DOA estimation results from Article VI. Reprinted from [VI], © 2008 IEEE.

If the fixed beam techniques are used, there is an optimum number of receiving antennas at each SNR level for which the minimum T_{MA} is obtained, as is shown in Fig. 15. In that case, it would be interesting to develop an adaptive system that is based on the estimated SNR, and would try to use the appropriate number of receiving antennas aiming at minimizing T_{MA}.

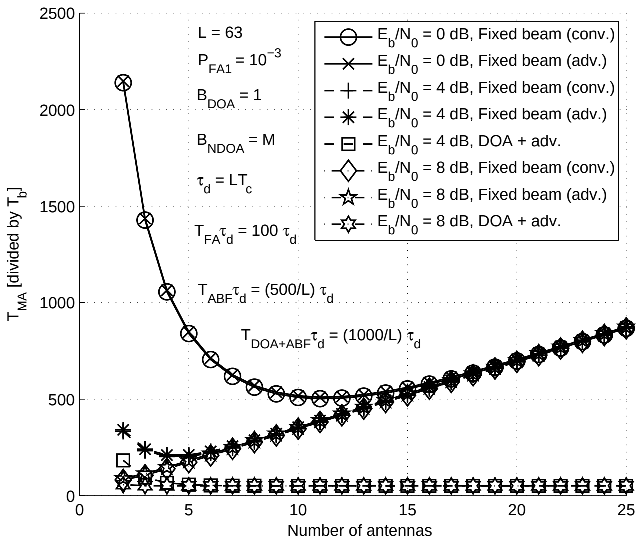

Fig 15. T_{MA} **results from Article VI. Reprinted from [VI], © 2008 IEEE.**

Article VII expands multi-antenna code acquisition research from Article VI into different serial search and maximum selection strategies when the first threshold crossings are verified using post detection integration (PDI) and another threshold comparison. Their T_{MA} performances are studied in the static, fast and slow fading channels. The presented T_{MA} analysis is also derived under an assumption that there is no overlapping between adjacent beams. Article VII introduces some novel ideas of performing maximum selection together with verification. When PDI is used, a maximum sample can be selected either before or/and after PDI. Also, the threshold comparison can be located either before or/and after PDI, as is shown in Fig. 10. Therefore, there are altogether $2^4 = 16$ combinations of selecting a maximum sample and performing threshold comparison. However, most of those combinations are not reasonable, e.g., there is no sense to select a maximum value both before and after PDI, if threshold comparison is not utilized at all. The 6 reasonable combinations are discussed:

– $Max(1)$, maximum selection before PDI,
– $Max(1)\ T_H(1)$, maximum selection and threshold comparison before PDI,
– $Max(V)$, maximum selection after PDI,

– $Max(V)\ T_H(V)$, maximum selection and threshold comparison after PDI,
– $Max(1\&V)\ T_H(1)$, maximum selection before and after PDI, and threshold comparison before PDI,
– $Max(1\&V)\ T_H(1\&V)$, maximum selection as well as threshold comparison before and after PDI.

Also in the serial search techniques, the threshold comparison can be located either before or/and after PDI. Thus, the following three combinations can be distinguished:

– $SS\ T_H(1)$, threshold comparison before PDI,
– $SS\ T_H(V)$, threshold comparison after PDI,
– $SS\ T_H(1\&V)$, threshold comparison before and after PDI.

Theoretical T_{MA} results indicate that the most appropriate method in each particular situation depends on SNR, fading rate, and on the number of antennas. Different values of parameter set may have an effect on the order between methods. The authors purpose is to give a theoretical tool for analyzing and comparing different alternatives. The system designers can use their own parameter set in the mean acquisition time equations to select a suitable method for their purposes. In the fading channel case of Article VII, angular spreads of arriving signals are assumed to be small. Otherwise, there would be multiple angular cells which lead to the correct code acquisition state. Therefore, the channel with large angular spread has to be analyzed in a slightly different way.

Because the amount of sample vectors needed for successful DOA estimation depends on the prevailing SNR (Fig. 14), Article VIII introduces an iterative method for code acquisition. The presented method first performs DOA estimation, then beamforming and finally makes a synchronization decision based on the maximum output of the MF. The method starts by collecting a small number of sample vectors for DOA estimation. If the DOA estimate is inaccurate, the mainbeam of the radiation pattern is steered toward an erroneous direction and code acquisition has failed. After a fail, more data is collected that improves DOA estimation accuracy. This process is repeated until angle and delay acquisition succeeds. The results show that the proposed method offers very short mean acquisition times with moderate SNR values. However, in this initial study, only a DS/SS signal and AWGN are arriving to the receiver. The time consumed for DOA estimation is assumed to be fixed in Articles VI - VII, but it is adjustable in Article VIII.

A principle of utilizing MMSE beamforming during code acquisition is proposed in (Zhang *et al.* 2003, Zhang *et al.* 2004), where correlators are used instead of MFs and the beamforming weights are obtained via a pilot channel. Article IX investigates a MMSE beamforming structure where only one PN code period is used as a training signal. Then there must be either a MF or a correlator in each antenna branch separately. A block diagram of the used MF+BF receiver structure with MMSE beamforming is shown in Fig. 16. Weight coefficient calculation in MMSE beamforming requires that a cross-correlation vector $\mathbf{d} = E\{\mathbf{x}(n)c^*(n)\}$ between spreading code and array input signals is estimated, as was described in (17). Using this receiver structure, an estimate of a cross-correlation vector is obtained by taking a sample vector from the outputs of MFs. Code acquisition performance under intentional interference is studied in Article IX, when there are one or three wideband interfering signals and acquisition is aided either by MMSE or MVDR beamforming. The performance of a single antenna receiver without any interference suppression unit is considered as a reference. P_D and T_{MA} are used as performance measures. The performance comparisons between beamformers show that the MVDR has better P_D performance but worse T_{MA} performance. This can be explained by DOA information, which is needed in MVDR but not in MMSE beamforming. Acquisition via the MVDR algorithm using a BF+MF structure needs searching through all DOAs (Fig. 12), which consumes so much time that T_{MA} performance of the MMSE beamformer becomes better. However, this advantage comes at the expense of increased receiver complexity due to multiple MFs. It is worth noting that the T_{MA} results presented for the MVDR beamformer are overall times needed for both angle and delay acquisition, whereas T_{MA} results for the MMSE beamformer contain only the time needed for delay acquisition. However, communication is possible in both cases, since the receiver is time synchronized. On the other hand, DOA estimation is easier from the outputs of MFs after code synchronization, because SNR is then higher. This can be seen from Fig. 17, where the RMSE of a DOA estimate is presented as a function of E_c/N_0.

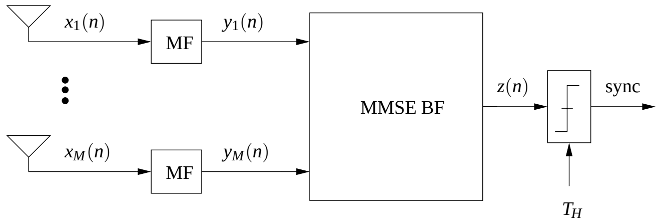

Fig 16. A block diagram of the MF+BF structure used in Article IX. Modified from [IX], © 2007 IEEE.

