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VITERBI DECODED LINEAR BLOCK CODES FOR NARROWBAND AND WIDEBAND WIRELESS COMMUNICATION OVER MOBILE FADING CHANNELS

By
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Submitted in partial fulfilment of the requirements for the degree
Master of Engineering (Electronic)
in the
Department of Electrical, Electronic and Computer Engineering
of the
Faculty of Engineering, Built Environment and Information Technology
at the
UNIVERSITY OF PRETORIA

Promoter: Professor L.P. Linde

July 2005

University of Pretoria etd – Staphorst, L (2005)

SUMMARY

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SINCE the frantic race towards the Shannon bound [1] commenced in the early 1950's, linear block codes have become integral components of most digital communication systems. Both binary and non-binary linear block codes have proven themselves as formidable adversaries against the impediments presented by wireless communication channels. However, prior to the landmark 1974 paper [2] by *Bahl et al.* on the optimal *Maximum a-Posteriori Probability* (MAP) trellis decoding of linear block codes, practical linear block code decoding schemes were not only based on suboptimal hard decision algorithms, but also code-specific in most instances. In 1978 *Wolf* expedited the work of *Bahl et al.* by demonstrating the applicability of a block-wise *Viterbi Algorithm* (VA) to *Bahl-Cocke-Jelinek-Raviv* (BCJR) trellis structures as a generic optimal soft decision *Maximum-Likelihood* (ML) trellis decoding solution for linear block codes [3].

This study, largely motivated by code implementers' ongoing search for generic linear block code decoding algorithms, builds on the foundations established by *Bahl*, *Wolf* and other contributing researchers by thoroughly evaluating the VA decoding of popular binary and non-binary linear block codes on realistic narrowband and wideband digital communication platforms in lifelike mobile environments. Ideally, generic linear block code decoding algorithms must not only be modest in terms of computational complexity, but they must also be channel aware. Such universal algorithms will undoubtedly be integrated into most channel coding subsystems that adapt to changing mobile channel conditions, such as the adaptive channel coding schemes of current *Enhanced Data Rates for GSM Evolution* (EDGE), 3$^{\text{rd}}$ *Generation* (3G) and *Beyond 3G* (B3G) systems, as well as future 4$^{\text{th}}$ *Generation* (4G) systems. In this study classic BCJR linear block code trellis construction is annotated and applied to contemporary binary and non-binary linear block codes. Since BCJR trellis structures are inherently sizable and intricate, rudimentary trellis complexity calculation and reduction algorithms are also presented and demonstrated. The block-wise VA for BCJR trellis structures, initially introduced by *Wolf* in [3], is revisited and improved to incorporate *Channel State Information* (CSI) during its ML decoding efforts.

In order to accurately appraise the *Bit-Error-Rate* (BER) performances of VA decoded linear block codes in authentic wireless communication environments, *Additive White Gaussian Noise* (AWGN), flat fading and multi-user multipath fading simulation platforms were constructed. Included in this task was the development of baseband complex flat and multipath fading channel simulator models, capable of reproducing the physical attributes of realistic mobile fading channels. Furthermore, a complex *Quadrature Phase Shift Keying* (QPSK) system were employed as the narrowband communication link of choice for the AWGN and flat fading channel performance evaluation platforms. The versatile B3G multi-user multipath fading simulation platform, however, was constructed using a wideband RAKE receiver-based complex *Direct Sequence Spread Spectrum Multiple Access* (DS/SSMA) communication system that supports unfiltered and filtered *Complex Spreading Sequence*s (CSS). This wideband platform is not only capable of analysing the influence of frequency selective fading on the BER performances of VA decoded linear block codes, but also the influence of the *Multi-User Interference* (MUI) created by other users active in the *Code Division Multiple Access* (CDMA) system. CSS families considered during this study include *Zadoff-Chu* (ZC) [4, 5], *Quadriphase* (QPH) [6], *Double Sideband* (DSB) *Constant Envelope Linearly Interpolated Root-of-Unity* (CE-LI-RU) filtered *Generalised Chirp-like* (GCL) [4, 7–9] and *Analytical Bandlimited Complex* (ABC) [7, 10] sequences.

