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Research on Key Technologies of Low-Latency Uplink Non-Orthogonal Multiple Access

by

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Certificate of Authorship/Originality

I, Jie Zeng, 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 reference 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 except as fully acknowledged within the text. This thesis is the result of a research candidature jointly delivered with Beijing University of Posts and Telecommunications as part of a Collaborative Doctoral Research Degree. This research is supported by the Australian Government Research Training Program.

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ABSTRACT

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5G is expected to significantly reduce latency in numerous emerging services in the Internet of Things (IoT). Non-orthogonal multiple access (NOMA) has been widely regarded as one promising technology to enable 5G. NOMA can allow multiple users to send signals in the same radio resource simultaneously, and can distinguish the signals of users with multi-user detection (MUD) at the receiver. NOMA can be combined with multiple-input and multiple-output (MIMO), advanced modulation and coding, and full-duplex (FD) to ensure low latency communications with high reliability. Generally speaking, the non-orthogonal superposition of signals from access users and grant-free scheduling can reduce the access latency; MIMO and FD can shorten the transmission latency by increasing spectrum efficiency. This thesis studies the design and enhancement of NOMA to guarantee low latency in the uplink (UL), under the assumption of massive accessed users, a few transmit antennas, shadow fading, and imperfect channel state information, which reflect the characteristics of IoT services. Meanwhile, the effectiveness of the proposed schemes is evaluated via the novel finite blocklength information theory, thereby complying with the small packet size in IoT. The main contributions of this thesis are summarized as follows.

1. The rate splitting algorithms and successive interference cancellation detection in multi-user MIMO (MU-MIMO) NOMA are proposed to minimize the maximum transmission latency of users. The achievable data rates are derived, and two corresponding rate splitting algorithms are proposed. Numerical results validate that the

rate splitting MU-MIMO NOMA can efficiently shorten the transmission latency and processing latency.

2. The sparse code multiple access enhanced FD (FD-SCMA) scheme is designed to operate UL and downlink (DL) simultaneously. This thesis derives the error probability with imperfect self-interference suppression in FD. FD-SCMA is proved to achieve lower transmission latency than existing SCMA and FD schemes in time-invariant flat-fading channels and time-invariant frequency-selective fading channels by theoretical calculation and simulation.

3. Low latency transmission of the emerging MU-MIMO NOMA is studied. Under log-normal shadow fading, this thesis derives the probability density function of effective SNRs, and calculates the error probability given transmission latency. Further, the error probability can be minimized by adjusting the length of pilots. Simulation results verify that the MU-MIMO NOMA enables low latency transmissions under moderate shadow fading for massive accessed users.

Overall, NOMA can remarkably lower access latency, transmission latency, and processing latency in UL.

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List of Publications

J-1 **J. Zeng, T. Lv, R. P. Liu, X. Su, Y. J. Guo, N. C. Beaulieu.** *"Enabling Ultra-reliable and Low Latency Communications Under Shadow Fading by Massive MU-MIMO" in* ***IEEE Internet of Things Journal***, vol. 7, no. 1, pp. 234–246, Jan. 2020.

J-2 **J. Zeng, T. Lv, Z. Lin,** ***et al.*** *"Achieving Ultrareliable and Low-Latency Communications in IoT by FD-SCMA" in* ***IEEE Internet of Things Journal***, vol. 7, no. 1, pp. 363–378, Jan. 2020.

J-3 **J. Zeng, T. Lv, W. Ni, R. P. Liu, N. C. Beaulieu, Y. J. Guo.** *"Ensuring Max-Min Fairness of UL SIMO-NOMA: A Rate Splitting Approach" in* ***IEEE Transactions on Vehicular Technology***, vol. 68, no. 11, pp. 11080–11093, Nov. 2019.

J-4 **J. Zeng, T. Lv, R. P. Liu, X. Su, N. C. Beaulieu, Y. J. Guo** *"Linear Minimum Error Probability Detection for Massive MU-MIMO With Imperfect CSI in URLLC" in* ***IEEE Transactions on Vehicular Technology***, vol. 68, no. 11, pp. 11384–11388, Nov. 2019.

J-5 **G. J. Sutton, J. Zeng, R. P. Liu,** ***et al.*** *"Enabling Technologies for Ultra-Reliable and Low Latency Communications: From PHY and MAC Layer Perspectives" in* ***IEEE Communications Surveys & Tutorials***, vol. 21, no. 3, pp. 2488–2524, Third Quart. 2019.

