ICC2019 Tutorials: Monday, 20 May

Morning: 9:00 – 12:30

1. **UAV Applications over Cellular Networks: Sensing, Communication, and Computation**
   Zhu Han; Lingyang Song
2. **Fog Computing: An Enabling Paradigm for Intelligent Services**
   Xiliang Luo; Xu Chen; Ai-Chun Pang; Ming-Tuo Zhou
3. **Communication Network Design: Model-Based, Data-Driven, or Both?**
   Marco Di Renzo; Alessio Zappone; Mérouane Debbah
4. **MIMO Transmission with Finite Input Signals**
   Chengshan Xiao; Yongpeng Wu
5. **Accessing from the Sky: UAV Communications for 5G and Beyond**
   Rui Zhang; Yong Zeng
6. **Quantum Internet: Wiring the Weirdness**
   Angela Sara Cacciapuoti; Marcello Caleffi
7. **Cognitive Backscatter Network: A New Paradigm of Energy- and Spectrum-Efficient IoT Communications**
   Ying-Chang Liang; Dusit Niyato
8. **5G Tactile Internet with Human-in-the-Loop**
   Frank H.P. Fitzek; Gerhard Fettweis

Afternoon: 14:00 – 17:30

1. **Deep Learning for Communications: A Hands-On Experience**
   Stephan ten Brink; Jakob Hoydis; Sebastian Cammerer; Sebastian Dörner
2. **Cyber-Security Solutions for Internet of Things based on Hardware Security Primitives**
   Biplab Sikdar
3. **Cellular-based V2X Communications**
   Yi Qian
4. **Channel measurement and modeling for fifth-generation (5G) system**
   Andreas Molisch; Jianhua Zhang
5. **Ultra-Low Latency and Machine-Learning Based Mobile Networking**
   Kwang-Cheng Chen; Shih-Chun Lin
6. **Sparse Signal Processing in Intelligent Communications: from Theory to Practice**
   Yue Gao; Zhijin Qin; Geoffrey Li
7. **A Unifying Data-Oriented Approach to Wireless Transmission of Big and Small Data**
   Hong-Chuan Yang; Mohamed-Slim Alouini
8. **Energy and Spectral Efficiency Tradeoffs in Future Communication Networks**
   Guowang Miao; Zhisheng Niu; Ender Ayanoglu

UAV Applications over Cellular Networks: Sensing, Communication, and Computation

Abstract

The emerging unmanned aerial vehicles (UAVs) have been playing an increasing role in the military, public, and civil applications. Very recently, 3GPP has approved the study item on enhanced support to seamlessly integrate UAVs into future cellular networks. Unlike terrestrial cellular networks, UAV communications have many distinctive features such as high dynamic network topologies and weakly connected communication links. In addition, they still suffer from some practical constraints such as battery power, no-fly zone, etc. As such, many standards, protocols, and design methodologies used in terrestrial wireless networks are not directly applicable to airborne communication networks. Therefore, it is essential to develop new communication, signal processing, and optimization techniques in support of the ultra-reliable and real-time sensing applications, but enabling high data-rate transmissions to assist the terrestrial communications in LTE. Typically, to integrate UAVs into cellular networks, one needs to consider two main scenarios of UAV applications as follows.

First, dedicated UAVs, also called drones, can be used as communication platforms in the way as wireless access points or relays nodes, to further assist the terrestrial communications. This type of applications can be referred to as **UAV Assisted Cellular Communications**. UAV-assisted cellular communications have numerous use cases, including traffic offloading, wireless backhauling, swift service recovery after natural disasters, emergency response, rescue and search, information dissemination/broadcasting, and data collection from ground sensors for machine-type communications. However, different from traditional cellular networks, how to plan the *time-variant placements* of the UAVs served as base station (BS)/relay is very challenging due to the complicated 3D propagation environments as well as many other practical constraints such as power and flying speed. In addition, *spectrum sharing* with existing cellular networks is another interesting topic to investigate.

Second type of application is to exploit UAVs for sensing purposes due to its advantages of on-demand flexible deployment, larger service coverage compared with the conventional fixed sensor nodes, and ability to hover. Specially, UAVs, equipped with cameras or sensors, have come into our daily lives to execute critical real-time sensing tasks, such as smart agriculture, security monitoring, forest fire detection, and traffic surveillance. Due to the limited computation capability of UAVs, the real-time sensory data needs to be transmitted to the BS for real-time data processing. In this regard, the cellular networks are necessarily committed to support the data transmission for UAVs, which we refer to as **Cellular assisted UAV Sensing**. Nevertheless, to support *real-time* sensing streaming, it is desirable to design *joint sensing and communication* protocols, develop novel beamforming and estimation algorithms, and study efficient distributed resource optimization methods.