Numerous simulated BER performance curves, obtained using the AWGN, flat fading and multi-user multipath fading channel performance evaluation platforms, are presented in this study for various important binary and non-binary linear block code classes, all decoded using the VA. Binary linear block codes examined include Hamming and *Bose-Chaudhuri-Hocquenghem* (BCH) codes, whereas popular burst error correcting non-binary *Reed-Solomon* (RS) codes receive special attention. Furthermore, a simple cyclic binary linear block code is used to validate the viability of employing the reduced trellis structures produced by the proposed trellis complexity reduction algorithm. The simulated BER performance results shed light on the error correction capabilities of these VA decoded linear block codes when influenced by detrimental channel effects, including AWGN, Doppler spreading, diminished *Line-of-Sight* (LOS) signal strength, multipath propagation and MUI. It also investigates the impact of other pertinent communication system configuration alternatives, including channel interleaving, code puncturing, the quality of the CSI available during VA decoding, RAKE diversity combining approaches and CSS correlation characteristics. From these simulated results it can not only be gathered that the VA is an effective generic optimal soft input ML decoder for both binary and non-binary linear block codes, but also that the inclusion of CSI during VA metric calculations can fortify the BER performances of such codes beyond that attainable by classic ML decoding algorithms.

Keywords, phrases and acronyms: 3G, 4G, adaptive channel coding, AWGN, B3G, BCH code, BCJR trellis, BER, CDMA, code puncturing, CSI, CSS, DS/SSMA, EDGE, flat fading, Hamming code, hard decision decoding, channel interleaving, linear block code, MAP decoding, ML decoding, MUI, multipath fading, QPSK, RAKE, RS code, Shannon bound, soft decision decoding, VA

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SAMEVATTING

VITERBI GEDEKODEERDE LINEÊRE BLOKKODES VIR NOUEBAND EN WYEBAND
KOMMUNIKASIE OOR MOBIELE DEINENDE KANALE
deur
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SEDERT die verwoede resies na die Shannon-grens [1] in die vroeë 1950's aanvang geneem het, het lineêre blokkodes integrale komponente van meeste digitale kommunikasiestelsels geword. Beide binêre en nie-binêre lineêre blokkodes het hulself bewys as gedugte teenstanders teen die belemmeringe wat draadlose kommunikasiekanale bied. Voor die mylpaal 1974 artikel [2] deur *Bahl et al.* oor die optimale *Maksimum a-Posteriori Waarskeinlikheid* (MAW) trellisdekodering van lineêre blokkodes, was praktiese lineêre blokkode dekoderingskemas egter nie net gebaseer op suboptimale harde beslissingsalgoritmes nie, maar ook kode-spesifiek in meeste gevalle. In 1978 het *Wolf* die werk van *Bahl et al.* aangehelp deur die toepasbaarheid van 'n bloktipe *Viterbi Algoritme* (VA) op *Bahl-Cocke-Jelinek-Raviv* (BCJR) trellisstrukture as 'n generiese optimale sagte beslissing *Maksimum Waarskeinlikheid* (MW) trellis dekoderingsoplossing vir lineêre blokkodes te demonstreer [3].

