Stellingen

Behorende bij het proefschrift

Multirate multi-user detectors for wideband code division multiple access

van

Tero Ojanperä

Delft, 23 november 1999
1. De prestatie van de parallele interferentieopheffingsontvanger (PIC) weerstaat schattingsfouten van vertraging, zelfs op een systeem voor meervoudig toegang door codeverdeling (CDMA) met een variabele spreidingsfactor. Alle datasequenties hebben een gelijk foutdegradatie als functie van de schattingsfout van vertraging.

* Dit proefschrift, hoofdstuk 5.

2. Het wegen van de interferentieopheffingsfactor met betrekking tot de datasequen- tie verbetert de prestatie van de parallele interferentieopheffingsontvanger (PIC) in een CDMA-systeem met een variabele spreidingsfactor in een kanaal met additieve witte Gaussische ruis (AWGN).

* Dit proefschrift, hoofdstuk 7.

3. De uitspraak van Arthur C. Clarke dat “....2025 directe invoer mogelijk wordt, zonder ogen, oren, huid, etc. welke leidt tot een metalen “Breinpet”. Eénieder kan met deze helm op, strak over de schedel, een geheel universum aan ervaringen betreden, echt of fantasie – en zelfs direct met andere geesten fuseren. Omdat de Breinpet alleen goed werkt op een geheel kaal hoofd, zal de pruikenindustrie floreer” kan niet als het ultieme doel van mobiele communicatie beschouwd worden. Innovatieve communicatiemethoden, die de privacy en integriteit van de menselijke geest bewaren, dienen gezocht te worden.

* Asiaweek, 20/27 augustus 1999

4. Mobiele telefoons zijn tegenwoordig het meest geliefd. Dit is bewezen door hun penetratie in de meest geavanceerde markten, zoals Finland (meer dan 60%), zowel als het feit dat het aantal mobiele abonnementen het aantal abonneelijnen overschrijdt.

5. De Wet van Metcalfe stelt dat “de waarde van enig communicatienetwerk groeit volgens het aantal gebruikers (in het netwerk) in het kwadraat”. De waarde van het huidige mobiele communicatienetwerk is hier duidelijk bewijs van.

6. Het economisch effect van mobiele communicatie en het Internet zijn over de laatste jaren enorm geweest. Het combineren van de twee in een mobiel Internet zal nieuwe diensten mogelijk maken, welke fundamenteelere veranderingen in de wereldwirtschaften zullen bewerkstelligen en de groei ervan versnellen.


8. Een verhoogd aantal te schatten parameters vermindert de nauwkeurigheid van het schattingsproces. Dit geldt in het bijzonder voor het voorspellen van het leven zelf, waarin het aantal parameters onbegrensd is, waardoor het voorspellen van de toekomst onmogelijk wordt.

9. Eenvoud is de sleutel naar innovatie.

10. Er is geen beloning zonder risico.
1. The performance of the parallel interference cancellation (PIC) receiver withstands delay estimation errors, even in a wideband code-division multiple access (CDMA) system with a variable spreading factor. All data rates have equal error degradation as a function of increasing delay estimation error. 

   *This thesis, chapter 5.*

2. Weighting the interference cancellation factor with respect to the data rate improves the performance of the parallel interference cancellation (PIC) receiver in a CDMA system with a variable spreading factor in an additive white Gaussian noise (AWGN) channel.

   *This thesis, chapter 7.*

3. Arthur C. Clarke’s statement that
   “....2025 direct inputs become possible, bypassing eyes, ears, skin, etc. leading to a metal “Braincap”. Anyone wearing this helmet, fitting tightly over the skull, can enter a whole universe of experience, real or imaginary – and even merge in real-time with other minds. As the Braincap can only function properly on a completely bald head, wig-making becomes a major industry” cannot be regarded as the ultimate goal of wireless communications. More innovative ways of communications, which preserve the privacy and integrity of the human mind, should be sought.

   *Asiaweek, August 20/27, 1999*

4. Today, mobile phones are the preferred telephones. This has been proven by their penetration into the most advanced markets, such as Finland (over 60%), as well as by the fact that number of wireless subscriptions exceeds the number of subscriber lines.

5. Metcalfe’s law states that
   “the value of any communication network grows as the square of the number of connected users (in the network)”.

   The value of mobile communications networks today is clear evidence of this.

6. The economic impact of both mobile communications and the Internet has been tremendous during recent years. Combining the two into a wireless Internet will enable new services, resulting in more fundamental changes to the world’s economy, accelerating its growth.

7. According to Moore’s law, which is empirical by nature, the number of devices per unit area that can be incorporated into a silicon integrated circuit doubles every 18 months. Moore’s law will facilitate implementation of interference cancellation receivers by the year 2002, when third-generation mobile communications networks will be deployed.

8. An increasing number of parameters to be estimated reduces the accuracy of the estimation process. This is especially true in predicting life itself, in which the number of parameters is infinite, making prediction of the future impossible.

9. Simplicity is the key to innovation.

10. Without risks there can be no rewards.
Multirate multi-user detectors for wideband code division multiple access
Multirate multi-user detectors for wideband code division multiple access

Proefschrift

ter verkrijging van de graad van doctor
aan de Technische Universiteit Delft,
op gezag van de Rector Magnificus Prof. ir. K.F.Wakker
in het openbaar te verdedigen ten overstaan van een commissie,
door het College voor Promoties aangewezen,
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doors

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Printed in Finland
To Tiina and Eerik, the sunshine of my life
Summary

The aim of the thesis is to evaluate and develop suitable receiver concepts for future wideband code division multiple access (CDMA) systems. Multiuser detection (MUD) receivers for asynchronous direct sequence (DS) CDMA system applying variable spreading factor (VSF) multirate scheme are studied.

A multirate DS-CDMA system model is presented and the most common multiuser detection algorithms are reviewed. A qualitative comparison of selected multiuser detection algorithms is performed. The criteria for comparison are derived, based on properties of third generation wideband CDMA systems for mobile communications. Based on the comparison a novel multiuser detection receiver, namely weighted multirate parallel interference cancellation, suitable for a variable spreading factor DS-CDMA system is proposed.

Several Gaussian approximations for performance analysis of DS-CDMA systems are reviewed. These include: standard (SGA), improved (IGA), simplified improved (SIGA) and accurate (AGA) Gaussian approximations. Performance of a variable spreading factor DS-CDMA system using the AGA is analysed. It is concluded that the bit error probabilities for different spreading factors (i.e., data rates) are different and that the high rate users have the best performance. Based on this, a groupwise multiuser receiver structure, exploiting the variable spreading factor signal characteristics, is motivated.

The performance of parallel interference cancellation (PIC) receiver is evaluated with and without delay estimation errors. A delay estimation error of 0.1 of the chip is found acceptable; the performance degrades fast at higher estimation errors. Users with different processing gains showed roughly the same level of degradation for a given delay estimation error. The PIC receiver is able to remove the near-far effect in a VSF CDMA system in AWGN and fading channels.

Several new interference cancellation structures based on groupwise successive interference cancellation (GSIC) are presented. Performance of matched filter, parallel interference cancellation, and different GSIC receivers in AWGN and Rayleigh fading channels in a VSF system are compared. GSIC structures are well suited for the VSF system. Delay estimation error of 0.1 of chip duration are acceptable, thereafter the performance degrades fast, especially for more complex receiver structures. In addition, complexity and performance comparisons of the matched filter, PIC and GSIC receivers are performed. An extended GSIC receiver with PIC within groups is found to be a good compromise from the complexity and performance points of views.

Performance of the weighted multirate PIC receiver is evaluated in a system with three different processing gains. Weighting is shown to improve performance of the PIC receiver in a VSF system in an AWGN channel. However, in a fading channel no improvement was observed. This is because the RAKE receiver weights the signal according to signal-to-noise ratio, and thus weaker signals contribute less to the decision than the stronger signals.

Keywords: groupwise successive interference cancellation, multirate multiuser detection, variable spreading factor direct-sequence code division multiple access, weighted cancellation, wideband CDMA.
Samenvatting (Summary in Dutch)

Het doel van dit proefschrift is het evalueren en ontwikkelen van geschikte ontvangerconcepten voor toekomstige breedbandsystemen voor meervoudige toegang door codeverdeling (CDMA). Ontvangers voor detectie van meerdere gebruikers (MUD) voor een asynchroon direct sequence (DS) CDMA systeem met gebruik van een schema van meerdere snelheden van de variabele spreidingsfactor (VSF) worden bestudeerd.

Er wordt een model van een DS-CDMA systeem met meerdere snelheden gepresenteerd en de meest gebruikelijke detectiealgoritmen voor meerdere gebruikers worden besproken. Er vindt een kwalitatieve vergelijking van geselecteerde detectiealgoritmen voor meerdere gebruikers plaats. De vergelijkingscriteria worden herleid, gebaseerd op eigenschappen van derde-generatie breedband CDMA systemen voor mobiele communicatie. Gebaseerd op de vergelijking wordt een nieuwe detectieontvanger voor meerdere gebruikers voorgesteld, namelijk gewogen parallelle interferentieopheffing op meerdere snelheden, geschikt voor een DS-CDMA systeem met variabele spreidingsfactor.

Er worden meerdere Gaussiaanse approximaten voor prestatieanalyse van DS-CDMA systemen besproken. Deze zijn o.a.: standaard (SGA), verbetterde (IGA), gesimplificeerde verbeterde (SITA) en accurate (AGA) Gaussiaanse approximaten. Prestaties van een DS-CDMA systeem met een variabele spreidingsfactor worden met behulp van de AGA geanalyseerd. Dit leidt tot de conclusie dat de biterrorprobabiliteiten voor diverse spreidingsfactoren (ofwel, gegevensnemers) verschillen en dat de hogesnelheidsgeschiktheid der beste prestaties ondervinden. Dit ondersteunt de motivatie van een groepsgewijze ontvangerstructuur voor meerdere gebruikers, waarbij de signaalmerkens van de variabele spreidingsfactor worden gebruikt.

De prestaties van parallelle interferentieopheffingsontvangers (PIC) worden geëvalueerd met en zonder schattingfouten van vertraging. Een schattingfout van chipvertraging van 0,1 wordt als acceptabel beschouwd; de prestaties degenereren snel bij hogere schattingfouten. Gebruikers met verschillende verwerkingstijgingen toonden ongeveer hetzelfde degeneratie niveau bij een gegeven schattingfout van vertraging. De PIC ontvanger kan het dichtbij-verf-effect in een VSF CDMA systeem in AWGN en wegstervende kanalen opheffen.

Verscheidene nieuwe interferentieopheffingsstructuren gebaseerd op groepsgewijze opeenvolgende interferentieopheffing (GSIC) worden gepresenteerd. Prestaties van gelijk filter, parallelle interferentieopheffing, en verschillende GSIC ontvangers in AWGN en kanalen met fading volgens de Rayleigh-verdeling in een VSF systeem worden vergeleken. GSIC structuren zijn zeer geschikt voor het VSF systeem. Schattingfouten van chipsnelheidsvertraging van 0,1 zijn acceptabel, daarna degenereren de prestaties snel, zeker bij complexere ontvangerstructuren. Bovendien
worden complexiteits- en prestatievergelijkingen van het gelijke filter, PIC en GSIC ontvangers uitgevoerd. Een uitgebreide GSIC ontvanger met PIC binnen groepen wordt als goed compromis vanuit het oogpunt van complexiteit en prestaties beschouwd.

Prestaties van de gewogen multisnelheid PIC ontvanger worden geëvalueerd in een systeem met drie verschillende verwerkingsstijgingen. Er wordt aangetoond dat weging de prestaties van de PIC ontvanger in een VSF systeem in een AWGN kanaal verbetert. Echter, er werd geen verbetering geobserveerd in een wegstervend kanaal. Dit wordt veroorzaakt doordat de RAKE ontvanger het signaal volgens de signaal-naar-geluid verdeling weegt, zwakkere signalen dragen dus minder bij aan de beslissing dan de sterkere signalen.

Trefwoorden: groepsgewijze opeenvolgende interferentieopheffing, detectie van meerdere snelheden voor meerdere gebruikers, variabele spreidingsfactor direct-sequence meervoudige toegang door codeverdeling, gewogen opheffing, breedband-CDMA.
Preface

System engineering research and development cannot be carried out in isolation. This thesis is based on my work that has been carried out in Nokia Mobile Phones, Nokia Research Center and Nokia Telecommunications. I became involved with CDMA in the early 1990s when an experimental wideband CDMA testbed project was started within Nokia. CDMA system studies were initiated in 1993. Based on these studies, a project called CSS2000 was started in 1994. I had the pleasure of being a project leader with a goal of producing a wideband CDMA air interface for UMTS (Universal Mobile Telecommunications System). Later the research was expanded to a research program investigating several aspects such as 2 Mbps transmission, radio resource management, and packet data for UMTS.

From 1995 to 1997, I worked in the FRAMES project, which brought together a number of talented individuals from several European companies, laboratories, and universities. The goal of FRAMES was to study and define a proposal for UMTS air interface. My role was to lead the multiple access scheme selection and subsequent air interface development. The wideband CDMA scheme developed in the project later formed the basis for the UMTS air interface. My participation in the third generation system development activities resulted in the book *Wideband CDMA for third generation Mobile Communications* (Artech House, 1998) by my supervisor Prof. Ramjee Prasad and me.

The wideband CDMA proposals for third generation mobile communications systems will provide multirate services using variable spreading factor scheme. Several multiuser detectors have been proposed for traditional DS-CDMA systems, but little attention has been paid to receivers for multirate systems. This and my involvement in various third generation CDMA projects motivated me to start this search for practical receiver structures for variable spreading factor CDMA systems.
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I wish to thank Dr. Heikki Huomo from Nokia Mobile Phones, who supported me in finding time for research at the time when we were with Nokia Research Center, and Dr J.T. Bergqvist from Nokia Telecommunications for the encouragement and opportunity to finalise this thesis.

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I want to thank my mother and parents-in-law for their support. In addition, my brother Aki has been of great help whenever required. My son Éerik has taught me to put my priorities right. Listening sessions of Moomin music together with him have taught me new ways of thinking. And naturally I want to thank my lovely wife Tiina, who has been so patient and supportive during the years, when I have been carrying out this research beside my other professional activities.

Espoo, October 1999

Tero Ojamperä
List of Symbols and Abbreviations

Symbols

\( A \)  
-diagonal matrix of the carrier amplitudes of all users over a data block of \( N_b \) symbols

\( A^{(n)} \)  
-diagonal matrix of the carrier amplitudes of all users over one symbol interval

\( A_k \)  
-carrier amplitude of the \( k \)th user

\( B \)  
-channel bandwidth; number of chip boundaries in the spreading waveform at which transition to a different value occurs

\( B_{coh} \)  
-coherence bandwidth

\( b \)  
-vector of data symbols of all users over \( N_b \) symbol intervals

\( b^{(n)} \)  
-vector of data symbols of all users over one symbol interval

\( b_k^{(n)} \)  
-data symbol of \( k \)th user at \( n \)th symbol interval

\( C \)  
-set of complex number

\( C^{(n)} \)  
-diagonal channel coefficient matrix of all users over \( N_b \) symbol intervals

\( C_k^{(n)} \)  
-diagonal channel coefficient matrix of all users over one symbol interval

\( c_k^{(n)} \)  
-channel coefficient vector of one user over one symbol interval

\( c_k^{(n)} \)  
-channel attenuation factor of \( k \)th user's \( l \)th path at \( n \)th symbol interval

\( E_b \)  
-bit energy

\( f_d \)  
-Doppler spread

\( f_c (\nu) \)  
-distribution function of variance of multiple access interference

\( G_r (f) \)  
-frequency response of the receiver filter

\( G_t (f) \)  
-frequency response of the transmitter filter

\( h_k (l) \)  
-channel impulse response

\( \hat{h} \)  
-estimate of matched filter output

\( h_k^{(n)} \)  
-desired matched filter output for \( k \)th user's \( l \)th path at \( n \)th symbol interval

\( \hat{h}_k^{(n)} \)  
-estimate of the desired matched filter output for \( k \)th user's \( l \)th path at \( n \)th symbol interval

\( I \)  
-identity matrix

\( I \)  
-the number of iterations for the preconditioned conjugate gradient (PCG) algorithm

\( j \)  
-imaginary unit, \( \sqrt{-1} \)

\( k \)  
-index for users

\( k' \)  
-index for users
$K$  total number of users
$l$  index for paths
$l'$  index for paths
$L$  number of paths
$L_k$  number of paths for the $k$th user
$M$  number of cancellation stages in the PIC algorithm
$n$  index for stages; index for symbols
$n'$  index
$N$  observation window size for the PCG algorithm; number of chips
$N_b$  number of bits in a data block
$N_c$  number of chips in code waveform per symbol interval
$N_0$  two-sided power spectral density of the noise
$N_{se}$  number of samples per chip
$n(i)$  additive white Gaussian noise
$n$  channel noise vector
$P$  length of the scrambling code
$P_k$  power of the $k$th user
$p_\tau(t)$  chip waveform
$p_\tau(r)$  Rayleigh probability density function
$p_{iT} = 1_{[0,T]}$  rectangular unit pulse of duration $T$
$Q_i$  independent random variable
$R$  the received discrete time signal over a data block of $N_b$ symbols
$r_{T(o)}$  the received discrete time signal over one symbol
$r(t)$  received signal
$R$  data rate; envelope of the complex impulse response
$R_{kl,kl'}(i)$  correlation function between users $k$ and $k'$ along the $l$th and $l'$th paths
$\hat{R}_{kl,kl'}(i)$  mismatched correlation function between users $k$ and $k'$ along the $l$th and $l'$th paths, one estimated parameter
$\hat{\hat{R}}_{kl,kl'}(i)$  mismatched correlation function between users $k$ and $k'$ along the $l$th and $l'$th paths, two estimated parameters
$R$  correlation matrix
$R_j$  independent random variable
$R(i)$  correlation matrix
$R_{k',k}(i)$  correlation matrix of $k$th user with $k'$th user
$\hat{R}$  the mismatched correlation matrix, one estimated parameter
$\hat{\hat{R}}$  the mismatched correlation matrix, two estimated parameters
$S$  spreading code matrix including the signature sequences with different delays over the multipath channel.
$s(t)$  signal
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$s_k(t)$</td>
<td>signature waveform of the $k$th user</td>
</tr>
<tr>
<td>$s_{k,j}^{(n)}$</td>
<td>$n$th chip of the $k$th user's signature waveform at the $n$th symbol interval</td>
</tr>
<tr>
<td>$s_{k,j} \in \pm 1$</td>
<td>$j$th chip of the $k$th user's signature waveform</td>
</tr>
<tr>
<td>$s[w_{k}]$</td>
<td>Walsh code of the user $k$</td>
</tr>
<tr>
<td>$s[q_{k}]$</td>
<td>scrambling code of the user $k$</td>
</tr>
<tr>
<td>$t$</td>
<td>continuous time-index</td>
</tr>
<tr>
<td>$t_0$</td>
<td>nominal delay</td>
</tr>
<tr>
<td>$T$</td>
<td>symbol duration of the lowest data rate user</td>
</tr>
<tr>
<td>$T_c$</td>
<td>chip duration</td>
</tr>
<tr>
<td>$T_s$</td>
<td>symbol duration</td>
</tr>
<tr>
<td>$T_{sn}$</td>
<td>sample interval</td>
</tr>
<tr>
<td>$T_0$</td>
<td>coherence time</td>
</tr>
<tr>
<td>$T$</td>
<td>linear operator</td>
</tr>
<tr>
<td>$u(t)$</td>
<td>unit function</td>
</tr>
<tr>
<td>$u_k(t)$</td>
<td>transmitted signal of user $k$</td>
</tr>
<tr>
<td>$v$</td>
<td>relative velocity of the terminal</td>
</tr>
<tr>
<td>$W_j$</td>
<td>diagonal weight matrix defining the amount of cancellation used at stage $j$</td>
</tr>
<tr>
<td>$W_j$</td>
<td>multiple access interference caused by the $j$th user</td>
</tr>
<tr>
<td>$w$</td>
<td>complex noise vector sample after detection</td>
</tr>
<tr>
<td>$w_{k,j}^{(n)}$</td>
<td>noise samples</td>
</tr>
<tr>
<td>$X_{i,n}$</td>
<td>independent random variable</td>
</tr>
<tr>
<td>$X_{wo}$</td>
<td>frequency response of filter</td>
</tr>
<tr>
<td>$y_k^{(n)}$</td>
<td>output vector of matched filter for the $k$th user at $n$th symbol interval</td>
</tr>
<tr>
<td>$y$</td>
<td>matched filter output</td>
</tr>
<tr>
<td>$Y_{j,n}$</td>
<td>independent random variable</td>
</tr>
<tr>
<td>$Z_k$</td>
<td>decision statistics of the $k$th user</td>
</tr>
<tr>
<td>$Z_{k,n}$</td>
<td>decision statistics of the $n$th bit of the $k$th user</td>
</tr>
<tr>
<td>$\beta$</td>
<td>roll-off factor of the chip waveform</td>
</tr>
<tr>
<td>$\delta(t)$</td>
<td>Dirac's delta function</td>
</tr>
<tr>
<td>$\varepsilon$</td>
<td>delay error</td>
</tr>
<tr>
<td>$\phi_{k,j}$</td>
<td>carrier phase of $k$th user's $j$th path</td>
</tr>
<tr>
<td>$\phi_k$</td>
<td>phase of the $k$th user's signal</td>
</tr>
<tr>
<td>$\hat{\phi}_k$</td>
<td>estimate of the phase of the $k$th user's signal</td>
</tr>
<tr>
<td>$\eta$</td>
<td>random variable representing noise samples after correlation process</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>wavelength</td>
</tr>
</tbody>
</table>
\( \mu \)\( \text{mean of \( k \)th user's power} \)

\( \mu_R \)\( \text{mean of the multiple access interference given \( B \)} \)

\( \mu_{k,l} \)\( \text{delay of the propagation paths and the delay offsets of the users (\( \tau_{k,l} + \Delta \tau_k \)) measured in sample intervals.} \)

\( \hat{\mu}_{k,l} \)\( \text{delay estimate of the propagation paths and the delay offsets of the users (\( \tau_{k,l} + \Delta \tau_k \)) measured in sample intervals.} \)

\( \sigma \)\( \text{standard deviation of the noise samples} \)

\( \sigma_B^2 \)\( \text{variance of the multiple access interference given \( B \)} \)

\( \sigma_{R_k}^2 \)\( \text{variance of \( k \)th user's power} \)

\( \sigma^2 \)\( \text{variance of the quadrature components of the complex impulse response} \)

\( \tau_{k,l} \)\( \text{delay of \( k \)th user's \( l \)th path} \)

\( \tau_k \)\( \text{delay of the \( k \)th user's signal} \)

\( \hat{\tau}_k \)\( \text{estimate of the delay of the \( k \)th user's signal} \)

\( \Delta \tau_k \)\( \text{transmission delay of the \( k \)th user} \)

\( \mathbb{R} \)\( \text{set of real number} \)

\( \omega_c \)\( \text{angular carrier frequency} \)

\( \psi_{k,j}^{(s)} \)\( \text{multiple access interference caused by \( k \)th user \( l \)th path at \( n \)th symbol interval} \)

\( \hat{\psi}_{k,j}^{(s)} \)\( \text{estimate of the multiple access interference caused by \( k \)th user \( l \)th path at \( n \)th symbol interval} \)

\( \psi^{(j)} \)\( \text{interference estimate of \( j \)th stage of the PIC receiver} \)

\( \varphi \)\( \text{variance of multiple access interference} \)

\( \zeta \)\( \text{the phase error} \)

\( \Xi \)\( \text{modulation alphabet} \)