Moreover, in the above two representative working scenarios, the concept of *Edge Computing* can be either applied into the UAV assisted cellular networks to enhance a larger area QoS or into cellular assisted UAV sensing for real-time applications. The aim of this tutorial is to bring

together control, signal processing engineers, computer and information scientists, applied mathematicians and statisticians, as well as systems engineers to carve out the role that analytical and experimental engineering has to play in UAV research and development. This proposal will emphasize on UAV technologies and applications for cellular networks. There are four main objectives. The first objective is to provide an introduction to the UAV paradigm, from 5G and beyond communication perspective. The second objective is to introduce the key methods, including optimization, game, and graph theory, for UAV applications, in a comprehensive way. The third objective is to discuss UAV assisted cellular communications. The fourth objective is to present the state-of-the-art for cellular network assisted UAV sensing. Many examples will be illustrated in details so as to provide wide scope for general audiences.

Detailed Outline of the Tutorial

1. Overview of 5G and Beyond Communications
   - 1.1. Background and Requirements
   - 1.2. UAV Applications
     - i Wireless Access Points
     - ii Aerial Sensing Users
   - 1.3. Current State of Art
     - i Channel Model
     - ii Signal Transmission Model
     - iii Network Interference Analysis
     - iv Flight Control Model
2. Basic Theoretical Background
   - 2.1. Graph Theory for UAV Networks
   - 2.2. Brief Introduction to Optimization Theory
   - 2.3. Basics of Game Theory
   - 2.4. Related Machine Learning Technology
3. UAV Assisted Cellular Communications and Networks
   - 3.1. UAV serving as Base stations
     - i UAV Spectrum Sharing
     - ii UAV Offloading
     - iii Altitude Optimization

3.2. UAV serving as Relays

i Power Control

ii Trajectory and Placement Optimization

iii Frequency and Time Allocation

3.3. Edge on the Sky

i Proactive Caching

ii Communication and Computing Tradeoff

iii Trajectory and Resource Optimization

4. Cellular Assisted UAV Sensing Networks

4.1. UAV serving as an Aerial User

i UAV-to-X Communications

ii Sense-and-Send Protocol Design

iii Trajectory, Speed, and Resource Optimization

4.2. Cooperative UAV Sensing

i Cooperative Sense-and-Send Protocol Design

ii Trajectory, Speed, and Power Optimization

4.3. Reinforcement Learning for UAV Sensing Networks

i Distributed Sense-and-Send Protocol Design

ii Q-Learning for Trajectory and Speed Optimization

4.4. Edge-computing aided UAV Sensing

i Age of Information and Edge Computing for Aerial IoTs

ii Computation offloading, Trajectory, and Resource Optimization

4.5. UAV Sensing Applications

i Deep-learning and CNN

ii UAV aided Fine-Grained Air Quality Index Monitoring and Demo

Length of the Tutorial

Half day

Tutorial Speakers

Lingyang Song, *Boya Distinguished Professor,*
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Houston, TX 77004 USA
Email: zhan2@uh.edu
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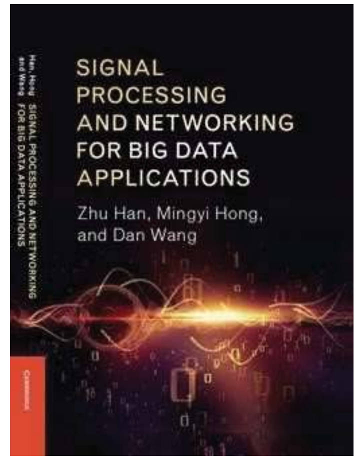
Short Biography of the Instructors

Lingyang Song received his PhD from the University of York, UK, in 2007, where he received the K. M. Stott Prize for excellent research. He worked as a postdoctoral research fellow at the University of Oslo, Norway, and Harvard University, until rejoining Philips Research UK in March 2008. In May 2009, he joined the School of Electronics Engineering and Computer Science, Peking University, China, as a full professor. His main research interests include cooperative and cognitive communications, physical layer security, and wireless ad hoc/sensor networks. He published extensively, wrote 6 text books, and is co-inventor of a number of patents (standard contributions). He received 9 paper awards in IEEE journal and conferences including IEEE JSAC 2016, IEEE WCNC 2012, ICC 2014, Globecom 2014, ICC 2015, etc. He is currently on the Editorial Board of IEEE Transactions on Wireless Communications and Journal of Network and Computer Applications. He served as the TPC co-chairs for the International Conference on Ubiquitous and Future Networks (ICUFN2011/2012), symposium co-chairs in the International Wireless Communications and Mobile Computing Conference (IWCMC 2009/2010), IEEE International Conference on Communication Technology (ICCT2011), and IEEE International Conference on Communications (ICC 2014, 2015). He is the recipient of 2012 IEEE Asia Pacific (AP) Young Researcher Award. Dr. Song is a senior member of IEEE, and IEEE ComSoc distinguished lecturer since 2015.