Hierdie studie, hoofsaaklik gemotiveer deur kode-implementeerders se voortdurende soeke na generiese lineêre blokkode dekoderingalgoritmes, bou op die fondasies wat deur *Bahl*, *Wolf* en ander bydraende navorsers gevestig is, deur die VA dekodering van gewilde binêre en nie-binêre lineêre blokkodes op realistiese noueband en wyeband digitale kommunikasieplatforms in lewenstroue mobiele omgewings deeglik te evalueer. Generiese lineêre blokkode dekoderingalgoritmes moet ideaal nie net beskeie wees in terme van bewerkingkompleksiteit nie, maar moet ook kanaal-bewus wees. Sulke universele algoritmes sal ongetwyfeld geïntegreer word in meeste kanaalkodering substelsels wat aanpas tot veranderende mobile kanaaltoestande, soos die aanpasbare kanaalkoderingskemas van huidige *Enhanced Data Rates for GSM Evolution* (EDGE), 3$^{\text{de}}$ *Generasie* (3G) en *Bokant* 3$^{\text{de}}$ *Generasie* (B3G) stelsels, asook toekomstige 4$^{\text{de}}$ *Generasie* (4G) stelsels. In hierdie studie word klasieke BCJR trelliskonstruksie verduidelik en toegepas op hedendaagse binêre en nie-binêre lineêre blokkodes. Aangesien BCJR trellisstrukture inherent groot en ingewikkeld is, word elementêre trelliskompleksiteit berekening- en verminderingalgoritmes ook voorgestel en gedemonstreer. Die bloktipe VA vir BCJR trellisstrukture, oorspronklike voorgestel deur *Wolf* in [3], word heroorweeg en verbeter om *Kanaaltoestand Informasie* (KTI) te inkorporeer gedurende sy MW dekoderingspogings.

Om die *Bisfout Tempo* (BFT) werkverrigting van VA gedekodeerde lineêre blokkodes in outentieke draadloses kommunikasieomgewings akkuraat te waardeer, was *Sommeerbare Wit Gaussiese Ruis* (SWGR), plat deining en multi-gebruiker multipad deining simulasieplatforms geskep. Ingesluit in hierdie taak was die ontwikkeling van komplekse basisband plat en multipad deinende kanaal simulatormodelle, wat instaat is om die fisiese eienskappe van realistiese mobiele deinende kanale te herproduseer. Verder was ’n komplekse *Kwadratuur Faseskuif Sleuteling* (KFSS) stelsel gebruik as die gekose nouband kommunikasieskakel vir die SWGR en plat deinende kanaal werkverrigting evaluasieplatforms. Die veelsydige B3G multi-gebruiker multipad deinende simulasieplatform was egter saamgestel deur gebruik te maak van ’n RAKE ontvanger gebaseerde komplekse wyeband *Direkte Sekwensie Spreispektrum Veelvuldige Toegang* (DS/SSVT) kommunikasiestelsel wat ongefilterde en gefilterde *Komplekse Spreisekwensie*s (KSS) ondersteun. Hierdie wyeband platform is nie net instaat om die invloed van frekwensie selektiewe deining op die BFT werkverrigting van VA gedekodeerde lineêre blokkodes te analiseer nie, maar so ook die invloed van die *Multi-gebruiker Steuring* (MGS) geskep deur die ander gebruikers wat aktief in die *Kode Divisie Veelvuldige Toegang* (KDVT) stelsel is. KSS families wat oorweeg is in hierdie studie sluit in *Zadoff-Chu* (ZC) [4,5], *Kwadratuur Fasige* (KF) [6], *Dubbele Syband* (DSB) *Konstante Omhulling Lineêr Geïnterpoleerde Eenheidswortel* (KO-LGI-EW) gefilterde *Algemene Tjirp-agtige* (ATA) [4,7,8] en *Analitiese Bandbeperkte Komplekse* (ABK) [7,10] sekwensies.

Talryke gesimuleerde BFT werkverrigtingkurwes, verkry deur van die SWGR, plat deining en multi-gebruiker multipad deining werkverrigting evaluasieplatforms gebruik te maak, word in hierdie studie voorgelê vir verskeie belangrike binêre en nie-binêre lineêre blokkode klasse, almal gedekodeer deur van die VA gebruik te maak. Binêre lineêre blokkodes wat ondersoek is, sluit in Hamming en *Bose-Chaudhuri-Hocquenghem* (BCH) kodes, terwyl gewilde sarsiefout korrigerende nie-binêre *Reed-Solomon* (RS) kodes spesiale aandag ontvang. Verder word ’n eenvoudige sikliese binêre lineêre blokkode gebruik om die lewensvatbaarheid van die gebruik van die vereenvoudigde trellisstrukture, geproduseer deur die voorgestelde trellis kompleksiteit verminderingsalgoritme, te bekragtig. Die gesimuleerde BFT werkverrigtingresultate werp lig op die foutkorreksie vermoëns van hierdie VA gedekodeerde lineêre blokkodes wanneer hulle beïnvloed word deur nadelige kanaaleffekte, insluitend SWGR, Doppler spreiding, verminderde *Lyn-van-Sig* (LVS) seinsterkte, multipad voortplanting en MGS. Dit ondersoek ook die impak van ander toepaslike kommunikasiestelsel konfigurasie-alternatiewe, insluitend kanaalintervlegging, kodeperforasie, die kwaliteit van die KTI beskikbaar gedurende VA dekodering, RAKE diversiteit samevoegingsbenaderings en KSS korrelasie karakteristieke. Vanuit hierdie gesimuleerde resultate kan dit nie net afgelei word dat die VA ’n effektiewe generiese optimale sagte inset MW dekodeerder is vir beide binêre en nie-binêre lineêre blokkodes nie, maar ook dat die insluiting van KTI gedurende VA metriekberekeninge die BFT werkverrigtinge van sulke kodes kan verbeter bo dit wat haalbaar is deur klassieke MW dekoderingsalgoritmes.

