Application of NOMA in 6G Networks: Future Vision and Research Opportunities for Next Generation Multiple Access

A Tutorial Proposal for ICCC'2021

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Abstract

User data traffic, especially large amount of video traffic and small-size internet-of-things (IoT) packets, has dramatically increased in recent years with the emergence of smart devices, smart sensors and various new applications such as virtual reality and autonomous driving. It is hence crucial to increase network capacity and user access to accommodate these bandwidth consuming applications and enhance the massive connectivity. As a prominent member of the next generation multiple access (NGMA) family, non-orthogonal multiple access (NOMA) has been recognized as a promising multiple access candidate for the sixth-generation (6G) networks. The main contents of this tutorial is to discuss the so-called "One Basic Principle plus Four New" concept. Starting with the basic NOMA principle to explore the possible multiple access techniques in *non-orthogonal* manner, the advantages and drawbacks of both the channel state information based successive interference cancelations (SIC) and quality-of-service based SIC are discussed. Then, the application of NOMA to meet the new 6G performance requirements, especially for *massive connectivity*, is explored. Furthermore, the integration of NOMA with new physical layer techniques is considered, followed by introducing new application scenarios for NOMA towards 6G. Finally, the application of machine learning in NOMA networks is investigated, ushering in the machine learning empowered NGMA era, for making multiple access in an *intelligent* manner for the next generation networks.

Tutorial Overview

As more and more new mobile multimedia rich services are becoming available to larger audiences, there is an ever increasing demand for higher data rate wireless communications as well as larger capacity networks. This demand is to be met under the scope of next generation mobile communication systems characterized by high speed, large capacity and good quality-of-service (QoS) for millions of subscribers. To meet these requirements, a number of energy and spectrally efficient technologies have been proposed for beyond 6G networks. The sixth-generation (6G) networks need breakthroughs beyond the current fifth-generation (5G) networks. The expected performance targets of 6G are: 1) The connectivity density is ten-fold larger compared to 5G; 2) The peak data rate reaches 1 terabit per second; 3) The energy efficiency is a hundred times higher than that of 5G; 4) The air interface latency decreases to 0.1 millisecond; and 5) The reliability increases to 99.99999%. To this end, highly efficient next-generation multiple access (NGMA) techniques are vital for 6G.

At the time of the writing of this proposal, the technical community has turned towards the standardization of 6G systems, with a special emphasis on the NOMA techniques. NOMA has been proposed to overcome the spectral inefficiency of OMA. Specifically, NOMA allows controllable interference via non-orthogonal resource allocation at the expense of a tolerable increase in receiver complexity. The signals transmitted to different users are superimposed into the same time and/or frequency band, and they are recovered with advanced receiver algorithms. Although NOMA has already been thoroughly investigated in the 5G and beyond networks , previous research focused on static devices and the data rate of broadband users. This ignores several fundamental problems for NGMA, e.g., the effect of mobility, the design tradeoffs in terms of connectivity, reliability, and latency. Realizing the full potential of NOMA in practical communication scenarios is challenging, and there are still many important open problems that have not been solved.

The aim of the tutorial is to fill this gap by investigating NOMA via the One Basic Principle plus Four New concept. More specifically, the basic principle is to deeply investigate the non-orthogonality from the SIC perspective. Building on this basic principle, we explore the following four new directions: 1) New requirements: Supporting massive connectivity by considering various QoS requirements including latency and reliability; 2) New techniques: Integrating NOMA with other 6G physical layer techniques; 3) New applications: Application in heterogeneous scenarios to support emerging 6G applications; and 4) New tools: Integration with artificial intelligence (AI) to design an adaptive resource allocation.