Zhu Han (S'01–M'04-SM'09-F'14) received the B.S. degree in electronic engineering from Tsinghua University, in 1997, and the M.S. and Ph.D. degrees in electrical engineering from the University of Maryland, College Park, in 1999 and 2003, respectively. From 2000 to 2002, he was an R&D Engineer of JDSU, Germantown, Maryland. From 2003 to 2006, he was a Research Associate at the University of Maryland. From 2006 to 2008, he was an assistant professor in Boise State University, Idaho. Currently, he is a Professor in Electrical and Computer Engineering Department as well as Computer Science Department at the University of Houston, Texas. His research interests include wireless resource allocation and management, wireless communications and networking, game theory, wireless multimedia, security, and smart grid communication. Dr. Han received an NSF Career Award in 2010, the Fred W. Ellersick Prize of the IEEE Communication Society in 2011, the EURASIP Best Paper Award for the Journal on Advances in Signal Processing in 2015, several best paper awards in IEEE conferences, and is currently an IEEE Communications Society Distinguished Lecturer. Dr. Han is top 1% highly cited researcher according to Web of Science 2017. Dr. Han published the following related book: Zhu Han, Mingyi Hong, and Dan Wang, Signal Processing and Networking for Big Data Applications, Cambridge University Press, UK, 2017.

Prior History of the Tutorial Presentation

- Lingyang Song and Zhu Han, "Signal Processing for Big Data Analytics: Fundamental and Applications," IEEE Global Communications Conference (Globecom), 2018.
- Lingyang Song and Zhu Han, "Big Data Signal Processing for Communication Networks," IEEE Global Communications Conference (Globecom), 2017.
- Lingyang Song and Zhu Han, "5G Wireless Communications: Enabling Technologies and Resource Management," IEEE Global Communications Conference (Globecom), 2016.
- Lingyang Song and Zhu Han, "Full-Duplex Communications and Networks," IEEE International Conference on Communications in China (ICCC), 2016.
- Lingyang Song and Zhu Han, "Distributed Resource Allocation for 5G Communications and Networks," IEEE International Conference on Communications (ICC), 2016.
- Lingyang Song and Zhu Han, "Full-Duplex Communications and Networks: Fundamentals, Technologies, and Applications," IEEE Global Communications Conference (Globecom) 2015.
- Lingyang Song and Zhu Han, "Resource Allocation for Full-Duplex Communication and Networks," IEEE International Conference on Communication (ICC) 2015.

- Lingyang Song and Zhu Han, “Full-Duplex Wireless Communication and Networks: Key Technologies and Applications", IEEE International Conference on Communication in China (ICCC) 2014.
- Lingyang Song and Zhu Han, “Game-theoretic Methods for Device-to-Device Communications", IEEE International Conference on Communication (ICC) 2014.
- Lingyang Song and Zhu Han, “Resource Allocation for Physical-Layer Security,” 2013 IEEE Wireless Communications and Networking Conference (WCNC), Shanghai China, Apr. 2013.
- Zhu Han and Lingyang Song, “Smart Grid Communications and Networking, IEEE International Conference on Communications (ICC), Budapest, Hungary, June 2013.
- Lingyang Song and Zhu Han, “Resource Allocation for Device-to-Device Communications,” IEEE ICCC, Xi’ An, China Aug. 2013.
- Lingyang Song and Zhu Han, “Device-to-Device Communications and Networks,” IEEE Globe Communication Conference (Globecom), Atlanta, USA, Dec. 2013.
- Zhu Han and Lingyang Song, “Smart Grid Communications and Networking,”7th International Conference on Communications and Networking in China (ChinaCom2012), Kunming, People's Republic of China, Aug. 8-10, 2012
- Ekram Hossain and Zhu Han, “Application of Game Theory for Designing Cognitive Radio Networks," IEEE ICC 2010.

Intended Audience

- Researchers and communications engineers interested to study the new applications and techniques of UAV.
- New comers interested in the state-of-the-art research on UAV.
- Engineers in the field of UAV deployment.
- Graduate and undergraduate students interested in obtaining comprehensive information on the design, evaluation, and applications of UAV.

Instructors’ Previous Work

- Haichao Wang, Jinlong Wang, Jin Chen, Guoru Ding, Yuzhou Li, and Zhu Han, “Spectrum Sharing Planning for Full Duplex UAV Relaying Systems with Underlaid D2D Communications," to appear IEEE Journal on Selected Areas in Communications, Special Issue on Airborne Communication Networks.
- S. Zhang, H. Zhang, B. Di, and L. Song, “Joint Trajectory and Power Optimization for UAV Sensing over Cellular Networks”, IEEE Commun. Lett., early access.
- Yuzhe Yang, Zijie Zheng, Kaigui Bian, Lingyang Song, and Zhu Han, “Realtime Profiling of Fine-Grained Air Quality Index Distribution using UAV Sensing," IEEE Transactions on Internet of Things, vol. 5, no. 1, pp. 186-198, February 2018.
- S. Zhang, H. Zhang, Q. He, K. Bian, and L. Song, “Power and Trajectory Optimization for UAV Relay Networks”, IEEE Commun. Lett., vol. 22, no. 1, pp. 161-164, Jan. 2018.