**Abbreviations**

3GPP \( \text{third generation partnership project} \)

A/D \( \text{analog to digital} \)

AGA \( \text{accurate Gaussian approximation} \)

AMPS \( \text{Advanced Mobile Phone System} \)

AWGN \( \text{additive white Gaussian noise} \)

BEP \( \text{bit error probability} \)

BER \( \text{bit error rate} \)

BPSK \( \text{binary phase shift keying} \)

CDMA \( \text{code division multiple access} \)

CG \( \text{conjugate gradient} \)

DF \( \text{decision feedback} \)

DL \( \text{downlink} \)
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>DLL</td>
<td>delay-locked loop</td>
</tr>
<tr>
<td>DS-CDMA</td>
<td>direct sequence code division multiple access</td>
</tr>
<tr>
<td>DSP</td>
<td>digital signal processing</td>
</tr>
<tr>
<td>ETSI</td>
<td>European Telecommunication Standards Institute</td>
</tr>
<tr>
<td>FDMA</td>
<td>frequency division multiple access</td>
</tr>
<tr>
<td>FEC</td>
<td>forward error correction</td>
</tr>
<tr>
<td>FH</td>
<td>frequency hopping</td>
</tr>
<tr>
<td>FIR</td>
<td>finite impulse response</td>
</tr>
<tr>
<td>flop</td>
<td>floating point operation</td>
</tr>
<tr>
<td>FMA</td>
<td>Frames Multiple Access</td>
</tr>
<tr>
<td>FPLMTS</td>
<td>future public land mobile telecommunication systems</td>
</tr>
<tr>
<td>GPIC</td>
<td>groupwise parallel interference cancellation</td>
</tr>
<tr>
<td>GSIC</td>
<td>groupwise successive interference cancellation</td>
</tr>
<tr>
<td>GSM</td>
<td>global system for mobile communications</td>
</tr>
<tr>
<td>HDM</td>
<td>hard decision method</td>
</tr>
<tr>
<td>IBI</td>
<td>isolation bit insertion</td>
</tr>
<tr>
<td>IGA</td>
<td>improved Gaussian approximation</td>
</tr>
<tr>
<td>iid</td>
<td>independent, identically distributed</td>
</tr>
<tr>
<td>IIR</td>
<td>infinite impulse response</td>
</tr>
<tr>
<td>IMT-2000</td>
<td>International Mobile Telephony 2000</td>
</tr>
<tr>
<td>IPI</td>
<td>interpath interference</td>
</tr>
<tr>
<td>IS-95</td>
<td>Interim Standard 95</td>
</tr>
<tr>
<td>ISI</td>
<td>intersymbol interference</td>
</tr>
<tr>
<td>ITU</td>
<td>International Telecommunications Union</td>
</tr>
<tr>
<td>LMMSE</td>
<td>linear minimum mean squared error</td>
</tr>
<tr>
<td>LMS</td>
<td>least mean square</td>
</tr>
<tr>
<td>LOS</td>
<td>line of sight</td>
</tr>
<tr>
<td>MAI</td>
<td>multiple access interference</td>
</tr>
<tr>
<td>MAP</td>
<td>maximum a-posteriori probability</td>
</tr>
<tr>
<td>MC</td>
<td>multicode</td>
</tr>
<tr>
<td>MF</td>
<td>matched filter</td>
</tr>
<tr>
<td>MHz</td>
<td>mega hertz</td>
</tr>
<tr>
<td>ML</td>
<td>maximum likelihood</td>
</tr>
<tr>
<td>MLSE</td>
<td>maximum likelihood sequence estimation</td>
</tr>
<tr>
<td>MMSE</td>
<td>minimum mean square error</td>
</tr>
<tr>
<td>MOE</td>
<td>minimum output energy</td>
</tr>
<tr>
<td>MRC</td>
<td>maximum ratio combining</td>
</tr>
<tr>
<td>MSE</td>
<td>mean square error</td>
</tr>
<tr>
<td>MUD</td>
<td>multiuser detection</td>
</tr>
<tr>
<td>MW-PIC</td>
<td>multirate weighted PIC</td>
</tr>
<tr>
<td>OFDM</td>
<td>orthogonal frequency division multiplexing</td>
</tr>
<tr>
<td>PC</td>
<td>power control</td>
</tr>
<tr>
<td>PGC</td>
<td>preconditioned conjugate gradient</td>
</tr>
<tr>
<td>PCS</td>
<td>personal communications systems</td>
</tr>
<tr>
<td>PG</td>
<td>processing gain</td>
</tr>
<tr>
<td>PIC</td>
<td>parallel interference cancellation</td>
</tr>
<tr>
<td>PN</td>
<td>pseudorandom noise</td>
</tr>
</tbody>
</table>
QAM  quadrature amplitude modulation
QoS  quality of service
QPSK  quadrature phase shift keying
RLS  recursive least square
SGA  standard Gaussian approximation
SIC  successive interference cancellation
SIGA  simplified improved Gaussian approximation
SIR  signal-to-interference ratio
SLWA  sliding window algorithm
SNR  signal-to-noise ratio
TDAF  time dependent adaptive algorithm
TDD  time division duplex
TDMA  time division multiple access
TH  time hopping
TIA  Telecommunications Industry Association
TTA  Telecommunication Technology Association
UL  uplink
UMTS  Universal Mobile Telecommunication System
UWC  Universal Wireless Communications
WLAN  wireless local area network
VSF  variable spreading factor
ZF  zero-forcing

Operators

*  convolution
A^H  conjugate transpose of A
A^{-1}  inverse of A
A^T  transpose of A
diag(...)  diagonal matrix with elements "" on main diagonal
[.]  integer smaller than or equal to argument (floor function)
[.]  integer larger than or equal to argument (ceiling function)
Re()  real part
sgn()  signum function
Q[]  Gaussian complementary error function
E[]  expected value
Pr{}  probability
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1.2 CDMA DEVELOPMENT  
1.3 MULTIUSER DETECTION  
1.4 MULTIRATE SYSTEMS  
1.5 AIM AND OUTLINE OF THESIS  
1.6 RESEARCH METHODOLOGY  
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Chapter 1

Introduction

"???????", N.N.

The world is going wireless. In Finland, the number of public cellular telephone subscriptions exceeded the number of fixed subscriptions in 1998 and the penetration of cellular terminals reached over 60% of the population in 1999. Similar developments are expected in other countries in the near future. Mobile phone development started by the introduction of first generation mobile communication systems such as Advanced Mobile Phone System (AMPS) based on analog transmission in the 1980’s. In the early 1990’s, second generation mobile communication systems such as the Global System for Mobile Communications (GSM) were introduced. These are still evolving with new data transmission capabilities [1]. Demand for higher and higher data rates has also resulted in the development of wireless local area network (WLAN) systems like Hiperlan [2] and IEEE 802.11, and point to multipoint wireless broadband access systems such as Hiperaccess.

Emerging requirements for higher-rate data services and better spectrum efficiency are also the main drivers identified for the third generation mobile radio systems [3]. At the world-level in the ITU (International Telecommunication Union), third generation is known as IMT-2000 (International Mobile Telecommunications by 2000)\(^1\). In Europe, the third generation of wireless personal communications is known as Universal Mobile Telecommunication Systems (UMTS) [4]. Several techniques including CDMA (code division multiple access), OFDM (orthogonal frequency division multiplexing), hybrid TD-CDMA (time division CDMA) and TDMA (time division multiple access) were proposed for third generation air interface in different standards bodies around the world [5, 6]. Currently, wideband CDMA based proposals and a TDMA based proposal called UWC-136 (Universal Wireless Communications 136) are being standardised for the air interface of third generation systems [6]. The high information transfer requirements for third generation systems can be achieved by designing more efficient coding methods, using better detection methods such as multiuser detection (MUD) [7] and by utilising more efficient radio resource management schemes.

The topic of this thesis is to assess the feasibility of multiuser detection for third generation wideband multirate CDMA systems. Multirate refers to simultaneous transmission of several different data rates with different quality of service requirements. This chapter begins with a classification of CDMA techniques and a description of CDMA development in Sections 1.1 and 1.2, respectively. Section 1.3

\(^1\) Previously IMT-2000 has been called FPLMTS (Future Public Land Mobile Telecommunication Systems)
motivates the use of multiuser detection techniques for demodulation of CDMA signals. Multirate techniques for wideband CDMA are described in Section 1.4. Section 1.5 describes the aim and outline of the thesis and Section 1.6 outlines the research methodology used in the thesis. The main contributions of the thesis are listed in Section 1.7.

1.1 CLASSIFICATION OF CDMA

There are several ways to classify CDMA schemes. The most common is the division based on the spreading method used to obtain the wideband signal from a pseudo-noise code. This division leads to three types of CDMA: direct sequence (DS), frequency hopping (FH), and time hopping (TH) as illustrated in Figure 1.1 [8]. In DS-CDMA, the spectrum is spread by multiplying the data signal with a pseudo-noise sequence code bits, resulting in a wideband signal. In frequency hopping spread spectrum, the pseudo-noise sequence defines the instantaneous centre frequency of the transmission. The bandwidth at each moment is small, but the total occupied bandwidth is large. Frequency hopping can either be fast (several hops over one symbol) or slow (several symbols transmitted during one hop). In the time hopping spread spectrum, the pseudo-noise sequence defines the transmission instant. Furthermore, combinations of these techniques are possible. In this thesis, we focus on DS-CDMA, since it is the technique which will be used for third generation wideband CDMA proposals. Wideband CDMA is defined here as a direct sequence spread spectrum multiple access scheme, where the data is spread over a bandwidth of approximately 5 MHz or more. The benefits of wideband CDMA include good robustness in a multipath channel, variable data rates and a maximum bit rate up to 2 Mbps.

![Diagram of Frequency Division: Direct sequence, Frequency hopping, Time hopping](image-url)
1.2 CDMA DEVELOPMENT

The origins of spread spectrum are in the military field and navigation systems. Techniques developed to counteract intentional jamming have also proved suitable for communication through dispersive channels in cellular applications. In this section, we highlight the milestones for CDMA development starting in the 1950's after the statement of the Shannon theorem [9]. An extensive review of spread spectrum history is given in [10].

In 1949, John Pierce wrote a technical memorandum, where he described a multiplexing system, in which a common medium carries coded signals that need not be synchronized. This system can be classified as a time hopping spread spectrum multiple access system [10]. Claude Shannon and Robert Pierce introduced the basic ideas of CDMA in 1949 by describing the interference averaging effect and the graceful degradation of CDMA [11]. In 1950, De Rosa-Rogoff proposed a direct sequence spread spectrum system and introduced the processing gain equation and noise multiplexing idea [10]. In 1956, Price and Green filed for the ant impaired "RAKE" patent [10]: signals arriving over different propagation paths can be resolved by a wideband spread spectrum transmit signal and combined by the RAKE receiver. The near-far problem (i.e., a high interference overwhelming a weaker spread spectrum signal) was first mentioned in 1961 by Magnuski [10].

The application of spread spectrum techniques in cellular radio systems was suggested by Cooper and Nettleton in 1978 [12]. During the 1980s, Qualcomm investigated DS-CDMA techniques, which finally led to the commercialisation of cellular spread spectrum communications based on the narrowband CDMA IS-95 standard in July 1993. Commercial operation of IS-95 systems started in 1996. Multiuser detection (MUD) has been the subject of extensive research since 1986 when Verdu formulated an optimum multiuser detection for the additive white Gaussian noise (AWGN) channel with a maximum likelihood sequence estimator (MLSE) [13].

During the 1990s, wideband CDMA techniques with a bandwidth of 5 MHz or more were studied intensively throughout the world, and several trial systems have been built and tested [3]. These include FRAMES FMA2 (FRAMES Multiple Access) in Europe, Core-A in Japan, the European/Japanese harmonised WCDMA scheme, cdma2000 in the United States, and the TTA I and TTA II (Telecommunication Technology Association) schemes in Korea [6]. Initially, the parameters of different wideband CDMA schemes were harmonised resulting in two main schemes, namely WCDMA and cdma2000. Further harmonisation led to a single wideband CDMA scheme with three modes: direct spread, multicarrier and time division duplex modes (TDD). The chip rate for direct spread and TDD modes is 3.84 Mchips/s (earlier 4.096 Mchips/s) and for the multicarrier mode \( n \times 1.2288 \) Mchips \((n=1,2,3,6,9 \text{ or } 12)\). Recently, a third generation partnership project (3GPP) has been established for the development of global wideband CDMA standard based on the WCDMA air interface and GSM core network. Introduction of third generation wireless communication systems using wideband CDMA is expected around the year 2002.

Based on the above description, the CDMA era is divided in three periods: (1) the pioneer CDMA era, (2) the narrowband CDMA era, and (3) the wideband CDMA era, as shown in Table 1.1.
Table 1.1
CDMA Eras

<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>1949</td>
<td>John Pierce: time hopping spread spectrum</td>
</tr>
<tr>
<td>1949</td>
<td>Claude Shannon and Robert Pierce: basic ideas of CDMA</td>
</tr>
<tr>
<td>1950</td>
<td>De Rosa-Rogoff: direct sequence spread spectrum</td>
</tr>
<tr>
<td>1956</td>
<td>Price and Green: antiumltpath “RAKE” patent</td>
</tr>
<tr>
<td>1961</td>
<td>Magunski: near-far problem</td>
</tr>
<tr>
<td>1970s</td>
<td>Several developments for military field and navigation systems</td>
</tr>
</tbody>
</table>

Narrowband CDMA Era

<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>1978</td>
<td>Cooper and Nettleton: cellular application of spread spectrum</td>
</tr>
<tr>
<td>1980s</td>
<td>Investigation of narrowband CDMA techniques for cellular applications</td>
</tr>
<tr>
<td>1984</td>
<td>DS-CDMA and hybrid CDMA/FDMA proposed as GSM multiple access</td>
</tr>
<tr>
<td>1986</td>
<td>Formulation of optimum multiuser detection by Verdu</td>
</tr>
<tr>
<td>1993</td>
<td>IS-95 standard</td>
</tr>
</tbody>
</table>

Wideband CDMA Era

<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>1995-1997</td>
<td>Europe: FRAMES FMA2; Japan: Core-A; USA: cdma2000; Korea: TTA I, TTA II</td>
</tr>
<tr>
<td>1999</td>
<td>Harmonisation of wideband CDMA proposals resulting to three modes: direct sequence, multicarrier and time division duplex</td>
</tr>
<tr>
<td>2000s</td>
<td>Commercialisation of wideband CDMA systems</td>
</tr>
</tbody>
</table>

Table 1.2 presents the key features of two main wideband CDMA schemes, namely WCDMA and cdma2000 (now forming the two modes, namely direct spread and multicarrier, of the harmonised wideband CDMA scheme), proposed for third generation cellular systems. They can be characterised by the following new advanced properties:

- Provision of multirate services;
- Packet data;
- Complex spreading of the data signal;
- A coherent uplink using a user-dedicated pilot;
- A user dedicated pilot channel in the downlink for antenna beamforming;
- Seamless interfrequency handover\(^2\);
- Fast power control in the downlink;
- Optional multiuser detection in the uplink.

The harmonised third generation wideband CDMA proposal has two operating modes: network asynchronous and synchronous. In network asynchronous schemes the base stations are not synchronized, while in network synchronous schemes the base stations are synchronized to each other within a few microseconds.

\(^2\) interfrequency handover means handover between two different carrier frequencies.
The nominal bandwidth for all third generation proposals is 5 MHz. There are several reasons for choosing this bandwidth. First, data rates of 144 and 384 Kbps, the main targets of third generation systems, are achievable within 5 MHz bandwidth with a reasonable capacity. Even a 2-Mbps peak rate can be provided under limited conditions. Second, lack of radio spectrum calls for reasonably small minimum spectrum allocation, especially if the system has to be deployed within the frequency bands already occupied by second generation systems. Third, the 5-MHz bandwidth can resolve (separate) more multipaths than narrower bandwidths, increasing diversity and thus improving performance. Larger bandwidths of 10, 15, and 20 MHz have been proposed to support higher data rates more effectively.

<table>
<thead>
<tr>
<th></th>
<th>WCDMA</th>
<th>cdma2000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chip rate</td>
<td>3.84 Mchips/s</td>
<td>1.2288 Mchips/s (n=1,3,6,9,12)</td>
</tr>
<tr>
<td>Carrier spacing</td>
<td>5 MHz</td>
<td>1.25, 5, 10, 15, 20 MHz</td>
</tr>
<tr>
<td>Frame length</td>
<td>10 ms</td>
<td>20 ms</td>
</tr>
<tr>
<td>Inter base station synchronisation</td>
<td>Asynchronous</td>
<td>Synchronous</td>
</tr>
</tbody>
</table>

### 1.3 MULTIUSER DETECTION

In practical CDMA systems, the user waveforms are not orthogonal. So, the cross-correlations between waveforms are non-zero. This may result in excessive interference especially in a "near-far" situation. Conventional receivers using matched filtering treat this interference as Gaussian noise, and thus the performance degrades as the number of users increases. In contrast to a conventional receiver, multiuser detection seeks to improve receiver performance by exploiting the deterministic structure of multiple access interference. An optimum multiuser detector, which obtains jointly optimum decisions for all users using maximum-likelihood sequence detection, selects the most likely sequence of transmitted bits [14]. Since the optimal multiuser detector suffers from very high computational complexity, several suboptimal schemes have been derived. These include the decorrelating or zero-forcing (ZF) receiver, the linear minimum mean square error (MMSE) receiver, parallel interference cancellation receiver (PIC), successive interference cancellation (SIC) receiver, and groupwise detectors. See, for example, [7,14-17] for an overview of multiuser detection.

Capacity improvement by MUD depends on how much of the interference can be cancelled. In the case of only "own-cell" interference being cancelled and the intercell interference amounting to the fraction \( f \) of the intracell interference, the upper bound for capacity increase is \((1-f)/f\). With the propagation power law of 4, the intercell interference is 55% of the intracell interference and, thus, MUD can improve the capacity of the system by a factor of 2.8 compared to a system without MUD [18]. However, in practice the MUD efficiency is not 100%, but depends on the cancellation scheme, channel estimation, delay estimation and power control error, thus reducing the maximum capacity gain.
The maximum cell radius of a CDMA system depends also on the number of users and interference generated by them, i.e., the system load [3]. Consequently, the cell range shrinks as the system load increases. Since multiuser detection removes interference, it can extend cell range and thus coverage area. The impact of MUD on cell range depends on the propagation environment, which determines the fraction of the intercell interference.

1.4 MULTIRATE SYSTEMS

The third generation systems will support a multitude of services, including speech, video, and high bit rate packet data up to 2 Mbps. Generally, different services will have different quality-of-service requirements. For example, well-encoded speech transmission requires a data rate of less than 10 kbps and a bit error rate of $10^{-3}$, while file transfer may require a data rate in excess of 100 kbps and a bit error rate of $10^{-6}$.

The third generation wideband CDMA systems will employ two types of schemes for multirate communication. A single code, variable spreading factor (VSF) scheme, modulates the data signals into the same chip rate, resulting in different processing gains for different data rates. Higher data rate users are therefore allocated more power to maintain equal bit energy-to-noise density ratio for different rates. A multicode (MC) scheme splits the high rate data stream into multiple, parallel spreading codes. The number of spreading codes depends on the required data rate. Furthermore, combinations of the two schemes can be used. In this thesis, the performance of the variable spreading factor scheme is studied.

1.5 AIM AND OUTLINE OF THESIS

The aim of this thesis is to develop practical multiuser receiver structures for multirate wideband CDMA systems. This thesis studies multiuser detectors within an asynchronous multirate DS-CDMA system in AWGN and Rayleigh fading channels. The wideband CDMA proposals for third generation mobile communications systems provide multirate services using the VSF scheme. Several multiuser detectors have been proposed for single rate DS-CDMA systems, but little attention has been paid on receivers for multirate system. Increased bit rates and lack of spectrum call for more spectrum-efficient receiver techniques. These factors motivate search for practical receiver structures for variable spreading factor CDMA systems.

In Chapter 2, a generic model for multirate DS-CDMA systems is formulated. Main receiver structures including MF, ZF, MMSE, PIC and SIC are introduced. Earlier and parallel work relevant to this thesis is reviewed.

In Chapter 3, a qualitative comparison of multiuser detectors is performed. Comparison criteria are derived based on evaluation of third generation wideband CDMA systems. Using the comparison, a novel multiuser detection receiver, weighted multirate parallel interference cancellation, suitable for a variable spreading factor DS-CDMA system is proposed.

Several Gaussian approximations for performance analysis of DS-CDMA are reviewed in Chapter 4. These include standard (SGA), simplified (IGA), simplified
improved (SIGA) and accurate (AGA) Gaussian approximations. Performance of the VSF DS-CDMA system using the accurate Gaussian approximation is analysed and based on this, a groupwise structure for multiuser detection in the VSF CDMA system is motivated. In addition, a comparison between variable spreading factor and multicode schemes is presented.

In Chapter 5, the performance of the PIC receiver is evaluated for a single-rate and a variable spreading factor system with three different data rates with and without delay estimation errors.

Chapter 6 presents several new interference cancellation structures based on groupwise successive interference cancellation (GSIC). Their performance is evaluated in a variable spreading factor system with three different data rates with and without delay estimation errors. In addition, performance and complexity of the MF, the PIC, and different GSIC receiver are compared.

In Chapter 7, performance of the weighted multirate PIC receiver is evaluated in a VSF system with three different data rates in AWGN and Rayleigh fading channels.

Chapter 8 concludes the thesis. The main results are summarised and discussed. Future research topics based on the thesis are outlined.

1.6 RESEARCH METHODOLOGY

The research is based on the system engineering viewpoint from which the most appropriate receiver solution is searched as a reasoned compromise between several quantitative and qualitative criteria. Evaluation of the different criteria and their relative importance is subjective, but performed within a well-defined framework of properties of the applied system, which in this case is a wideband CDMA system.

The starting point for research has been the existing methods for multiuser detection. These have been surveyed in an extensive literature search. Known multiuser detection algorithms have been compared using a set of criteria. The set of criteria has been derived based on careful analysis of the third generation wideband CDMA air interface design and the constraints set by it. The comparison has been qualitative rather than quantitative due to the complex nature of the system at hand. Based on the qualitative comparison, the most feasible structures of multiuser detection have been identified. These have then been chosen as the basis for further improvements. The improved solutions have been tested in a more realistic environment, namely the multirate scenario. In addition to the qualitative comparison, the performance of the matched filter in a VSF CDMA system has been analysed using the accurate Gaussian approximation. The BER performance for different data rates has been further used to motivate new receiver structures for multirate CDMA systems.

The performance assessment has been performed with Monte-Carlo computer simulations. The results have been verified against an analytical model, where possible, and compared with results obtained by independent research teams.
1.7 CONTRIBUTIONS OF THE THESIS

The purpose of this research is the development of practical receiver structures for third generation wideband CDMA systems. The work presented here makes a number of novel contributions to the field, which include:

- Qualitative comparison of MUD receivers leading to a novel multiuser detection structure, called weighted multirate PIC, which is suitable for variable spreading factor multirate DS-CDMA system.
- Performance analysis of the VSF DS-CDMA system motivating the use of novel groupwise successive interference cancellation methods.
- Performance assessment of the PIC receiver for VSF system in the presence of delay estimation errors. This receiver is shown to be robust against delay estimation errors also in VSF system, and all data rates show equal degradation as a function of increasing delay error.
- Performance evaluation of GSIC receivers in VSF multirate system, in AWGN and fading channels, as well as in the presence of delay estimation errors. Assessment of performance versus complexity tradeoffs of such receivers.
- Performance evaluation of the weighted multirate PIC receiver, showing that weighting improves its performance in a VSF CDMA system in the AWGN channel.