This tutorial also will provide a comprehensive overview of the state-of-the-art on NOMA, with a focus on the theoretical NOMA principles, multiple antenna leased NOMA design, on the interplay between NOMA and reconfigurable intelligent surfaces (RIS)/intelligent reflecting surfaces (IRS) networks, Grant-Free NOMA for massive connectivity in IoT Networks, and on the co-existence of NOMA with other emerging potential 6G techniques. Necessary analytical tools are presented to study them (such as stochastic geometry, matching theory, convex optimization and machine learning). This tutorial will take a comprehensive and coordinated approach in presenting the ways of realizing the the potential advantages for NOMA in next general wireless systems and identify promising research opportunities for the future. There are four main objectives of this tutorial:

- **Basic Principle—Non-orthogonality**: the first objective is to provide a general introduction to next generation mobile communication and networking including the history of standardization, requirements, key working scenarios and major evolutionary techniques from physical to MAC and network layer issues. The possible '**non-orthogonal**' multiple access for next generation networks will be identified.
- **New requirements—Massive Connectivity**: the seconde objective is to demonstrate '**Massive**', with the particular focus on utilizing QoS-oriented and semi-grant-free techniques for NOMA in IoT networks for achieving massive connectivity.
- **New techniques—Integration**: The third objective is to illustrate how such shifting paradigm on multiple access will '**Compatible**' with other emerging phycial layer techniques, such as orthogonal time frequency space (OTFS) techniques, Terahertz (THz), integrated sensing and communications (ISaC), Visible Light Communication (VLC), etc.
- **New applications—Heterogeneity**: The fourth objective is to investigate applications in heterogeneous scenarios to support emerging 6G networks, such as Integrated Terrestrial and Aerial Networks, reconfigurable intelligent surfaces aided wireless communications, Robotic Communications, VR/AR Multi-Layer Video Transmission, E-Health, etc.
- **New Tools—AI enhancement**: The fifth objective is to demonstrate '**Intelligent**', with the focus on showing how the recent signal processing advances such as machine learning (e.g., reinforcement learning, deep learning, federated learning, etc.) can enhance the development of massive NOMA technique.

Detailed Outline

- Basic Principles of NOMA- present the basics, challenges, recent progress, and open issues for NGMA:
  1) What will be different for 6G in terms of multiple access?
  2) Rethinking the importance of SIC
- New Requirements: Massive Connectivity for NOMA
  1) QoS-based NOMA for Downlink Transmission
  2) Semi-GF NOMA for Uplink Transmission
- New Techniques: integration of NOMA with Emerging Physical Layer Techniques
  1) OTFS-NOMA
  2) Interplay between RIS and NOMA
  3) THz-NOMA
- New Scenarios: Application of NOMA to Heterogeneous Scenarios
  1) NOMA in Integrated Terrestrial and Aerial Networks
  2) NOMA in Robotic Communications
- New Tools: Machine Learning Empowered NOMA-based Networks
  1) Reinforcement Learning for NOMA-based Networks
  2) Deep Learning for NOMA-based Networks
  3) Other Machine Learning for NOMA-based Networks
- Outlook and Discussion for research challenges and opportunities.

Importance and Timeliness of the Tutorial:

This tutorial presents a timely overview on how to achieve high spectral efficiency, the holy grail of modern wireless communications, particularly for emerging 6G networks as 5G networks have been commercialized. The tutorial will shed light on some fundamental challenges in the design of such spectrally efficient networks from the system engineering perspective. In presenting the tutorial, all concepts are built up from basic concepts. Therefore, the audience only requires a moderate level of prior knowledge in communications and signal processing. Furthermore, the instructors newly published research results on the impact of NOMA communications on the overall system performance trade-offs will be presented. Generic design guidelines are provided for implementing massive NOMA in a general 6G network architecture. Methods are then presented to adjust and engineer the system behaviour to improve the spectrum efficiency while a quantitative vision is given regarding the costs and implications of such changes. The analytical tools and concepts provided in this tutorial as well as the techniques used are in line with the objectives and interests of ICCC attendees.

