Low-Complexity Equalisation and Channel Estimation over Fast Fading Channels

by

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CERTIFICATE OF ORIGINAL AUTHORSHIP

I, Hongyang Zhang declare that this thesis, is submitted in fulfilment of the requirements for the award of Doctor of Philosophy, in the Faculty of Engineering and Information Technology at the University of Technology Sydney.

This thesis is wholly my own work unless otherwise referenced or acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

This document has not been submitted for qualifications at any other academic institution.

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Abstract

The next generation wireless communication systems aim to achieve high capacity and low latency with high-mobility scenario as an important channel condition for various new applications. With the significantly increased data rate and Doppler frequency shift, the systems' ability to cope with fast channel variations is of significant importance. This thesis develops effective and efficient solutions to improve the performance of both conventional and emerging modulations over fast fading channels.

The recently proposed orthogonal time frequency space (OTFS) modulation shows outstanding performance over fast fading channels. However, existing research on OTFS is mostly focused on its delay-Doppler domain structure. In this thesis, channel and system models in different signal domains are firstly derived in both continuous and discrete forms, providing the basis for exploiting the full potential of OTFS with low complexity. Particularly, a circular stripe diagonal structure in the frequency-Doppler domain channel matrix for arbitrary multipath delays and Doppler shifts is identified through analyses and simulations, paving the way for low-complexity techniques to be adopted to combat fast channel fading.

Exploiting the circular stripe diagonal nature of the frequency-Doppler channel matrix, a low-complexity frequency-domain minimum mean-square-error (MMSE) equalisation for OTFS systems with long signal frames and fully resolvable Doppler spreads is then formulated. It is also demonstrated that the proposed MMSE equalisation is applicable to conventional modulations with short signal frames and partially resolvable Doppler spreads.

The diversity performance analyses for OTFS are further provided under both maximum likelihood and linear equalisations. Inspired by the frequency-domain precoding structure, an adaptive transmission scheme with frequency-domain precoding matrix composed of the eigenvectors of the channel matrix is proposed to improve the system performance under MMSE equalisation, and its optimised performance is derived with simple analytical expressions. Considering two extreme channel conditions, the lower and upper bounds for the diversity performance of the adaptive transmission scheme are also derived. The derived performance bounds can serve as performance benchmarks for OTFS and other precoded OFDM systems.

Based on the re-formulation of OTFS as precoded-OFDM, three variants of the original OTFS system for low-complexity channel estimation over fast fading channels are finally proposed in this thesis. They enable one-dimensional channel estimation and corresponding equalisation to be applied in either frequency or time domain. Simulation results demonstrate that the proposed frequency-domain pilot aided OTFS scheme is the most effective transmission technique for high-mobility wireless communications in terms of diversity performance, signalling overhead, and power efficiency.

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LIST OF PUBLICATIONS

Journal Papers

J-1. **H. Zhang**, X. Huang and J. A. Zhang, "Adaptive Transmission With Frequency-Domain Precoding and Linear Equalization Over Fast Fading Channels," in IEEE Transactions on Wireless Communications, vol. 20, no. 11, pp. 7420-7430, Nov. 2021, doi: 10.1109/TWC.2021.3083652.

J-2. **H. Zhang**, X. Huang and J. A. Zhang, "Low-Overhead OTFS Transmission with Frequency or Time Domain Channel Estimation," submitted to IEEE Transactions on Wireless Communications.

J-3. **H. Zhang**, X. Huang and J. A. Zhang, "Low-Complexity Frequency Domain Equalization over Fast Fading Channels," submitted to IEEE Wireless Communications Letters.

Conference Papers

C-1. **H. Zhang**, X. Huang and J. A. Zhang, "Comparison of OTFS Diversity Performance over Slow and Fast Fading Channels," 2019 IEEE/CIC International Conference on Communications in China (ICCC), 2019, pp. 828-833, doi: 10.1109/ICCChina.2019.8855898.

C-2. **H. Zhang**, X. Huang, J. A. Zhang and Y. J. Guo, "Adaptive Transmission Based on MMSE Equalization over Fast Fading Channels," 2020 IEEE 92nd Vehicu-

lar Technology Conference (VTC2020-Fall), 2020, pp. 1-5, doi: 10.1109/VTC2020-Fall49728.2020.9348563.

C-3. **H. Zhang**, X. Huang and J. A. Zhang, "Frequency Domain Pilot-Aided Channel Estimation for OTFS over Fast Fading Channels," 2021 IEEE 94th Vehicular Technology Conference (VTC2021-Fall), 2021, pp. 1-5, doi: 10.1109/VTC2021-Fall52928.2021.9625551.