REFERENCES


Chapter 2

A Survey of Multiuser Detectors for DS-CDMA

This chapter presents a survey of multiuser detectors for DS-CDMA systems. First, Section 2.1 defines a mathematical model for an asynchronous multirate multiuser CDMA system. Different multiuser detection receivers, starting from the optimum receiver, are presented in Section 2.2. Section 2.3 reviews earlier and parallel work regarding multiuser detection for practical CDMA systems. Conclusions are presented in Section 2.4, motivating the qualitative comparison in Chapter 3 and the focus of this thesis on multiuser detection for multirate DS-CDMA systems.

2.1 SYSTEM MODEL

A general multiuser CDMA system is illustrated in Figure 2.1. We consider a mobile communication system and specifically the uplink direction, i.e., transmission from mobile station to base station. Each user is transmitting data bits, which are spread by pseudo-random codes. This set-up can be modelled as a system where users share the same communications media and the signals transmitted by the users pass through separate and independent channels, which are modelled as discrete fading multipath channel. The joint output of the channels is added to a common noise process. In the receiver, the received signal is correlated with replicas of the individual user spreading codes, i.e., matched filtered. Multiuser detection processes the signal from the correlators jointly to remove the unwanted multiple access interference from the desired signal. The output of a multiuser detection block are the estimated data bits. The conventional receiver consists of matched filters only, i.e., without joint processing of users’ signals.

![Figure 2.1 System model of multiuser DS-CDMA](image-url)
2.1.1 Multirate Definitions

The system model for multirate DS-CDMA system can be formulated in a similar manner as in a single rate systems [1]. For this purpose, a distinction between a physical and an effective user of the system must be made. A physical user is a mobile station, which transmits using some processing gain. A physical user transmitting with the largest processing $N_c$ available in the system corresponds to one effective user; the symbol rate of the user(s) with the largest processing gain is assumed to be $1/T$, where $T$ is the corresponding symbol interval. It is assumed that the other users have symbol rates which are integer multiples of $1/T$. Thus, a physical user with symbol rate $m/T$, where $m$ is an integer, corresponds to $m$ effective users. This modulation is called subcode modulation [2]. It is assumed that there are $K$ effective users in the system, i.e., during a symbol interval of length $T$, $K$ symbols are transmitted. The $k$th effective user is designated to have the signature waveform $s_k(t)$ with properties

$$ s_k(t) = 0, \text{if } t \notin [0, T), \quad (2.1) $$

and

$$ \int_0^T |s_k(t)|^2 \, dt = 1. \quad (2.2) $$

The $K$ symbols transmitted during a symbol interval may belong to $K$ distinct physical users, as in a single rate system, or to a smaller number of physical users so that a physical user may occupy several communication channels (signature waveforms $s_k(t)$) simultaneously to support higher rate transmission. In a system with a spreading factor, the support of the waveform varies; for example, a physical user with a symbol rate $2/T$ is assumed to use waveforms $s_k(t)$ with support in $t \in \left[0, \frac{T}{2}\right)$, and $s_{k+1}(t)$ with support in $t \in \left[\frac{T}{2}, T\right)$. Since all the signature waveforms are normalised to have a unit energy, a signature waveform with a support of length $\frac{T}{2}$ has $\sqrt{2}$-fold amplitude in comparison to a signature waveform with a support of length $T$. Thus, the lower the processing gain the more powerful interference a user is to other users.

2.1.2 Transmitted CDMA Signal

Each effective user $k \in \{1, \ldots, K\}$ transmits in the $n$th symbol interval a complex signal

$$ u_k(n) = b_k^{(n)} A_k s_k^{(n)}(t - \Delta \tau_k), \quad (2.3) $$

where $b_k^{(n)}$ is the data symbol, $A_k$ is the carrier amplitude, $\Delta \tau_k$ is the transmission delay of the $k$th signal (effective users corresponding to the same physical user have the same
delay). Since one physical user corresponds to $2^m$ ($m = 0, 1, 2, \ldots$) effective users, a physical user transmits $2^m$ ($m = 0, 1, 2, \ldots$) data bits. The signature waveforms are given by

$$s_k^{(n)}(t) = \frac{1}{\sqrt{N_c T_c}} \sum_{i=0}^{N_c-1} s_{k,i}^{(n)} p_c(t - iT_c) u(t), \quad (2.4)$$

where $N_c$ is the number of chips, $T_c$ is the duration of a chip, $p_c(t)$ is the chip waveform, $N_c = T/T_c$ is the processing gain, $s_{k,i}^{(n)}$ is the $i$th chip of the $k$th user’s signal waveform at $m$th symbol interval and $u(t)$ is a function that is one during the transmission of data bit of an effective user. For example, if a user has a data rate of $R$ then $u(t) = 1$ for $t \in \left[0, T\right)$ and, while if the user’s data rate is $2R$ then for the effective user $k$

$$u(t) = \begin{cases} 1 & \text{for } t = \left[0, \frac{T}{2}\right) \\ 0 & \text{for } t = \left[\frac{T}{2}, T\right) \end{cases}, \quad (2.5)$$

and for the effective user $k+1$

$$u(t) = \begin{cases} 0 & \text{for } t = \left[0, \frac{T}{2}\right) \\ 1 & \text{for } t = \left[\frac{T}{2}, T\right) \end{cases}, \quad (2.6)$$

It is assumed that the chips are binary and balanced, i.e., $s_{k,i}^{(n)} \in \{-1, 1\}$. If the signature waveform are periodic with period $T$, i.e., $s_{k,i}^{(n)} = s_{k,i}^{(j)} \forall n, j$, they will be called \textit{time-invariant} or \textit{short codes}, otherwise \textit{time-varying} or \textit{long codes}.

### 2.1.3 Channel Model

The transmitted signal passes through a multipath channel, which is modelled as a time-variant linear filter. The impulse response for the $k$th user’s radio channel is given as
\[ h_k(t) = \sum_{l=1}^{L_k} c_{k,l}(t) \delta(t - \tau_{k,l}) e^{j\phi_{k,l}}, \]  

(2.7)

where \( L_k \) is the number of propagation paths, \( c_{k,l}(t) \) is the attenuation factor, \( \delta(t) \) is Dirac's delta function and \( \phi_{k,l} \) is the phase of the \( k \)th user's \( l \)th path (\( c_{k,l}(t) e^{j\phi_{k,l}} \) forms the complex attenuation factor). Each propagation path has a different delay \( \tau_{k,l} \), which varies in time. The number \( L_k \) is assumed to be the same for all users, so in the following \( L \) is used instead of \( L_k \). The phase of the impulse response, \( \phi_{k,l} \), is uniformly distributed over the interval \([0,2\pi)\). Note that in the following treatment we use superscript \(^{\text{o}}\) to denote the dependence of the delays and phases on the symbol interval.

The envelope \( R \) of the complex impulse response in a mobile communication system can be described statistically by a Rayleigh probability density function (pdf)

\[
    p_R(r) = \begin{cases} 
    \frac{r}{\sigma_r^2} e^{-\frac{r^2}{2\sigma_r^2}} & r \geq 0 \\
    0 & \text{otherwise}
    \end{cases},
\]

(2.8)

where \( \sigma_r^2 \) is the variance of the quadrature components.

The coherence bandwidth \( B_{\text{coh}} \) is the statistical average bandwidth over which the channel transfer function remains practically constant. A channel is called frequency selective when the coherence bandwidth is smaller than the signal bandwidth \( B \) [3]:

\[
    B_{\text{coh}} < B = \frac{1}{T_c}.
\]

(2.9)

This is usually true in spread spectrum systems, and the channels in wideband CDMA systems are therefore frequency selective.

The time over which the channel response remains approximately the same is called the coherence time, denoted by \( T_0 \). The coherence time satisfies [3]

\[
    T_0 \approx \frac{1}{f_d},
\]

(2.10)

where \( f_d \) is the Doppler spread given by

\[
    f_d = \frac{v}{\lambda},
\]

(2.11)
where $v$ is the relative velocity of the terminal and $\lambda$ is the signal wavelength. The channel is said to be slowly fading if $T_0 \gg T_s$ ($f_dT_s \ll 1$) and fast fading if $T_0 < T_s$ ($f_dT_s > 1$). If $T_0 > T_s$ ($f_dT_s < 1$), the channel is called relatively fast fading. It should be noted that in a variable spreading factor system for rate $2^m R$, the symbol duration is $T_s = T/2^m$.

### 2.1.4 Received CDMA Signal

The received signal can be written as the convolution between the transmitted signal and the channel impulse response, with addition of noise.

$$r(t) = \sum_{k=1}^{K} u_k(t) * h_k(t) + n(t)$$  \hspace{1cm} (2.12)

Using the formulas (2.3) and (2.7), (2.12) can be written as

$$r(t) = \sum_{m=0}^{N_b-1} \sum_{k=1}^{K} A_k b_k^{(n)} \sum_{i=1}^{L} c_{k,i}^{(n)} e^{j\phi_{k,i}^{(n)}} s_k(t - mT - \tau_{k,i} - \Delta \tau_k) + n(t),$$

where $N_b$ is the number of transmitted bits by each user, and $n(t)$ is white Gaussian noise process with double-sided spectral density of $\sigma^2$ modelling the thermal noise plus other noise sources unrelated to the transmitted signals. The noise power in a frequency band with a bandwidth of $B$ is $2\sigma^2 B$. In this thesis, the channel attenuation factors $c_{k,i}^{(n)}$ and phases $\phi_{k,i}^{(n)}$ are assumed to be perfectly known, while the channel delays $\tau_{k,i}$ may have a fixed error, which is the same for all users and propagation paths.

The received signal is time-discretised by anti-alias filtering and sampling $r(t)$ at the rate $T_n^{-1} = (N_{sc}N_c)/T$, where $N_{sc}$ is the number of samples per chip and $N_c$ is the number of chips. In matrix notation, the received discrete –time signal over a data block of $N_b$ symbols is

$$r = SCAb + n \in C^{(N_b+2)N_cN_{sc} \times 1},$$  \hspace{1cm} (2.13)

where the additional two symbol intervals are included to account for transmitter asynchronism (different propagation delays) and channel multipath spread, which are both assumed to be less than one symbol interval. The model can be easily generalised to a case where propagation delays and multipath spread are larger than one symbol interval. In (2.13) $r$ is a column vector of samples of the received signal.
\[ r = \left[ r^{T(0)}, ..., r^{T(N_b-1)} \right]^T \in \mathbb{C}^{(N_b+2)N_cN_{sc}+1}, \]  

where

\[ r^{T(n)} = \left[ r(T_n(nN_cN_{sc}+1)), ..., r(T_n((n+1)N_cN_{sc}) \right] \in \mathbb{C}^{N_cN_{sc}+1}. \]  

S is the code matrix including the signature sequences with different delays over the multipath channel. We assume that the users are ordered according to their delay, such that the first user has the lowest delay, and the Kth user the largest. Furthermore it is assumed that maximum multipath spread is smaller than symbol interval:

\[ \tau_{k,i} + \Delta \tau_k - (\tau_{1,i} + \Delta \tau_1) < T. \]  

Without loss of generality it can be assumed that time is chosen such that \( \tau_{1,i} + \Delta \tau_1 \) is zero. With fixed propagation delays the code matrix can be defined as:

\[
S = [S^{(0)}, S^{(1)}, ..., S^{(N_b-1)}] \in \mathbb{C}^{(N_b+2)N_cN_{sc} \times KN_b}
\]

\[
\begin{bmatrix}
S(0) & 0 & 0 & 0 & 0 \\
S(1) & S(0) & 0 & 0 & 0 \\
S(2) & S(1) & S(0) & 0 & 0 \\
0 & S(2) & S(1) & S(0) & 0 \\
0 & 0 & S(2) & S(1) & S(0) \\
0 & 0 & 0 & S(2) & S(1) \\
0 & 0 & 0 & 0 & S(2)
\end{bmatrix},
\]

where

\[
S^{(n)} = [s^{(n)}_{1,1}, ..., s^{(n)}_{1,L}, ..., s^{(n)}_{K,L}] \in \mathbb{C}^{(N_b+2)N_cN_{sc} \times KL},
\]

and

\[
s^{(n)}_{k,l} = [0, ..., s^{T}_{k,l}, ..., 0]^T \in \mathbb{C}^{(N_b+2)N_cN_{sc}},
\]

where

\[
s_{k,l} = (s_{k,l}(t - T_n - \tau_{k,l} - \Delta \tau_k) s_{k,l}(t - 2T_n - \tau_{k,l} - \Delta \tau_k)...
\]

\[
S_{k,l}(t - (N_cN_{sc} - 1)T_n - \tau_{k,l} - \Delta \tau_k))^T \in \mathbb{C}^{N_cN_{sc}+1}
\]
is the vector corresponding to the sampled multipath component having delay \( \tau_{k,l} + \Delta \tau_k \). The first non-zero element in (2.19) is in position

\[
i = \left\lfloor \frac{nT + \tau_{k,l}}{T_n} \right\rfloor,
\]

(2.21)

where \( \left\lfloor \cdot \right\rfloor \) denotes ceiling function, i.e., integer larger than or equal to argument. The channel coefficient matrix \( \mathbf{C} \) consists of the channel attenuation factors and the random carrier phases:

\[
\mathbf{C} = \text{diag}(\mathbf{C}^{(0)}, \ldots, \mathbf{C}^{(N_b-1)}) \in \mathbb{C}^{KL \times KN_b},
\]

(2.22)

and

\[
\mathbf{C}^{(n)} = \text{diag}(\mathbf{c}_1^{(n)}, \ldots, \mathbf{c}_K^{(n)}) \in \mathbb{C}^{KL \times K},
\]

(2.23)

and the \( k \)th user’s taps are

\[
\mathbf{c}_k^{(n)} = \left( c_{k,1}^{(n)}, e^{j \theta_{k,1}^{(n)}}, \ldots, c_{k,L}^{(n)}, e^{j \theta_{k,L}^{(n)}} \right)^T \in \mathbb{C}^L.
\]

(2.24)

The matrix \( \mathbf{A} \) contains the carrier amplitudes of the users

\[
\mathbf{A} = \text{diag}(\mathbf{A}^{(0)}, \ldots, \mathbf{A}^{(N_b-1)}) \in \mathbb{R}^{KN_b \times KN_b},
\]

(2.25)

\[
\mathbf{A}^{(n)} = \text{diag}(A_1^{(n)}, \ldots, A_K^{(n)}) \in \mathbb{R}^{K \times K}.
\]

(2.26)

The vector \( \mathbf{b} \) contains the symbols with the modulation symbol alphabet \( \Xi \) (we assume BPSK modulation, i.e., \( \Xi = \{-1,1\} \)):

\[
\mathbf{b} = (\mathbf{b}^{(0)}, \ldots, \mathbf{b}^{(N_b-1)}) \in \Xi^{KN_b},
\]

(2.27)

and

\[
\mathbf{b}^{(n)} = [b_1^{(n)}, \ldots, b_K^{(n)}]^T \in \Xi^K.
\]

(2.28)

The channel noise vector \( \mathbf{n} \in \mathbb{C}^{(N_b+2)N_cN_x \times 1} \) consists of independent white Gaussian noise samples and has the covariance matrix
\[ \Sigma_n = E[\mathbf{n}\mathbf{n}^H] = \sigma^2 \mathbf{I} \tag{2.29} \]

The cross-correlation matrix for the spreading sequences can be formed as

\[
\mathbf{R} = \mathbf{S}^T \mathbf{S} \in \mathbb{C}^{N_bK_L \times N_bK_L} \tag{2.30}
\]

\[
\begin{bmatrix}
\mathbf{R}(0) & \mathbf{R}^T(1) & \mathbf{R}^T(2) & 0 & \cdots & 0 & 0 \\
\mathbf{R}(1) & \mathbf{R}(0) & \mathbf{R}^T(1) & \mathbf{R}^T(2) & \vdots & \vdots \\
\mathbf{R}(2) & \mathbf{R}(1) & \mathbf{R}(0) & \mathbf{R}^T(1) & \vdots \\
0 & \mathbf{R}(2) & \mathbf{R}(1) & \mathbf{R}(0) & \mathbf{R}(0) & \mathbf{R}^T(1) \\
\vdots & & & & & \\
0 & \cdots & \mathbf{R}(0) & \mathbf{R}^T(1) \\
0 & \cdots & \mathbf{R}(1) & \mathbf{R}(0)
\end{bmatrix}, \tag{2.31}
\]

where

\[
\mathbf{R}(0) = \mathbf{S}^T(0)\mathbf{S}(0) + \mathbf{S}^T(1)\mathbf{S}(1) + \mathbf{S}^T(2)\mathbf{S}(2),
\]

\[
\mathbf{R}(1) = \mathbf{S}^T(0)\mathbf{S}(1) + \mathbf{S}^T(1)\mathbf{S}(2),
\]

\[
\mathbf{R}(2) = \mathbf{S}^T(1)\mathbf{S}(2). \tag{2.32}
\]

It is easy to show that

\[
\mathbf{R}^T(i) = \mathbf{R}(-i), \quad i = 0,1,2. \tag{2.33}
\]

The elements of the correlation matrix can be written as

\[
\mathbf{R}(i) = \begin{bmatrix} R_{1,1}(i) & \cdots & R_{1,K}(i) \\ \vdots & \ddots & \vdots \\ R_{1,K}(i) & \cdots & R_{1,K}(i) \end{bmatrix}, \tag{2.34}
\]

and

\[
\mathbf{R}_{k,k'}(i) = \begin{bmatrix} R_{k1,k1}(i) & \cdots & R_{k1,k'L}(i) \\ \vdots & \ddots & \vdots \\ R_{kL,k1}(i) & \cdots & R_{kL,k'L}(i) \end{bmatrix}, \tag{2.35}
\]

where
\[
R_{m,k,l}(i) = \sum_{n=-\infty}^{\infty} s_k^{(n-\mu_{k,l})} s_{k'}^{(n-\mu_{k',l'})+\Delta \tau_k} 
\]  

(2.36)

represents the correlation between users \( k \) and \( k' \) along the \( l \)th and \( l' \)th paths. The delays \( \mu_{k,l} \) correspond to the delays of the propagation paths and the delay offsets of the users \( (\tau_{k,l} + \Delta \tau_k) \) measured in sample intervals.

If the delay estimation is not perfect, then estimation errors will occur. The mismatched correlation functions are defined based on correlation function in (2.36) with estimated delays:

\[
\hat{R}_{m,k,l}(i) = \sum_{n=-\infty}^{\infty} s_k^{(n-\hat{\mu}_{k,l})} s_{k'}^{(n-\hat{\mu}_{k',l'})+\Delta \hat{\tau}_k} ,
\]

(2.37)

\[
\hat{R}_{m,k,l}(i) = \sum_{n=-\infty}^{\infty} s_k^{(n-\hat{\mu}_{k,l})} s_{k'}^{(n-\hat{\mu}_{k',l'})+\Delta \hat{\tau}_k} ,
\]

(2.38)

where \( \hat{\mu}_{k,l} \) is the estimated delay of \( k \)th user's \( l \)th path in sample intervals. \( \hat{R}_{k,l}(i) \) is the correlation function when the true delay of user \( k \) and path \( l \) is known but the delay of user \( k' \) and path \( l' \) is estimated at the receiver. \( \hat{R}_{m}(m) \) is the correlation function when the delays of user \( k \) and path \( l \) as well as of user \( k' \) and path \( l' \) are estimated at the receiver. The mismatched correlation matrices \( \hat{R} \) and \( \hat{\hat{R}} \) are defined based on (2.37) and (2.38) similar to equations (2.30)–(2.36).

### 2.2 MULTIUSER DETECTION ALGORITHMS

A multiuser algorithm classification tree is depicted in Figure 2.2. The optimal receiver for multiuser detection is the maximum likelihood sequence estimator (MLSE). Due to its complexity several suboptimum multiuser detection algorithms have been developed. Suboptimal multiuser detection algorithms can be classified into linear equaliser and interference cancellation type algorithms. Furthermore, a few schemes not fitting this classification have been proposed. These include partial trellis-search algorithms [4,5] and neural networks proposed for AWGN channels [6,7].

Another proposed way to classify multiuser detection algorithms is by linear and non-linear algorithms [8]. However, in this classification the same algorithm can belong to both categories depending on its implementation.
2.2.1 Optimum Detection

Optimal multiuser detection consists of a matched filter followed by a maximum likelihood sequence detector implemented via a dynamic programming algorithm (e.g., Viterbi algorithm) [9]. The formulation of the optimal multiuser detector for an AWGN channel, MLSE, was published in 1986 by Verdú [9]. MLSE selects the most probable sequence based on the received signal and it is a globally optimal detector. The locally optimal minimum probability of error detector [9] has a complexity of a same order as the MLSE, but a slightly better performance at low signal-to-noise ratios. Presentations of an optimal detector in a Rayleigh fading channel can be found in [10,11]. Since the complexity of the optimal multiuser detector is exponential as a function of the number of users, a large number of studies to find suboptimal detectors have been carried out.

2.2.2 Conventional Detector

A conventional detector does not exploit the waveform information of the other users in the system but only the desired user’s waveform. If a signal $s(t)$ is corrupted by AWGN, the filter that maximises the output signal-to-noise ratio has an impulse response matched to $s(t)$ [12]. Since in the conventional receiver the received signal is correlated with the signature waveform of the user of interest, it is called matched filter. The conventional receiver is only optimal in a single user channel. The output of the matched filter for the $i$th path of the $k$th user can be written as:
\[
\begin{align*}
    y_{k,l}(t) &= \int_{nT + \tau_k + \Delta \tau_k}^{(n+1)T + \tau_k + \Delta \tau_k} s_k(t - nT - \tau_{k,l} - \Delta \tau_k) \varphi(t) \, dt. \quad (2.39)
\end{align*}
\]

In a fading channel with \( L \) resolvable paths, the output of a matched filter is

\[
\begin{align*}
    y_{k,l}^{(n)} &= A_k e^{j\phi_k^{(n)}} c_{k,l}^{(n)} b_k^{(n)} \\
    &+ \sum_{l' = 1}^{L} \sum_{n' = 0}^{N_k - 1} A_k e^{j\phi_{k,l'}^{(n)}} c_{k,l'}^{(n)} b_k^{(n')} \\
    &+ \sum_{k' = 1, k' \neq k}^{K} \sum_{l = 1}^{L} \sum_{n = 0}^{N_k - 1} A_k e^{j\phi_{k,l}^{(n)}} b_{k'}^{(n)} \\
    &+ \int_{-\infty}^{\infty} s_k(t - nT - \tau_{k,l} - \Delta \tau_k) s_{k'}(t - n' T - \tau_{k',l'} - \Delta \tau_k) \, dt \\
    &+ \int_{-\infty}^{\infty} n(t) s_k(t - nT - \tau_{k,l} - \Delta \tau_k) \, dt \\
    &= A_k e^{j\phi_k^{(n)}} c_{k,l}^{(n)} b_k^{(n)} + \psi_{k,l}^{(n)} + w_{k,l}^{(n)}. \quad (2.40)
\end{align*}
\]

The first term in (2.40) contains the desired information of the transmitted data symbol \( b_k^{(n)} \). The second term represents the influence of the other fading paths of user \( k \). This term is referred to as \textit{interpath interference} (IPI). The \textit{multiple access interference} (MAI) is represented by the third term which, in many cases, has greater influence on performance than the IPI. The power of MAI is determined by the cross-correlations between the signature waveform of the user of interest and the waveforms of the interfering users. From (2.41) it is seen that the matched filter output consists of the desired term, interference (IPI and MAI) and noise components.