Note that NOMA has attracted considerable attention from both industry and academia, and has been included as a key enabling technique in various whitepapers published by DoCoMo, SK Telecom, METIS, and ZTE in 2015. In Aug. 2015, NOMA was also proposed for 3GPP LTE to improve the spectral efficiency of downlink LTE by Qualcomm, Huawei, Samsung, Nokia, etc. In addition, NOMA has also been included in the next generation digital TV standard, ATSC 3.0, where it is referred to as LDM. These fast-growing industrial activities are synchronized with the efforts from the academic research community. Both lecturers are Guest Editors for the following special issues which are the first in IEEE journals on NOMA

1. IEEE JSAC Special Issue on Non-Orthogonal Multiple Access for 5G Systems, 2017.
2. IEEE Wireless Communications Special Issue on Non-Orthogonal Multiple Access for 5G, 2017.
3. IEEE JSTSP Special Issue on Signal Processing Advances for Non-Orthogonal Multiple Access in Next Generation, 2018.
4. IEEE Access Special Issue on Advances in Signal Processing for Non-Orthogonal Multiple Access, 2019.
5. IEEE JSAC Special Issue on Next Generation Multiple Access, 2021.

For the JSAC and JSTSP special issues, 96 papers and 79 papers were submitted, respectively, which is irrefutable evidence for the huge amount of effort dedicated to this important research area by industry and academia. The pace of the current activities demonstrates the timeliness of the proposed tutorial.

Past Tutorials

The lecturers have delivered some tutorials on NOMA in the past, as listed in the following. Note that compared to these existing tutorials which focus on power domain NOMA, the new tutorial proposed will provide a more systematic overview of the state of the art of NOMA based on the "*One Basic Plus Four New*" concept, more emerging applications on NOMA, such as Grant-Free NOMA, NOMA-UAV, NOMA-IRS, etc, will also be presented. The use of advanced signal processing tools on NOMA, such as machine learning will be discussed as well.

An early version (4-hour) of this tutorial has been presented at

- IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC2020), Virtual Conference
- IEEE Global Communications Conference (Globecom), Waikoloa, HI, USA, (GC2019)
- Global Communications Conference (Globecom), Abu Dhabi, UAE, (GC2018)
- IEEE Intern. Conf. Commun., Paris, France, 2017 (ICC-2017)
- IEEE 85th Veh. Technol. Conf., Sydney, Australia, (VTC2017-Spring)
- The 28th Biennial Symp. Commun., British Columbia, Canada, (BSC-2016).
- IEEE Veh. Technol. Conf., Montreal, Canada, (VTC2016-Fall)
- IEEE Veh. Technol. Conf., Chicago, USA, (VTC2018-Fall)
- The fifth IEEE Intern. Conf. Commun. in China, Chengdu, China, July 2016 (ICCC- 2016)
- The fifth IEEE Intern. Conf. Commun., Chengdu, China, July 2016 (ICCC- 2016)
- The fifth IEEE Intern. Conf. Commun., Beijing, China, July 2016 (ICCC- 2018)

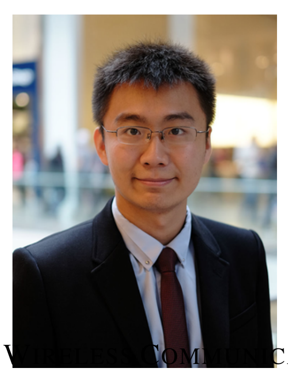
A 2-hour version of this tutorial was given at Tsinghua University and Xidian University, China, in January 2016.

Zhiguo Ding has also recently delivered invited talks on 5G Communications at VTC Spring 2015, AICWC 2015, and the Energy Harvesting special sessions at EUSIPCO 2015 and ICCS 2014.

Yuanwei has delivered invited talks in VTC-fall 2018, ICCC 2018, GC 2019, PIMRC 2020. He has also delivered a NOMA twenty hours short Course in Beijing Jiaotong University and Northeast University.

Intended Audience

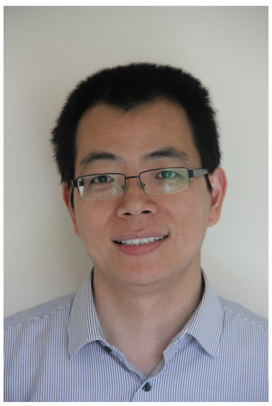
Whilst this overview is ambitious in terms of providing a research-oriented outlook for 6G, potential attendees require only a modest background in wireless networking and communications. The mathematical contents are kept to a minimum and a conceptual approach if adopted. Postgraduate students, researchers and signal processing practitioners as well as managers looking for cross-pollination of their experience with other topics may find the coverage of the presentation beneficial.



