ITERATIVE DETECTION ALGORITHMS FOR HIGH SPECTRAL EFFICIENCY WIRELESS COMMUNICATION SYSTEMS

by
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under the supervision of

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CERTIFICATE OF ORIGINAL AUTHORSHIP

I, QIAOLIN SHI, 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.

I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of the requirements for a degree at any other academic institution except as fully acknowledged within the text. This thesis is the result of a Collaborative Doctoral Research Degree program with Beijing Institute of Technology.

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ABSTRACT

With the ever-growing of the number of devices and new applications (e.g., in industry automation, intelligent transportation systems, healthcare) and given the severe bandwidth congestion observed at the sub-6GHz frequency bands, it is critical to develop high spectral efficiency transmission techniques. However, the detection of new transmission signalling becomes more challenging compared to that of its conventional counterpart. In this thesis, advanced iterative detection algorithms for index modulation-aided and faster-than-Nyquist (FTN) signalling-aided communication systems are investigated. First, factor graph-based message passing algorithms are proposed for the joint phase noise (PHN) estimation and signal detection in orthogonal frequency division multiplexing with index modulation (OFDM-IM) systems. The solutions are superior to conventional extended Kalman filter and variational approaches in terms of the robustness to severe PHN, as well as the realistic imperfect channel state information and residual carrier frequency offset. Second, amalgamated belief propagation and mean field message passing methods based iterative detection algorithms are developed for satellite communication systems relying on the dual mode-aided index modulation (Sat-DMIM) over nonlinear dispersive satellite channels. The computational complexity of the proposed detector is further reduced by approximating the nonlinear messages using a Taylor series expansion technique. The bit error rate performance of Sat-DMIM is improved compared with the conventional linear equalizer which directly linearizes the

nonlinear system model. Third, frequency-domain joint channel estimation and signal detection methods using the variational Bayesian framework for FTN systems over frequency-selective fading channels are designed. Taking into account the structured inter-symbol interference imposed by FTN signalling and dispersive channels, reliable estimates of channel coefficients and FTN symbols are obtained by minimizing the variational free energy without the aid of the cyclic prefix. Simulation results show that the FTN system relying on the proposed iterative detection algorithm can significantly improve the spectral efficiency compared to its conventional Nyquist counterpart.

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Journal publications

- **Qiaolin Shi**, Nan Wu, Hua Wang, Xiaoli Ma, Lajos Hanzo, "Factor Graph Based Message Passing Algorithms for Joint Phase-Noise Estimation and Decoding in OFDM-IM", *IEEE Transactions on Communications (TCOM)*, 2020, 68(5), 2906 – 2921. (Corresponding to Chapter 2)

- **Qiaolin Shi**, Nan Wu, Diep N. Nguyen, Xiaojing Huang, Hua Wang, Lajos Hanzo, "Low-Complexity Iterative Detection for Dual-Mode-Aided Index Modulation in Nonlinear Dispersive Satellite Channels", to be submitted to *IEEE Transactions on Communications (IEEE TCOM)*. (Corresponding to Chapter 3)

- **Qiaolin Shi**, Nan Wu, Xiaoli Ma, Hua Wang, "Frequency-Domain Joint Channel Estimation and Decoding for Faster-than-Nyquist signaling", IEEE Transactions on Communications", *IEEE Transactions on Communications (IEEE TCOM)*, 2018, 66(2), 781-795. (Corresponding to Chapter 4)

- **Qiaolin Shi**, Nan Wu, Hua Wang, Weijie Yuan, "Joint channel estimation and decoding in the presence of phase noise over time-selective flat-fading channels", in *IET Communications*, 2016, 10(5): 577-585.