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Abbreviations

1G - first generation

2D - two-dimensional

3GPP - 3rd generation partnership project

4G - fourth generation

5G - fifth generation

6G - sixth generation

ADC - analog-to-digital converter

ADS - autonomous driving system

AR - augmented reality

AWGN - additive white Gaussian noise

BER - bit error rate

CDSC - continuous-Doppler-spread channel

CFO - carrier frequency offset

CP - cyclic prefix

CSI - channel state information

DAC - digital-to-analog converter

DFS - Doppler frequency shift

DFT - discrete Fourier transform

eMBB - enhanced mobile broadband

ETSI - European telecommunications standards institute

FBMC - filter bank multicarrier

FD-PA - frequency-domain pilot aided

FT - Fourier transform

Gbps - Gigabit per second

GFDM - generalized frequency division multiplexing

H2H - human to human

HD - high-definition

IAI - inter antenna interference

ICI - inter-carrier interference

IDFT - inverse discrete Fourier transform

IDI - inter Doppler interference

IFT - inverse Fourier transform

ISFFT - inverse symplectic finite Fourier transform

ISTNs - integrated space and terrestrial networks

JRC - joint radar communication

LDPC - low-density parity-check

LOS - line-of-sight

LTE - long term evolution

M2M - machine to machine

MAP - maximum A Posteriori probability

MCMC - Markov chain Monte Carlo

MIMO - multiple-input multiple-output

ML - maximum-likelihood

MLSE - maximum likelihood sequence estimation

MMSE - minimum mean square error

mMTC - massive machine type communication

mmWave - millimeter-wave

MP - message passing

MSE - mean-square-error

NLOS - non-line-of-sight

OFDM - orthogonal frequency division multiplexing

OTFS - orthogonal time frequency space

PA - power amplifiers

PAPR - peak to average power ratio

PDF - probability density function

QAM - quadrature amplitude modulation

RHS - right-hand-side

SC-FDE - single carrier frequency domain equalisation

SFFT - symplectic finite Fourier transform

SISO - single-input single-output

SNR - signal-to-noise ratio

TDL - tapped delay line

TD-PA - time-domain pilot aided

TD-TS - time-domain training sequence

TF - time-frequency

UAV - unmanned aerial vehicle

UMa - urban macrocell

uRLLC - ultra-reliable and low latency communication

V2V - vehicle-to-vehicle

VR - virtual reality

ZC - Zadoff Chu

ZF - zero forcing

Notations

Table 1: Signals, Channel Representations and System Parameters

Expressions	**Definitions**
Bold letters	Matrices and vectors signal
$(.)^{\mathbf{T}}$	Transpose operation
$(.)^{*}$	Conjugate operation
$(.)^{\mathbf{H}}$	Conjugate transpose operation
$\mathbf{X}_{m\times n}$	m by n matrix
$\mathbf{I}_m$	m by m identity matrix
$\mathbf{F}_m$	m-point normalised DFT matrix
$\mathbf{1}_{m\times n}$	m by n matrices with all 1 elements
$\mathbf{0}_{m\times n}$	m by n matrices with all 0 elements
$vec(\cdot)$	Vectorisation operation
$diag\{\mathbf{X}\}$	Extracting the diagonal elements from matrix $\mathbf{X}$
$diag\{\mathbf{x}\}$	Forming a diagonal matrix with vector $\mathbf{x}$
$\odot$	Hadamard product
$\otimes$	Kronecker product
$(\cdot)_M$	Modulo M operation
$\lceil\cdot\rceil$	Ceiling operation
$\lfloor\cdot\rfloor$	Flooring operation
$\mathbf{X}(i,:)$	i-th row of $\mathbf{X}$
$\mathbf{X}(:,j)$	j-th column of $\mathbf{X}$

List of Symbols

Table 2: Signals, Channel Representations and System Parameters

Symbols	**Definitions**
$s(t)$	Time domain continuous transmitted signal
$r(t)$	Time domain continuous received signal
$w(t)$	Time domain continuous noise
$S(f)$	Frequency domain continuous transmitted signal
$R(f)$	Frequency domain continuous received signal
$W(f)$	Frequency domain continuous noise
$s[i]$	Time domain discrete transmitted signal
$r[i]$	Time domain discrete received signal
$w[i]$	Time domain discrete noise
$S[i]$	Frequency domain discrete transmitted signal
$R[i]$	Frequency domain discrete received signal
$W[i]$	Frequency domain discrete noise
h_i, τ_i, and ν_i	The path gain, delay and Doppler shift of the i-th path in sparse P-path channel model
P	Number of multipaths in sparse P-path channel model.
τ	Delay
ν	Doppler frequency shift
t	Time variables
f	Frequency variables
$h(\tau,\nu)$	Continuous delay-Doppler channel representation
$h_t(\tau,t)$	Continuous delay-time channel representation
$H_\nu(f,\nu)$	Continuous frequency-Doppler channel representation
$H(f,t)$	Continuous time-frequency channel representation
M	Number of subcarriers
N	Number of OFDM/SC-FDE Symbols