The conventional receiver may separate all \( L \) resolvable paths. The data symbol is detected using a so-called RAKE receiver where \( L \) correlator outputs corresponding to the symbol \( n \) are combined coherently and detected using a decision device. The combining is usually done by maximal ratio combiner (MRC), where each of the correlator outputs is weighted by the complex conjugate of the corresponding channel gain prior to an adder. A RAKE matched filter produces a vector.
\[ y = (y^{(0)}, \ldots, y^{(N_b)}) \in \mathbb{C}^{NLb}, \]  
(2.42)

\[ y^{(n)} = (y^{(n)}, \ldots, y^{(n)}_L)^T \in \mathbb{C}^{KL} \]  
(2.43)

\[ y^{(n)}_k = (y^{(n)}_{k,1}, \ldots, y^{(n)}_{k,L})^T \in \mathbb{C}^L. \]  
(2.44)

The symbol \( n \) is the detected with hard decision device using signum function:\(^3\)

\[ \hat{b}_i(i) = \text{sgn}\{\text{Re}\{c_i^{H(n)}y^{(n)}_k\}\}. \]  
(2.45)

The amount of multiple access interference depends on the crosscorrelations between signature waveforms. In an asynchronous CDMA system, the cross-correlations are non-zero since it is impossible to design a set of completely orthogonal waveforms for all possible values of delays. From (2.41) it can be seen that amplitudes of interfering users will also have impact on the amount of MAI. If an interfering user has much larger amplitude than the desired user then the performance will degrade drastically. This is referred as to the near-far effect. Power control has been proposed as a solution to alleviate the near-far problem. Multiuser detection exploits the structure of the multiple access interference and improves the near-far performance of the system by eliminating the multiple access interference.

### 2.2.3 Linear Equalisers

Linear equaliser type receivers create data estimates based upon linear transformations of the matched filter outputs. In a general form, the linear equaliser can be formulated as \( \hat{h} = Ty \) where \( T \) is a linear operator on \( y \). Most common linear equalisers are the decorrelator (zero-forcing) and linear minimum mean square error receivers. MAI-whitening filters modelling the multiple access interference as coloured noise are also examples of linear equaliser receivers [13].

**Decorrelator**

The decorrelator (also called zero-forcing detector) proposed by Lupas and Verdú in [14,15] multiplies the matched filter outputs by the inverse of the cross-correlation matrix:

\[ \hat{h} = R^{-1}y. \]  
(2.46)

\(^3\) The signum function is defined as \( \text{sgn}(d) = \begin{cases} -1, & d < 1 \\ 0, & d = 0 \\ 1, & d > 1 \end{cases} \).
It should be noted that (2.46) assumes that multipath combining is performed after the decorrelation process. Therefore the decorrelation process has introduced noise correlation among the paths and this needs to be taken into account in the detection. The multipath combing can also be performed before the decorrelation process. This results to slightly better performance but also in a more complex receiver structure [16].

An advantage of the decorrelator detector is that the received signal amplitudes do not have to be known. On the other hand, the received noise process is also filtered with the inverse matrix and hence increases the noise power. This is proportional to the users’ mutual crosscorrelations. Since the decorrelator is a sequence detector, the detection process cannot be started until the whole transmitted sequence is received at the receiver. In practice this is not feasible and would result in a very long delay. Therefore, several finite delay decorrelator schemes have been proposed: isolation bit insertion (IBI), multishot sliding window algorithm (SLWA) and hard decision method (HDM) [17,18], improved one-shot detection scheme [19], and finite impulse response (FIR) and infinite impulse response (IIR) schemes [10]. The partial decorrelator forces the MAI from past symbols to zero, while the MAI due to future symbols might be suppressed, for example, by interference cancellation (see 2.2.4). The partial decorrelator belongs to the family of non-linear decision feedback (DF) detectors, which are typically characterised by a linear feedforward filter and a non-linear feedback filter [20].

**MMSE**

Another linear receiver is the linear minimum mean square error [21], which, unlike the decorrelator, doesn’t enhance the noise. The MMSE receiver performs a linear transformation on the matched filter outputs that minimises the mean square error (MSE). The detected bits are obtained from

$$\hat{b}(i) = \text{sgn}[(\hat{R} + \sigma^2 E[(CA \text{A}^H C^H)^{-1}])^{-1} y].$$  \hspace{1cm} (2.47)

Even though LMMSE has also been proposed for centralised receivers in AWGN and known fading channels, the main interest has been in decentralised adaptive implementations, which are especially attractive for implementation in mobile stations [22]. A modified LMMSE receiver for fading channels has been presented in [23].

### 2.2.4 Interference Cancellation Receivers

The idea of interference cancellation is to estimate the multiple access and multipath induced interference and then to subtract this [24]. Based on (2.40) the matched filter output can be written as

$$y_{k,j}^{(n)} = h_{k,j}^{(n)} + \psi_{k,j}^{(n)} + w_{k,j}^{(n)},$$ \hspace{1cm} (2.48)
where $h_{k,l}^{(n)}$ is the desired term. If the detector is able to generate an estimate of the interference $\hat{\psi}_{k,l}^{(n)}$, the desired term can be estimated by cancelling the interference as

$$\hat{h}_{k,l}^{(n)} = y_{k,l}^{(n)} - \hat{\psi}_{k,l}^{(n)},$$ (2.49)

which can be utilised in recovering the transmitted symbol.

Successive interference cancellation (SIC) works on a user-by-user basis, while parallel interference cancellation (PIC) works on all users simultaneously [25]. Groupwise interference cancellation algorithms detect symbols within a given group and cancel the interference on that group from other users. In wideband CDMA, the grouping can be performed based on data rate. Multistage interference cancellation algorithms improve the interference estimates iteratively. If tentative data decisions are used, the scheme is called hard decision (HD) interference cancellation. If tentative data decisions are not used, the scheme is called soft decision (SD) interference cancellation.

**Parallel Interference Cancellation**

The PIC receiver detects all users at the same time and then cancels interference simultaneously. It applies the multistage principle, and bit decisions at stage $n$ is given by

$$\hat{b}(n) = \text{sgn}[y_0 - (R - I)A\hat{b}(n)],$$ (2.50)

where $\hat{b}(n-1)$ contains the bit decisions from the previous stage. The cancellation can be performed on wideband domain or 'chip' level by regenerating the interference after detection or on the symbol level using the crosscorrelation matrix. Both methods are analytically identical but require different implementation (see Section 3.2).

Complete subtraction of the MAI in PIC has been shown to result in biased decision statistics [26]. Therefore, partial cancellation has been proposed to reduce the effect of bias in SD-PIC [26] and HD-PIC [27].

**Successive Interference Cancellation**

The SIC receiver cancels one user at a time. It ranks the users according to their powers, cancelling first the higher power users. This is because the strongest users can be detected more reliably and are likely to cause significant interference to the weaker users. In fading channels the ranking of users have to be performed on-line because the received powers of the users vary from symbol to symbol.

### 2.3 REVIEW OF EARLIER WORK ON MULTIUSER DETECTION

This section reviews earlier and parallel work to motivate the topic of the thesis. First, the general development of multiuser detection techniques is presented. Next, an
overview of practical implementation, limitations and problems of MUD schemes is
given. Topics covered are coded systems, multirate systems, adaptive implementation,
channel estimation, delay estimation, power control, complexity, multicell aspects and
adaptive antennas. Each of these topics is of interest when selecting suitable multiuser
detection algorithms for third generation wideband CDMA systems. Channel coding is
an essential part of any system. Since the status of the system will change over time,
receiver algorithms need to be adaptive. Channel and delay estimation are of crucial
importance for good system performance and multiuser detector algorithms need to be
robust against delay and phase estimation errors. Power control is part of the proposed
CDMA systems, and thus the interaction of MUD with power control needs to be
understood. Near-far performance is related to both multirate performance and to power
control errors. MUD in multicell environment needs to be studied to find out how well
MUD algorithms work in real cellular systems. Complexity aspects need to be
considered to find out whether the concepts are implementable. Adaptive antennas are
means to improve the system performance and thus interaction between them and MUD
needs to be understood.

2.3.1 Development of Multiuser Detection

The idea of multiuser detection was first mentioned in 1979 by Schneider [28]. In 1983,
Kohno et al. published a study on multiple access interference cancellation receivers
[29]. In 1984, Verdú proposed and analysed the optimal multiuser detector and the
maximum likelihood sequence detector, which, unfortunately, is too complex for
practical implementation since its complexity grows exponentially as a function of the
number of users [30]. Consequently, Verdú’s work [9,30] inspired many researchers to
find multiuser detectors which could achieve a close to optimal performance with
reasonable implementation complexity.

The first studies concentrated on finding suboptimal detectors for the AWGN
channel [15]. The following wave in the research of multiuser detection were studies on
suitable detectors for fading multipath channels, first in slowly fading channels and then
in relatively fast fading channels. Both flat fading and multipath channels have been
considered. Since the multiuser detector parameters such as amplitude, phase, and
cross-correlations between users change over time, studies of adaptive multiuser
detectors that self-tune the detector parameters based on the received signal were started
[32]. In the real world, perfect parameters required for signal detection are never
available. Consequently, studies taking into account the impact of nonideal estimation
of phase, amplitude, and delays have been initiated [33,34]. Channel coding is an
essential part of all proposed wideband CDMA air interfaces. However, so far,
relatively few studies have considered multiuser detection together with channel coding
[4,5,37]. Third generation wideband CDMA systems will have multiple data rates.
Recently, multiuser detectors for multirate CDMA systems have been proposed [1].
2.3.2 Coded Systems

MUD with channel coding can be either partitioned or integrated. Partitioned approaches treat the multiuser interference equalisation problem and decoding problem separately. Integrated approaches perform both the equalisation and decoding operations together [4]. Partitioned approaches can be further divided into hard and soft decision approaches. In the soft decision approach a multiuser detection algorithm feeds the soft symbols after detection into a channel decoder.

The optimum MLSE receiver for BPSK, rate 1/2 convolutional code asynchronous CDMA system in AWGN channel has been presented in [4]. Asymptotic efficiency is upper and lower bounded. Furthermore BER simulations are performed for a two user case for different near-far ratios.

Linear decorrelator, decision feedback and trellis/tree-based approaches have been investigated for partitioned and integrated approaches for a two user asynchronous CDMA in AWGN channel in [4]. Furthermore, BER is simulated for a four user AWGN channel.

The formulation and BER analysis of optimum receiver, integrated multistage and reduced tree search algorithm for trellis-based modulation in an asynchronous AWGN channel have been presented in [5].

The HD-PIC scheme with rate 1/2 convolutional coding has been simulated in Rayleigh fading channel in single cell and multicell cell environments in [35]. HD-PIC with orthogonal codes has been investigated in [36]. The performance of the HD-PIC receiver with channel coding in frequency selective fading channels is studied in [37]. In addition, partial interference cancellation scheme in conjunction with joint decoding is studied.

An integrated SIC scheme where decoding of the channel code is done at each step of the successive cancellation process has been presented in [38]. Performance of the scheme has been compared with a partitioned SIC scheme on a flat Rayleigh fading channel with perfect channel and delay estimates. Since with the integrated approach power ranking of the users according to their power can only be performed blockwise, performance is not good as with symbolwise ranking in the partitioned SIC scheme. An issue for further study is the impact of imperfect channel estimates in multipath channel since these are needed already for Viterbi decoding in all stages in contrast to the partitioned approach where they are not needed until RAKE combining is performed [38].

In [39] an iterative multiuser receiver with turbo codes is derived and simulated in AWGN channel. The receiver is derived based on maximum a-posteriori probability (MAP) criteria and it takes a-priori information from the forward error correction (FEC) decoding block to improve probabilistic estimates.

A trade-off between coding and spreading for the LMMSE receiver in synchronous and asynchronous AWGN channels has been investigated in [40].

2.3.3 MUD for Multirate Systems

Formulation of optimum receiver for a dual rate system has been presented and analysed for variable spreading factor and multicode receivers in AWGN channel in
[41]. The decorrelator for dual rate system in synchronous AWGN channel has been studied in [42]. Asynchronous CDMA two- and three-rate systems with multicore or variable spreading gain using decorrelator, PIC, groupwise SIC with either PIC or decorrelator within the group have been compared in the AWGN channel in [1]. The partial decorrelator with subtractive pilot signal cancellation in downlink has been studied for a multicore system in multipath channel in [43].

The HD-PIC multistage receiver is extended into a multirate asynchronous CDMA with variable spreading factor and diversity reception in [44]. Simulations are performed in Rayleigh fading channel (pico and micro cell channels) using channel estimator modified for the multirate receiver.

The SIC scheme for a multirate DS-CDMA system using either 16-QAM (quadrature amplitude modulation) modulation or multicore transmission for high rate users in 2-path frequency selective slow Rayleigh fading channel has been studied in [45].

The soft decision GSIC receiver for the variable spreading factor and multicore transmission schemes has been investigated in [46].

2.3.4 Adaptive Implementations

In a realistic communication scenario the system and its status will change over time: users will enter and leave the system frequently; a user might change its communication parameters such as data rate or coding scheme during a connection; and the channel parameters such as delays will change over time. An adaptive receiver uses an adaptive law to adjust its linear transformation. An overview of adaptive multiuser detection can be found in [32].

For multiuser detection adaptive implementations concern linear receivers such as decorrelator and MMSE receivers. Since we shall use adaptive implementations of these receivers later to assess complexity of linear receivers, adaptive implementations of such receivers are reviewed in the following.

Adaptive implementation of the decorrelator has been presented in [47] using Cholesky factorisation and iterative algorithms (conjugate gradient, steepest descent and iterative sliding window detection). Iterative algorithms are suitable for a system with time-variant signature waveforms, i.e., long codes. Another adaptive implementation of a decorrelator combining the matched filter and decorrelator operations together has been simulated in an asynchronous 2-path Rayleigh fading channel [48]. An adaptive decorrelator detecting the new user’s code and that a user has left communication has been studied in [49].

There exists a large variation of adaptive MMSE algorithms: N-tap MMSE algorithm (a MF with adaptive weights), oversampling scheme and cyclically shifted filter bank [21] and optimum complexity reduction scheme [22]; fractionally spaced adaptive LMMSE receivers include complex weight and TDAF (time dependent adaptive filter) based receivers that exploit the spectral correlation inherent to DS-modulation [22]. Adaptation of the MMSE receiver can be either trained or blind. Receivers suitable for blind adaptation utilise often minimum output energy (MOE) criterion. The proposed adaptation algorithms are well known from other applications: least-mean-square (LMS), recursive least-square (RLS) and a number of blind
algorithms (Griffiths’ algorithm, constant modulus algorithm, linearly constrained constant modulus algorithm) [22]. Performance of the above mentioned MMSE algorithms have been simulated in synchronous AWGN channel [22]. A modified MMSE receiver suitable for fading channels has been presented in [23].

2.3.5 Channel Estimation

Studies for channel estimation concentrate into two categories: 1) developing channel estimators for specific MUD detectors and 2) analysing sensitivity of a multiuser detection for channel estimation errors.

Optimum MLSE receiver estimates the received complex amplitudes and multiplies the matched filter bank output with it [50]. In a suboptimum implementation data detection and complex channel coefficient estimation are decoupled from each other. In this case the optimum channel estimator would be LMMSE [51]. However, since the channel co-variance matrix required in the LMMSE estimator changes according to fading rate and signal-to-noise ratios it is very difficult to implement in practice. However, it can be approximated by an adaptive channel estimator filter such as FIR or recursive IIR predictors or smoothers [10].

Sensitivity of different implementations of decorrelator for carrier phase and frequency estimation errors has been simulated in AWGN channel for different near-far ratios with uniform distribution of phase and frequency errors in [17,18].

Performance of different channel estimators with the decorrelator and HD-PIC schemes in 1- and 2-path Rayleigh fading channels have been studied in [10]. Performance of decorrelator, MMSE, multistage SD-PIC and SD-SIC have been simulated in flat and 2-path Rayleigh fading channels in [52]. Adaptive joint LMMSE channel estimation and detection schemes has been studied in frequency selective Rayleigh fading channel in [53].

A modified LMMSE detector has been presented and simulated in 2 path synchronous channel (downlink) in [23]. Channel estimation was performed from pilot signal using a conventional (moving average) channel estimator. The modified LMMSE detector, in contrast to standard LMMSE receiver, depends only on the crosscorrelation matrix and the average channel profiles of the users. Another modified adaptive LMMSE algorithm has been studied in a 3-path Rayleigh fading channel for different fading rates [54]. The scheme allows multiple step-sizes for both training and decision feedback stages, allows multiple training or decision feedback passes over the received signal and uses the MSE value produced at the end of each region to indicate the quality of the output signal.

Sensitivity of SD-PIC for channel estimation errors has been analysed in AWGN channel and simulated in 3-path Rayleigh fading channel in [55]. Performance of adaptive HD-PIC, SIC and decorrelator based channel estimators have been compared in an 1-path Rayleigh fading channel [56]. The rough channel estimates are found by subtracting the MAI estimates from the matched filter outputs and by multiplying the remainder by the conjugate of the symbol estimate. After MAI has been subtracted the channel estimation problem can be divided into separate filtering tasks for each user and propagation path. The optimum predictor, which would require knowledge of the channel correlation function, can be approximated by using iterative
gradient based algorithms such as linear FIR or recursive IIR adaptive LMS predictors. Impact of using fixed LMMSE channel estimator for single user systems in HD-PIC multiuser receiver performance has been simulated in an 1-path Rayleigh fading channel in [57].

BER performance of HD-SIC with reference symbol aided channel estimation using non-ideal fixed, linear phase low-pass filter was analysed and simulated flat and frequency selective fading channel [58]. Furthermore, performance was simulated in multicell environment with 1 dB standard deviation power control error and different path loss attenuations.

2.3.6 Delay Estimation

Delay estimation can be divided into code acquisition and code tracking. Similar to the channel estimation delay estimation studies for multiuser detectors can be classified into two categories 1) studies of specific delay estimation techniques for MUD schemes and 2) sensitivity of different detectors into delay estimation errors.

Multiuser delay estimation methods include optimum maximum likelihood (ML) estimation [50], subspace methods (MUSIC algorithm) [59], hierarchic ML method [60] and PIC based delay estimators [56]. However, subspace methods seem not to be suitable for fast fading, multipath channels with SNR less than 10 dB [59]. In a PIC based delay tracker with early-late delay-locked loop technique the MAI estimates are subtracted from matched filter outputs before the processing in early, late and on-time branches to generate the correct timing. The mean square error performance of the tracker has been simulated in 1-path Rayleigh fading channel with different number of users and power distributions in [56].

Sensitivity of the optimum and HD-PIC receivers for channel mismatch in asynchronous AWGN channel with two users has been analysed in [34]. The performance of the HD-PIC receiver with delay estimation in frequency selective fading channel has been studied in [61]. Sensitivity of linear receivers, especially the decorrelator, for timing errors for different near-far ratios has been analysed in AWGN channel with Gaussian distributed delay error [33]. Sensitivity of different implementations of decorrelator for timing errors has been simulated in AWGN channel for different near-far ratios of two users with uniformly distributed timing error in [17].

The sensitivity of the SD-PIC performance to timing errors has been analysed in the AWGN channel and simulated in a three ray multipath channel with fixed timing error in [55]. Furthermore, the performance of SD-PIC and SIC with imperfect delay estimation were compared in AWGN channel with perfect power control. Acquisition and the impact of non-synchronized users on SD-PIC performance has been analysed and simulated in [62].

Effect of delay tracking errors on the SD-SIC have been analysed and simulated in the AWGN channel in [63]. Tracking error was modelled as iid zero mean normal random variable. Impact of delay estimation errors into the HD-SIC have been simulated in flat and 3-path frequency selective Rayleigh fading channel with imperfect power control (std=1 dB) in multicell environment with different path attenuation factors in [65].
The performances of decorrelator, LMMSE, multistage PIC and SIC have been compared in the presence of delay estimation errors in [8]. Delay error was modelled as a Gaussian distributed random variable.

2.3.7 Multiuser Detection and Power Control

As mentioned earlier all third generation wideband CDMA proposals use fast power control. Since the power distribution after power control will impact the performance of multiuser detection, it is important to analyse this problem. Power control and SD-PIC have been analysed with improved Gaussian approximation in [64].

The impact of different standard deviations of power control error into performance of reference symbol assisted HD-SIC has been simulated in flat and 3-path frequency selective Rayleigh fading channel [65]; non-ideal channel estimation was assumed, and in 2-path Rayleigh fading channel with standard deviation of 2.3 dB for the power control error [66].

The convergence of iterative power control based on MSE at the output of the detector in synchronous CDMA employing MMSE receiver has been analysed in [67]. An iterative, distributed MMSE power control scheme has been presented in [68].

Multistage HD-PIC and fast power control in downlink of a DS-CDMA system with multicode transmission in a 2-path Rayleigh fading channel was studied in [69].

2.3.8 Complexity and Implementation Aspects

The implementation complexity of adaptive decorrelator, MMSE and HD-PIC has been analysed in terms of flops\(^4\), and the number of clock cycles required by synchronous digital signal processing (DSP) hardware has been analysed in [10]. Furthermore, computational complexity of the decorrelator, LMMSE, multistage PIC and SIC has been compared in [52]. Another complexity comparison of SD-PIC and SIC has been presented in [55] using the number of instruction cycles per bit decision based on standard assembly language. The comparison included estimation and cancellation but not tracking.

Finite word length effects on the performance of MMSE receiver on synchronous Rayleigh fading channel assuming perfect power control have been studied in [70]. Finite precision arithmetic degrades the receiver performance with increasing MAI and the analog to digital (A/D) converter input signal scaling causes variations in desired signal power due to MAI power changes, further degrading performance.

Quantization effects have been analysed using improved Gaussian approximation and simulated for SD-PIC multistage receiver in [62]. An asynchronous two-stage SD-PIC with partial-cancellation has been implemented in baseband using ADSP2100 EZLAB board. The processing gain of the system was 15 and each of the four users had a bit rate of 5 kbps. The system has been tested in AWGN channel [71].

\(^4\) A floating point operation (flop) is defined to be a multiplication or addition [10].
2.3.9 MUD in Multicell Systems

Uplink cellular capacity of a system using 2-stage HD-PIC receiver in macro and micro cell environments with imperfect close loop power control and antenna diversity has been simulated and analysed in [35]. HD-SIC with quadriphase modulation has been simulated in flat and frequency selective Rayleigh fading channel with perfect and imperfect power control (std=1 dB) in multicell environment with different path attenuation factors in [72]. In the all above studies asynchronous interference from other cells is modelled as Gaussian noise. This might not be true especially with only a few high capacity users

Uplink range increase and transmission power savings with base station MUD were analysed in [73].

In downlink cancelling intra-cell interference provides very marginal capacity increase. One possibility would be to cancel the worst intercell interferers.

2.3.10 MUD and Adaptive Antennas

Combining multiuser detection with adaptive antennas yields further performance improvements. Decorrelator and adaptive antennas have been studied in [74]. Spatial-temporal HD-PIC receiver has been investigated in [75]. The SIC scheme is studied with adaptive antennas in [76] and SD-PIC with adaptive antennas has been studied in [8].

2.4 OBSERVATIONS AND CONCLUSIONS

A multirate system model was formulated. Different multiuser detection algorithms were reviewed. Several different aspects related to multiuser detection such as coded systems, multirate, adaptive multiuser detectors, power control, delay and phase estimation, multicell environment, complexity and adaptive antennas were studied in an extensive literature survey.

In general multiuser detection within a single cell with AWGN and fading channels is well understood. Coded MUD systems have been mainly studied for AWGN channel and for small number of users. Only few of the proposed MUD schemes have been studied with coding. Thus, coded MUD systems in Rayleigh fading channel need more analysis and investigations. Also, only few studies have looked into multirate systems performance in Rayleigh fading channels.