Sleutelwoorde, frases en akronieme: 3G, 4G, aanpasbare kanaalkodering, B3G, BCH kode, BCJR trellis, BFT, DS/SSVT, EDGE, Hamming kode, harde beslissingsdekodering, kanaalintervlegging, KDVT, KFSS, kodeperforasie, KTI, KSS, lineêre blokkode, MAW dekodering, MGS, multipad deining, MW dekodering, plat deining, RAKE, RS kode, sagte beslissingsdekodering, Shannon-grens, SWGR, VA

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This dissertation is dedicated to:

God Almighty, for blessing me with many talents, and granting me countless opportunities to use them;
My loving family and friends, whose continuous support and encouragement carried me through the arduous times.

* * *

”The next best thing to a good education, is a pushy mother.”

M.P. Staphorst

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ACKNOWLEDGMENTS

I wish to extend my heartfelt gratitude to the following people and institutions who supported this study in one way or another:

First and foremost, my appreciation and thanks go to my parents, my aunt Joey and my sister Ronell. Their enduring love, support and encouragement were indispensable driving forces, especially during the gruelling times when completion of this study seemed like an unsurmountable task. A special mention goes to my mother for the time and effort she vested in proofreading this document.

I am especially grateful to my study leader and promotor, Prof. L.P. Linde, for his continued latitude, support and guidance during this study. To my informal signal processing and digital communication mentors, Jacques Cilliers and Danie van Wyk, I wish to extend this same gratitude.

My thanks goes to my fellow engineering friends Stefan Swanepoel, Jacques van Wyk, Ben Waldeck, Werner Büttner, Pieter de Villiers, Momin Jamil, Fernando Camisani-Calzolari, Pieter-Jan Vlok and Christian Bruwer, with whom I shared many insightful and intellectual discussions on our respective postgraduate projects. These discussions fuelled much of my motivation for this study.

Credit goes to the *University of Pretoria* and the *National Research Foundation* for the financial sponsorship of my Masters degree studies through personnel and prestigious postgraduate bursaries, respectively. Furthermore, I am indebted to *Intel* for their donation of the *I-percube* high performance computing cluster, as well as Paul Greeff, Jan Gütter and Simeon Miteff for their invaluable support in the usage thereof.

Last, but definitely not least, my thanks and gratitude go to my best friend and companion, Betsie van der Westhuizen. Her love, patience and fantastic cooking carried me during the last few difficult months leading to the conclusion of this study. I will always be indebted to her for not only sacrificing her time and social life to stand by my side, but also listening to countless, monotonous explanations on the work that I was doing.