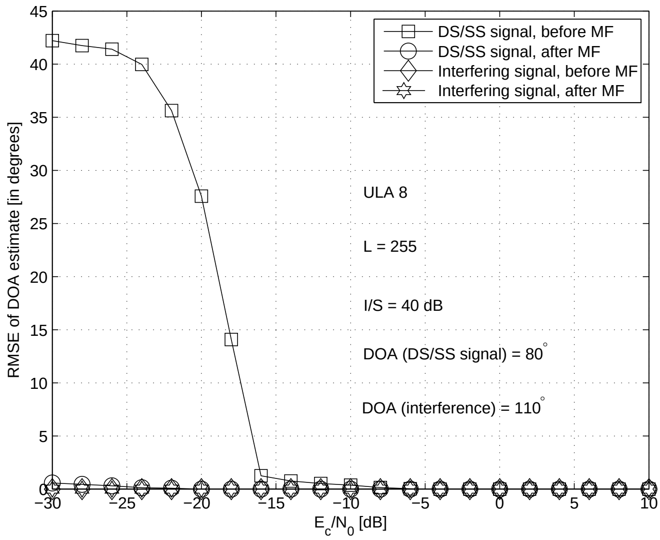

Fig 17. DOA estimation performance as a function of E_c/N_0 using the Root-MUSIC algorithm.

The MF+BF structure used in Article IX has the advantage that it does not need pilot symbols if only one PN code period is used as a reference signal. However, if the communication system utilizes a separate synchronization channel where, e.g., constant bits are always transmitted, then MMSE beamforming can take advantage of a longer training sequence (Zhang *et al.* 2003, Zhang *et al.* 2004). In MF acquisition, this means that multiple PN code periods are combined according to pilot symbols before beamforming, as is illustrated in Fig. 18. P_D performance improvements of this kind of structure, without and with interference, are shown in Figs. 19 and 20, when 1-4 code periods are combined. When two PN code periods are combined, then P_D performance is almost the same as in MVDR beamforming. If the training signal length is more than two code periods, then the P_D performance of the MMSE beamformer becomes better than that of the MVDR beamforming. T_{MA} performance also improves because P_D becomes higher and only a small amount of additional processing is required. This additional processing time does not affect the T_{MA} equation of MMSE beamforming, providing that the time spent for code periods combining is smaller or equal than the time spent for inverse correlation matrix estimation. The correlation matrix is typically estimated from several hundreds of snapshots, so during that time, few code periods can be combined without an effect on T_{MA}.

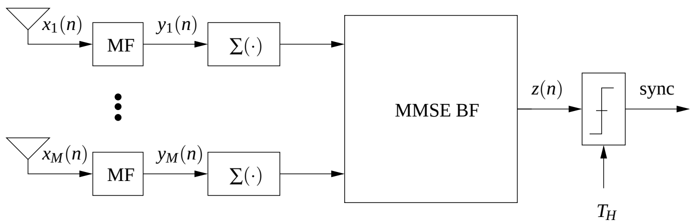

Fig 18. A block diagram of the MF+BF receiver structure with MMSE beamforming and a pilot channel.

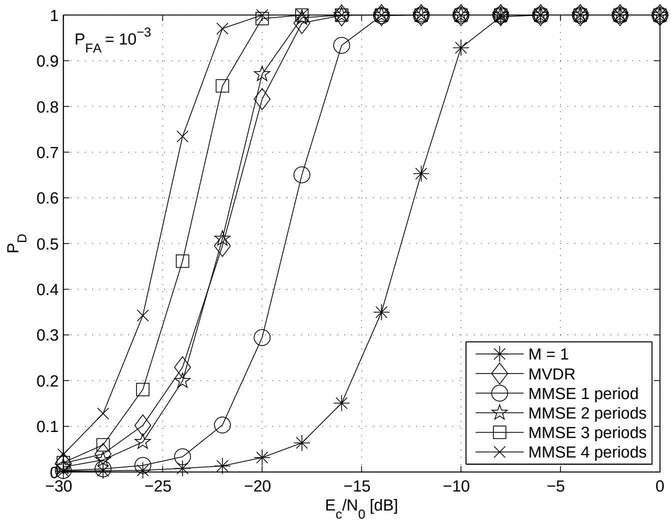

Fig 19. P_D **results of the pilot channel aided MMSE beamforming without interference.**

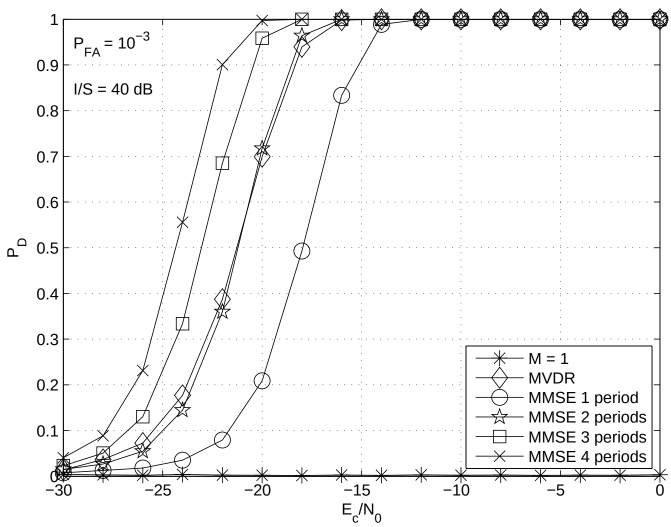

Fig 20. P_D **results of the pilot channel aided MMSE beamforming with interference.**

5 Conclusion and discussion

In this thesis, code acquisition of the DS/SS system was studied when a smart antenna was used in the receiver. The thesis was divided into three parts. In the first part, a literature review of code acquisition was presented. Therein, the basic code acquisition methods as well as different performance measures were studied. A review of the results in the literature under fading, data modulation, Doppler, intentional interference, multiple-access interference, other system interference and multiple antennas was given. In the second part of the thesis, an overview on smart antennas was presented, particularly focusing on digital beamforming and DOA estimation algorithms. The third part of the thesis concentrated on the author's contribution to the field.

Original articles were classified according to their contents into two groups. The first group (I-IV) covered DS/SS code acquisition performance under intentional interference, when the DOA of the desired signal was assumed to be known. Code acquisition performance was studied in many kinds of interference scenarios, because each of them might appear in practice. This part of the study was based on computer simulations and the BF+MF was used as a receiver structure. The used performance measure was mainly an RMSE of time delay estimate. The following spatial beamforming algorithms were studied: classical, nullsteering, MVDR, maxSINR, GSC and whitening filter. It was shown that most of them are capable of cancelling multiple and different types of interfering signals, if angle separation between desired and interfering signals is sufficient. Required angle separation depends on the prevailing SNR, I/S and on the used antenna array configuration. If SNR or the number of antennas is high, or I/S is low, then angle separation can be smaller. Classical beamforming was the only one that is not capable of eliminating interfering signals. If an interfering signal is arriving from the same direction as the desired signal, then more complex methods, like space-time processing, must be applied. Also some other methods against mainlobe interference were studied, like the method where a separate interference cancellation unit was located after the spatial beamformer. It turned out that this structure gives additional tolerance against mainlobe interference compared to spatial beamforming, but it does not have such good performance as the space-time algorithm has. Cancellation of impulsive interfering signals with smart antennas was studied using a structure, where an additional interference cancellation (i.e., pre-processing) unit was located before the space-time beamforming. The results indicate that many pre-processing algorithms are powerful methods against impulsive interferences. It can be concluded from the results carried out in Articles I-IV, that in the case of mainlobe interference, the most suitable interference cancellation method depends on the type of interference and on the amount of *a priori* information about the signal environment.