Yuanwei Liu (S'13, M'16, SM'19) received the Ph.D. degree in Electrical Engineering from the Queen Mary University of London, U.K., in 2016. He has been a Lecturer (Assistant Professor) with the School of Electronic Engineering and Computer Science, Queen Mary University of London, since 2017. He was with the Department of Informatics, King's College London, from 2016 to 2017, where he was a Post-Doctoral Research Fellow. His research interests include non-orthogonal multiple access, 5G/6G, RIS, UAV communications, stochastic geometry, and matching theory.

Dr. Liu is currently an Editor on the Editorial Board of the IEEE TRANSACTIONS ON WIRELESS COMMUNICATIONS, the IEEE TRANSACTIONS ON COMMUNICATIONS, and IEEE COMMUNICATIONS

LETTERS. He serves as the leading Guest Editor for IEEE JSAC special issue on Next Generation Multiple Access, a Guest Editor for IEEE JSTSP special issue on Signal Processing Advances for Non-Orthogonal Multiple Access in Next Generation Wireless Networks. He has served as a TPC Member for many IEEE conferences, such as GLOBECOM and ICC. He received IEEE ComSoc Outstanding Young Researcher Award for EMEA in 2020. He received the Exemplary Reviewer Certificate of IEEE WIRELESS COMMUNICATIONS LETTERS in 2015, IEEE TRANSACTIONS ON COMMUNICATIONS in 2016 and 2017, and IEEE TRANSACTIONS ON WIRELESS COMMUNICATIONS in 2017 and 2018. He has served as the Publicity Co-Chair for VTC 2019-Fall. He is the leading contributor for "Best Readings for Non-Orthogonal Multiple Access (NOMA)" and the primary contributor for "Best Readings for Reconfigurable Intelligent Surfaces (RIS)". He serves as the chair of Special Interest Group (SIG) in Signal Processing and Computing for Communications (SPCC) Technical Committee on the topic of signal processing Techniques for next generation multiple access (NGMA), the vicechair of SIG Wireless Communications Technical Committee (WTC) on the topic of Reconfigurable Intelligent Surfaces for Smart Radio Environments (RISE), and the Tutorials and Invited Presentations Officer for Reconfigurable Intelligent Surfaces Emerging Technology Initiative.



Zhiguo Ding received his B.Eng in Electrical Engineering from the Beijing University of Posts and Telecommunications in 2000, and the Ph.D degree in Electrical Engineering from Imperial College London in 2005. From Jul. 2005 to Apr. 2018, he was working in Queen's University Belfast, Imperial College, Newcastle University and Lancaster University. Since Apr. 2018, he has been with the University of Manchester as a Professor in Communications. From Sept. 2012 to Sept. 2020, he has also been an academic visitor in Princeton University.

Dr Ding' research interests are 5G networks, game theory, cooperative and energy harvesting networks and statistical signal processing. He has been serving as an Editor for IEEE Transactions on Communications, IEEE Transactions on Vehicular Networks, and Journal of Wireless Communications and Mobile Computing, and served as an editor for IEEE Wireless Communication Letters and IEEE Communication Letters. He was the TPC Co-Chair for the 6th IET International Conference on Wireless, Mobile & Multimedia Networks (ICWMMN2015), Symposium Chair for International Conference on Computing, Networking and Communications. (ICNC 2016), and the 25th Wireless and Optical Communication Conference (WOCC), and Co-Chair of WCNC-2013 Workshop on New Advances for Physical Layer Network Coding. He received the best paper award in IET Comm. Conf. on Wireless, Mobile and Computing, 2009 and the 2015 International Conference on Wireless Communications and Signal Processing (WCSP 2015), IEEE Communication Letter Exemplary Reviewer 2012, the EU Marie Curie Fellowship 2012-2014, IEEE TVT Top Editor 2017, 2018 IEEE Communication Society Heinrich Hertz Award, 2018 IEEE Vehicular Technology Society Jack Neubauer Memorial Award, and 2018 IEEE Signal Processing Society Best Signal Processing Letter Award. He is a Web of Science Highly Cited Researcher and a Fellow of the IEEE.