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LIST OF ABBREVIATIONS

2G	2^{nd} Generation
3G	3^{rd} Generation
4G	4^{th} Generation
ABC	Analytical Bandlimited Complex
AC	Alternating Current
ADC	Analogue-to-Digital Converter
ASIC	Application Specific Integrated Circuit
ATM	Asynchronous Transfer Mode
AWGN	Additive White Gaussian Noise
B3G	Beyond 3G
BCH	Bose-Chaudhuri-Hocquenghem
BCJR	Bahl-Cocke-Jelinek-Raviv
BEF	Bandwidth Expansion Factor
BER	Bit-Error-Rate
BPSK	Binary Phase Shift Keying
BSC	Binary Symmetric Channel
CC	Constituent Code
CD	Compact Disc
CD-ROM	Compact Disc Read Only Memory
CDMA	Code Division Multiple Access
CE-LI-RU	Constant Envelope Linearly Interpolated Root-of-Unity
CLT	Central Limit Theorem
CSI	Channel State Information
CSS	Complex Spreading Sequence
DPC	Differential Phase Combining
DPSK	Differential Phase Shift Keying
DS/SSMA	Direct Sequence Spread Spectrum Multiple Access
DSB	Double Sideband
DSP	Digital Signal Processor
DSSS	Direct Sequence Spread Spectrum
ECC	Error Control Coding
EDGE	Enhanced Data Rates for GSM Evolution
EGC	Equal Gain Combining
FDMA	Frequency Division Multiple Access
FEC	Forward Error Correction
FFCS	Flat Fading Channel Simulator
FHSS	Frequency Hopping Spread Spectrum
FIR	Finite Impulse Response
FPGA	Field Programmable Gate Array
GA	Gaussian Approximation

GCL	Generalised Chirp-like
GNU	GNU is Not Unix
GPRS	General Packet Radio Service
GSM	Global System for Mobile Communication
HCC	Hybrid Concatenated Code
HEC	Header Error Control
HPC	High Performance Computing
IID	Independent Identically Distributed
IIR	Infinite Impulse Response
IOWEF	Input-Output Weight Enumerating Function
JPL	Jet Propulsion Labs
LDPC	Low Density Parity-Check Code
LLR	Log-Likelihood Ratio
LOS	Line-of-Sight
MA	Multiple Access
MAP	Maximum a-Posteriori Probability
MC	Multi-Carrier
MFCS	Multipath Fading Channel Simulator
ML	Maximum-Likelihood
MLC	Multi-Level Code
MLSE	Maximum Likelihood Sequence Estimation
MRC	Maximal Ratio Combining
MUI	Multi-User Interference
NASA	National Aeronautical and Space Association
NLOS	Non-Line-of-Sight
NSC	Non-Systematic Convolutional
OFDM	Orthogonal Frequency Division Multiplexing
OOP	Object Orientated Programming
OS	Operating System
OSI	Open Standards Interface
PCC	Parallel Concatenated Code
PCCC	Parallel Concatenated Convolutional Code
PDF	Probability Density Function
PG	Processing Gain
PHY	Physical
PN	Pseudo-Noise
PSAM	Pilot Symbol Assisted Modulation
PSD	Power Spectral Density
QPH	Quadriphase
QPSK	Quadrature Phase Shift Keying
QoS	Quality of Service
RF	Radio Frequency
RMS	Root-Mean-Square
ROM	Read Only Memory
RS	Reed-Solomon
RSC	Recursive Systematic Convolutional
RU	Root-of-Unity
SCC	Serial Concatenated Code
SCCC	Serial Concatenated Convolutional Code

SDMA	Spatial Division Multiple Access
SF	Spreading Factor
SISO	Soft-Input Soft-Output
SMS	Short Message Service
SNR	Signal-to-Noise Ratio
SOVA	Soft Output Viterbi Algorithm
SOVE	Soft Output Viterbi Equaliser
SS	Spread Spectrum
SSB	Single Sideband
SSLD	Spreading Sequence Length Diversity
STC	Space Time Code
TC	Turbo Code
TCM	Trellis Coded Modulation
TCP	Transmission Control Protocol
TDMA	Time Division Multiple Access
UMTS	Universal Mobile Telephony System
VA	Viterbi Algorithm
VHF	Very High Frequency
WEF	Weight Enumerating Function
WLL	Wireless Local Loop
ZC	Zadoff-Chu