The second group of Articles (V-IX) focused on a theoretical analysis of synchronization probabilities and mean acquisition times. In this part of the study, the assumptions were changed so that also the DOA of the desired signal was unknown. Because the mean acquisition time is a function of the synchronization probabilities P_D and P_{FA}, the effects of DOA errors on these probabilities were researched. It was concluded from the results that the advanced beamforming algorithms are more sensitive to DOA errors than the classical beamformer. However, the robustness of the advanced beamformer against DOA errors can be improved using e.g., the adaptive diagonal loading algorithm. When BF+MF is used as a receiver structure, there is a two-dimensional acquisition problem because both angle and delay must be found. In this case, the whole angular uncertainty region (360°) can be divided into multiple small angular cells using beamforming techniques as is proposed in the literature. In this thesis, the research work of that area was extended to cover also the advanced beamforming techniques, because they offer interference suppression capability. It was shown that code acquisition performance can be improved by adding a DOA estimator into the system, since it reduces the number of required beams if the number of arriving signals is low. However, estimation of the DOA of DS/SS signal may be difficult if SNR in the channel is very low, i.e., if the length of the spreading code is large. In that case, the methods which do not need DOA information must naturally be used. Also, an iterative method for code acquisition was proposed, where the amount of data used for DOA estimation is progressively increased. The method was shown to offer short mean acquisition times with moderate SNR values. In addition, a MMSE beamforming structure, where only one period of the known spreading code is used as a training signal, was proposed. This structure requires that there must be a correlator or a MF in each antenna branch separately. The method was shown to have worse P_D but better T_{MA} performance than a delay-angle method has. Worse P_D performance comes from noncoherent antenna combining whereas the better T_{MA} performance is a consequence from the fact that DOA information is not needed in MMSE beamforming. Thus, it avoids time consuming searching through all angular cells. It was also shown that the P_D and T_{MA} performance of the MMSE beamforming can be improved, if the communication system involves a separate channel for synchronization. Then, a longer training sequence can be exploited already in the initial code acquisition stage.

As a conclusion of the research performed in this thesis, it is important to highlight the fact that there is not a single approach which outperforms the rest of the methods, but different scenarios, array configurations, *a priori* information, and other factors have a great impact on the performance of the explored schemes.

For further research, some interesting situations are worth considering. 1) Performance improvement via MMSE beamforming comes at the expense of increased implementation complexity due to multiple MFs. If M matched filters were used also in the delay-angle method, then parallel acquisition would be used to decrease its T_{MA}. This type of algorithm comparison, where the complexities of receivers are equal, is worth investigating. 2) The MMSE beamformer has an advantage that it does not need array calibration, which makes its implementation easier. Investigation of the effects of nonidealities, like amplitude and phase imbalances, on code acquisition is also an interesting topic. 3) Since it was concluded that there is not a single approach which gives the best performance in all scenarios, it would be interesting to research adaptive methods that according to some previous or estimated information select the best configuration or approach for acquisition. 4) Interference cancellation and other code acquisition methods were investigated mainly in the channel where there are no multipath components of signals. Performances of the methods under different types of multipath channels are also worth considering. 5) It would be interesting to investigate what is a powerful method in a scenario where all DOAs are unknown and an interfering signal is arriving from the same direction as the desired signal. The delay-angle method probably works also in this particular scenario, if scanning is performed using e.g., the space-time MVDR algorithm. However, it would be interesting to know if it is possible to develop space-time versions of the whitening filter and MMSE beamformers, and what is their performance.

References

Barabell AJ (1983) Improving the resolution performance of eigenstructure-based direction finding algorithms. Proc. of IEEE International Conference on Acoustics, Speech, and Signal Processing, 8: 336–339.

Baum C & Veeravalli V (1994) Hybrid acquisition schemes for direct sequence CDMA systems. Proc. of IEEE International Conference on Communications, New Orleans, USA, 3: 1433–1437.

Bezueha P (2002) Mean acquisition time of serial spread spectrum PN acquisition system in the presence of Doppler code. Proc. of IEEE Seventh International Symposium on Spread Spectrum Techniques and Applications, Prague, Czech, 3: 751–755.

Bharadwaj V & Buehrer RM (2004) Acquisition in CDMA systems using parallel interference cancellation. Proc. of IEEE Vehicular Technology Conference (Spring), Milan, Italy, 2: 1078–1081.

Braun W (1982) Performance analysis for the expanding search PN acquisition algorithm. IEEE Transactions on Communications 30(3): 424–435.

Caini C, Corazza GE & Vanelli-Coralli A (2004) DS-CDMA code acquisition in the presence of correlated fading-part II: application to cellular networks. IEEE Transactions on Communications 52(8): 1397–1407.

Capon J (1969) High resolution frequency-wavenumber spectral analysis. Proc. of the IEEE 57(8): 1408–1418.

Chang HS, Lee KM & Lee Y (2000) Adaptive acquisition for DS-SS systems with antenna diversity. Proc. of IEEE Vehicular Technology Conference (Fall), Boston, USA, 1: 467–472.

Chawla K & Sarwate D (1994) Parallel acquisition of PN sequences in DS/SS systems. IEEE Transactions on Communications 42(5): 2155–2164.

Chen W, Wong KM & Reilly JP (1991) Detection of the number of signals: a predicted eigenthreshold approach. IEEE Transactions on Signal Processing 39(5): 1088–1098.

Chen ZJ, Zhao J, Guo SL & Zhao YB (2007) A PN code acquisition scheme in the presence of data modulation and Doppler shift. Proc. of the Sixth International Conference on Machine Learning and Cybernetics, Hong Kong, 5: 2653–2656.

Cheng U (1988) Performance of a class of parallel spread-spectrum code acquisition schemes in the presence of data modulation. IEEE Transactions on Communications 36(5): 596–604.

Cheng U, Hurd WJ & Statman JI (1990) Spread-spectrum code acquisition in the presence of Doppler shift and data modulation. IEEE Transactions on Communications 38(2): 241–250.

Chuang CY, Yu X & Kuo CJ (2003) Joint PN code acquisition and DOA estimation in asynchronous DS-CDMA systems. Proc. of IEEE Vehicular Technology Conference (Spring), Jeju , Korea, 3: 1667–1671.

Chung CD (1995) Differentially coherent detection technique for direct-sequence code acquisition in a Rayleigh fading mobile channel. IEEE Transactions on Communications 43(234): 1116–1126.

Compton RT (1978) An adaptive array in a spread-spectrum communication system. Proc. of the IEEE 66(3): 289–298.

Compton RT (1988) The bandwidth performance of a two-element adaptive array with tapped delay-line processing. IEEE Transactions on Antennas and Propagation 36(1): 5–14.