- Jingjing Wang, Chunxiao Jiang, Zhu Han, Yong Ren, and Hanzo Lajos, "Taking Drones to the Next Level: Cooperative Distributed Unmanned-Aerial-Vehicular Networks for Small and Mini Drones," IEEE Vehicular Technology Magazine, vol. 12, no. 3, pp. 73-82, September 2017.
- Walid Saad, Zhu Han, Tamer Basar, Merouane Debbah, and Are Hjorungnes, "Hedonic Coalition Formation for Distributed Task Allocation among Wireless Agents," IEEE Transactions on Mobile Computing, vol. 10, no.9, pp.1327-1344, September 2011.
- Zhu Han, A. Lee Swindlehurst, and K. J. Ray Liu, "Optimization of MANET Connectivity Via Smart Deployment/Movement of Unmanned Air Vehicles," IEEE Transactions on Vehicular Technology, vol.58, no.7, pp.3533-3546, September 2009.
- Hongliang Zhang, Lingyang Song, Zhu Han, and Geoffrey Ye Li, "Cellular Network Controlled UAV-to-X Communications for 5G," submitted to IEEE Wireless Communication Magazine, special issue on U2X communication in 5G.
- Jinlong Wang, Haichao Wang, Zhen Xue, Linyuan Zhang, Guoru Ding, Yuhua Xu, and Zhu Han, "Robust Spectrum Sharing in Air-Ground Integrated Networks: Opportunities and Challenges," submitted to IEEE Wireless Communications, Special Issue on Integrating UAVs into 5G and Beyond.
- Haichao Wang, Jinlong Wang, Guoru Ding, Feifei Gao, and Zhu Han, "Path Planning in Heading-Constrained UAV Communications," submitted to IEEE Transactions on Wireless Communications.
- Yuzhe Yang, Zijie Zheng, Kaigui Bian, Lingyang Song, and Zhu Han, "Real-time profiling of fine-grained air quality index distribution using uav sensing," IEEE Internet of Things Journal, vol. 5, no. 1, pp. 186-198, Feb. 2018.
- Jinlong Wang, Haichao Wang, Zhen Xue, Linyuan Zhang, Guoru Ding, Yuhua Xu, and Zhu Han, "Robust Spectrum Sharing in Air-Ground Integrated Networks: Opportunities and Challenges," submitted to IEEE Wireless Communications, Special Issue on Integrating UAVs into 5G and Beyond.
- Lixin Li, Zihe Zhang, Xu Li, Ang Gao, Wei Chen, Miao Pan, and Zhu Han, "Downlink Interference Control in Dense Interference-Aware Drone Small Cells Networks: A Mean Field Game Approach," submitted to IEEE Transactions on Communications.
- J. Hu, H. Zhang, and L. Song, "Reinforcement Learning for Decentralized Trajectory Design in Cellular UAV Networks with Sense-and-Send Protocol", IEEE Internet Things J., under revision.
- S. Zhang, H. Zhang, B. Di, and L. Song, "Cellular Controlled Cooperative Unmanned Aerial Vehicle Networks with Sense-and-Send Protocol", IEEE Internet Things J., under revision.
- S. Zhang, H. Zhang, B. Di, and L. Song, "Cellular UAV-to-X Communications: Design and Optimization for Multi-UAV Networks", IEEE Trans. Wireless Commun., submitted.
- J. Hu, H. Zhang, L. Song, Z. Han, and H. V. Poor, "Reinforcement Learning for Cellular Unmanned Aerial Vehicle Networks", IEEE Commun. Mag., submitted.
- Z. Hu, Z. Zheng, T. Wang, L. Song and X. Li, "UAV Offloading: Spectrum Trading Contract Design for UAV Assisted Offloading in Cellular Networks," submitted to IEEE Transactions on Wireless Communications
- Zihe Zhang, Lixin Li, Xiaomin Liu, Wei Liang, Zhu Han, "Matching-Based Resource Allocation and Distributed Power Control Using Mean Field Game in the NOMA-Based UAV Networks," Asia-Pacific Signal and Information Processing Association Annual Summit and Conference, Honolulu, Hawaii, November 2018.
- Yang Xu, Lixin Li, Zihe Zhang, Kaiyuan Xue, and Zhu Han, "A Discrete-Time Mean Field Game in Multi-UAV Wireless Communication System," IEEE/CIC International Conference on Communications in China, Beijing, China, August 2018.
- Yuzhe Yang, Zijie Zheng, Kaigui Bian, Yun Jiang, Lingyang Song, and Zhu Han, "Arms: A Fine-grained 3D AQI Realtime Monitoring System by UAV," IEEE Globecom, Singapore, December 2017.
- Yawei Pang, Yanru Zhang, Yunan Gu, Miao Pan, Pan Li and Zhu Han, "Efficient Data Collection for Wireless Rechargeable Sensor Clusters in Harsh Terrains Using UAVs," IEEE Global Communications Conference, December, Austin, TX, 2014.