Adaptive implementations have been studied in AWGN and in Rayleigh fading channels and in the presence of parameter estimation errors. However, studies of adaptive schemes together with coding appear to be missing.

Delay and channel estimation have been studied separately, but combined analysis is still missing for several multiuser detection schemes. Furthermore, theoretical analysis of delay estimation in fading channels is an open problem. Since MUD schemes loose their near-far resistance in the presence of synchronisation errors, the impact of power control errors on performance should be analysed. Modelling of the delay error would require further attention.
Some initial complexity estimations for MUD schemes have been performed. However, a comprehensive analysis of all receiver parts including channel and delay estimation is missing. In addition, a more realistic complexity assessment would also require analysis of application specific integrated circuit (ASIC) architectures.

MUD has been mainly studied for single cell systems. Only few papers address spectrum efficiency and coverage aspects of multiuser systems in a multicell environment. Furthermore, downlink multiuser detection in a multicell DS-CDMA system has not been studied at all. Very few papers address multiuser detection and power control together.

From the above observations it can be concluded that no comprehensive comparison of multiuser detection schemes, including the impact of imperfect parameter estimation (channel and delay), multirate aspects, channel coding and complexity considerations in a multicell environment, has yet been performed. Such a comparison is given in the next chapter. Furthermore, multiuser detection in variable spreading factor DS-CDMA systems have received very little attention in the literature. This is the main focus of this thesis.

REFERENCES


Chapter 3

Qualitative Comparison of Multiuser Detection Algorithms

This chapter presents a qualitative comparison of different suboptimum multiuser detection receivers. This approach has been chosen due to the extensive amount of research in fundamental multiuser detection algorithms. The existing literature references are used to assess multiuser detection algorithms based on the criteria derived from the analysis of wideband CDMA air interfaces [1].

In Section 3.1 the comparison criteria are derived. Complexity comparisons are presented in Section 3.2 and performance comparisons in Section 3.3. Recommendations are given in Section 3.4, and a description of multirate weighted PIC (MW-PIC) in Section 3.5, respectively. Conclusions are presented in Section 3.6.

3.1 COMPARISON CRITERIA

In this section, criteria used in the qualitative comparison are derived based on analysis of the proposed third generation wideband CDMA air interface structures. The main parameters of wideband CDMA schemes were already discussed in Section 1.2. The WCDMA system is selected as an example, which is used to derive the evaluation criteria. The system parameters of WCDMA are listed in Table 3.1.

Spreading modulation is QPSK and data modulation is BPSK. Modulation does not have an impact on the selection of multiuser detection algorithm. The system model presented in Chapter 2 for BPSK spreading modulation can easily be generalised to QPSK. In the receiver, coherent detection is used and thus performance in the presence of phase and amplitude estimation errors is important. Also robustness for delay estimation errors should be considered. In practical implementation, pilot symbols can be utilised for coherent detection.

The data of the \( k \)th user is spread by multiplying the data-modulated signal by a binary pseudo-random noise sequence, which consists of the Walsh code \( s_{[w|k]} \) used for orthogonal channelisation and a long spreading code for scrambling \( s_{[x|k]} \). The combination of these two codes results in the spreading sequence

\[
s_k(t) = \sum_{g=1}^{F/N_e} \sum_{j=0}^{N_e-1} s_{[w|k]}(j)s_{[x|k]}(j + (g - 1)N_e) p_e(t - jT_e)
\]

(3.1)
where $N_c$ is the actual spreading factor used (the length of the Walsh code), $P$ is the length of the scrambling code, and $p_c(t)$ is the chip waveform.

**Table 3.1**
Parameters of WCDMA [2]

<table>
<thead>
<tr>
<th>Channel bandwidth</th>
<th>5 MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Downlink RF channel structure</td>
<td>Direct spread</td>
</tr>
<tr>
<td>Chip rate</td>
<td>3.84 Mchips/s</td>
</tr>
<tr>
<td>Roll-off factor for chip shaping</td>
<td>0.22</td>
</tr>
<tr>
<td>Frame length</td>
<td>10 ms</td>
</tr>
</tbody>
</table>
| Spreading modulation | Balanced QPSK (downlink)  
Dual channel QPSK (uplink)  
Complex spreading circuit |
| Data modulation | QPSK (downlink)  
BPSK (uplink) |
| Coherent detection | User dedicated time multiplexed pilot  
(downlink and uplink), common pilot in downlink |
| Channel multiplexing in uplink | Control and pilot channel time multiplexed  
I&Q multiplexing for data and control channel |
| Multirate | Variable spreading and multicode |
| Spreading factors | 4–256 |
| Power control | Open and fast closed loop (1.6 kHz) |
| Spreading (downlink) | Variable length orthogonal sequences for channel separation  
Gold sequences $2^{18}$ for cell and user separation (truncated cycle 10 ms) |
| Spreading (uplink) | Variable length orthogonal sequences for channel separation, Gold sequence $2^{41}$ for user separation (different time shifts in I and Q channel, truncated cycle 10 ms) |
| Handover | Soft handover  
Interfrequency handover |

3.1.1 Differences between Uplink and Downlink Transmission with WCDMA

This section discusses the differences between uplink and downlink transmission and the impact on MUD receivers. Based on the discussion we motivate the MUD approach for the uplink, which is the main focus of this thesis.

The uplink and downlink have different characteristics, which impact the design of the MUD scheme. The uplink is asynchronous (i.e., the users’ transmission times are independent of each other). Propagation delays for cell ranges of 1 to 30 km vary between 3 to 100 µs, introducing a significant amount of intersymbol interference between the symbols of different users. The downlink is synchronous, and, in contrast to base stations, a mobile station needs to detect only its own signal. Typically, orthogonal codes are used in the downlink, but multipath propagation partially destroys the orthogonality. The additional gain from multiuser detection depends on the multipath profile. Multipath spread in outdoor systems typically ranges from a few microseconds up to 20 µs.
Since a mobile station needs only to demodulate its own signal, another multiuser detection strategy than in the base station could be applied in order to reduce the complexity in the mobile station, while still improving the performance over conventional detection. Many of the proposed multiuser detectors can also be modified for single user detectors. For multirate users, one possibility is to cancel only the self-interference caused by ISI from different parallel codes of the same user. In the downlink, the common control channels also cause interference. Since a mobile station has to detect the pilot signal, it could cancel the pilot signal, as proposed in [3].

The uplink direction is selected as the focus of the comparison in this study. This is because a base station is required to demodulate all signals anyhow and has more processing power available. In the downlink, the gain from the multiuser detection algorithms is smaller due to orthogonality. Also, other techniques such as transmitter diversity can be used to enhance the downlink performance [4].

3.1.2 Multirate System

The most important new capability to be offered by third generation systems is variable data rate connections, i.e., multirate scheme. In the proposed third generation CDMA systems, the data rate can be increased by using either the multicode or the variable spreading factor scheme.

In the multicode approach, the processing gain is fixed and a higher data rate is implemented by transmission of parallel codes. In the variable spreading factor scheme, the processing gain is varied according to the data rate. Also combinations of these two basic approaches are possible. In WCDMA, the variable spreading factor is used for low and medium bit rate services and the multicode scheme is used for high bit rate services [2]. Therefore, the selected multiuser detection algorithm should be able to handle multirate connections.

3.1.3 Coding Aspects

Typical bit energy to noise density ratio ($E_b/N_0$) for wideband CDMA in a fading multipath channel is around 5 dB, or less with diversity. This is enough to produce a BER of $10^{-3}$ with convolutional coding of rate $\frac{1}{2}$ and constraint length 9. Since most of the multiuser detection research has been done for uncoded systems, the results can be interpreted for partitioned multiuser detection approach, i.e., MUD and coding are considered separately.

The channel coding schemes for wideband CDMA schemes are based on convolutional or Turbo coding [2]. These provide bit error rates of $10^{-5}$ or $10^{-6}$. Based on link level performance simulations this kind of BER is achieved with raw BER of

---

5 Multiuser detectors that make a joint detection of the symbols of different users are also called centralised multiuser detectors. Single-user detectors, also called decentralised multiuser detectors, demodulate a signal of one desired user only [5].
$10^1 - 10^2$ and $E_b/N_0$ of $1-5$ dB. Therefore this range of $E_b/N_0$ values is a comparison point for different algorithms.

### 3.1.4 System Scenario

In order to set requirements from the system perspective for receiver algorithms, we analyse the spectrum efficiency of the WCDMA system. For satisfactory 8 kbit/s speech service (with 50% voice activity, 20 ms interleaving, BER $10^{-3}$), WCDMA has the nominal uplink capacity of 159 users/cell and 204 users in the downlink in a microcell environment [6]. In a vehicular macrocell environment with three sectors/cell, capacities were 123 and 98 users/cell for uplink and downlink, respectively [6]. Since these results are with 100% loading but without multiuser detection, which would at most increase capacity by 1.5–2 times, we conclude that the MUD algorithm should be able to handle around 100–150 speech users/cell, if a 5-MHz bandwidth is used.

### 3.1.5 Comparison Criteria

Based on the analysis of the proposed third generation wideband CDMA systems the following comparison criteria are proposed to be used [1]:

- Computational complexity, especially in a system with long spreading codes;
- Performance in AWGN and Rayleigh fading channels with $E_b/N_0$ less than 5 dB;
- Robustness against phase and delay errors;
- Near-far performance and feasibility for multirate system.

### 3.2 COMPLEXITY ANALYSIS

The final implementation complexity of a multiuser detector receiver depends on the selected architecture and cannot be estimated without a detailed implementation analysis of algorithms down to the ASIC and DSP implementation level. However, rough estimates of the implementation complexity can be obtained by estimating the number of arithmetic operations per second and the number of clock cycles required by a synchronous DSP [5]. It should also be noted that an arithmetic operation could be implemented using either an integer or a floating point operation depending on the requirements of the selected algorithm. This might cause further significant differences in the implementation complexities of the algorithms. When assessing the required number of arithmetic operations, we follow the methodology in [5] and consider only the dominant term.

The ideal implementation of the linear detectors, such as decorrelator and MMSE, has cubic dependence on the number of the users times the number of multipath components [8]. Therefore, iterative algorithms such as the conjugate gradient (CG) method have been proposed to implement them [7]. The preconditioned
conjugate gradient algorithm (PCG) appears to be one of the simplest algorithms for linear multiuser detection [5].

Tables 3.2 and 3.3 summarise the computational complexities of the algorithms considered here. Based on Section 3.1.4, the number of users is assumed to be $K = 150$. The number of multipaths is $L = 4$, the number of samples per chip is $N_{sc} = 4$, and the code length is $N_c = 256$. The symbol rate after channel coding is 20 ksymbols/s (i.e., the symbol duration is $T = 50 \mu s$). The number of iterations for the PCG algorithm is $I = 124$, and the observation window size is $N = 13$. The number of cancellation stages in the PIC algorithm is $M = 2$ and in the SIC algorithm $M = 1$.

The iterative PCG algorithm is the most complex and hardly feasible from an implementation point of view, especially if long spreading codes are used. An alternative implementation for a decorrelator, an approximate decorrelator, has been proposed to relieve the processing requirement [9]. Even though it does not require matrix inversion, cross-correlations between different user codes have to be calculated for every symbol, requiring $O(2(KL)^2 N_c N_{sc})/T \approx 15$ Tflops. The symbol-level PIC is the least complex multiuser detection algorithm. However, for long spreading codes, the correlation matrix needs to be updated for every symbol, thereby increasing complexity much further. It should be noted that cross-correlations could be calculated in parallel. The regenerative PIC is only five times more complex than the conventional matched filter detector and is well suited for long spreading codes. The regenerative SIC algorithm also has low complexity. Its high clock rate, however, limits the number of users in the cancellation process. The high clock rate can be reduced by increasing the detection delay. The architecture presented in [10] would, however, introduce one symbol delay for each user in the detection process, making, for example, fast power control impossible for a large number of users. Thus, from a complexity point of view, the PIC receiver would seem best suited for systems with long spreading codes.

### Table 3.2
Implementation Complexity Requirements

<table>
<thead>
<tr>
<th></th>
<th>Operations/s</th>
<th>Clock Cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional</td>
<td>$O((4N_c N_{sc} K L)/T)$</td>
<td>$2/T$</td>
</tr>
<tr>
<td>PCG</td>
<td>$O((12N_c N_{sc} K L)/T)$</td>
<td>$16M/T$</td>
</tr>
<tr>
<td>PIC (symbol level)</td>
<td>$O((4M K L)/T)$</td>
<td>$4M/T$</td>
</tr>
<tr>
<td>PIC (regenerative)</td>
<td>$O((8 M N_c N_{sc} K L)/T)$</td>
<td>$5M/T$</td>
</tr>
<tr>
<td>SIC (regenerative)</td>
<td>$O((8 M N_c N_{sc} K L)/T)$</td>
<td>$4M K /T$</td>
</tr>
</tbody>
</table>

### Table 3.3
Implementation Complexity

<table>
<thead>
<tr>
<th></th>
<th>Operations/s</th>
<th>Clock Cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional (MF)</td>
<td>49 Gflops/s</td>
<td>40 kHz</td>
</tr>
<tr>
<td>PCG</td>
<td>139 Tflops/s</td>
<td>40 MHz</td>
</tr>
<tr>
<td>PIC (symbol level)</td>
<td>57 Gflops/s</td>
<td>160 kHz</td>
</tr>
<tr>
<td>PIC (regenerative)</td>
<td>196 Gflops/s</td>
<td>200 kHz</td>
</tr>
<tr>
<td>SIC (regenerative)</td>
<td>98 Gflops/s</td>
<td>12 MHz</td>
</tr>
</tbody>
</table>
3.3 PERFORMANCE

In this section, the performance of the decorrelator, MMSE, PIC and SIC detectors is assessed for use in AWGN and Rayleigh fading channels. Furthermore, the impact of imperfect phase and delay estimation is evaluated. Special attention is paid into the near-far performance and multirate capability.

3.3.1 Performance in AWGN Channel

According to [7,11] the decorrelator, MMSE, and SD-PIC receivers have almost equal performance in the AWGN channel with $E_b/N_0$ less than 10 dB. The MMSE detector is slightly better than the decorrelator due to the noise enhancement property of the decorrelator [11]. The SD-SIC is considerably worse than the other schemes. The HD-PIC performs better than the SD-PIC receiver because of larger residual interference due to less reliable soft decisions.

3.3.2 Performance with Phase Errors

The impact of phase errors alone is not very large on any multiuser detection receiver and much less severe than the delay errors [7]. Furthermore, it seems that all detectors have about the same degradation as the phase error increases [11].

3.3.3 Performance in Rayleigh Fading Channel

In flat Rayleigh fading, the performance of all detectors is almost equal [7]. The performance of the SIC scheme improves compared to AWGN channel, since the instantaneous powers of the users are different. To obtain this higher performance requires, of course, ranking of the users according to their relative powers on a symbol-by-symbol basis.

In frequency selective Rayleigh fading, the SD-PIC and SD-SIC receivers perform slightly worse than linear receivers. The reason is multipath-induced additional multiple access interference, which degrades the estimation of channel gains [7]. The decorrelator and MMSE receivers do not need separate estimation of channel gains. Since the HD-PIC can use separate estimates of channel gains, its performance is not degraded as much. Actually, for moderate channel gain estimation errors, the HD-PIC still outperforms the decorrelator receiver [5].

3.3.4 Performance with Delay Errors

The sensitivity of the decorrelator, MMSE, SD-PIC and SD-SIC receivers for delay estimation errors has been compared in [7,11]. In an AWGN channel all detectors degrade equally fast as the delay error increases. In a Rayleigh fading channel, however, the performance of the decorrelator and MMSE receivers degrades faster up
to the standard deviation of 0.1 chip. Thus, the performances of the receivers approach each other and for larger delay errors the performances are almost equal.

In order to interpret the sensitivity result, we need to know how large error the delay tracking scheme will produce. The most commonly used delay tracking device in the conventional CDMA receiver is the Delay-Locked Loop (DLL). We assume that the variance of delay tracking error is less than 0.01 chip [12]. Of course in a near-far situation the variance would be larger. A variance of 0.01 (standard deviation 0.1 chips) still leads to significant degradation of multiuser detector performance [7,11]. For the conventional detector the degradation is smaller. This can easily be explained by the fact that in the conventional detector the performance degrades only due to reduced energy in the correlation process. In the multiuser detection algorithms the error impacts also MAI estimates, and thus the delay error of one user impacts all other users as well.

3.3.5 Near-far Performance

Two issues concerning the near-far performance of multiuser detectors exist. For the variable spreading factor scheme different data rates have different powers resulting in a constant near-far situation. For the multicode scheme imperfect power control leads to variations in received user powers.

Some conclusions for performance of multiuser detectors in variable spreading factor system can be drawn from the results presented in [7,11]. One high power user degraded the performance of the SD-PIC scheme significantly. The reason for this is that the cancellation of the weak user is inaccurate at the first stage due to the interference from the high power user [7]. A similar behaviour has been observed in the HD-PIC receiver in real multirate simulations [13]. The SIC scheme benefits from unequal powers. However, the SIC algorithm is not sensitive to the power of the strongest user but to the power of the second strongest user [7]. This is because in the existence of two very strong users, the second strongest user degrades the estimation of the first user. This further reduces the attractiveness of the SIC algorithm. The decorrelator is insensitive to user powers as long as there is no delay estimation error. However, with imperfect delay estimation it also looses its near-far resistance. In the presence of delay estimation errors, the near-far performance degrades and all schemes approach each other.

The performance of different multiuser detection schemes for the variable spreading factor scheme has been studied in [13]. The most promising scheme was groupwise SIC, where users were grouped according to their spreading factors and the PIC or decorrelator was applied within a group. Users with the lowest spreading factor were detected first and their multiple access interference subtracted from the matched filter outputs of the other users, which are then further detected by the PIC or decorrelator. However, the performance of the high bit rate users was not satisfactory, because undetected low bit rate users degrade the performance of high bit rate users.
3.3.6 MUD and Power Control

Third generation wideband CDMA uses fast closed loop power control both in the uplink and the downlink. Since all multiuser detectors are in practice limited by the near-far effect, power control will be required even if MUD is used. In the uplink, fast power control improves the performance in three ways: by equalising the user powers detrimental near-far effect is mitigated; by compensating the channel fading the $E_b/N_0$ is improved; and by minimisation of transmit power the battery life of mobile terminals is increased and intercell interference reduced. Thus, even with multiuser detection it is important to use power control.

In the downlink, power control also improves the performance against fading, but contrary to the uplink, it increases differences between the received signal powers at the mobile station. Multiuser detection can mitigate larger differences in power levels and offers better compensation of deep fades [14].

Fast power control seeks to compensate for the effect of fast fading. Power control has the largest impact on the performance of the SIC scheme. The SIC scheme performs best when the user powers are different. This is obviously the case for instantaneous powers in Rayleigh fading. By ranking the users on a symbol basis, equal performance compared to the other schemes can be obtained. To relieve the implementation complexity of SIC receiver with respect to power ranking, it has been proposed to apply signal-to-interference ratio (SIR) based power control [15]. The user that is detected first experiences the interference from all other users, and the user that is detected last experiences only noise and other cell interference. Consequently, given an equal quality goal, power control will adjust the user powers so that the first user has the largest power and the last user the smallest power. The performance of the first user would be equal to conventional detector. Further gain can be obtained by taking into account the spatial distribution of the users within a cell. In order to minimise intercell interference, the first user in the detection process should be closest to the base station [15]. For highly mobile users this kind of assignment would be difficult.

It is well known that imperfect power control degrades the performance of the conventional detector. Imperfect power control has two effects on receiver performance. Since fading is not compensated perfectly, the performance is degraded. Furthermore, nonequal powers due to imperfect power control lead to a near-far situation. As was discussed earlier, none of the multiuser detection receivers is near-far resistant, when considering imperfect parameter estimation. Thus, imperfect power control will degrade also the performance of multiuser detectors. Power control error can be modelled as a log-normally distributed random variable. The combined control error in the reverse link caused by the fast power control loop and open loop power control is of the order of 1.5 to 2.5 dB. Based on the studies available so far it seems that all detectors will have similar performance degradation under imperfect power control. Furthermore, multiuser detectors require as stringent power control as does the conventional matched filter detector.
3.4 RECOMMENDATIONS

The decorrelator, MMSE, PIC, and SIC detection schemes have been compared with respect to complexity and performance. From the complexity point of view only interference cancellation type algorithms appear feasible alternatives for third generation systems. The use of long spreading codes makes the regenerative algorithms operating at chip level more attractive than the symbol level algorithms. The SIC receiver suffers from high clock cycle requirements and long delay. Thus, from the complexity point of view, the regenerative PIC algorithm appears the most desirable alternative. With regenerative algorithms, a cleaned residual signal is obtained. This can be used for synchronisation purposes. This makes the regenerative schemes even more attractive.

The performance comparison in the AWGN and Rayleigh fading channel did not reveal any significant differences, except for the poor performance of the 1-stage SIC in the AWGN channel. Furthermore, the proposed combination of SIC and power control, simplifying the implementation, is not expected to improve the performance of the basic 1-stage SIC algorithm. Hard decision interference cancellation receivers perform better than soft decision. It should be noted that a comprehensive analysis of the combined impact of delay, phase and amplitude estimation errors is still missing for all multiuser detectors.

In a near-far environment, the decorrelator and the MMSE outperforms the other schemes. However, in the presence of parameter estimation errors, they loose their near-far resistance. In the PIC receiver, the cancellation of weak users is inaccurate in the first stage due to the interference from high power users.

Based on the above considerations, the regenerative HD-PIC receiver is proposed for third generation wideband CDMA. Furthermore, in order to improve the performance, it is proposed to apply weighting of the users according to their power levels in the first cancellation stage. Earlier this type of weighting has been proposed for single rate systems to mitigate bias in the SD-PIC receiver [7], to reduce unreliable initial bit estimates in the HD-PIC receiver [16] and to improve performance of the PIC receiver with channel coding [17]. The proposed new receiver, termed multirate weighted PIC (MW-PIC), is presented in the next section.

In addition to the MW-PIC scheme, the GSIC scheme is proposed as a good compromise between PIC and SIC receivers. When received user powers are equal PIC should be applied and when they are different SIC gives better results [7]. Based on this, a GSIC receiver for multirate scenario is suggested. A more detailed motivation and analysis for different structures of GSIC receivers will be given in Chapters 4 and 6.

3.5 MULTIRATE WEIGHTED PIC: A PROPOSAL

In the MW-PIC, a partial cancellation is performed according to the spreading factor (i.e., data rate) of each user group. The basic principle of the solution is shown in Figure 3.1. The received signal is matched filtered and tentative decisions are made. These decisions are multiplied by the energy estimates. Thereafter, a spread signal is regenerated. Different groups are weighted (i.e., only partially cancelled) according to
their reliability. The weighting is proposed to be based on spreading factors, i.e., the lower the spreading factor (the higher the data rate) the higher the weighting factor, since high bit rate user are detected at the first stage more reliably. Thereafter, the regenerated signals are subtracted from the delayed received signal and for each user own regenerated signal is added back before the matched filtering. In the second stage, both users are considered without weighting. However, if desired, weighting can be applied at this stage, too.

Figure 3.1  Multirate weighted PIC receiver.

3.6 CONCLUSIONS

A qualitative comparison of multiuser detectors have been performed. Interference cancellation (i.e., regenerative algorithms) was observed to suit for wideband CDMA systems with long spreading codes best. A multiuser receiver called the weighted multirate PIC was proposed for multirate CDMA systems. The weighting of different groups is expected to improve the performance compared to an equal weighting for all groups. In addition, groupwise successive interference cancellation was proposed as a good compromise between PIC and SIC receivers in a variable spreading factor wideband CDMA system.