Corazza GE (1996) On the MAX/TC criterion for code acquisition and its application to DS-SSMA systems. IEEE Transactions on Communications 44(9): 1173–1182.
Corazza GE, Caini C, Vanelli-Coralli A & Polydoros A (2004) DS-CDMA code acquisition in the presence of correlated fading - part I: theoretical aspects. IEEE Transactions on Communications 52(7): 1160–1168.
Corazza GE & Degli-Esposti V (1994) Acquisition-based capacity estimates for CDMA with imperfect power control. Proc. of IEEE Third International Symposium on Spread Spectrum Techniques and Applications, Oulu, Finland, 1: 325–329.
Davidovici S & Kanterakis EG (1989) Narrow-band interference rejection using real-time Fourier transforms. IEEE Transactions on Communications 37(7): 713–722.
Davidovici S, Milstein LB & Schilling DL (1984) A new rapid acquisition technique for direct sequence spread-spectrum communications. IEEE Transactions on Communications 32(11): 1161–1168.
Davisson L & Flikkema P (1988) Fast single-element PN acquisition for the TDRSS MA system. IEEE Transactions on Communications 36(7): 593–600.
Delva JGR & Howitt I (2001) A coherent acquisition method for a PN sequence using binary search and an auxiliary sequence. IEEE Journal on Selected Areas in Communications 19(12): 2432–2440.
DiCarlo D & Weber C (1980) Statistical performance of single dwell serial synchronization systems. IEEE Transactions on Communications 28(8): 1382–1388.
DiCarlo D & Weber C (1983) Multiple dwell serial search: performance and application to direct sequence code acquisition. IEEE Transactions on Communications 31(5): 650–659.
Dlugos DM & Scholtz RA (1989) Acquisition of spread spectrum signals by an adaptive array. IEEE Transactions on Acoustics, Speech, and Signal Processing 37(8): 1253–1270.
El-Tarhuni MG & Sheikh AUH (1998a) An adaptive filtering PN code acquisition scheme with improved acquisition based capacity in DS/CDMA. Proc. of IEEE International Symposium on Personal, Indoor and Mobile Radio Communication, Boston, USA, 3: 1486–1490.
El-Tarhuni MG & Sheikh AUH (1998b) Code acquisition of DS/SS signals in fading channels using an LMS adaptive filter. IEEE Communications Letters 2(4): 85–88.
Eynon AJ & Tozer TC (1995) A comparison of multiple-dwell cell testing strategies in serial search direct sequence spread spectrum code acquisition. Proc. of IEEE Military Communications Conference, San Diego, USA, 1: 357–361.
Fuxjaeger AW & Iltis RA (1994) Acquisition of timing and Doppler-shift in a direct-sequence spread-spectrum system. IEEE Transactions on Communications 42(10): 2870–2880.
Gardner WA (1993) Cyclic Wiener filtering: theory and method. IEEE Transactions on Communications 41(1): 151–163.
Garrett AL & Noneaker DL (1998) Multipath acquisition for Rake reception in DS-packet radio systems. Proc. of IEEE Military Communication Conference, Boston, USA, 3: 837–841.
Glisic S & Katz MD (2001) Modeling of the code acquisition process for RAKE receivers in CDMA wireless networks with multipath and transmitter diversity. IEEE Journal on Selected Areas in Communications 19(1): 21–32.
Glisic SG (1988a) Automatic decision threshold level control (ADTCL) in direct sequence spread spectrum systems based on matched filtering. IEEE Transactions on Communications 36(4): 519–527.
Glisic SG (1988b) Automatic decision threshold level control in direct sequence spread spectrum systems. IEEE Transactions on Communications 39(2): 187–192.

Godara LC (1997) Applications of antenna arrays to mobile communications, part II: Beamforming and direction-of-arrival considerations. Proceedings of the IEEE 85(8): 1195–1245.
Gottesman LD & Milstein LB (1990) The effect of a narrowband interference rejection filter on coarse acquisition in direct sequence spread spectrum. Proc. of IEEE Global Telecommunication Conference, San Diego, USA, 1: 256–260.
Gottesman LD & Milstein LB (1996) The coarse acquisition performance of a CDMA overlay system. IEEE Journal on Selected Areas in Communications 14(8): 1627–1635.
Gu Z, Gunawan E & Yu Z (2001) Joint spatiotemporal parameter estimation for DS-CDMA system in fast fading multipath channel. Proc. of IEEE Vehicular Technology Conference (Spring), Rhodes, Greece, 1: 28–32.
Gumacos C (1963) Analysis of an optimum sync search procedure. IEEE Transactions on Communications 11(1): 89–99.
Hansen RC (1998) Phased antenna arrays. John Wiley & Sons Inc., New York, USA.
Haykin S (1996) Adaptive filter theory. Prentice Hall, 3rd edition, Upper Saddle River, NJ, USA.
Henttu P (2000) Cyclic SVD method for broadband interference cancellation in FH/DS communications. Proc. of IEEE 6th International Symposium on Spread Spectrum Techniques and Applications, Parsippany, USA, 1: 68–72.
Henttu P & Aromaa S (2002) Consecutive mean excision algorithm. Proc. of IEEE 7th International Symposium on Spread Spectrum Techniques and Applications, Prague, Czech Republic, 2: 450–454.
Holmes J & Chen C (1977) Acquisition time performance of PN spread-spectrum systems. IEEE Transactions on Communications 25(8): 778–784.
Ibrahim B & Aghvami H (1994) Direct sequence spread spectrum matched filter acquisition in frequency-selective Rayleigh fading channels. IEEE Journal on Selected Areas in Communications 12(5): 885–890.
Iinatti J (1996) Robust method for threshold setting in a DS/DS-CDMA code acquisition. Proc. of IEEE International Conference on Universal Personal Communications, Cambridge, USA, 1: 145–153.
Iinatti J (1997) Matched filter code acquisition employing a median filter in direct sequence spread-spectrum systems with jamming. Acta Universitatis Ouluensis C102, Doctoral thesis, University of Oulu, Oulu, Finland.
Iinatti J (2000a) On the threshold setting principles in code acquisition of DS/SS signals. IEEE Journal on Selected Areas in Communications 18(1): 62–72.
Iinatti J (2000b) Performance of DS code acquisition in static and fading multipath channels. IEE Communication Proceedings 147(6): 355–360.
Iinatti J & Latva-aho M (1998) Matched filter acquisition for CDMA systems in multipath channels. Proc. of IEEE Global Telecommunications Conference, Sydney, Australia, 6: 3449–3454.
Iinatti J & Latva-aho M (2001) A modified CLPDI for code acquisition in multipath channel. Proc. of IEEE International Symposium on Personal, Indoor and Mobile Radio Communication, San Diego, USA, 2: 6–10.
Iinatti J & Pouttu A (1999) Differentially coherent code acquisition in jamming and data modulation. Proc. of IEEE Military Communications Conference, Atlantic City, USA, 1: 579–583.
Iinatti J & Pouttu A (2000) Differentially coherent code acquisition in wideband jamming. Proc. of IEEE Military Communications Conference, Los Angeles, USA, 2: 1129–1133.
Ikai Y, Katayama M, Yamazato T & Ogawa A (1999) A new acquisition scheme of a DS/SS