Fog Computing: *An Enabling Paradigm for Intelligent Services*

1. Abstract, objectives and motivation

A key networking trend during the past decade is to push various capabilities, such as computation, control, and storage, to the cloud. Such an over-dependence on the cloud, however, indicates that availability and fault tolerance issues in the cloud would directly impact millions of end-users. Such a cloud-centric architecture is not suitable for those many delay-sensitive applications in 5G and IoT. To deal with these challenges, the cloud is now "descending" to the network edges and diffuses among the client devices in both mobile and wireline networks. Such a transition leads to the new paradigm of fog computing and networking.

This tutorial will provide an overview of fog computing and networking, both in terms of industry practices and academic researches, with emphases on various intelligent services enabled by fog computing. The key topics are: (1) Overview of Fog Computing and Networking; (2) Computation Offloading and Resource Pooling for Fog Networking; (3) Distributed Learning and Applications in Fog Networks; (4) Enabling Low-Latency Applications in Fog Access Network; and (5) Fog Computing Technologies for 5G and IoT Applications.

2. Timeliness and intended audience

Timeliness:

The emerging Internet of Things (IoT), 5G wireless systems, and a wide range of new applications such as embedded Artificial Intelligence (AI) have created the needs for a new computing and networking paradigm – Fog. Rather than limiting computing to a small number of massive Clouds, Fog distributes computing, storage, control, and networking services closer to the end users along the Cloud-to-Thing continuum. The immersive Fog can address many challenges that Cloud alone cannot effectively address, such as meeting stringent latency requirements, supporting a large number of resource-constrained devices, overcoming network bandwidth constraints, and handling many new security concerns that arise from the emerging IoT. Fog also enables new and disruptive business models. In addition to allowing services to be provided closer to users, Fog will enable unified end-to-end service platforms and services that combine resources distributed in the Cloud, between the Cloud and the Things, and on the Things. This new Fog computing paradigm can fundamentally reshape computing and networking architectures and the industry landscapes.

Intended audience:

The target audience of this tutorial will be researchers and engineers in the telecommunications industry, with a basic understanding of modern communications and networking systems.

3. Name, affiliation, and a short biography of each tutorial speaker

Name: Xiliang Luo

Affiliation: ShanghaiTech University, China

Bio: Xiliang Luo (S'03-M'06-SM'18) received the B.Sc. degree in physics from Peking University, Beijing, China, in 2001, and the M.Sc. and Ph.D. degrees in electrical engineering from the University of Minnesota, Minneapolis, MN, USA, in 2003 and 2006, respectively. After finishing his Ph.D. studies, he joined Qualcomm Research and carried out cutting edge research at different posts as a Senior Engineer (2006), a Staff Engineer (2010), and then a Senior Staff Engineer (2013), where he was involved in the system designs, analyses, and standardization of 4G LTE. He was the designer of various enhancements to Qualcomm's current LTE solutions and led the designs of Qualcomm's next generation LTE modem for heterogeneous networks from initial concept to final completion. Since 2014, he has been with the School of Information Science and Technology, ShanghaiTech University, Shanghai, China, as an Associate Professor. He has authored or coauthored over 70 research papers in top journals and conferences. He is the co-inventor of over 70 US and international patents, the majority of which have been adopted into current LTE and LTE-Advanced standards. His current research interests include signal processing, communications, and information theory. In particular, he is interested in researches combining information theory and signal processing theory that can shape and guide the designs of next generation data and information processing networks. In 2017, he received the Excellent Paper Award from the IEEE ICUFN. He is currently the Co-Director of Shanghai Institute of Fog Computing Technology (SHIFT). He is also serving as an Editor for the IEEE Transactions on Wireless Communications.