Symbols	Definitions
M_1	Number of pilot sections in frequency domain for FD-PA-OTFS
N_1	Number of precoded data symbols in frequency domain in each pilot section for FD-PA-OTFS
M_2	Number of precoded data symbols in time domain in each pilot or training sequence section for TD-PA-OTFS or TD-TS-OTFS
N_2	Number of pilot or training sequence sections in time domain for TD-PA-OTFS or TD-TS-OTFS
d_r	Delay resolution
f_r	Doppler resolution
T	Duration of OFDM symbol
L	Length of channel impulse response
$L_{\max}$	Maximum number of resolvable multipaths
$K_{\max}$	Maximum number of resolvable Doppler frequency shifts
L_{cp}	Length of CP
T_{cp}	Duration of CP
σ_x^2	Time domain data symbol power
σ_s^2	Time domain signal power (the same as σ_x^2)
σ_w^2	Time domain noise power
σ_S^2	Frequency domain signal power
σ_W^2	Frequency domain noise power
γ_{in}	Input SNR before equalisation
γ_{out}	Output SNR after equalisation

Table 3: Matrices and Vectors

Symbols	**Definitions**	**Dimensions**
$\mathbf{r}$	Time domain received sequence	MN by 1
$\mathbf{s}$	Time domain transmitted sequence	MN by 1
$\mathbf{w}$	Time domain noise sequence	MN by 1
$\mathbf{H}_t$	Delay-time channel matrix	MN by MN
$\mathbf{R}$	Frequency domain received sequence	MN by 1
$\mathbf{S}$	Frequency domain transmitted sequence	MN by 1
$\mathbf{W}$	Frequency domain noise sequence	MN by 1
$\mathbf{H}_\nu$	Frequency-Doppler channel matrix	MN by MN
$\mathbf{h}$	Discrete version of $h(\tau,\nu)$	MN by MN
$\mathbf{H}$	Discrete version of $H(f,t)$	MN by MN
$\mathbf{h}_t$	Discrete version of $d_r h_t(\tau,t)$	MN by MN
$\mathbf{h}_\nu$	Discrete version of $f_r H_\nu(f,\nu)$	MN by MN
$\hat{\mathbf{s}}$	Estimate of $\mathbf{s}$	MN by 1
$\hat{\mathbf{S}}$	Estimate of $\mathbf{S}$	MN by 1
$\mathbf{G}_t$	Time domain MMSE matrix	MN by MN
$\mathbf{G}_\nu$	Frequency domain MMSE matrix	MN by MN
$\mathbf{X}$	Data symbol matrix for original OTFS	M by N
$\mathbf{x}$	Data symbol vector	MN by 1
$\mathbf{y}$	Received signal after MMSE equalisation	MN by 1
$\mathbf{X_1}$	Data symbol matrix for FD-PA-OTFS	M_1 by N_1
$\mathbf{X}_2$	Data symbol matrix for TD-PA-OTFS and TD-TS-OTFS	M_2 by N_2
$\mathbf{S}_{data}$	Precoded data matrix in frequency domain for FD-PA-OTFS	M_1 by N_1
$\mathbf{s}_{data}$	Precoded data matrix in time domain for TD-PA-OTFS and TD-TS-OTFS	M_2 by N_2

Symbols	Definitions	Dimensions
$\mathbf{\Theta}$	Frequency domain interpolation matrix	MN by N_1
$\mathbf{\Psi}$	Time domain interpolation matrix	N_2 by MN
$\mathbf{\Phi}$	Doppler domain phase shifting matrix	$L_{max}+1$ by MN
$\mathbf{E}$	Doppler domain phase shifting matrix composed of columns from $\mathbf{\Phi}$	$L_{max}+1$ by N_2
$\mathbf{z}$	ZC sequence	$L_{max}+1$ by 1
$\mathbf{q}$	Toeplitz-form matrix composed of ZC sequence	$L_{max}+1$ by $L_{max}+1$
$\mathbf{Q}$	Unitary matrix composed of eigenvectors of $\mathbf{H}_v^{\mathbf{H}}\mathbf{H}_v$	MN by MN
$\mathbb{Q}$	Diagonal matrix composed of rows from $\mathbf{q}$	$L_{max}+1$ by $(L_{max}+1)^2$
Λ	Diagonal matrix composed of eigenvalues of $\mathbf{H}_v^{\mathbf{H}}\mathbf{H}_v$	MN by MN
$\mathbf{V}$	Modulation matrix in general	Dimensions vary for different modulations