signal with transmit and receive antenna diversity. Proc. of IEEE International Conference on Communication, Vancouver, Canada, 2: 1256–1261.
Je HW, Shin OS & Lee KB (2003) Acquisition for DS/CDMA systems with multiple antennas in frequency-selective fading channels. IEEE Transactions on Wireless Communications 2(4): 787–798.
Jianlin L & Tantaratana S (1995) Optimal and suboptimal coherent acquisition schemes for PN sequences with data modulation. IEEE Transactions on Communications 43(2): 554–564.
Jovanovic VM (1988) Analysis of strategies for serial-search spread-spectrum code acquisition-direct approach. IEEE Transactions on Communications 36(11): 1208–1220.
Jovanovic VM (1992) On the distribution function of the spread-spectrum code acquisition time. IEEE Journal on Selected Areas in Communications 10(4): 760–769.
Kanterakis EG (1994) A novel technique for narrowband/broadband interference excision in DS-SS communications. Proc. of IEEE Military Communication Conference, Fort Monmouth, USA, 2: 628–632.
Kataoka T, Taoka H, Higuchi K & Sawahashi M (2004) Field experiments on adaptive antenna array-beam forming with simultaneous path timing and its DOA estimations employing directive-beam reception for broadband CDMA packet access in reverse link. Proc. of IEEE International Symposium on Personal, Indoor and Mobile Radio Communication, Barcelona, Spain, 2: 1257–1262.
Katz M (2002) Code acquisition in advanced CDMA networks. Acta Universitatis Ouluensis C175, Doctoral thesis, University of Oulu, Oulu, Finland.
Katz M & Glisic S (1998) Modelling of code acquisition process in CDMA networks: Quasi-synchronous systems. IEEE Transactions on Communications 46(12): 1564–1568.
Katz M & Glisic S (2000) Modelling of code acquisition process in CDMA networks: Asynchronous systems. IEEE Journal on Selected Areas in Communications 18(1): 73–86.
Katz M, Iinatti J & Glisic S (2000) Performance of two-dimensional code acquisition in radio environments with spatially colored interference. Proc. of IEEE Third International Symposium on Wireless Personal Multimedia Communications, Bangkok, Thailand, 1: 512–517.
Katz M, Iinatti J & Glisic S (2001a) Search strategies for two-dimensional code acquisition in environments with nonuniform spatial distribution of interference. Proc. of IEEE Vehicular Technology Conference (Spring), Rhodes, Greece, 2: 1454–1458.
Katz M, Iinatti J & Glisic S (2001b) Two-dimensional code acquisition in time and angular domains. IEEE Journal on Selected Areas in Communications 19(12): 2441–2451.
Katz M, Iinatti J & Glisic S (2002a) A comparative study of code acquisition using antenna diversity and beamforming techniques. Proc. of IEEE 7th International Symposium on Spread Spectrum Techniques and Applications, Prague, Czech Republic, 1: 223–227.
Katz M, Iinatti J & Glisic S (2002b) Two-dimensional code acquisition in slow- and fast-fading channels. Proc. of IEEE 7th International Symposium on Spread Spectrum Techniques and Applications, Prague, Czech Republic, 1: 248–252.
Katz M, Iinatti J & Glisic S (2004) Two-dimensional code acquisition in environments with a spatially nonuniform distribution of interference: algorithms and performance. IEEE Transactions on Wireless Communications 3(1): 1–7.
Kay SM (1998) Fundamentals of statistical signal processing. volume II: detection theory. Prentice Hall, Upper Saddle River, New Jersey.
Khalaj BH, Paulraj A & Kailath T (1994) 2D RAKE receivers for CDMA cellular systems. Proc. of IEEE Global Telecommunications Conference, San Francisco, USA, 1: 400–404.

Kim JH, Sarin SV, Yasunaga M & Oh H (2001) Robust noncoherent PN-code acquisition for CDMA communication systems. IEEE Transactions on Vehicular Technology 50(1): 278–286.

Kim JY (2001) NBI suppression for code acquisition, in a DS/CDMA overlay environment. Proc. of IEEE Vehicular Technology Conference (Spring), Rhodes, Greece, 3: 1684–1688.

Kim JY & Lee JH (1997) Performance of PN code acquisition in a DS/CDMA overlay environment with imperfect power control. Proc. of IEEE Vehicular Technology Conference, Phoenix, USA, 3: 2108–2112.

Kim S (2004) Acquisition performance of CDMA systems with multiple antennas. IEEE Transactions on Vehicular Technology 53(5): 1341–1353.

Kim S (2005) Effect of spatial fading correlation on CDMA code-acquisition performance. IEE Communication Proceedings 152(1): 103–112.

Kwon H, Kang H, Bae J, Park S, Kim S & Song I (2006) Adaptive code acquisition with receive diversity in nonhomogeneous fading channels. Proc. of IEEE Military Communication Conference, Washington, USA, 3: 1–7.

Kwon H, Song I, Kim S & Yoon S (2007) Noncoherent constant false-alarm rate schemes with receive diversity for code acquisition under homogeneous and nonhomogeneous fading circumstances. IEEE Transactions on Vehicular Technology 56(4): 2108–2120.

Kwon HM & Tarafder MR (1996) Noncoherent PN code acquisition with data modulation-on under static and fading environments. Proc. of IEEE Military Communication Conference, McLean, USA, 3: 998–1002.

Lee H & Li F (1994) An eigenvector technique for detecting the number of emitters in a cluster. IEEE Transactions on Signal Processing 42(9): 2380–2388.

Lee S & Kim J (2001) Effects of multiple threshold values for PN code acquisition in DS-CDMA systems. Electronics Letters 37(6): 363–365.

Lee S & Kim J (2002) Performance analysis of DS-SS PN code acquisition systems using soft-decision techniques in a Rayleigh-fading channel. IEEE Transactions on Vehicular Technology 51(6): 1587–1595.

Li J & Compton RT (1993) Maximum likelihood angle estimation for signals with known waveforms. IEEE Transactions on Signal Processing 41(9): 2850–2861.

Li J & Tantaratana S (1995) Optimal and suboptimal coherent acquisition schemes for PN sequences with data modulation. IEEE Transactions on Communications 43(2/3/4): 554–564.

Liberti JC & Rappaport TS (1999) Smart antennas for wireless communications: IS-95 and third generation CDMA applications. Prentice Hall, New Jersey, USA.

Lilja P & Saarnisaari H (2005) Robust adaptive beamforming in software defined radio with adaptive diagonal loading. Proc. of IEEE Military Communication Conference, Atlantic City, USA, 4: 2596–2601.

Lin JC (2002) Noncoherent sequential PN code acquisition using sliding correlation for chip-asynchronous direct-sequence spread-spectrum communications. IEEE Transactions on Communications 50(4): 664–676.

Litva J & Lo TKY (1996) Digital beamforming in wireless communications. Artech House, Norwood, Massachusetts.

Madhow U (1997) Blind adaptive interference suppression for the near-far resistant acquisition and demodulation of direct-sequence CDMA signals. IEEE Transactions on Signal Processing 45(1): 124–136.

Madhow U & Pursley MB (1993) Acquisition in direct-sequence spread-spectrum communica-