REFERENCES


Chapter 4

Analysis of Multirate DS-CDMA

In this chapter, the performance of multirate DS-CDMA system is analysed using a new Gaussian approximation technique called the accurate Gaussian approximation (AGA). Analytical results obtained are used to motivate receiver structures that exploit the nature of multirate DS-CDMA systems.

In Section 4.1, different approximation methods for analysis of DS-CDMA bit error probability (BEP) performance are shortly reviewed. Section 4.2 presents an analysis of a variable spreading factor (VSF) CDMA system using AGA, for different processing gains and numbers of users. Section 4.3 compares multicode and variable spreading factor CDMA systems.

4.1 PERFORMANCE APPROXIMATION TECHNIQUES

In this section, different performance approximation techniques are presented and discussed. First, the DS-CDMA system model to derive the approximations is introduced. Next, four different approximation techniques are presented: standard (SGA) [1], improved (IGA) [1], simplified improved (IGA) [2] and accurate Gaussian approximations [3]. Finally, a comparison of these approximation techniques is presented.

4.1.1 System Model

A system model similar to that presented in Chapter 2 is assumed. However, only the AWGN channel is considered here. It should also be noted that the concept of physical and effective users in Chapter 2, is not used here.

The total received signal can be written as

\[ r(t) = \sum_{k=1}^{K} \sqrt{2P_k} s_k(t - \tau_k) h_k(t - \tau_k) \cos(\omega_c t + \phi_k) + n(t), \]

(4.1)

where \( P_k \) is the power of the \( k \)th user, \( \omega_c \) is the angular carrier frequency, \( \tau_k \) and \( \phi_k \) are the delay and phase of the \( k \)th user’s signal, respectively, and \( n(t) \) is an additive white Gaussian noise (AWGN) process with two-sided power spectral density \( \sigma^2 \). The data signal is a deterministic sequence of positive and negative rectangular pulses with unit amplitude, i.e.,
\[ b_k(t) = \sum_{n=0}^{\infty} b_k^{(n)} P_T(t-nT), \quad (4.2) \]

where \( b_k^{(n)} \) is the \( n \)th data bit of the \( k \)th user and \( P_T = 1_{[0,T]} \) is a rectangular unit pulse of duration \( T \). The spreading waveform \( s_k(t) \) is given by

\[ s_k(t) = \sum_{i=1}^{N} s_{k,i} p_c(t-iT_c), \quad (4.3) \]

where \( N \) is the number of chips, \( s_{k,i} \in \{1,-1\} \) is the \( i \)th chip of the \( k \)th user, and \( p_c(t) \) is the pulse shape of a chip with duration \( T_c \).

We observe the demodulation of the first user as a reference. In the demodulation process at the receiver, the composite signal \( r(t) \) is multiplied by a synchronized replica of the original spreading waveform \( s_i(t-\tau) \cos(\omega_c + \phi) \). In practice, the variables \( \tau \) and \( \phi \) are not known exactly, so estimates \( \hat{\tau} \) and \( \hat{\phi} \) are used. Therefore, we define \( \hat{\tau} = \tau + \varepsilon \) and \( \hat{\phi} = \phi + \zeta \), where \( \varepsilon \) is the delay error and \( \zeta \) is the phase error. It is assumed that synchronisation errors \( 0 \leq \varepsilon \leq T \) and \( 0 \leq \zeta \leq \pi/2 \) are fixed. After the correlation process the decision statistics of the \( n \)th bit of the first user can be written [4]

\[ Z_{1,n} = \int_{nT + \hat{\tau}}^{nT + \hat{\tau} + T} r(t) s_i(t-\hat{\tau}) \cos(\omega_c + \hat{\phi}) dt, \quad (4.4) \]

It is assumed that all delays and phases are taken with respect to the first user, so that \( \hat{\tau} = \hat{\phi} = 0 \), i.e., \( \tau = \varepsilon \) and \( \phi = \zeta \).

Based on the spread spectrum literature [1-10] it can be derived that the decision statistics (4.4) is equal in distribution to

\[ Z_1 = \frac{d}{2} \sqrt{2P_1 [N - \varepsilon (2B + 1 + Q_1)] \cos \zeta \beta^{(n)}_1} + \sum_{j=2}^{K} \frac{1}{2} \sqrt{2P_j W_j \cos \phi_j + \eta}, \quad (4.5) \]

where \( N_\varepsilon, b_{1,n}, \varepsilon, \) and \( \zeta \) are deterministic. Equation (4.5) can be used to derive approximations suitable for evaluation of a DS-CDMA system. The random vectors \([P_1,\ldots,P_K],[W_2,\ldots,W_K],[\phi_2,\ldots,\phi_K]\), and \( \eta \) are independent. The random scalar variables \( P_j, 1 \leq j \leq K \) are mutually independent, but not necessarily identically distributed. The random variable \( B \) represents the number of chip boundaries in the spreading waveform \( s_i(t) \) at which transition to a different value occurs. Consequently, it can be interpreted as a measure for spreading and has a binomial distribution.
\[ P\{B = n\} = 2^{1-N} \binom{N-1}{n} , \quad n \in \{0, \ldots, N-1\} \]  

(4.6)

Given the event \( \{B = n\} \), the random variables \( W_j, 2 \leq j \leq K \) representing multiple access interference, are mutually independent and their conditional distribution can be specified as

\[ P\{W_j | B = n\} = R_j + (1-R_j)Q_j + X_{j,n} + (1-2R_j)Y_{j,n} , \]  

(4.7)

where \( R_j, Q_j, X_{j,n} \) and \( Y_{j,n} \) are independent random variables with distribution given in [1]. The random variable \( \eta \), representing the noise samples after the correlation process, has a normal distribution with zero mean and the variance of \( N_0 N_c^2 / (4T) \). The random variables \( \phi_j, 2 \leq j \leq K \) are uniformly distributed on \([0, 2\pi]\). In particular, note that \( Q_1 \) is independent of all other random variables and satisfies

\[ P\{Q_1 = 1\} = P\{Q_1 = -1\} = \frac{1}{2} . \]  

(4.8)

### 4.1.2 Standard Gaussian Approximation (SGA)

The BEP for the matched filter receiver is defined as

\[ P_e = \Pr\{Z_1 < 0\} = \Pr\left\{ N + \sum_{j=2}^{K} W_j \cos \phi_j + \eta < 0 \right\} . \]  

(4.9)

If the multiple access interference is approximated by an Gaussian random variable with zero mean and variance \( \sigma^2 \), then the BEP (without noise) is approximated by\(^6\)

\[ \Pr\{Z_1 < 0\} = \Pr\left\{ \frac{Z_1 - N}{\sigma} < -\frac{N}{\sigma} \right\} \approx 1 - Q\left[ \frac{-N}{\sigma} \right] = Q\left[ \frac{N}{\sigma} \right] . \]  

(4.10)

---

\(^6\) Function \( Q \) is defined as \( Q[u] = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{u} \exp(-u^2 / 2) du \).
The Gaussian assumption is justified by the central limit theorem. Now, in order to obtain the standard Gaussian approximation it is necessary to calculate the conditioned variance of multiple access interference in (4.5). The calculating of the variance of MAI $\psi$ is facilitated by conditioning on $B$, and by conditioning on the relative delays $S_j$ and phases $\phi_j$ of all interfering signals, i.e.,

$$\psi = \text{var}(\{\text{MAI} \mid B, S_k, \phi_k\}) = \text{var}\left(\sum_{r=2}^{K} W_r \cos \phi_r \mid B, S_k, \phi_k\right).$$ (4.11)

After some manipulation the approximation of BER can be derived to be (for a complete derivation, see [4]):

$$P_e = Q\left[\sqrt{\frac{N}{\text{SNR} + (K - 1)N/3}}\right],$$ (4.12)

where $\text{SNR} = \frac{N_t^2 N_0}{2P_1 T}$. For randomly distributed powers the BER is approximated by substituting

$$\text{SNR} = \frac{N \mu \sqrt{R}}{\sqrt{N \sigma^2 \sqrt{R} + h + \sum_{j=2}^{K} \mu_{P_j} N/3}},$$ (4.13)

in the $Q$-function. It should be noted that the variances $\sigma_{P_j}^2$ for the interfering users are not included in Equation (4-13). Therefore, it is obvious that for randomly distributed powers the SGA gives less accurate results than in the case of all powers being deterministic.

### 4.1.3 Improved Gaussian Approximation (IGA)

The improved Gaussian approximation is based on the premise that the MAI converges to the Gaussian variable as $N_c$ becomes large for any $K$, when the chip delays and carrier phases are fixed. When the distribution of $\psi$ is found, the IGA is given by [1]

$$P_e = \int_{0}^{\infty} Q\left(\frac{N}{\sqrt{\psi}}\right) f_{\psi}(\psi) d\psi.$$ (4.14)
This approximation gives very accurate results. However, it is computationally very complex since finding $f_\psi(\psi)$ requires that the distribution for a MAI term in (4.11) be determined and convolved with itself $K-2$ times.

4.1.4 Simplified Improved Gaussian Approximation (SIGA)

Calculation of the expectation $E_\psi Q[N/\sqrt{\psi}]$ in IGA is very time consuming. By approximating this expectation calculation is simplified. The simplified improved Gaussian approximation uses an expansion in differences (Stirling formula) to approximate the expectation. The SIGA is given by [2]:

$$P_\psi = EP(\theta) \approx \frac{2}{3} P(\mu) + \frac{1}{6} P(\mu - \sigma \sqrt{3}) + \frac{1}{6} P(\mu + \sigma \sqrt{3}),$$  \hspace{1cm} (4.15)

where

$$P(\psi) = \frac{N^2}{\psi},$$  \hspace{1cm} (4.16)

and

$$\mu = \frac{(K-1)N}{3},$$  \hspace{1cm} (4.17)

and

$$\sigma^2 = (K-1) \left( \frac{23}{360} N^2 + \left( \frac{1}{20} + \frac{K-2}{36} \right) N - \frac{1}{20} \frac{K-2}{36} \right).$$  \hspace{1cm} (4.18)

As can be seen, SIGA requires only that the mean $\mu$ and variance $\sigma$ be determined. Thus, it is very simple to calculate but still accurate in most situations.

When user powers are randomly distributed the SIGA is given by [4]

$$P_\psi = EP(N^2 \sigma_\psi^2 + \psi) \approx \frac{2}{3} P(N^2 \sigma_\psi^2 \frac{\mu - \sigma \sqrt{3}}{\sqrt{N}}) + \frac{1}{6} P(N^2 \sigma_\psi^2 \frac{\mu - \sigma \sqrt{3}}{\sqrt{N}} + \frac{1}{6} P(N^2 \sigma_\psi^2 \frac{\mu + \sigma \sqrt{3}}{\sqrt{N}}),$$  \hspace{1cm} (4.19)

where

$$\mu = \frac{N}{3} \sum_{j=2}^{K} \mu_{P_j},$$  \hspace{1cm} (4.20)

and
\[ \sigma^2 = (K-1) \frac{23N^2 + 2N - 2}{360} \sum_{j=2}^{K} \mu_{i,j}^2 + \frac{7N^2 + 2N - 2}{40} \sum_{j=2}^{K} \sigma_{i,j}^2 + \frac{N-1}{36} \sum_{j=2}^{K} \sum_{i=2 \atop i \neq j}^{K} \mu_{i,j}^2 \mu_{i,j}^2. \]  

(4.21)

In case all powers are deterministic, 0 is substituted for \( \sigma_{i,j}^2, 2 \leq j \leq K \).

### 4.1.5 Accurate Gaussian Approximation (AGA)

The so-called accurate Gaussian approximation has been derived in [3,4,10]. It is slightly more complex than SIGA, but more accurate and can be applied to several scenarios. The AGA is, like the IGA, based on the assumption that \( Z_1 \), if conditioned on \( B \), all normalised time delays, and phase differences, is approximately Gaussian distributed. Furthermore, the fact that

\[ \psi = \sum_{j=2}^{K} Z_j, \quad (4.22) \]

where \( Z_2, \ldots, Z_K \) are identically distributed and defined in [1] and conditionally independent, given \( B \). Therefore, a good approximation for the distribution is a normal distribution with mean \( \mu_B \) and variance \( \sigma_B^2 \). Hence, BEP can be approximated by

\[ P_e = E_B \left[ Q \left( \frac{N}{\sqrt{x}} \right) f_{\psi|B}(x) \right] = \]

\[ = E_B \left[ Q \left( \frac{N}{\sqrt{x}} \right) \frac{1}{\sigma_B \sqrt{2\pi}} \exp \left( -\frac{(x - \mu_B)^2}{2\sigma_B^2} \right) \right] \]

\[ = \sum_{j=1}^{N-1} \left( N-1 \right) \int_{0}^{\infty} Q \left( \frac{N}{\sqrt{x}} \right) \frac{1}{\sigma_B \sqrt{2\pi}} \exp \left( -\frac{(x - \mu_B)^2}{2\sigma_B^2} \right) dx, \quad (4.23) \]

where

\[ \mu_B = E[\psi|B = j] = \frac{3N - 2j - 1}{6} \sum_{i=2}^{K} \mu_i, \quad (4.24) \]
\[ \sigma_b^2 = \frac{K-1}{360} \left( 8(2j+1 - \frac{15}{8} N)^2 + \frac{135}{8} N^2 \right) \sum_{i=2}^{K} \mu_n^2 + \frac{1}{80} \left( 4(2j+1 - \frac{5}{2} N)^2 + 5N^2 \right) \sum_{i=2}^{K} \sigma_n^2, \]

(4.25)

where \( \mu_n \) and \( \sigma_n^2 \) are the mean and variance of \( P_l, l = 1, \ldots, K \). It can be easily seen that different scenarios can be evaluated.

### 4.1.6 Comparison of Approximation Techniques

A comparison of different CDMA performance approximation techniques has been presented in [3,4,10]. The SGA is very simple to calculate. However, it is not very accurate, when the number of users is small or when users have very large differences in the received powers. The IGA is very accurate, but is difficult to calculate. The SIGA is easy to implement and in most situations gives accurate results. In some situations, more accurate results would be desirable. The AGA is simple to calculate and, moreover, gives also accurate results for different scenarios, such as AWGN, synchronisation errors, and imperfect power control. Based on these considerations, the AGA is selected for further use in the following sections.

### 4.2 ANALYSIS OF VARIABLE SPREADING FACTOR SYSTEM

In this section, the VSF system is analysed using the accurate Gaussian approximation. The purpose of the analysis is to study the VSF system both with nonequal and equal loading.

In the first analysed case, nonequal loading, the processing gain is varied for each scenario, while the number of users for each data rate group is kept the same (i.e., the system load changes for each scenario). The parameters used in the analysis are shown in Table 4.1.

Figure 4.1 shows the impact of different processing gains on the performance. For all processing gains the performance of high bit rate users is the best. This is because the interference is the total interference decreased by the amount of interference generated by the desired user. A high bit rate user also generates the highest amount of interference and consequently has the best performance.

The performance decreases as the processing gains are decreased, since the system load is increased. At low processing gains, the relative difference in BER between different groups is higher. This is due to earlier saturation of performance, which again is due to higher multiple access interference (lower processing gains give less protection against interference).
Table 4.1
Parameters for numerical analysis

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<tr>
<td>#2</td>
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<td>4 4 2</td>
</tr>
<tr>
<td>#3</td>
<td>64 32 16</td>
<td>4 4 2</td>
</tr>
<tr>
<td>#4</td>
<td>128 64 32</td>
<td>4 4 2</td>
</tr>
<tr>
<td>#5</td>
<td>256 128 64</td>
<td>4 4 2</td>
</tr>
</tbody>
</table>

Figure 4.1  Performance of variable spreading factor system with different processing gains. The three most upper curves correspond to the scenario #1 and the three most lower curves correspond to the scenario #5.
Table 4.2
Parameters for numerical analysis

<table>
<thead>
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<th>Scenario</th>
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<th>Number of users</th>
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<tbody>
<tr>
<td>#1</td>
<td>16</td>
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</tr>
<tr>
<td>#2</td>
<td>32</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>2</td>
</tr>
<tr>
<td>#3</td>
<td>64</td>
<td>16</td>
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<tr>
<td></td>
<td>32</td>
<td>8</td>
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<tr>
<td></td>
<td>16</td>
<td>4</td>
</tr>
<tr>
<td>#4</td>
<td>128</td>
<td>32</td>
</tr>
<tr>
<td></td>
<td>64</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>32</td>
<td>8</td>
</tr>
</tbody>
</table>

In the second analysed case both the processing gain and the number of users are varied. The parameters used in numerical analysis are shown in Table 4.2. This means that the system load (number of users/processing gain) is kept the same for all scenarios. Bit error rate performance, however, is not the same. Effective interference is the total interference decreased by the amount of interference generated by the desired user [11]. Thus, the lower the processing gain and the lower the number of users, the larger the contribution of interference by one user. This effect can be clearly seen in Figure 4.2.

![Graph showing bit error rate probability](image)

**Figure 4.2** Performance of VSF system with equal system load. The three lowest curves correspond to the scenario #1. For scenarios #2-#4 the curves are almost equal.
Figures 4.3 and 4.4 show the impact of one dominant high bit rate interferer on the performance. In Figure 4.3, the number of users was 10 and 1 for processing gains 64 and 8, respectively. Figure 4.4 the number of users was 8 and 1 for processing gains 32 and 4, respectively. As can be seen the performance of the high bit rate user is significantly better since this user experiences less interference than a low rate user.

![Graph showing bit error probability vs. Eb/No in [dB] for different processing gains (PG=64, PG=8).](image)

**Figure 4.3** Performance of the matched filter receiver in a two processing gain system with processing gains of 64 and 8. There are ten low bit rate users and one high bit rate user.

### 4.3 COMPARISON OF VARIABLE SPREADING FACTOR AND MULTICODE DS-CDMA SYSTEMS

In this section, results of an analytical comparison of VSF and multicode DS-CDMA previously, variable spreading factor and multicode DS-CDMA systems have been analysed using standard Gaussian and simple improved Gaussian approximations [11,12]. These analyses have shown that VSF and multicode schemes have equal performance. Here AGA is used to verify this conclusion.

Figure 4.5 shows BER performance as a function of $E_b/N_0$ for multicode and VSF systems. In the VSF case we have processing gains of 64 and 32 with 7 and 1 users, respectively. For the multicode system, the spreading factor is 64 for all users and the high rate user has 2 parallel codes. The number of users is the same as for the VSF system.
Figure 4.4  Performance of the matched filter receiver in a two processing gain system with processing gains of 32 and 4. There are eight low bit rate users and one high bit rate user.

The system behaves as follows, when variable processing gain is used to increase the data rate. For the low rate users, the processing gain remains the same. Interfering high bit rate user starts transmitting at higher powers and thus the interference experienced by the low bit rate users increases. For the high rate users the processing gain decreases, but power increases.

When the data rate is increased using the multicode scheme, the low rate users experience more interfering users. However, these new users are fully synchronized. The high rate users see no change, since the parallel users (additional codes to increase data rate) are perfectly orthogonal. In conclusion, the difference between the two schemes is negligible [12].

The fact that some interfering users are mutually synchronized, does not influence the system greatly. As long as these users remain asynchronous with the desired user, their impact is almost negligible.

If the high rate users for the two cases presented in Section 4.2 are implemented using the multicode scheme, the performances of the multicode user coincide with the lower processing gain users in Figures 4.3 and 4.4. Thus, the VSF and multicode schemes perform equally well.
4.4 CONCLUSIONS

The bit error probability of the matched filter receiver was observed to be different for different spreading factors, i.e., processing data rates, in a VSF DS-CDMA system. Especially with low spreading factors, the performance differences of different data rates are rather large. This is because the effective interference is the total interference decreased by the amount of interference generated by the desired user [11]. Therefore, a high rate user contributes more interference than a low rate user. Consequently, a high rate user also sees less interference than a low rate user and thus its performance is better. Also, the lower the processing gain and the lower the number of users, the larger the contribution of interference by any one user. This motivates groupwise receiver structures for multiuser detection. It was shown that performance of variable spreading factor and multicode multirate systems is equal for the moderate processing gain differences analysed here.

REFERENCES


Chapter 5

Parallel Interference Cancellation in a Multirate CDMA System

In this chapter, the performance of the hard decision PIC receiver is studied by simulation of a VSF system. The receiver performance is evaluated for a single-rate and a three-rate system using Monte-Carlo simulations in the AWGN and Rayleigh fading channels. The bit error rates of the matched filter and the PIC detector with and without timing errors are compared. The impact of timing error on the PIC receiver has been studied previously for a single rate system [1,2]. Here, it is studied how do the characteristics of a VSF system impact the performance of the PIC receiver in the presence of timing errors [3,4].

The PIC receiver structure is presented in Section 5.1. The simulation assumptions are presented in Section 5.2. Performance results in the AWGN and Rayleigh fading channels are presented in Sections 5.3 and 5.4, respectively. The impact of delay estimation errors is studied in Section 5.5. Conclusions are drawn in Section 5.6.

5.1 RECEIVER STRUCTURE

The receiver structure considered in this chapter is the hard decision PIC receiver illustrated in Figure 5.1. It obtains the tentative decisions for the MAI estimations from a conventional RAKE receiver. Interference cancellation is performed in the chip domain, i.e., after symbol decisions the MAI is regenerated by respreading and it is subtracted from the received signal.

5.2 SIMULATION ASSUMPTIONS

Table 5.1 lists the assumptions used in the computer simulations. The simulation program applies the principle of effective users, which was explained in Section 2.1.1. This facilitates easy parameterisation of the simulation program as a function of the number of users and processing gains. In all simulations, all users have equal received energies.
In a nondispersive channel the intersymbol interference (ISI) is zero, when using a raised cosine frequency spectrum. The desired frequency response is achieved by applying two filters, one in the transmitter and one in the receiver combined with the desired frequency response \(X_\tau(f)\):

\[
X_\tau(f) = \begin{cases} 
\frac{T}{2} \left[1 + \cos \left( \frac{\pi T}{\beta} \left[ |f| - \frac{1-\beta}{2T} \right] \right) \right] & \text{for } 0 \leq |f| \leq \frac{1-\beta}{2T} \\
0 & \text{for } |f| > \frac{1+\beta}{2T} 
\end{cases} 
\tag{5.1}
\]

where \(\beta\) is the roll-off factor of the chip waveform which varies between \(0 \leq \beta \leq 1\).

Due to the smooth characteristics of the raised cosine spectrum, it is possible to design practical filters for the transmitter and the receiver that approximate the overall desired frequency response. In the ideal case, when the channel has no influence, we have

\[
X_\tau(f) = G_T(f)G_R(f) 
\tag{5.2}
\]
where $G_T(f)$ and $G_R(f)$ are the frequency responses of the two filters. If the receiver filter is matched to the transmitter filter, we have $X_{\infty} = G_T(f)G_R(f) = |G_T(f)|^2$. Ideally

$$G_T = \sqrt{|X_{\infty}(f)|} e^{-i2\pi t_0}$$  

(5.3)

and $G_R = G_T^*(f)$, where $t_0$ is the nominal delay, that is required to ensure physical implementation of the filter. Thus, the overall raised cosine spectral characteristic is split evenly between the transmitter filter and the receiving filter. Both have the square root raised cosine frequency response.