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- **Qiaolin Shi**, Nan Wu, Hua Wang, Diep N. Nguyen, Xiaojing Huang, "Low-Complexity Message Passing Receiver for OFDM-IM in the Presence of Phase Noise", in *IEEE Global Communications Conference (GLOBECOM)*, Dec 2020, pp. $1-6$. (Corresponding to Chapter 2)

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Abbreviations

1G	The First Generation
4G	The Fourth Generation
5G	The Fifth Generation
AMP	Approximate Message Passing
AWGN	Additive White Gaussian Noise
AR	Auto Regressive
BER	Bit Error Rate
BP	Belief Propagation
BPSK	Binary Phase Shift Keying
CFO	Carrier Frequency Offset
CIR	Channel Impulse Response
CP	Cyclic Prefix
CS	Compressed Sensing
CSI	Channel State Information
dB	Decibel

DCT	Discrete Cosine Transforms
DFT	Discrete Fourier Transform
EM	Expectation Maximization
EP	Expectation Propagation
EXIT	Extrinsic Information Transfer
FBMC	Filter Bank Multi Carrier
FFT	Fast Fourier Fransform
FTN	Faster-than-Nyquist
GAMP	Generalized Approximate Message Passing
GFDM	Generalized Frequency Division Multiplexing
GMP	Gaussian Message Passing
ICI	Inter-Carrier Interference
IM	Index Modulation
IMUX	Input Demultiplexer
IoT	Internet of Things
IRC	Iterative Residual Check
ISI	Inter Symbol Interference
KLD	Kullback-Leibler Divergence
LDPC	Low Density Check Code
LLR	Log Likelihood Ratio

LMMSE Linear Minimum Mean Squared Error

LS Least Square

LTE Long Term Evolution

MAP Maximum *A Posteriori*

MF Mean Field

MIMO Multiple-Input Multiple-Output

ML Maximum Likelihood

MMSE Minimum Mean Squared Error

mm-Wave MillimeterWave

OFDM Orthogonal Frequency Division Multiplexing

OFDM-IM OFDM with Index Modulation

OMUX Output Multiplexer Filter

PA Power Amplifier

pdf probability density function

PHN Phase Noise

pmf probability mass function

PSK Phase Shift Keying

QAM Quadrature Amplitude Modulation

QPSK Quadrature Phase Shift Keying

RSC Recursive Systematic Convolutional

SC-IM Single-Carrier with Index Modulation

SIC Successive Interference Cancellation

SISO Soft-In Soft-Out

SM Spatial Modulation

SNR Signal-to-Noise Ratio

SPA Sum Product Algorithm

VB Variational Bayesian

VMP Variational Message Passing

Notation

Boldface capital (small) letters denote matrices (vectors).

$\mathbf{A}_{:,i}$ denotes the ith column of matrix $\mathbf{A}$.

$\mathbf{A}_{i,:}$ denotes the ith row of matrix $\mathbf{A}$.

$\mathbf{A}_{i,k}$ denotes the i,kth element of matrix $\mathbf{A}$.

$\mathcal{D}(\mathbf{a})$ denotes the diagonal matrix constructed from the vector $\mathbf{a}$.

$\mathcal{D}(\mathbf{A})$ denotes the diagonal matrix with the diagonal elements of square matrix $\mathbf{A}$ on its diagonal.

$E\{\cdot\}$ denotes the expectation operation.

$V\{\cdot\}$ denotes the (co)variance operation.

$\text{tr}(\cdot)$ denotes the trace operator.

$\mathbb{R}$ denotes the field of reals.

$\mathbb{C}$ denotes the field of complex.

$\propto$ denotes proportionality.

$\mathbf{F}$ denotes the unitary DFT matrix.

$\mathbf{\Phi}$ denotes the unitary DCT matrix.

$\mathbf{I}$ denotes the identity matrix.

$\mathbf{0}$ denotes the all-zeros matrix.

$\mathbf{1}$ denotes the all-one column-vector.

$(\cdot)^*$ denotes the conjugate operation.

$(\cdot)^T$ denotes the transpose operation.

$(\cdot)^H$ denotes the Hermitian operation.

$(\cdot)^{-1}$ denotes the inverse operation.

$\star$ denotes the linear convolution.

$\otimes$ denotes the cyclic convolution.

$\odot$ denotes the element-wise product.

$\hat{m}_x$ denotes the mean of the random variable x.

$\hat{v}_x$ denotes the mean of the random variable x.

$p(\cdot)$ denotes the pdf of a continuous random variable.

$P(\cdot)$ denotes the pmf of a discrete random variable.