tion networks: An asymptotic analysis. IEEE Transactions on Information Theory 39(3): 903–912.
Madhow U & Pursley MB (1995) Mathematical modelling and performance analysis for a two-stage acquisition scheme for direct-sequence spread-spectrum CDMA. IEEE Transactions on Communications 43(9): 2511–2520.
Mathews CP & Zoltowski MD (1994) Eigenstructure techniques for 2-D angle estimation with uniform circular arrays. IEEE Transactions on Signal Processing 42(9): 2395–2407.
Mauss OC, Classen F & Meyr H (1993) Carrier frequency recovery for a fully digital direct-sequence spread-spectrum receiver: A comparison. Proc. of IEEE Vehicular Technology Conference, Secaucus, USA, : 392–395.
Mendoza R, Reed JH & Hsia TC (1989) Interference rejection using a hybrid of a constant modulus algorithm and the spectral correlation discriminator. Proc. of IEEE Military Communication Conference, Boston, USA, 2: 491–497.
Meyr H & Polzer G (1983) Performance analysis for general PN-spread-spectrum acquisition techniques. IEEE Transactions on Communications 31(12): 1317–1319.
Miller SL (1995) Performance of code acquisition for DS-CDMA overlay. Proc. of IEEE Military Communications Conference, San Diego, USA, 2: 626–630.
Milstein L, Gevargiz J & Das P (1985) Rapid acquisition for direct sequence spread-spectrum communications using parallel SAW convolvers. IEEE Transactions on Communications 33(7): 593–600.
Milstein LB (1988a) Interference rejection techniques in spread spectrum communications. Proceedings of the IEEE 76(6): 657–671.
Milstein LB (1988b) Interference suppression to aid acquisition in direct-sequence spread-spectrum communications. IEEE Transactions on Communications 36(11): 1200–1207.
Pan SM, Madill DH & Dodds DE (1995) A unified time-domain analysis of serial search with application to spread spectrum receivers. IEEE Transactions on Communications 43(12): 3046–3054.
Park MK & Oh SK (1998) Performance of serial acquisition schemes using antenna arrays in the DS-SS system. Proc. of IEEE Global Telecommunications Conference, Sydney, Australia, 1: 195–200.
Peterson RL, Ziemer RE & Borth DE (1995) Introduction to spread spectrum communications. Prentice Hall. Inc., USA.
Pirhonen P & Ristaniemi T (2002) Advanced differentially non-coherent code acquisition in jamming and data modulation. Proc. of IEEE International Symposium on Personal, Indoor and Mobile Radio Communication, Lisbon, Portugal, 4: 1820–1823.
Polydoros A (1982) On the synchronization aspects of direct sequence spread-spectrum systems. Ph.D Dissertation, Dept. of Electrical Engineering, University of Southern California.
Polydoros A (1984) Generalized serial search code acquisition: The equivalent circular state diagram approach. IEEE Transactions on Communications 32(12): 1260–1268.
Polydoros A & Weber C (1984a) A unified approach to serial search spread-spectrum code acquisition – part I: General theory. IEEE Transactions on Communications 32(5): 542–549.
Polydoros A & Weber C (1984b) A unified approach to serial search spread-spectrum code acquisition – part II: A matched-filter receiver. IEEE Transactions on Communications 32(5): 550–560.
Proakis JG (1995) Digital communications. McGraw-Hill, Inc., New York, USA.
Proakis JG (1996) Interference suppression in spread spectrum systems. Proc. of IEEE 4th Inter-

national Symposium on Spread Spectrum Techniques and Applications, Mainz, Germany, 1: 259–266.
Puska H, Saarnisaari H, Iinatti J & Lilja P (2005) Correlator code acquisition employing smart antennas in DS/SS systems. Proc. of IEEE Military Communications Conference, Atlantic City, USA, 5: 3004–3009.
Raleigh GG & Boros T (1998) Joint space-time parameter estimation for wireless communication channels. IEEE Transactions on Signal Processing 46(5): 1333–1343.
Rappaport S (1969) On practical setting of detection thresholds. Proc. of the IEEE 57(8): 1420–1421.
Rappaport S & Grieco D (1984) Spread-spectrum signal acquisition: Methods and technology. IEEE Communications Magazine 22(6): 6–21.
Ravi KV & Ormondroyd RF (1991) Simulation performance of a quantized log-likelihood sequential detector for PN code acquisition in the presence of data modulation and Doppler shift. Proc. of IEEE Military Communications Conference, McLean, USA, 2: 798–803.
Ravi KV & Ormondroyd RF (1992) Effect of CW and pulse jamming on direct-sequence spread-spectrum code acquisition using a sequential detector. Proc. of IEEE Military Communications Conference, San Diego, USA, 2: 638–643.
Reed MC (2004) Return link 2-D code acquisition for DS-CDMA in a high capacity multi-user system. Proc. of IEEE Vehicular Technology Conference (Spring), Milan, Italy, 3: 1451–1455.
Reed MC, Hanlen LW & Corazza GE (2008) Return-link code acquisition for 1-D and 2-D with DS-CDMA for high-capacity multiuser systems. IEEE Transactions on Vehicular Technology 57(1): 324–334.
Rick RR & Milstein LB (1997) Parallel acquisition of spread-spectrum signals with antenna diversity. IEEE Transactions on Communications 45(8): 903–905.
Rick RR & Milstein LB (1998) Optimal decision strategies for acquisition of spread-spectrum signals in frequency-selective fading channels. IEEE Transactions on Communications 46(5): 686–694.
Ristaniemi T (1999a) Accurate pilot assisted PN code acquisition. Proc. of IEEE Vehicular Technology Conference (Fall), Amsterdam, Netherlands, 2: 723–727.
Ristaniemi T (1999b) Code acquisition in CDMA communication system with fictitious pilot signals. Proc. of IEEE International Conference on Electronics, Circuits and Systems, Pafos, Cyprus, 3: 1273–1277.
Ristaniemi T & Joutsensalo J (2001) Code timing acquisition for DS-CDMA in fading channels by differential correlations. IEEE Transactions on Communications 49(5): 899–910.
Ristaniemi T & Pirhonen P (2002) Advanced differentially coherent code acquisition in jamming. Proc. of IEEE Vehicular Technology Conference (Spring), Birmingham, UK, 3: 1443–1447.
Rodgers WE & R T Compton J (1979) Adaptive array bandwidth with tapped delay-line processing. IEEE Transactions on Aerospace and Electronic Systems 15(1): 21–28.
Roy R & Kailath T (1989) ESPRIT-estimation of signal parameters via rotational invariance techniques. IEEE Transactions on Acoustics, Speech, and Signal Processing 37(7): 984–995.
Rui W & Ristaniemi T (2005) The performance analysis of EV-T method for two-dimensional code acquisition. Proc. of IEEE Workshop on Computational Advances in Multi-Sensor Adaptive Processing, Puerto Vallarta, Mexico, : 229–232.
Ryu WH, Park MK & Oh SK (2002) Code acquisition schemes using antenna arrays for DS-SS

systems and their performance in spatially correlated fading channels. IEEE Transactions on Communications 50(8): 1337–1347.

Saarnisaari H (2000) Phase interference extractor interference canceller in DS/SS code synchronization. Proc. of IEEE EUROCOMM 2000, Munich, Germany, : 111–115.

Saarnisaari H (2001) Interference rejection in DS/SS-systems with an improved RLS-whitening filter. Proc. of IEEE International Conference on Communications, Helsinki, Finland, 6: 1871–1875.

Saarnisaari H & Henttu P (2003) Impulse detection and rejection methods for radio systems. Proc. of IEEE Military Communications Conference, Boston, USA, 2: 1126–1131.

Saarnisaari H, Henttu P & Puska H (2005) Narrowband main beam interference mitigation algorithms for space-time adaptive processing. EURASIP Signal Processing 85(3): 457–461.

Sage G (1964) Serial synchronization of pseudonoise systems. IEEE Transactions on Communications 12(12): 123–127.

Salih M & Tantaratana S (1996) A closed-loop coherent acquisition scheme for PN sequences using an auxiliary sequence. IEEE Journal on Selected Areas in Communications 14(8): 1653–1659.

Salih M & Tantaratana S (1999) A closed-loop coherent PN acquisition system with a pre-loop estimator. IEEE Transactions on Communications 47(9): 1394–1405.

Saunders SR (1999) Antennas and propagation for wireless communication systems. John Wiley and Sons, Inc., New York, USA.

Schell SV, Calabretta RA, Gardner WA & Agee BG (1989) Cyclic MUSIC algorithms for signal-selective direction estimation. Proc. of IEEE International Conference on Acoustics, Speech, and Signal Processing, Glasgow, UK, 4: 2278–2281.

Schmidt RO (1979) Multiple emitter locations and signal parameter estimation. Proc. of RADC Spectrum Estimation Workshop, Rome, USA, : 243–258.