<table>
<thead>
<tr>
<th>Transmission mode</th>
<th>Asynchronous</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spreading modulation</td>
<td>BPSK</td>
</tr>
<tr>
<td>Processing gains</td>
<td>32,16,8</td>
</tr>
<tr>
<td>Code family</td>
<td>Gold</td>
</tr>
<tr>
<td>Basic Code length</td>
<td>32</td>
</tr>
<tr>
<td>Number of samples/chip</td>
<td>4</td>
</tr>
<tr>
<td>Chip waveform/Roll-off factor</td>
<td>Root-raised-cosine/0.75</td>
</tr>
<tr>
<td>Number of real users</td>
<td>Low: 4 (4 virtual); Medium: 4 (8 virtual); High: 2 (8 virtual)</td>
</tr>
<tr>
<td>Channel</td>
<td>AWGN</td>
</tr>
<tr>
<td>Frame size</td>
<td>500</td>
</tr>
<tr>
<td>Number of iteration</td>
<td>20</td>
</tr>
<tr>
<td>Channel estimation</td>
<td>Assumed known</td>
</tr>
<tr>
<td>Near-far-user-ratio</td>
<td>0 dB</td>
</tr>
<tr>
<td>Delay error in chip durations (the same for all users)</td>
<td>0, 0.1, 0.2, 0.3, and 0.4</td>
</tr>
</tbody>
</table>

5.3 PERFORMANCE IN THE AWGN CHANNEL

To examine the performance of the PIC receiver in a VSF multirate CDMA system, the performance of the matched filter and the PIC receivers were simulated in the AWGN channel.
Figure 5.2 shows the results of the matched filter detector. Users with the lowest processing gain, i.e., users with the highest data rate, perform the best and the lowest data rate the worst. As already discussed in Chapter 4, this is because the interference is the total interference reduced by the amount of interference generated by the desired user. A high bit rate user generates highest amount of interference and consequently has the best performance. The simulated results agree with the analytical results presented in Chapter 4.

![Figure 5.2](image)

**Figure 5.2** Average BER as a function of $E_b/N_0$ for the MF receiver for a three processing gain system.

**Figure 5.3** presents the BER performance of the 2-stage PIC detector. The performance has improved by one order of magnitude compared to the MF detection. Also the performance differences between different data rates are smaller, especially for the low $E_b/N_0$ values. Thus, the PIC is near-far robust in a VSF system with moderate power differences. For high $E_b/N_0$ values the performance of the lowest data rate users seems to improve most. It can also be seen that there is an irreducible BER due to the decision errors in the multiple access interference estimate [5]. The decision errors bias the decision variable.

### 5.4 PERFORMANCE IN THE FADEING CHANNEL

In this section, the performance of the PIC receiver in a frequency selective Rayleigh fading channel is presented. The fading channel model is described in Section 2.1.3. Fading is assumed to be constant over a symbol time of the highest data rate user. The complex amplitude and delays are assumed to be known exactly. The vehicle speed is 5 or 40 km/h and the carrier frequency is assumed to 2 GHz. The basic data rate is 16 kbps. Otherwise, the same assumptions as for the AWGN channel are used.
Figure 5.3 Average BER as a function of $E_b/N_0$ for the PIC receiver in a three processing gain system.

The performance of the PIC receiver with vehicle speeds of 5 and 40 km/h is shown in Figures 5.4 and 5.5, respectively. The performance of all groups is the same, i.e., the near-far effect has been removed. The vehicle speed of 40 km/h results in slightly better performance.

Figure 5.4 Average BER as a function of $E_b/N_0$ for a 2-stage PIC receiver in the one path fading channel with a vehicle speed of 5 km/h.
5.5 IMPACT OF TIMING ERRORS ON THE MULTIRATE PIC RECEIVER

5.5.1 Performance in the AWGN Channel

In this section, the impact of timing errors on the multirate PIC receiver is investigated in an AWGN channel. The mismatched correlation functions due to timing errors were defined in Equations (2.36) and (2.37) and were used to define the mismatched correlation matrices \( \hat{R} \) and \( \hat{R} \). \( \hat{R} \) denotes the correlation function when the true delay of user \( k \) and path \( l \) is known but delay of user \( k' \) and path \( l' \) is estimated at the receiver; \( \hat{R} \) denotes the correlation matrix when the delays of user \( k \) and path \( l \) as well as user \( k' \) and path \( l' \) are estimated at the receiver. The output of a matched filter in the AWGN channel can now be written as

\[
y = \hat{R}Ab + w
\]  

(5.4)

where \( A \) contains the carrier amplitudes of the users, \( b \) contains the transmitted bits and \( w \) contains the noise samples. The output of the multistage PIC receiver for the stage \( n+1 \) can be written as
\[ \hat{b}(n) = \text{sgn} \left[ y - (\hat{R} - I) \hat{A} \hat{b}(n-1) \right] \] (5.5)

where \( \hat{b}(n-1) \) contains the bit decisions from the previous stage. It can be seen from Equation (5.4) that the impact of imperfect delay estimation on the performance of the matched filter receiver is simply reduced power. For the PIC receiver, as can be seen from (5.5), the effect of imperfect timing estimation is two-fold. First, the correlation with the desired user's spreading code is imperfect, again resulting in reduced power in the correlation process. Second, the cancellation will be imperfect due to the time offset between the actual interfering signal and the estimated interfering signal, i.e., the quality of the multiple access interference estimates degrades.

To understand the impact of delay estimation error in a multirate system, a three processing gain system was examined. The delay error had a fixed value, which ranged from 0 to 0.4\( T_c \). Figures 5.6 to 5.11 show the BER performance separately for the matched filter and 2-stage PIC detector for the data rates of \( R \), 2\( R \) and 4\( R \), corresponding to processing gains of 32, 16 and 8, respectively.

![Figure 5.6: Average BER as a function of \( E_b/N_0 \) using the matched filter receiver for 4 active users with a data rate of \( R \) in a three processing gain system with and without fixed delay error.](image)

It can be seen from Figures 5.6 and 5.7 that the performance degradation in the PIC receiver due to delay estimation errors is relatively larger than in the matched filter receiver. As discussed above, this is because the performance of the matched filter receiver degrades only due to reduced power in the correlation process. In the PIC receiver the delay estimation error impacts also the MAI estimate, and thus the delay estimation error of one user impacts all other users as well and consequently the performance degradation is more severe. However, up to delay estimation errors of about 0.3\( T_c \), the performance the PIC receiver remains superior to the performance of the matched filter receiver.
Figure 5.7. Average BER as a function of $E_b/N_0$ using the 2-stage PIC for 4 active users with the data rate $R$ in a three processing gain system with and without fixed delay error.

The performance of the users using data rate of $2R$ is presented for the matched filter and PIC receivers in Figures 5.8 and 5.9, respectively. Similar to the rate $R$, the performance degrades as the delay error increases. The amount of degradation is equal to rate $R$ users and the performance degradation is relatively worse for the PIC receiver.

Figure 5.8 Average BER as a function of $E_b/N_0$ using the matched filter receiver for 4 active users with a data rate of $2R$ in a three processing gain system with and without fixed delay error.
Figure 5.9  Average BER as a function of $E_b/N_0$ using the 2-stage PIC receiver for 4 active users with a data rate of $2R$ in a three processing gain system with and without fixed delay error.

The performance of rate $4R$ users is presented in Figures 5.10 and 5.11 for the matched filter and PIC receivers, respectively. Similar to the rates $R$ and $2R$, the performance degrades as the delay error increases and is relatively worse for the PIC receiver. The amount of degradation is equal to the previous cases.

Figure 5.10  Average BER as a function of $E_b/N_0$ using the matched filter receiver for 4 active users with a data rate of $2R$ in a three processing gain system with and without fixed delay error.
Figure 5.11 BER as a function of $E_b/N_0$ using the 2-stage PIC receiver for 4 active users with a data rate of 4R in a three processing gain system with and without fixed delay error.

5.5.2 Performance in the Fading Channel

In this section the performance of the PIC receiver with delay estimation errors is assessed in a 1-path fading channel with a vehicle speed of 40 km/h. The fading channel model is described in Section 2.1.3. Fading is assumed to be constant over a symbol time of the highest data rate user. The complex amplitudes and delays are assumed to be known exactly. The carrier frequency is assumed to 2 GHz. The basic data rate is 16 kbps. Otherwise, the same assumptions as for the AWGN channel are used.

The performance of the PIC receiver as a function of delay error is shown in figures 5.12 and 5.13. It can be seen that the performance of the different groups are almost equally affected by the delay errors for both the 1-stage PIC and the 2-stage PIC. In general, the performance decreases rapidly as the delay error increases. For larger delay errors the 1-stage and 2-stage PIC show equal performance.

5.6 CONCLUSIONS

The performance of PIC receiver has been evaluated in a VSF multirate DS-CDMA system. In particular, the impact of delay estimation errors on the system performance has been studied.

The performance of the MF and PIC receivers were evaluated in the AWGN and fading channels. Similar to a single rate system the PIC receiver improves the performance of the system by order of magnitude and removes the near-far effect also in a VSF system with moderate processing gain differences.
Figure 5.12 Impact of delay error on the BER of a 1-stage PIC in a 1-path fading channel with a vehicle speed of 40 km/h.

Figure 5.13 Impact of delay error on the BER of a 2-stage PIC in a 1-path fading channel with a vehicle speed of 40 km/h.
The impact of delay estimation errors on the performance of a three-rate system was simulated in AWGN and fading channels. An important observation is that users with different processing gains within a VSF multirate system showed roughly the same level of degradation for a given delay error. Fixed delay estimation errors of $0.1T_c$ appear to be acceptable, as they do not degrade the performance significantly. Larger delay estimation errors lead to a significantly worse performance. The performance of the PIC receiver degrades faster than the performance of the matched filter receiver if timing errors occur. This is because the performance of the matched filter receiver degrades only due to reduced power in the correlation process. In the PIC receiver the delay estimation error impacts also the MAI estimate and thus the delay error of one user impacts all other users as well and consequently the performance degradation is more severe. Up to delay estimation errors of $0.3T_c$ the performance of the PIC receiver is superior to the performance of the matched filter receiver.

REFERENCES


Chapter 6

Groupwise Multiuser Detectors

In this chapter, the groupwise serial interference cancellation (GSIC) is studied. Searching for the optimum trade-off between performance and complexity results in receiver structures that are tailor-made specifically for a VSF system [1,2]. As was noted in Chapter 4, the performance differences of the different data rates after matched filtering motivate the use of groupwise multiuser detector structures. The basic principle of the groupwise receiver for a fixed processing gain system has been presented in [3].

Sections 6.1 and 6.2 introduce the basic GSIC and extended GSIC receivers, respectively. The extended GSIC receiver with PIC reception within each group is presented in Section 6.3. Simulation assumptions are discussed in Section 6.4. Performance in AWGN and fading channels is studied in Sections 6.5 and 6.6, respectively. The impact of delay estimation errors on the GSIC receiver is investigated in Section 6.7. Complexity and performance comparisons of the GSIC and other multiuser receivers are presented in Sections 6.8 and 6.9, respectively. Finally, conclusions are drawn in Section 6.10.

6.1 BASIC MULTIRATE GSIC RECEIVER

Figure 6.1 depicts the structure of the basic GSIC receiver in a system with three groups of users: high, medium and low data rate users. In the GSIC detector, cancellation is performed in successive order, starting with the group of users transmitting at the highest data rate. This is because a high rate user has a higher power to maintain the same $E_b/N_0$. Thus, it causes more interference to the other users and is itself less sensitive to the interference from the other users.
First, the group of users with the highest data rate is processed and an estimate of multiple access interference (MAI) is generated by spreading the detected bits by the signature waveform (respreading block). The sum of the regenerated wideband signals forms the MAI estimate, which is subtracted from the received signal and the medium bit rate users are detected. This process is repeated until the lowest data rate users have been detected.

Interference cancellation is performed by regenerating and subtracting the estimated signals of the interfering users from the received signal $r(t)$ to form the new received signal after cancellation of each group. The new received signal after cancellation of the first group is

$$r_1(t) = r(t) - \sum_{j=1}^{K_1} \hat{s}_j(t - \tau_j), \quad (6.1)$$

where $K_1$ is the number of users in the first group, $\hat{s}_j(t)$ is the regenerated signal for the $j$th user and $\tau_j$ is the delay of the $j$th user.

![Diagram](image)

**Figure 6.1** Structure of the basic GSIC receiver.

### 6.2 EXTENDED MULTIRATE GSIC RECEIVER

In the basic GSIC receiver, only the interference of the higher rate users to the lower rate users was considered. The performance of the basic GSIC receiver can be improved
if interference of the lower rate users is cancelled from the higher rate users. The new structure, called the extended GSIC receiver, is shown in Figure 6.2. Now, after the basic GSIC structure the interference estimates of the low and medium rate users are subtracted from the received signal and the high rate users are detected. Similarly, interference estimate of the low rate users is subtracted from the medium rate users. Within groups matched filter detector is used. The extended GSIC receiver will outperform the basic GSIC, especially when there is a large number of users in the lower data rate groups causing a considerable amount of multiple access interference to the higher rate users.

![Figure 6.2 Structure of the extended GSIC receiver with matched filters within the groups.](image)

### 6.3 EXTENDED GSIC WITH ADDITIONAL PIC STAGES

In the above described basic GSIC and extended GSIC receivers, detection within each group is performed using matched filters. Thus, the MAI inside the groups is ignored and only the intergroup interference is cancelled. Performance can be improved by cancelling also the intragroup interference, for example, by the PIC or decorrelating receiver [4]. The PIC receiver is very suitable to be used within a group, since the powers are approximately equal for all users within a group. In the case of approximately equal powers, a parallel structure performs better than a serial structure, because it is difficult to find the strongest user to start serial cancellation. The structure of a groupwise receiver can also consist of multiple stages. After the initial cancellation stage, stages can be added until the desired performance is achieved. Depending on the initial stage, groupwise structure (basic GSIC/extended GSIC), number of stages, and the receiver structure within each group, different variations of the groupwise detector can be derived.

### 6.4 SIMULATION ASSUMPTIONS

Since exact analysis of the bit error probability of interference cancellation receivers is very difficult due to their non-linear decision-feedback nature, Monte-Carlo computer
simulations are used. A direct sequence spread spectrum system with BPSK data and spreading modulation in AWGN and fading channels is considered. Three different data rates are simulated: low rate with processing gain (PG) of 32, medium rate with PG of 16, and high rate with PG of 8. There are 4, 4 and 2 users for processing gains of 32, 16 and 8, respectively. The spreading codes are Gold sequences extended with a random chip resulting in a code length of 32. The pulse shape is root-raised cosine with roll-off factor of 0.75. The delays of the users are assumed to be uniformly distributed over [0,T]. Number of samples per chip was four. The simulation program is the same as used in Chapter 5.

6.5 PERFORMANCE IN THE AWGN CHANNEL

In this section, performance results for the matched filter, the basic GSIC, and the extended GSIC with and without intragroup PIC receivers are presented.

Figure 6.3 shows the average BER of the matched filter receiver for low, medium and high data rate users. As can be expected, the high rate users have the best BER performance and the low rate users the worst. This is because the powers of the medium and high rate users are higher, i.e., the low rate users see the medium and high bit rate users as strong interferers. The results are similar to [4] where, besides the pulse shape, the same simulation assumptions were used.

![Figure 6.3](image)

**Figure 6.3** Average BER as a function of $E_b/N_0$ of the matched filter receiver for low (PG=32), medium (PG=16) and high (PG=8) bit rate users.

Figure 6.4 shows the average BER of the basic GSIC receiver for low, medium and high data rate users. Now, the performance of low rate users has improved
considerably, since the interference from the high rate and medium rate users has been removed, using the scheme depicted in Figure 6.2. The bit error rate of the medium bit rate users has improved as well, since interference from high bit rate users has been removed. However, the low bit rate users still interfere the medium bit rate users. The performance of the high bit rate users is the same as with the matched filter.

![Figure 6.4](image)

Figure 6.4 Average BER as a function of $E_b/N_0$ of the basic GSIC receiver for low (PG=32), medium (PG=16) and high (PG=8) bit rate users.

The upper curves in Figure 6.5 show the average BER of the extended GSIC receiver for low, medium and high data rate users. Compared to the results of the basic GSIC presented in Figure 6.4, the performance of high rate users has improved, since interference due to the low and medium bit rate users is now removed from the high rate users. The performance of the medium bit rate users also improves, but relatively less than for the high bit rate users since, compared to the basic GSIC receiver, only interference from the low bit rate users is removed, resulting in equal performance of these two groups. The performance of the low bit rate user group, i.e., the users with the highest processing gain, is still the best. However, a simulation performed by another set of codes resulted in similar performance for all groups, thus indicating that the extended GSIC can remove the inherent near-far effect of a variable spreading factor system. The lower curves in Figure 6.5 present a case where a PIC receiver stage has been added for each group after the extended GSIC structure, thus cancelling intragroup interference. This improves the performance considerably, since now the intragroup interference is also suppressed.

In Figure 6.6, one more PIC stage has been added into the groupwise structure. There is a slight improvement in performance compared to the one PIC stage GSIC receiver presented in Figure 6.5. However, the performance improvement is only marginal, and may not be worth the increased implementation complexity.
It can be concluded that the GSIC can significantly improve the receiver performance, compared to the conventional matched filter receiver. The application of a PIC receiver to suppress the intragroup interference yields another significant performance gain. Since the interference cancellation receivers are relatively simple to implement, they appear as viable alternatives for the future multirate CDMA systems. To get a more realistic picture of their performance in a practical wireless environment, evaluation in a fading channel is performed in the next section.

Figure 6.5  Average BER as a function of $E_b/N_0$ of the extended GSIC receiver (upper curves) and the extended GSIC with one PIC stage (lower curves) for low (PG=32), medium (PG=16) and high (PG=8) bit rate users.
**Figure 6.6** Average BER as a function of $E_b/N_0$ of extended GSIC with two PIC stages for low (PG=32), medium (PG=16) and high (PG=8) bit rate users.

### 6.6 PERFORMANCE IN THE FADING CHANNEL

In this section, the performance of different groupwise interference cancellation receiver structures in a frequency selective Rayleigh fading channel is presented. The fading channel model was described in Section 2.1.3. Fading is assumed to be constant over a symbol time of the lowest data rate user. The complex amplitude and delays are assumed to be known exactly. The terminal speed is 80 km/h and the carrier frequency is assumed to 2 GHz. The basic rate is 16 kbps. Otherwise, the same assumptions as for the AWGN channel are used.

The impact of diversity on the receiver performance is shown in Figure 6.7. Clearly, the 2-path channel results in improved performance, due to the larger order of diversity since RAKE receiver was used.

The performance of the GSIC receivers in a two-path Rayleigh fading channel is shown in Figures 6.8 and 6.9. The results are similar to the AWGN channel. From Figure 6.9, it can be seen that the extended GSIC structure clearly improves the performance compared to the basic GSIC structure, whose BER performance is shown in Figure 6.8. Also shown in Figure 6.9, the extended GSIC receiver with one PIC stage clearly further improves the performance. This is due to the removal of intragroup multiple access interference. However, similar to the AWGN channel, adding one more PIC stage improves the performance only marginally. Therefore, it can be concluded that one PIC stage is sufficient to remove the intragroup interference.
Figure 6.7  Average BER as a function of $E_b/N_0$ of the extended GSIC receiver with two PIC stages in one (upper curves) and two (lower curves) path Rayleigh fading channels.

Figure 6.8  Average BER as a function of $E_b/N_0$ of the basic GSIC receiver in a two path Rayleigh fading channel.
6.6.1 Performance with Unequal Transmit Power Strategies

In this section, the impact of raised bit energy for higher rate users is studied. This kind of scenario might be justified if higher quality for high rate users is desired. When implementing a system with multiple data rates, increasing the power of the higher data rate users results in a better BER for these users. On the other hand, increasing their power, these users also affect the users transmitting at a lower rate more, because of increased multiple access interference. In this section the impact of unequal transmit power strategies, is studied (i.e. when a higher $E_b/N_0$ is used for users transmitting at a higher data rate).

Again a system with three data rates is considered. The low rate users transmit with an unchanged power level. The users with two times this basic data rate transmit with 5 dB power increase. Finally the highest data rate users transmit with an extra 10 dB power, compared to the power of the low rate users.
Figure 6.10  Average BER as a function of $E_b/N_0$ with unequal received energies of an extended GSIC with one stage using PIC receivers for detection in fading channel. One resolvable path and 4, high, 4 medium and 2 low rate users.

The performance of a system transmitting with equal energies is the same as the performance of the low rate users in Figure 6.10. The performance of the users transmitting at twice and four times the rate is, compared to the system applying equal energies, shifted by approximately 5 and 10 dB respectively.

This shift can be explained when looking into two opposite effects, namely the extra MAI introduced by the increase of power and deteriorating the system performance and the better quality of the tentative decisions resulting in a more efficient interference cancellation. These two effects compensate each other. Thus, the bit error rates are mainly shifted as a result of the difference in bit energy.

6.7 PERFORMANCE WITH DELAY ERRORS

In this section, the impact of delay estimation errors on the GSIC performance is studied. In the basic groupwise structure the impact of delay error is different for different groups. For the high bit rate users the impact is only due to the reduced energy in the correlation process. For the medium bit rate users the performance is also degraded due to poorer quality of the MAI estimate of the high bit rate user group. The same applies to the low bit rate users. For extended GSIC structures, the impact of delay estimation errors is similar for all groups.

Figure 6.11 shows the average BER as a function of a fixed delay error for the basic GSIC receiver and for the extended GSIC receiver with 2 PIC stages. The delay error is assumed to be same for all users. Both structures are relatively robust against delay errors up to 0.1 of a chip interval. Thereafter the performance, however, degrades
rapidly and already with delay error of 0.3 of a chip interval the more advanced receiver structure has nearly lost its performance advantage.

![Figure 6.11](image)

**Figure 6.11** Average BER as a function of $E_b/N_0$ of the basic GSIC and the extended GSIC with 2 PIC stages for low (PG=32), medium (PG=16) and high (PG=8) bit rate users as a function of delay error. Squares correspond to basic GSIC, circles correspond to extended GSIC with MF, diamonds correspond to extended GSIC with one stage of PIC detection and stars to extended GSIC with two stages of PIC detection. $E_b/N_0$ = 8 dB.

### 6.8 COMPLEXITY AND PERFORMANCE COMPARISON

In this section, the complexity and performance of different multiuser detectors are compared. First complexity comparison is presented and thereafter performance comparison in AWGN and fading channels is presented.

Rough estimates of the implementation complexity can be obtained by estimating the number of floating point operations per second (flops/s) and the number of clock cycles required by a synchronous digital signal processor (DSP). It was concluded in Chapter 3 that the most attractive MUD algorithms from the complexity point of view are regenerative PIC algorithms. Therefore, we compare the proposed new GSIC algorithms in a VSF system with MF, PIC and SIC algorithms, respectively. The methodology used in the comparison is similar to Chapter 3.

Table 6.1 summarises the computational complexities of the MF, PIC, SIC receivers and different GSIC algorithms. We assume three data groups with processing gains of 256, 128 and 64 with data rates 20 kbps, 40 kbps and 80 kbps, respectively. The number of users is 60, 20 and 5. The number of multipaths components is $L = 2$ and the number of samples per chip is $N_s = 4$. 
The basic GSIC receiver is only slightly more complex than normal matched filter. The complexity of extended GSIC receiver is about the same as a one stage PIC receiver. The extended GSIC receiver with one PIC stage has almost equal complexity with the 2-stage PIC receiver.