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LIST OF IMPORTANT SYMBOLS

$\alpha_i(t)$	Instantaneous fading amplitude of the i^{th} multipath component
$\overline{\alpha}_m$	Vector of average fading amplitude values associated with $\overline{y}_m$
$\hat{\overline{\alpha}}_m$	Vector of estimates of the average fading amplitude values associated with $\overline{y}_m$
$AN(C)$	Number of active nodes in the expurgated trellis of linear block code C [nodes]
$A(W,Z)$	Input-Output weight enumerating function of a linear block code [code words]
$A_{w,h}$	Coefficients of a linear block code's input-output weight enumerating function [symbols]
B_C	Coherence bandwidth [Hz]
B_D	Maximum Doppler spread [Hz]
$\beta_i(t)$	Instantaneous amplitude of the i^{th} multipath component [V]
$\overline{\beta}_i$	Average amplitude of the i^{th} multipath component [V]
$b_i(t)$	i^{th} received multipath component [V]
$BM^{(j)}_{m,i,l}$	m^{th} decoded code word's branch metric associated with the j^{th} branch entering node (l,i) of a trellis
B_{sig}	Signal bandwidth [Hz]
CG^{hard}_{BC}	Asymptotic coding gain for a hard decision decoded linear block code [dB]
CG^{soft}_{BC}	Asymptotic coding gain for a soft decision decoded linear block code [dB]
CG^{hard}_{CC}	Asymptotic coding gain for a hard decision decoded convolutional code [dB]
CG^{soft}_{CC}	Asymptotic coding gain for a soft decision decoded convolutional code [dB]
$\overline{c}_m$	m^{th} vector of code word symbols [V]
$\hat{\overline{c}}_m$	Decoder estimate of the m^{th} vector of code word symbols [V]
$\overline{c}_m(D)$	m^{th} vector sequence of code bits generated by a binary convolutional code [V]
$c_m(p)$	m^{th} transmitted code word polynomial of a linear block code [V]
$CM_{m,i,l}$	m^{th} decoded code word's cumulative metric associated with the j^{th} branch leaving node (l,i) of a trellis
d_{free}	Minimum free distance of a convolutional code [bits]
$DF(z)$	Doppler spectral shaping infinite impulse response filter transfer function
$d_H\left(\overline{c}^1_m, \overline{c}^2_m\right)$	Hamming distance between vectors $\overline{c}^1_m$ and $\overline{c}^2_m$ [symbols]
$d_H\left(\overline{y}_{m,i}, \overline{u}^{(j)}_{i,l}\right)$	Hamming distance between vectors $\overline{y}_{m,i}$ and $\overline{u}^{(j)}_{i,l}$ [symbols]
$\overline{d}_m$	m^{th} vector of original message word symbols [V]
$\hat{\overline{d}}_m$	Decoder estimate of the m^{th} vector of original message word symbols [V]
$\overline{d}_m(D)$	m^{th} vector sequence of data bits entering a binary convolutional code [V]
d_{min}	Minimum Hamming distance of a linear block code [symbols]
$d_m(p)$	m^{th} message word polynomial of a linear block code [V]
E_b	Energy per uncoded data bit [J]
E_c	Energy per coded bit [J]
$e_m(p)$	m^{th} error word polynomial of a linear block code [V]
E_s	Energy per modulated symbol [J]