Schweppe FC (1968) Sensor array data processing for multiple signal sources. IEEE Transactions on Information Theory 14(2): 294–305.

Shan TJ, Wax M & Kailath T (1985) On spatial smoothing for direction-of-arrival estimation of coherent signals. IEEE Transactions on Acoustics, Speech, and Signal Processing 33(4): 806–811.

Sheen WH & Wang HC (2001) A new analysis of direct-sequence pseudonoise code acquisition on Rayleigh fading channels. IEEE Journal on Selected Areas in Communications 19(11): 2225–2232.

Shin OS & Lee KB (2001) Utilization of multipaths for spread-spectrum code acquisition in frequency-selective Rayleigh fading channels. IEEE Transactions on Communications 49(4): 734–743.

Shin OS & Lee KB (2003) Use of multiple antennas for DS/CDMA code acquisition. IEEE Transactions on Wireless Communications 2(3): 424–430.

Siess EW & Weber CL (1986) Acquisition of direct sequence signal with modulation and jamming. IEEE Journal on Selected Areas in Communications 4(2): 254–272.

Simon M, Omura J, Scholtz R & Levitt B (1994) Spread spectrum communications handbook. McGraw-Hill, Inc., USA.

Simsa J (1996) DS-SS serial search code acquisition in time-variant channel. Proc. of IEEE 4th International Symposium on Spread Spectrum Techniques and Applications, Mainz, Germany, 2: 771–775.

Simsa J & Triska I (1994) Comparison of multiple-dwell code acquisition detector rules in DS-SS

serial search by envelope correlator. Proc. of IEEE 3th International Symposium on Spread Spectrum Techniques and Applications, Oulu, Finland, 2: 614–618.
Smith RF & Miller SL (1999) Acquisition performance of an adaptive receiver for DS-CDMA. IEEE Transactions on Communications 47(9): 1416–1424.
Sourour E & Gupta S (1989) Direct sequence spread spectrum parallel acquisition in a fading mobile channel. Proc. of IEEE 39th Vehicular Technology Conference, San Francisco, USA, 2: 774–779.
Sourour E & Gupta S (1992) Direct-sequence spread-spectrum parallel acquisition in nonselective and frequency-selective Rician fading channels. IEEE Journal on Selected Areas in Communications 10(3): 535–544.
Sourour EA & Gupta SC (1990) Direct-sequence spread-spectrum parallel acquisition in a fading mobile channel. IEEE Transactions on Communications 38(7): 992–998.
Srinivasan M & Sarwate D (1996) Simple schemes for parallel acquisition of spreading sequences in DS/SS systems. IEEE Transactions on Vehicular Technology 45(3): 593–598.
Stojanovic NM & Jovanovic VK (1992) New robust threshold setting method for frequency-hopping acquisition. Electronics Letters 28(9): 815–817.
Ström EG & Malmsten F (1998) Maximum likelihood synchronization of DS-CDMA signals transmitted over multipath channels. Proc. of IEEE International Conference on Communications, Atlanta, USA, 3: 1546–1550.
Ström EG & Parkvall S (1995) Joint parameter estimation and detection of DS-CDMA signals in fading channels. Proc. of IEEE Global Telecommunications Conference, Singapore, 2: 1109–1113.
Ström EG, Parkvall S, Miller SL & Ottersten BE (1996a) DS-CDMA synchronization in time-varying fading channels. IEEE Journal on Selected Areas in Communications 14(8): 1636–1642.
Ström EG, Parkvall S, Miller SL & Ottersten BE (1996b) Propagation delay estimation in asynchronous direct-sequence code-division multiple access systems. IEEE Transactions on Communications 44(1): 84–93.
Su SL, Yen NY & Hsieh SC (1995) Code acquisition of direct-sequence spread spectrum communication with Doppler shift. Proc. of IEEE International Conference on Communications, Seattle, USA, 3: 1663–1667.
Su YT & Weber CL (1990) A class of sequential tests and its applications. IEEE Transactions on Communications 38(2): 165–171.
Su YT, Wen-Chang L & Ru-Chwen W (1998) Optimal and suboptimal noncoherent detectors for PN code acquisition in the presence of data modulation. Proc. of IEEE Vehicular Technology Conference, Ottawa, Canada, 3: 2426–2430.
Takao K & Kikuma N (1987) An adaptive array utilizing an adaptive spatial averaging technique for multipath environments. IEEE Transactions on Antennas and Propagation 35(12): 1389–1396.
Tantaratana S, Lam AW & Vincent PJ (1995) Noncoherent sequential acquisition of PN sequences for DS/SS communications with/without channel fading. IEEE Transactions on Communications 43(2/3/4): 1738—1745.
Tazebay MV & Akansu AN (1995) Adaptive subband transforms in time-frequency excisers for DSSS communications systems. IEEE Transactions on Signal Processing 43(11): 2776–2782.
Trees HLV (2002) Optimum array processing. John Wiley & Sons Inc., New York.

Triska I & Simsa J (1994) Multiple-dwell serial-search code acquisition of DS spread-spectrum receiver. Proc. of 7th Mediterranean Electrotechnical conference, Antalya, Turkey, 1: 35–38.
van der Veen AJ, Vanderveen M & Paulraj A (1998) Joint angle and delay estimation using shift-invariance techniques. IEEE Transactions on Signal Processing 46(2): 405–418.
Visuri S, Oja H & Koivunen V (2001) Subspace-based direction-of-arrival estimation using non-parametric statistics. IEEE Transactions on Signal Processing 49(9): 2060–2073.
Vook FW & R T Compton J (1992) Bandwidth performance of linear adaptive arrays with tapped delay-line processing. IEEE Transactions on Aerospace and Electronic Systems 28(3): 901–908.
Wang B & Kwon HM (2000a) PN code acquisition using smart antenna for DS-CDMA wireless communications. Proc. of IEEE Military Communications Conference, Los Angeles, USA, 2: 821–825.
Wang B & Kwon HM (2000b) PN code acquisition with adaptive antenna array and adaptive threshold for DS-CDMA wireless communications. Proc. of IEEE Global Telecommunication Conference, San Francisco, USA, 1: 152–156.
Wang B & Kwon HM (2003a) PN code acquisition for DS-CDMA systems employing smart antennas - part II. IEEE Transactions on Wireless Communications 2(1): 108–117.
Wang B & Kwon HM (2003b) PN code acquisition using smart antenna for spread-spectrum wireless communications - part I. IEEE Transactions on Vehicular Technology 52(1): 142–149.
Wang HC & Sheen WH (2000) Variable dwell-time code acquisition for direct-sequence spread-spectrum systems on time-variant Rayleigh fading channels. IEEE Transactions on Communications 48(6): 1037–1046.
Wax M & Kailath T (1985) Detection of signals by information theoretic criteria. IEEE Transactions on Acoustics, Speech, and Signal Processing 33(2): 387–392.
Weinberg A (1983) Generalized analysis for the evaluation of search strategy effects on PN acquisition performance. IEEE Transactions on Communications 31(1): 37–49.
Wetzker G, Sieborger C, Kaage U & Jondral F (1998) Maximum likelihood DSSS code acquisition in the presence of multipath propagation, Doppler shift and data modulation. Proc. of IEEE 5th International Symposium on Spread Spectrum Techniques and Applications, Sun City, South Africa, 2: 441–445.
Xu G & Kailath T (1994) Fast subspace decomposition. IEEE Transactions on Signal Processing 42(3): 539–550.
Yang HL & Wu WR (2005) A novel adaptive code acquisition using antenna array for DS/CDMA systems. Proc. of IEEE International Workshop on Antenna Technology, Singapore, : 458–461.
Yang HL & Wu WR (2007) A novel adaptive antenna array for DS/CDMA code acquisition. IEEE Transactions on Signal Processing 55(9): 4567–4580.
Yang Y, Park H, Shin HS & Choi J (1999) Performance of acquisition using antenna array in the DS-SS system. Proc. of IEEE International Symposium on Personal, Indoor and Mobile Radio Communication, Osaka, Japan, 2: 6–10.
Yoon S, Kim SC, Heo J, Song I & Kim SY (2008) Twin-cell detection (TCD): A code acquisition scheme in the presence of fractional Doppler frequency offset. IEEE Transactions on Vehicular Technology, Accepted for future publication.
Zarrabizadeh MH & Sousa ES (1997) A differentially coherent PN code acquisition receiver for CDMA systems. IEEE Transactions on Communications 45(11): 1456–1465.