Name: Xu Chen

Affiliation: Sun Yat-sen University, China

Bio: Dr. Xu Chen is a full Professor with Sun Yat-sen University, Guangzhou, China. He received the Ph.D. degree in information engineering from the Chinese University of Hong Kong in 2012, and worked as a Postdoctoral Research Associate at Arizona State University, Tempe, USA from 2012 to 2014, and a Humboldt Scholar Fellow at Institute of Computer Science of University of Goettingen, Germany from 2014 to 2016. He has published over 60 scientific papers at the leading international conferences and journals, which include top-tier conferences such as MOBIHOC, ICDCS and INFOCOM and top-tier journals such as IEEE JSAC, IEEE TMC and IEEE TON. He is the winner of the prestigious Humboldt research fellowship awarded by Alexander von Humboldt-Foundation, the Honorable Mention Award (first runner-up of best paper award) in 2010 IEEE international conference on Intelligence and Security Informatics (ISI), the Best Paper Runner-up Award of 2014 IEEE International Conference on Computer Communications (INFOCOM), 2017 the Best Paper Award of IEEE International Conference on Computer Communications (ICC), and 2017 IEEE ComSoc Young Professional Best Paper Award.

Dr. Chen has served an Associate Editor of IEEE Access Journal, EURASIP Journal on Wireless Communications and Networking, Section Editor of Springer Handbook of Cognitive Radios, guest editor of International Journal of Big Data Intelligence, the general co-chair of GameNet'17, the chair of 2018 Wi-Opt EFC-IoT workshop and 2018 ICCCN ECN workshop, the Fog and Edge Computing track chair of IEEE ICPADS'18, the wireless network symposium chair of IEEE WCNC'17, the special track co-chair of ISVC'15, publicity co-chair of NetGCoop'14, and serves as a technical program committee (TPC) member for many leading conferences including ACM MOBIHOC, IEEE INFOCOM, GLOBECOM, ICC, and WCNC.

Name: Ai-Chun Pang

Affiliation: National Taiwan University

Bio: Prof. Ai-Chun Pang received the B.S., M.S., and Ph.D. degrees in Computer Science and Information Engineering from National Chiao Tung University, Taiwan, in 1996, 1998 and 2002, respectively. She joined the Department of Computer Science and Information Engineering (CSIE), National Taiwan University (NTU), Taipei, Taiwan in 2002. She is now a Professor in CSIE and INM, and is also an Adjunct Research Fellow of Research Center for Information Technology Innovation, Academia Sinica, Taiwan. Her research interests include the design and analysis of wireless and multimedia networking, mobile communications, and cloud datacenter networking.

Name: Ming-Tuo Zhou

Affiliation: Shanghai Institute of Microsystem and Information Technology (SIMIT), Chinese Academy of Sciences

Bio: Ming-Tuo Zhou (S'01-M'04-SM'11) received his PhD degree in 2003. He joined Shanghai Research Center for Wireless Communications (WiCO) and Shanghai Institute of Microsystem and Information Technology (SIMIT), Chinese Academy of Sciences (CAS) in September 2016, and now is a professor. He was a senior research scientist at the Smart Wireless Laboratory of the (Japan) National Institute of Information and Communications Technology (NICT) Singapore Representative Office during July 2004 to August 2016. He has co-authored about 70 technical papers, 6 book chapters, and co-edited two technical books. He was the Technical Co-Editor of IEEE 802.16n and IEEE 802.16.1a, a voting member and technical contributor of IEEE 802.11, 802.15, and 802.16 Working Groups, and a member of the Test and Certification Working Group of Wi-SUN Alliance. He is the chair of Testbed Working Group of OpenFog Consortium since September 2017. He has served as Technical Program Committee member, Finance Chair, Local Arrangement Chair, and Session Chair at more than 40 international conferences including ICC, GLOBECOM, and PIMRC. His current research interests include fog computing, 5G, wireless sensor networks, industrial Internet of things, Industry 4.0, and cyber-physical systems.

4. A description of the technical issues that the tutorial will address, emphasizing its timeliness

The industry and academia have begun to devote significant efforts to develop Fog computing technologies. A global industry-academia consortium – the Open Fog Consortium – has been launched with participation from major industry movers to accelerate the development and market adoption of the Fog computing technology and to develop an open Fog reference architecture. The many profound research challenges in Fog computing and networking are also drawing a booming interest in the academia.

First, we will provide an overview of the fog computing and networking. In particular, this tutorial will try to answer the following questions including "what is fog computing", "how it is different", and "why now". Furthermore, we will present a set of selected use cases for fog computing. We will also shed light on selected technical challenges and future research directions.

Second, fog computing enables computation offloading and resource pooling for fog networking. In this tutorial, we will overview recent advances and studies in both competitive computation offloading and cooperative computation offloading in fog networks. Further, we will also discuss mobile edge resource pooling for fog networks.

Third, we will present distributed learning and applications in fog networks. As the fog network becomes denser and more complicated, solutions based on global knowledge about the system become inapplicable and distributed algorithms are becoming more and more important. In this part, we will present distributed resource management for fog networks, distributed learning for computation task offloading, and the algorithms to learn and pick the right fog node to access the fog network.