$\eta(t)$	Additive white Gaussian noise amplitude [V]
$\eth\left(\Pi\right)$	Interleaver fundamental permutation
$\eth\left(\Pi^{-1}\right)$	De-interleaver fundamental permutation
f	Frequency [Hz]
F	Interleaver width [symbols]
f_{bit}	Uncoded bit rate [b/s]
f_c	Carrier frequency [Hz]
f_{cut}	Filter cutoff frequency [Hz]
$f_{d,i}(t)$	Doppler frequency shift of the i^{th} multipath component [Hz]
f_{samp}	Sampling frequency [Hz]
$\gamma_{b,m,i}$	Signal to noise ratio per uncoded bit for the i^{th} bit of the m^{th} vector of bits
$\gamma_{c,m}$	Signal to noise ratio per code word for the m^{th} code word
$\Gamma_{m,i,a}$	Erasure value for the a^{th} bit in the i^{th} symbol of the m^{th} set of received code word symbols [V]
$\gamma_{s,m,i}$	Signal to noise ratio per modulated symbol for the i^{th} symbol of the m^{th} vector of channel symbols
G_{BC}	Generator matrix of a linear block code
$G_{CC}(D)$	Generator matrix of a binary convolutional code
$g_{BC}(p)$	Generator polynomial of a linear block code
$GF\left(2^{\xi}\right)$	Extended Galois field with 2^{ξ} elements
$g_{ip}(p)$	Irreducible polynomial
$G_{\pi}(D)$	Interleaver generator matrix
$G_{\pi^{-1}}(D)$	De-interleaver generator matrix
$h_{ave}(t)$	Fading amplitude averaging filter impulse response
H_{BC}	Linear block code parity check matrix
$h_b(\tau)$	Time-invariant baseband channel impulse response
$H_{CC}(D)$	Binary convolutional code's parity check matrix
$h_m^I(t)$	I-channel matched filter impulse response
$h_m^Q(t)$	Q-channel matched filter impulse response
$h_p^I(t)$	I-channel pulse shaping filter impulse response
$h_p^Q(t)$	Q-channel pulse shaping filter impulse response
$H_{Rx}(f)$	Receive filter frequency response
$h_{sqrt-Nyq}(t)$	Square-root Nyquist pulse shape
J	Interleaver depth [symbols]
k	Number of message word symbols processed per encoding instance [symbols]
k_{η}	Normal Gaussian distribution power scaling factor
K_i	Rician factor of the i^{th} multipath component
L	Number of discrete multipath components [paths]
λ	Wavelength [m]
$\Lambda(C)$	Dimension distribution of linear block code C
$\Lambda^{-1}(C)$	Inverse dimension distribution of linear block code C
$\ln\left(\text{Prob.}\left(\overline{y}_m \mid \hat{\overline{c}}_m\right)\right)$	Log-likelihood function of the conditional probability Prob. $\left(\overline{y}_m \mid \hat{\overline{c}}_m\right)$
$\max\left\{f_d(t)\right\}$	Maximum Doppler frequency [Hz]
M_{fam}	Spreading sequence family size [sequences]
M_{punct}	Puncturer period [bits]
M_{seq}	Spreading sequence length [chips]
M_{users}	Number of users in a CDMA system [users]
$\overline{\mu}^{in}(D)$	N-dimensional interleaver input vector sequence [V]
$\overline{\mu}_m^{in}$	m^{th} length-N interleaver input [V]