Zhang J, Wong KM, Luo ZQ & Ching PC (1999) Blind adaptive FRESH filtering for signal extraction. IEEE Transactions on Signal Processing 47(5): 1397–1402.
Zhang Y, Bao Z, Zhang L & Liao G (2004) Joint acquisition of PN code and adaptive beamforming weight in spread spectrum systems. IEE Electronics Letters 40(1): 52–53.
Zhang Y, Zhang L & Liao G (2003) PN code acquisition and beamforming weight acquisition for DS-CDMA systems with adaptive array. Proc. of IEEE Personal, Indoor and Mobile Radio Communication, Beijing, China, 2: 1385–1389.
Zhuang W (1996) Noncoherent hybrid parallel PN code acquisition for CDMA mobile communications. IEEE Transactions on Vehicular Technology 45(4): 643–656.
Ziemer RE & Peterson RL (1985) Digital communications and spread spectrum systems. MacMillan Publishing Company, New York, 750 p.
Ziskind I & Wax M (1988) Maximum likelihood localization of multiple sources by alternating projection. IEEE Transactions on Acoustics, Speech, and Signal Processing 36(10): 1553–1560.
Zoltowski MD, Kautz GM & Silverstein SD (1991) Development, performance analysis, and experimental evaluation of beamspace Root-MUSIC. Proc. of IEEE International Conference on Acoustics, Speech, and Signal Processing, Toronto, Canada, 5: 3049–3052.
Zoltowski MD, Kautz GM & Silverstein SD (1993) Beamspace Root-MUSIC. IEEE Transactions on Signal Processing 41(1): 344–364.

Original articles

I Puska H, Saarnisaari H & Iinatti J (2003) Utilizing beamformers as interference cancellers in code synchronization of DS/SS system. Proc. of IEEE Finnish Signal Processing Symposium, Tampere, Finland, on CD: 5p.

II Puska H, Saarnisaari H & Iinatti J (2005) Comparison of antenna array algorithms in DS/SS code acquisition with jamming. Proc. of IEEE Military Communication Conference, Atlantic City, USA, 4: 2074–2080.

III Puska H & Saarnisaari H (2004) Performance comparison of robust array algorithms in delay estimation. Proc. of IEEE Sensor Array and Multichannel Signal Processing Workshop, Barcelona, Spain, 1: 332–336.

IV Puska H, Saarnisaari H & Iinatti J (2005) Comparison of matched filter acquisition using beamforming and CME algorithm in impulsive interference. Proc. of IEEE Vehicular Technology Conference (Spring), Stockholm, Sweden, 3: 1988–1992.

V Puska H, Saarnisaari H, Iinatti J & Lilja P (2007) Synchronization probabilities using conventional and MVDR beam forming with DOA errors. Proc. of IEEE Personal Indoor and Mobile Radio Communication, Athens, Greece, on CD: 5p.

VI Puska H, Saarnisaari H, Iinatti J & Lilja P (2008) Serial search code acquisition using smart antennas with single correlator or matched filter. IEEE Transactions on Communications 56(2): 299–308.

VII Puska H, Iinatti J & Saarnisaari H (2009) Serial search and maximum selection based code acquisition techniques for single and multi antenna systems. IEEE Transactions on Wireless Communications 8(3). In press.

VIII Puska H, Saarnisaari H & Iinatti J (2005) An iterative method for code acquisition using DOA estimation and beamforming. Proc. of IEEE Personal Indoor and Mobile Radio Communication, Berlin, Germany, 2: 1165–1169.

IX Puska H, Saarnisaari H, Iinatti J & Lilja P (2007) Performance comparison of DS/SS code acquisition using MMSE and MVDR beamforming in jamming. Proc. of IEEE Military Communication Conference, Orlando, USA, on CD: 7p.

Original publications are not included in the electronic version of the dissertation.

302. Teräs, Jukka (2008) Regional science-based clusters. A case study of three European concentrations

303. Lahti, Markku (2008) Gravure offset printing for fabrication of electronic devices and integrated components in LTCC modules

304. Popov, Alexey (2008) TiO_2 nanoparticles as UV protectors in skin

305. Illikainen, Mirja (2008) Mechanisms of thermomechanical pulp refining

306. Borkowski, Maciej (2008) Digital Δ-Σ Modulation. Variable modulus and tonal behaviour in a fixed-point digital environment

307. Kuismanen, Kimmo (2008) Climate-conscious architecture—design and wind testing method for climates in change

308. Kangasvieri, Tero (2008) Surface-mountable LTCC-SiP module approach for reliable RF and millimetre-wave packaging

309. Metsärinta, Maija-Leena (2008) Sinkkivälkkeen leijukerrospasutuksen stabiilisuus

310. Prokkola, Jarmo (2008) Enhancing the performance of ad hoc networking by lower layer design

311. Löytynoja, Mikko (2008) Digital rights management of audio distribution in mobile networks

312. El Harouny, Elisa (2008) Historiallinen puukaupunki suojelukohteena ja elinympäristönä. Esimerkkeinä Vanha Porvoo ja Vanha Raahe. Osa 1

312. El Harouny, Elisa (2008) Historiallinen puukaupunki suojelukohteena ja elinympäristönä. Esimerkkeinä Vanha Porvoo ja Vanha Raahe. Osa 2

313. Hannuksela, Jari (2008) Camera based motion estimation and recognition for human-computer interaction

314. Nieminen, Timo (2009) Detection of harmful microbes and their metabolites with novel methods in the agri-food production chain

315. Marjala, Pauliina (2009) Työhyvinvoinnin kokemukset kertomuksellisina prosesseina–narratiivinen arviointitutkimus

316. Ahola, Juha (2009) Reaction kinetics and reactor modelling in the design of catalytic reactors for automotive exhaust gas abatement

317. Koskimäki, Heli (2009) Utilizing similarity information in industrial applications

Book orders:
OULU UNIVERSITY PRESS
P.O. Box 8200, FI-90014
University of Oulu, Finland

Distributed by
OULU UNIVERSITY LIBRARY
P.O. Box 7500, FI-90014
University of Oulu, Finland

UNIVERSITY OF OULU P.O.B. 7500 FI-90014 UNIVERSITY OF OULU FINLAND

ACTA UNIVERSITATIS OULUENSIS

ISBN 978-951-42-9048-0 (Paperback)
ISBN 978-951-42-9049-7 (PDF)
ISSN 0355-3213 (Print)
ISSN 1796-2226 (Online)

UNIVERSITY of OULU
OULUN YLIOPISTO