Table 6.1  
Implementation Complexity

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<tr>
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<th>Gflops/s</th>
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<td>MF</td>
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<td>240</td>
</tr>
<tr>
<td>PIC (one stage)</td>
<td>24,4</td>
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<td>PIC (two stage)</td>
<td>41,8</td>
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<td>SIC (one stage)</td>
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<td>Basic GSIC</td>
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<tr>
<td>Extended GSIC</td>
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<td>Extended GSIC with one PIC stage</td>
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<td>Extended GSIC with two PIC stages</td>
<td>70,0</td>
<td>5400</td>
</tr>
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</table>

Figure 6.12  
Average BER as a function of $E_b/N_0$ for a three processing gain system, averaged over the users of all groups. The solid curve is for matched filter, dashed dot is 2 stage HD-PIC and dashed is GSIC with 2 PIC stages.

Figure 6.12 shows performance of the matched filter, PIC and GSIC receivers in the AWGN channel. Clearly the GSIC receiver with two PIC stages outperforms both
the matched filter and PIC receivers. As was noted earlier the GSIC receiver with one PIC stage performs almost equally well to the GSIC receiver with two PIC stages.

Figure 6.13 shows a comparison between matched filter, PIC and GSIC receivers in a 2-path fading channel with vehicle speed of 40 km/h. Now the differences between receivers are smaller. The GSIC receiver with one PIC stage, however, still slightly outperforms the 2-stage PIC receiver. Thus, the GSIC receiver with one PIC stage appears to be a practical receiver structure for a multirate CDMA system, both from the complexity and performance point of view.

![Graph showing BER vs. E_b/N_0 for different receivers](image)

**Figure 6.13** Average BER as a function of $E_b/N_0$ for a three processing gain system, averaged over the users of all groups in a 2-path fading channel with vehicle speed of 40 km/h as a function of $E_b/N_0$.

### 6.9 CONCLUSIONS

In this chapter, the performance of different GSIC receivers for a multirate DS-CDMA system has been studied in AWGN and fading channels. The impact of delay estimation errors was studied using fixed delay error. In addition, complexity and performance comparison of matched filter, PIC and GSIC receivers was performed.

The structures for the basic GSIC and extended GSIC receiver were described, and numerical results were presented for the matched filter, basic GSIC and extended GSIC receivers. The performance of the matched filter receiver depends linearly on the user bit rate, so the performance of the high rate users is the best and the performance of the low rate users the worst. For the basic GSIC receiver, the order was reversed, so
now the low rate user performs best since the interference from both the high and medium rate users is cancelled. With the extended GSIC receiver, the performances of the different groups move closer to each other, and the impact of the inherent near-far effect caused by the VSF multirate scheme has been removed. The extended GSIC structure with one PIC stage results in further improvement due to removal of the intragroup interference. Addition of a second PIC stage did not appear to result in significant performance improvement, especially not in the Rayleigh fading channel.

All types of GSIC receivers are robust against delay error of 0.1 of a chip interval. However, a delay error of 0.3 of a chip interval and more results in significant degradation of performance of the GSIC receiver with one or two PIC stages, which almost lost its performance advantage compared to the basic and extended GSIC receiver with matched filter within the groups.

The complexity of the 2 stage PIC receiver and the extended GSIC receiver with one PIC stage are fairly similar. However, the performance of the GSIC receiver appears to be better and thus, considering the performance and complexity trade-off, the extended GSIC receiver with one PIC stage is more desirable structure.

REFERENCES


Chapter 7
Multirate Weighted PIC

The multirate weighted PIC (MW-PIC) structure described in Chapter 3 cancels the MAI partially by applying weighting on the MAI estimate. In the normal PIC receiver, an interference estimate can be very poor, so instead of clearing the signal from interference, interference may be added to the received signal. Instead of attempting full cancellation, the estimated interference can be partially cancelled by applying weighting factors [1–4]. In this chapter, the performance of the weighted multirate PIC is studied using Monte-Carlo simulations. Especially the impact of different weighting factors in a VSF CDMA system is studied both in AWGN and fading channels.

In Section 7.1, a system model for the weighted multirate PIC is presented. Performance in AWGN and fading channels is studied in Sections 7.2 and 7.3, respectively. Conclusions are presented in Section 7.4.

7.1 SYSTEM MODEL

This section presents the system model for the multirate weighted PIC receiver. The same notation as in the previous chapters is used. Figure 7.1 depicts the structure of the jth stage of the weighted PIC receiver. The interference-cancelled output of the jth stage in the weighted PIC receiver can be written as [2]

\[ \hat{h}(j) = W_j (h - \hat{\nu}(j)) + (I - W_j) \hat{h}(j-1), \quad (7.1) \]

where the interference estimate \( \hat{\nu}(j) \) used by the jth stage is based on the decisions of the previous stage j-1 and may be written in the form

\[ \hat{\nu}(j) = (R - I)CA\hat{h}(j-1). \quad (7.2) \]

The diagonal matrix \( W_j \) \((j=1, \ldots, J)\) defines the amount of cancellation used at the jth stage. The elements of the matrix may vary from symbol to symbol and have values ranging from zero (no cancellation) to one (full cancellation).

A closer examination of the weighted PIC receiver reveals that the outputs of the first stage (7.3) and second stage (7.4) are:

\[ \hat{y}(l) = W_l (h - \hat{\nu}(l)) + (I - W_l) y = y - W_l \hat{\nu}(l) \quad (7.3) \]

and
\[ \hat{y}(2) = y - W_1 \hat{p}(1) - W_2 (\hat{p}(2) - W_1 \hat{p}(1)) = \hat{h}(1) - W_2 (\hat{p}(2) - W_1 \hat{p}(1)). \]  

Figure 7.1  Stage \( j \) of a weighted PIC receiver.

Thus, each interference cancellation stage removes from the output of the previous stage an amount of interference, which is obtained as a difference between the new interference estimate and the interference which the previous stages have already
cancelled. If the weight matrices are identity matrices, the WPIC scheme reduces to a PIC scheme.

The received power of a signal determines the quality of the MAI estimate. A high power signal will have a better MAI estimate than a signal with less power. In a multirate environment, signal powers with different data rates are different. For this reason the weighting factors could be chosen in a groupwise way. This means that all users with the same data rate, thus with the same power, will have the same weighting factor. This receiver structure is termed multirate weighted PIC.

The weights can be optimised in different ways. A general rule is that the more unreliable the decision is, the smaller the weight. The performance improvement depends on the spreading factors and number of users. Earlier studies of single rate system have shown that the higher the near-far ratio, the smaller the improvement due to weighting [1]. This is because a large amount of MAI is caused by the interference from the high rate user, which already has good reliability.

7.2 PERFORMANCE IN THE AWGN CHANNEL

In this section, the performance of the MW-PIC receiver is studied in the AWGN channel. First, the same weighting factor is applied to all users regardless of their group. Then, different weighting factors are applied to different groups. The same simulation scenario as in Chapter 4 is investigated.

7.2.1 Simulation Assumptions

Table 7.2 lists the main simulation assumptions. Processing gains are 32, 16 and 8 and the numbers of users are 4, 4 and 2, respectively.

<table>
<thead>
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<th>Simulation parameters</th>
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<td>Channel estimation</td>
<td>Assumed known</td>
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7.2.2 Performance Results

Figure 7.2 shows performance of the weighted multirate PIC receiver as a function of weighting factor, i.e., the fraction of cancellation, averaged over all users. Weighting is applied only at the first cancellation stage. It can be seen that partial cancellation clearly improves the performance. For the 1-stage MW-PIC receiver optimum weighting factor at the first cancellation stage is 0.7 and for the 2-stage receiver 0.6.

Figure 7.3 shows the performances of the matched filter, PIC and MW-PIC receivers, respectively, as a function of the fraction of cancellation at the first cancellation stage for different data rates. The optimum performance is occurring with different weighting factors, depending on the data rate. From Figures 7.1 and 7.2 it can also be noted that with optimum weighting factor the 1-stage MW-PIC receiver achieves almost the same performance as the 2-stage standard PIC receiver.

![Graph showing performance of the matched filter, 1- and 2-stage MW-PIC receivers as a function of weighting factor in AWGN channel averaged over all users.](image-url)
Figure 7.3. Performance of the matched filter, 1- and 2-stage MW-PIC receivers in an AWGN channel for different data rates. Circles = low rate users, triangles = medium rate users, stars = high bit rate users.

Figure 7.4 shows performance of the matched filter, 2-stage PIC and 2-stage MW-PIC receiver as a function of $E_b/N_0$. It can be seen that low and medium rate users gain more in performance than the high rate users.

Figure 7.4 Performance of the PIC and MW-PIC receiver with a weighting factor of 0.6 in an AWGN channel. Circles = low rate users, triangles = medium rate users, stars = high bit rate users.
7.2.3 Different Weighting Factors for Different Processing Gains

In this section, the impact of different weighting factors for different processing gains on the system performance is studied. As was analysed in Chapter 4, different processing gains have different reliability. Therefore, one could expect that performance improves by applying different weighting factors for users in different groups. The processing gains in the studied system are 32, 16 and 8, and the corresponding number of users is 4, 4 and 2.

The starting point is the weighting factor producing best result in the previous section. The weighting factors are varied around this value to see their impact on the performance of different groups. First, the weighting factor of low rate users is reduced to 0.4, since the corresponding symbol estimates are expected to be less reliable, whereas weighting factor for high rate user is increased to 0.8. As can be seen from Figure 7.5 this results in slightly improved performance for low rate users, but no change in the performance of medium and high rate users.

Next, the weighting factor for high rate users is further increased into 1.0 (i.e., full cancellation) and the weighting factor for low rate users is reduced into 0.2. For medium rate users, the weighting factor is kept at 0.6. As can be seen from Figure 7.6 the performance is worse compared to previous case.

Optimisation the weights according to spreading factors seems to have only minor impact on the performance. More studies are required to quantify the impact of different weighting factors on the performance using different sets of processing gains and number of users.

![Performance of the MW-PIC as a function of $E_b/N_0$ in the AWGN channel for different data rates. The weighting factor for high rate users is 0.8, for medium rate users 0.6, and for low rate users 0.4.](image)

Figure 7.5 Performance of the MW-PIC as a function of $E_b/N_0$ in the AWGN channel for different data rates. The weighting factor for high rate users is 0.8, for medium rate users 0.6, and for low rate users 0.4.
Figure 7.6 Performance of MW-PIC as a function of $E_b/N_0$ in the AWGN channel for different data rates. The weighting factor for high rate users is 1.0, for medium rate users 0.6, and for low rate users 0.2.

### 7.3 PERFORMANCE IN THE FADING CHANNEL

In this section, the performance of MW-PIC in fading channels is investigated. Performance of the MW-PIC receiver is compared to the standard PIC receiver.

#### 7.3.1 Simulation Assumptions

Table 7.2 lists the simulation assumptions. A similar multirate scenario as for the AWGN channel is used. Processing gains are 32, 16 and 8, and the corresponding number of users is 4, 4 and 2. One and two path fading channels are studied. In the two-path channel the energy is equally divided between the two propagation paths. The mobile terminal speed is 80 km/h. The channel model was described in Section 2.1.3.
Table 7.2
Simulation parameters

<table>
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<th>Transmission mode</th>
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<td>Spreading modulation</td>
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<td>2-path channel</td>
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<td>Mobile speed</td>
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<tr>
<td>Samples per chip</td>
<td>4</td>
</tr>
<tr>
<td>Channel estimation</td>
<td>Assumed known</td>
</tr>
</tbody>
</table>

7.3.2 Performance Results

Figures 7.7 and 7.8 show the performance of the MF, and 1- and 2-stage MW-PIC receivers in a 1-path fading channel and Figures 7.9 and 7.10 in a 2-path fading channel as a function of the weighting factor (i.e., fraction of cancellation). $E_b/N_0$ is 8 dB in all simulations. As can be seen from Figures 7.7 and 7.8 full cancellation gives the best result in a 1-path channel. Furthermore, the 2-stage PIC receiver gives only slight improvement over the 1-stage PIC receiver.
Figure 7.7  Performance in an 1-path channel as a function of weighting factor averaged over all users. Circles = low rate users, triangles = medium rate users, stars = high bit rate users.

Figure 7.8  Performance in an 1-path channel average over all users as a function of weighting factor for different data rates. Circles = low rate users, triangles = medium rate users, stars = high bit rate users.
The performance of weighted PIC receiver in the 2-path channel are shown in Figures 7.8 and 7.9. Similar results to the 1-path channel are obtained. From Figure 7.9 it can also be seen that the performance of the 1-stage PIC is equal to the 2-stage PIC.

Figure 7.9 Performance of the MF and MW-PIC receivers as a function of weighting factor in a 2-path fading channel averaged over all users. Circles = low rate users, triangles =medium rate users, stars = high bit rate users.

Figure 7.10 Performance of the MF, and MW-PIC receivers as a function of weighting factor in a 2-path fading channel for different data rates. Circles = low rate users, triangles =medium rate users, stars = high bit rate users.
Figures 7.11 and 7.12 show the performance of the matched filter, PIC and MW-PIC receivers as a function of $E_b/N_0$ in a 2-path fading channel averaged over all users and for different data rates, respectively. The performance difference between the MW-PIC using a weighting factor of 0.7 and the standard PIC receiver is the same over the range of $E_b/N_0$ values considered here.

Figure 7.11  Performance of the MF, PIC and MW-PIC receivers as a function of $E_b/N_0$ in a 2-path fading channel averaged over all users. Circles = PIC, stars = MW-PIC, squares = MF.

7.4 CONCLUSIONS

The performance of the MW-PIC receiver has been studied for a VSF CDMA system with three different processing gains in AWGN and fading channels. The impact of different weighting factors, i.e., fraction of multiple access interference cancellation, on the performance has been investigated. In the AWGN channel, partial cancellation of the MAI clearly improves the performance. Applying different weighting factors for different processing gains (i.e., data rates) appears to improve the performance of low rate data users slightly compared to equal weighting of all groups.

In a fading channel weighting does not result in performance improvement. This is because the RAKE receiver weights the signal according to signal-to-noise ratio and thus a weak signal is not contributing to the decision as much as strong signals. Thus, RAKE receiver performs weighting implicitly in the receiver, and therefore further weighting apparently does not improve performance.
Figure 7.12  Performance of MF, PIC and MW-PIC in 2-path fading channel as a function of $E_b/N_0$ for different data rates. Circles = low rate users, triangles = medium rate users, stars = high bit rate users.

REFERENCES


Chapter 8

Conclusions

Multirate multiuser detection receivers for future wideband CDMA systems for mobile use have been considered in this thesis. This research has presented and discussed new types of multiuser receivers, which are believed to lead to practical receiver designs for third generation wideband CDMA systems. Special attention has been paid to the multirate environment. Multiuser receiver structures for the variable spreading factor (VSF) CDMA system were presented and their performance evaluated in different channels. In the presence of delay estimation errors, different data rates were noticed to have equal degradation as the delay error increased for the PIC and GSIC receivers. The weighted PIC receiver improved the performance in the AWGN channel but not in fading channel. The GSIC receiver structure was noted to perform well in both types of channels and is recommended for further study.

8.1 SUMMARY OF RESULTS AND DISCUSSION

In the introductory chapter, classification of CDMA and development of CDMA techniques was presented. Third generation wideband CDMA systems were reviewed.

Chapter 2 presented a survey of multiuser detectors for direct-sequence CDMA systems. System model for multirate CDMA systems was presented. Different multiuser detection algorithms were reviewed. An extensive literature review of multiuser detection related to the topic of the thesis was presented. Based on the review it was concluded that comprehensive evaluation of MUD schemes including impact of imperfect parameter estimation, multirate aspects, channel coding, complexity and multicell environment had so far not been performed.

In Chapter 3, a qualitative comparison of MUD receiver types was presented. Comparison criteria were derived, based on evaluation of the expected third generation wideband CDMA system characteristics. Decorrelator, MMSE, PIC and SIC receivers were compared with respect to performance in both AWGN and Rayleigh fading channels, as well as with phase and delay errors, with the near-far effect and with power control. The regenerative receiver structures performing the interference cancellation at CDMA chip level were assessed to be most suitable for a wideband system with long spreading codes. Since weighting has been noticed to improve the system performance, a novel multiuser detection structure was proposed, entitled multirate weighted PIC, which is suitable for variable spreading factor multirate DS-CDMA. The multirate weighted PIC cancels the interference at the first stage only partially based on the data rate. For users with higher data rate more interference is cancelled since their detection is more reliable. In addition, groupwise successive interference cancellation structures were
proposed as an alternative method to improve the system performance. In the GSIC scheme, signals belonging to the same user group are detected together, whereas signals from different groups are detected in a serial manner.

Chapter 4 presented an analysis of a multirate DS-CDMA system. First, five different performance approximation techniques (namely, standard, improved, simplified improved and accurate Gaussian approximations) were reviewed. The accurate Gaussian approximation was selected to be used in the further analysis due to its combination of simplicity and accuracy. Second, analysis of a VSF system was presented. It was shown that the higher the data rate the better the performance. This is because the interference is the total interference reduced by the amount of interference generated by the desired user. A high bit rate user generates the highest amount of interference and consequently has the best performance. The results motivate the use of novel groupwise serial interference cancellation methods, which exploit the characteristics of multirate system. In addition, results of an analytical comparison of VSF and multicode DS-CDMA systems were presented, showing equal performance.

The performance of the PIC receiver in multirate CDMA system in AWGN and fading channels was studied in Chapter 5. Similar to a single rate system the PIC receiver improves the performance of the system by an order of magnitude and also removes the near-far effect in a VSF system with moderate processing gain differences. The PIC receiver was observed to be robust against delay estimation errors also in a VSF system, and all data rates suffer equal degradation as a function of increasing delay error.

In Chapter 6, groupwise multiuser detectors were studied. Different groupwise receiver structures (a basic GSIC receiver, an extended GSIC receiver and an extended GSIC with additional PIC stages with groups) were introduced. Their performance was simulated in AWGN and fading channels, and with delay estimation errors. The basic GSIC structure improves only the performance of medium and low rate users while the high rate users' performance remains the same as for the matched filter. The extended GSIC receiver with matched filters within the groups removes the impact of the inherent near-far effect caused by the variable spreading factor multirate scheme. The extended GSIC structure with one PIC stage resulted in a further improvement, due to removal of intragroup interference. Adding a second PIC stage does not result in significant performance improvement, especially not in Rayleigh fading channels. Both the basic GSIC and the most complex receiver structure GSIC with 2 PIC stages were robust against delay estimation error of up to 0.1 of a chip interval; thereafter the performance degrades rapidly. In addition, complexity and performance comparison of the matched filter, PIC and GSIC receivers was performed. The extended GSIC receiver with one PIC stage within the groups was found to be a good compromise from the complexity and performance point of views.

In Chapter 3, a novel receiver structure, the multirate weighted PIC, was introduced. In Chapter 7, its performance was simulated in AWGN and fading channels. It was shown that weighting, i.e., partial cancellation, improves performance of the PIC receiver in variable spreading factor system in an AWGN channel but not in a fading channel. This is because RAKE receiver weights the signal according to signal-to-noise ratio and thus a weak signal is not contributing to the decision as much as strong signals.
Apparently, it performs a kind of weighting already implicitly in the RAKE receiver and thus further weighting hardly improves performance.

8.2 FUTURE WORK

The research of this thesis leads naturally to several extensions. These include considerations of more realistic channel models, more realistic multirate environments, multicell environments, and the impact of imperfect channel estimation, and development of delay estimation and complex channel coefficient estimation methods.

A limited set of different spreading factors was used in the evaluation of the PIC and GSIC receivers. In future studies, larger sets of different spreading factors should be considered. Also the multicode scheme should be studied in order to find out how suitable the developed receiver structures are for this scheme.

In order to see the benefit of advanced receiver techniques in practical CDMA systems, more realistic system design scenarios should be considered. The evaluation of the multiuser detection receivers has been performed in a single cell scenario; further work should also consider multicell scenarios. Power control will be a crucial part of third generation CDMA system, and must be included into any multicell study in order to obtain realistic results.

In these studies rather simple (one and two path fading) channel models were used. Further studies should consider also more realistic multipath channels.

It is known that the estimation of the complex channel gain is very crucial for the multiuser detection receiver. In this thesis, the channel estimates were assumed to be known. Future studies should concentrate on the impact of imperfect channel estimation on the performance of the multirate multiuser detectors. Furthermore, attention must be paid on finding and designing reliable channel estimators in the presence of fading. In addition to the channel gain estimation, accurate delay estimation is usually also needed in the interference cancellation receivers.

It was found that static weighting in the PIC receiver did not improve the performance in a fading channel. Therefore, dynamic weighting on a symbol-by-symbol basis should be studied. Weighting could be applied also on other receiver structures, e.g., on the GSIC receiver.
Appendix A

Previous Work by the Author Related to this Thesis

A.1 LIST OF PUBLICATIONS


This thesis is based, in part, on the previously published results listed above. The following table provides a good overview of the major and minor relations between these publications and the individual chapters of this thesis.

Table A.1
Relations between the publications and the chapters of this thesis. • = major relation, O = minor relation.

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A.2 CONTRIBUTIONS BY OTHERS

The author has participated in supervision of several students from Delft University of Technology who have made relevant contributions to the thesis. The contributions by students are listed below.

- Chapter 4: The new approximation, Accurate Gaussian Approximation (AGA), for bit error probability performance analysis of DS-CDMA system, was developed by the student Marten Klok. In addition, he produced the numerical results under guidance of the author.

- Chapter 5: The simulation program was extended into multirate system by students Jami Alam and Carl Wijting. Jami Alam performed the numerical simulations for the PIC receiver in the AWGN channel. Student Said Arrass performed the simulations for the fading channel.

- Chapter 6: The groupwise multiuser detector structures used in the simulation program were implemented and simulated by Carl Wijting. Simulations were also performed by Said Arrass.

- Chapter 7: The weighted PIC structure was implemented and simulated by student Alwin van Meeteren.
Curriculum Vitae

Tero Ojanperä was born in Korsnäs, Finland, on November 12, 1966. He received his M.Sc. degree from the University of Oulu, Finland, in 1991. He joined Nokia Mobile Phones, Oulu, Finland, in 1990 and worked as a research engineer from 1991 to 1992. From 1992 to 1995, he led a radio systems research group concentrating on wideband CDMA, GSM wireless local loop, and US TDMA. From 1994 to 1995, he was also a project manager of the wideband CDMA concept development within Nokia. Later, this concept formed the basis for the FRAMES Wideband CDMA.

From 1995 to 1997, he was a research manager in Nokia Research Center, Helsinki, Finland, heading Nokia’s third generation air interface research program, consisting of several air interface projects such as wideband CDMA, packet data, radio resource management algorithms, OFDM, and wideband TDMA. He was actively involved setting up the FRAMES project and during 1995-1996, he was also leader of the technical area air interface and the multiple access work package in the project, responsible for the selection of the FRAMES Multiple Access (FMA) scheme. The FRAMES Wideband CDMA was the basis for the UMTS WCDMA concept in ETSI. From 1994 to 1997, he was a Nokia representative for the UMTS radio interface issues in the ETSI standardisation committees SMG5 and SMG2.

From August 1997 to August 1998, he worked as a principal engineer in Nokia Research Center, Irving, TX. His was involved in the US third generation standards activities for the cdma2000. In addition, he was involved in technical/strategic work for Nokia’s proposal for the UWC-136 standard.

In September 1998, he joined Nokia Telecommunications (now renamed as Nokia Networks), Finland, as a Head of Research, Radio Access Systems. In July 1999 he was promoted to Vice President, Radio Access Systems Research. In addition, he is currently General Manager, Nokia Telecommunications, Korea.


Mr. Ojanperä is a member of the IEEE, and during 1996 he was secretary of the IEEE Finland Section. He was a member of the Technical Program Committee of IEEE’s Vehicular Technology Conference 1999 in Amsterdam and holds a Vice Chair of the IEEE ICC’2001 Conference. He is member of the Board in the Center for Wireless Communications, University of Oulu, Finland.