$\overline{\mu}^{out}(D)$	N-dimensional interleaver output vector sequence [V]
$\overline{\mu}_m^{out}$	m^{th} length-N interleaver output [V]
n	Number of code word symbols generated per encoding instance [symbols]
N	Interleaver length [symbols]
$NB(C)$	Number of branches in the expurgated trellis of linear block code C [branches]
N_0	Single-sided power spectral density of additive white Gaussian noise [W/Hz]
$\overline{o}_{i,l}^{(j)}$	Decoder output branch vector associated with the j^{th} branch entering node (l,i) of a trellis [V]
ω	Sliding window Viterbi algorithm window size [trellis sections]
$P_b(e)$	Bit error probability
P_{BSC}	Binary symmetric channel crossover probability
$\phi_i(t)$	Instantaneous phase of the i^{th} multipath component [rad]
PG	Processing gain [dB]
$\overline{\phi}_i$	Average phase of the i^{th} multipath component [rad]
$\Pi(i)$	Interleaver mapping function
$\Pi^{-1}(i)$	De-interleaver mapping function
$PM_{m,i,l}^{sur}$	m^{th} decoded code word's survivor path metric associated with the survivor path ending in node (l,i) of a trellis
$P_s(e)$	Symbol error rate
$P(\tau)$	Time-invariant power delay profile [W]
R_c	Code rate
$\rho(\eta(t))$	Additive white Gaussian noise amplitude probability density function
$\rho\left(\phi_i(t)\right)$	Probability density function of the phase of the i^{th} multipath component
$\rho\left(\varepsilon_i(t)\right)$	Probability density function of the envelope of the i^{th} multipath component
$r_m(t)$	m^{th} received signal [V]
R_p	Punctured code rate
$r_{m,filtered}^q(t)$	User-q's received signal after filtering [V]
$R_{S(t),S(t)}$	Periodic auto-correlation of the spreading sequence $S(t)$
$R_{S_1(t),S_2(t)}$	Periodic cross-correlation between spreading sequences $S_1(t)$ and $S_2(t)$
$SD_{b_i(t)}(f)$	Doppler spectrum of the i^{th} received multipath component [W/Hz]
$\sigma^2_{b_i^{LOS}(t)}$	Variance in the i^{th} multipath component's line-of-sight part [W]
$\sigma^2_{b_i^{NLOS}(t)}$	Variance in the i^{th} multipath component's non-line-of-sight part [W]
$\sigma^2_{\eta(t)}$	Additive white Gaussian noise variance [W]
σ^2_{MUI}	Variance of the multi-user interference [W]
$\sigma^2_{r(t)}$	Received signal variance [W]
$\sigma^2_{s(t)}$	Transmitted signal variance [W]
σ_τ	Root-mean-square delay spread [s]
$s_m(t)$	m^{th} transmitted signal [V]
SF	Spreading Factor
$S_{ASB}^q(t)$	User-q's ABC sequence [V]
$S_{DSB}^q(t)$	User-q's DSB-CE-LI-RU filtered GCL sequence [V]
$S_{ZC}^q(t)$	User-q's Zadoff-Chu sequence [V]
$S_I^q(t)$	User-q's I-channel spreading sequence [V]
$S_Q^q(t)$	User-q's Q-channel spreading sequence [V]
$S_{QPH}^q(t)$	User-q's Quadriphase sequence [V]
$SSC(C)$	State space complexity of linear block code C
$SSP(C)$	State space profile of linear block code C
t	Time [s]

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τ	Time delay [s]
$\overline{\tau}$	Mean excess delay [s]
τ_i	Time delay of the i^{th} multipath component [s]
τ_{max}	Maximum excess delay [s]
T_b	Duration of an uncoded data bit [s]
$T_{C,i}$	Coherence time of the i^{th} multipath component [s]
$t_{correct}$	Number of correctable code word symbol errors [symbols]
t_{detect}	Number of detectable code word symbol errors [symbols]
$\theta_{A,i}(t)$	Angle of arrival of the i^{th} multipath component [rad]
T_p	Pre-pulse shaping symbol duration [s]
T_s	Duration of a modulator output symbol [s]
T_{samp}	Sampling period [s]
T_{sig}	Reciprocal signal bandwidth [s]
$\overline{u}_{i,l}^{(j)}$	Trellis branch weight vector for the j^{th} branch entering node (l, i) [V]
υ	Constraint length of a binary convolutional code encoder
Υ	Puncturing profile
$\varepsilon_i(t)$	Envelope of the i^{th} multipath component [V]
φ	Primitive element of $GF\left(2^{\xi}\right)$
$\overline{\varrho}^{in}(D)$	N-dimensional de-interleaver input vector sequence [V]
$\overline{\varrho}_m^{in}$	m^{th} length-N de-interleaver input [V]
$\overline{\varrho}^{out}(D)$	N-dimensional de-interleaver output vector sequence [V]
$\overline{\varrho}_m^{out}$	m^{th} length-N de-interleaver output [V]
ς	Square-root Nyquist pulse roll-off factor
$v_r(t)$	Relative velocity between the transmitter and receiver [m/s]
$w_H\left(\overline{c}_m\right)$	Hamming weight of the vector $\overline{c}_m$ [symbols]
$w_H\left(\overline{c}_m(D)\right)$	Hamming weight of the vector sequence $\overline{c}_m(D)$ [symbols]
$W(i)$	Hilbert transformer tap weights
$x^I(t)$	I-channel pulse shaping filter excitation signal
$x^Q(t)$	Q-channel pulse shaping filter excitation signal
$y_m(p)$	m^{th} demodulated code word polynomial of a linear block code [V]
$\overline{y}_m$	m^{th} vector of demodulated symbols [V]