Fourth, the ultra low-latency operations of communications and computing enable many potential IoT applications and thus have gained widespread attention recently. Existing mobile devices and telecommunication systems may not be able to provide the highly desired low-latency computing and communications services. To meet the needs of those applications, we introduce Fog-Radio Access Network (F-RAN) architecture, which brings the efficient computing capability of the cloud to the edge of network. We first introduce the F-RAN and its rationale in serving ultra low-latency applications. Then we depict the need of a service framework for F-RAN to cope with the complex tradeoff among the performance, the computing cost, and communication cost. We will also present some other technical challenges and open issues for deploying F-RAN in future mobile telecommunications networks.

Finally, 5G network is conceived as an extremely flexible and highly programmable E2E connect-and-compute infrastructure. Unlike dedicated hardware platform employed by current 4G system, General Processing Platform (GPP) based architecture is believed to be more suitable to achieve a software defined mobile network and resource/network function virtualization in diversified 5G use cases and fog communication scenarios. We will introduce the overall open 5G Platform based on GPP. Then we will describe the detailed architecture of the platform, including the software defined RAN, software defined mobile network and EPC. We also show the IoT applications based on this GPP-based 5G network and the challenges for implementing Open 5G Platform is also discussed in this tutorial. Developed fog testbed and applications will also be discussed.

5. An outline of the tutorial content, including its tentative schedule

Outline:

- Overview of Fog Computing and Networking (X. Luo)
    - What is fog computing, how it is different, and why now?
    - Selected use cases for fog computing
    - Selected technical challenges and future research directions
- Computation Offloading and Resource Pooling for Fog Networking (X. Chen)
    - Competitive computation offloading in fog networks

- Cooperative computation offloading in fog networks
    - Mobile edge resource pooling for fog networks
- Distributed Learning and Applications in Fog Networks (X. Luo)
    - Distributed resource management for fog networks
    - Distributed learning for computation task offloading
    - Learn and pick the right serving node to access
- Enabling Low-Latency Applications in Fog Access Network (A.-C. Pang)
    - Low-latency realization in 5G
    - How Fog-Radio Access Network (F-RAN) works
    - Resource management in F-RAN
    - Container-based service provisioning for F-RAN
- Fog Computing Technologies for 5G and IoT Applications (M.-T. Zhou)
    - General Processing Platform (GPP) based Open 5G platform
    - IoT applications based on the GPP Open 5G platform
    - Challenges for implementing the GPP Open 5G platform
    - Fog Testbed based on Open 5G and AI Technologies

Schedule:

- 09:00-09:25am Overview of Fog Computing and Networking (X. Luo)
- 09:25-10:00am Computation Offloading and Resource Pooling for Fog Networking (X. Chen)
- 10:00-10:35am Distributed Learning and Applications in Fog Networks (X. Luo)
- 10:35-11:05am Tea Break
- 11:05-11:40am Enabling Low-Latency Applications in Fog-Radio Access Network (A.-C. Pang)
- 11:40-12:15pm Fog Computing Technologies for 5G and IoT Applications (M.-T. Zhou)

6. If appropriate, a description of the past/relevant experience of the speaker(s) on the topic of the tutorial

- 2017 GLOBECOM tutorial: "Fog as a Service Technology (FA^{2}ST): a New Approach for the Development of 5G Applications", by Tao Zhang, Xiliang Luo, Ai-Chun Pang, and Yang Yang
- 2018 ICC tutorial: "Fog Services and Enabling Technologies", by Yang Yang, Jianwei Huang, Xiliang Luo, and Tao Zhang

7. A description of previous tutorial experience of the speaker(s), and past versions of the tutorial

See also the answer to previous question. The speakers have delivered tutorials on fog computing in GLOBECOM2017 and ICC2018.

The following components of the tutorial were delivered at ICC2018 "Fog Services and Enabling Technologies":

- Overview of Fog Computing and Networking
- Distributed Resource Management/Allocation in Fog Networks

8. State if a similar tutorial has been offered in recent ICC & Globecom (last two years) and how your tutorial differs

Please refer to the answers to previous two questions. With new developments of fog computing technologies and standardization, e.g., the recently launched OpenFog reference architecture, the IEEE Fog Computing and Networking Standards, and related technologies, this tutorial at ICC'19 (if accepted) will be significantly improved **with more emphases on new use cases and various intelligent services enabled by fog**.

Communication Networks Design: Model-Based, Data-Driven, or Both?

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I. Proposed Format

The present tutorial can be given either as a half-day (3 hours) or as a full-day (6 hours) event depending on the interest of organizers and audience.