J-6 **C. Xiao, J. Zeng, W. Ni, R. P. Liu, X. Su, J. Wang.** *"Delay Guarantee and Effective Capacity of Downlink NOMA Fading Channels" in* ***IEEE Journal of Selected Topics in Signal Processing***, vol. 13, no. 3, pp. 508–523, Jun. 2019.

J-7 **C. Xiao, J. Zeng, W. Ni,** ***et al.*** *"Downlink MIMO-NOMA for Ultra-*

Reliable Low-Latency Communications" in ***IEEE Journal on Selected Areas in Communications***, vol. 37, no. 4, pp. 780–794, Apr. 2019.

J-8 **J. Zeng, T. Lv, R. P. Liu, *et al.*** *"Investigation on Evolving Single-Carrier NOMA Into Multi-Carrier NOMA in 5G" in* ***IEEE Access***, vol. 6, pp. 48268–48288, 2018.

J-9 **T. Lv, Y. Ma, J. Zeng, P. T. Mathiopoulos.** *"Millimeter-Wave NOMA Transmission in Cellular M2M Communications for Internet of Things" in* ***IEEE Internet of Things Journal***, vol. 5, no. 3, pp. 1989–2000, Jun. 2018.

J-10 **G. J. Sutton, J. Zeng, R. P. Liu, *et al.*** *"Enabling Ultra-Reliable and Low-Latency Communications through Unlicensed Spectrum" in* ***IEEE Network***, vol. 32, no. 2, pp. 70–77, Mar. 2018.

J-11 **J. Zeng, D. Kong, B. Liu, X. Su, T. Lv.** *"RIePDMA and BP-IDD-IC Detection" in* ***EURASIP Journal on Wireless Communications and Networking***, vol. 2017, no. 1, pp. 1-12, Dec. 2017.

Contents

List of Figures

Abbreviation

3rd generation partnership project - 3GPP

Additive white Gaussian noise - AWGN

Base station - BS

Belief propagation - BP

Bits per channel use - bpcu

Block error rate - BLER

Channel use - CU

Channel state information - CSI

China academy of telecommunications technology - CATT

Co-channel interference - CCI

Downlink - DL

Enhanced mobile broadband - eMBB

The fifth generation - 5G

Finite blocklength - FBL

Full-duplex - FD

Golden section search method - GSSM

Infinite blocklength - IBL

Interference cancellation - IC

International telecommunication union - ITU

Internet of Things - IoT

Large-scale fading - LSF

Length of pilots - LoP

Lower bound - LB

Massive machine-type communications - mMTC

Maximal-ratio combining - MRC

Maximal-ratio combining SIC - MRC-SIC

Maximum a posteriori - MAP

Maximum likelihood - ML

Message passing algorithm - MPA

Minimum mean square error - MMSE

Minimum mean square error SIC - MMSE-SIC

Multi-carrier NOMA - MC-NOMA

Multiple access channel - MAC

Multiple-input and multiple-output - MIMO

Multiple-input multiple-output NOMA - MIMO-NOMA

Multi-user detection - MUD

Multi-user interference - MUI

Multi-user multiple-input multiple-output - MU-MIMO

Multi-user shared access - MUSA

New radio - NR

Non-orthogonal multiple access - NOMA

Next generation node B - gNB

Ordered SIC - OSIC

Orthogonal frequency division multiple access - OFDMA

Orthogonal frequency division multiplexing - OFDM

Orthogonal multiple access - OMA

Pattern division multiple access - PDMA

Perfect interference cancelation - PIC

Pilot-assistant channel estimation - PACE

Power-domain NOMA - PD-NOMA

Probability density function - pdf

Receiving antennas - Rx antennas

Resource block - RB

Right-hand side - RHS

Resource element - RE

SCMA enhanced FD - FD-SCMA

Self-interference suppression - SIS

Signal to interference plus noise ratio - SINR

Signal to noise ratio - SNR

Small-scale fading - SSF

Sparse code multiple access - SCMA

Spectral efficiency - SE

Successive interference cancellation - SIC

System-level simulation - SLS

Transmit antennas - Tx antennas

Transmit power - Tx power

Ultra-reliable and low latency communications - URLLC

Uplink - UL

Upper bound - UB

User equipment - UE

Zero forcing – ZF