II. Importance and Timeliness

Data-driven approaches are not new to wireless communications, but their implementation through deep learning techniques has never been considered in the past, even though deep learning is the most widely used machine learning approach in other fields than wireless communication. In our opinion, this is mainly due to the fact that, unlike other fields of science where theoretical modeling is particularly hard, thus motivating the use of data-driven approaches, wireless communications could always rely on strong mathematical models for system design. However, the situation is rapidly changing, and very recently the use of deep learning has started being envisioned for wireless communications too. Indeed, the increasing complexity of wireless networks makes it harder and harder to come up with theoretical models that are at the same time accurate and tractable. The rising complexity of 5G and beyond 5G networks is exceeding the modeling and optimization possibilities of standard mathematical tools. In addition, the use of deep learning for communications is further facilitated by:

- The recent exponential growth of connected devices, which provides an increasing amount of data to process.
- Recent technological improvements (e.g. the use of GPUs), which make deep learning algorithms practical for wireless networks.
- Recent technologies (e.g. Blockchain) facilitate the secure and accurate processing of large databases distributed over multiple network nodes.

As evidence of the rising interest for applications of deep learning to communication systems, the European Telecommunication Standards Institute recently formed the *Experiential Network Intelligence Group*, with the aim of initiating the standardization process towards an AI-based wireless networks architecture.

Nevertheless, purely data-driven approaches require a huge amount of data to operate, which might be difficult and/or expensive to acquire in practical large-scale scenarios. This issue has been acknowledged also by the deep learning community, for which one major research trend lies precisely in the development of techniques able to exploit any prior information that is available about the problem at hand in order to reduce the amount of data needed to achieve given performance levels. In this context, the specific field of communication theory presents a major opportunity thanks to the availability of many more theoretical models compared to other fields of science. Indeed, despite being usually inaccurate and/or cumbersome, available communication models still provide important prior information that should be exploited. Accordingly, the overall aim of this tutorial is to put forth the idea that theoretical modeling and data-driven approaches are not two contrasting paradigms, but should rather be used jointly to get the most out of them.

This tutorial will cover the most recent approaches to merge advanced deep learning techniques with the latest model-based methodologies for system-level design and optimization of wireless networks. The tutorial is based on the following publications by the tutorial's authors:

- A. Zappone, M. Di Renzo, M. Debbah, "From Model-Based to Data-Driven Wireless Communications. When is Deep Learning the answer?", invited paper at *IEEE Transactions on Communications*, submitted, October 2018.
- A. Zappone, M. Di Renzo, M. Debbah, T. T. Lam, X. Qian, "Model-Aided Wireless Artificial Intelligence: Embedding Expert Knowledge in Deep Neural Networks Towards Wireless Systems Optimization", *IEEE Communications Maga-*

zine, submitted, August 2018, available online at http://de.arxiv.org/pdf/1808.01672.pdf

- M. Di Renzo, A. Zappone, T. T. Lam, M. Debbah, "System-Level Modeling and Optimization of the Energy Efficiency in Cellular Networks - A Stochastic Geometry Framework", *IEEE Transactions on Wireless Communications*, vol. 17, no. 4, pp. 2539 - 2556, April 2018.

The detailed description of the tutorial content is provided next.

III. Outline

The tutorial is organized in the following main parts.

A. *Data-driven design of wireless networks*

The data-driven paradigm to the design of wireless networks is presented. This part of the tutorial will first introduce the fundamental notions of machine learning, explaining how it can be used to carry out a fully data-driven design of wireless networks. The notions of underfitting, overfitting and algorithm capacity will be explained and the main advantages and drawbacks of machine learning approaches will be discussed.

Deep Learning. Next, the tutorial will describe in detail the deep learning approach. It will be explained how its distinctive feature compared to generic machine learning methods is the use of artificial neural networks, and the resulting advantages that are granted. Afterwards, the main artificial neural networks architectures will be described, focusing in particular on feedforward, convolutional, and recurrent neural networks. The peculiar features of each class of networks, as well as its application domains will be discussed. Finally, the main methods for neural network training will be introduced and tips and tricks to improve the training process will be explained.

B. *Model-based design of wireless networks*

The key performance metrics to be optimized when designing a wireless communication network will be introduced, such as throughput, spectral efficiency, energy efficiency, motivating their importance and mathematical properties that can be exploited for their optimization. The mathematical tools at the basis of the design of modern wireless networks will be introduced in more detail, focusing in particular on the frameworks of stochastic geometry and fractional/sequential programming.

Stochastic geometry. The theory of point processes and stochastic geometry constitute essential mathematical tools to provide general and accurate models for dense and heterogeneous networks. At first, the audience will be given a solid background and comprehensive description of stochastic geometry modeling, by introducing key theorems and by explaining how to formulate problems from the standpoint of system-level analysis and optimization. Next, it will be shown how recent stochastic geometry results enable to come up with a realistic, yet tractable, expression for the users' spectral/energy efficiency. Also, the suitability of stochastic geometry for modeling and analyzing wireless networks is substantiated with the aid of experimental data for the locations of cellular base station and for the footprints of buildings, which are taken from two publicly available databases.

Sequential fractional programming. Most resource allocation problems commonly encountered in realistic wireless networks are not convex, requiring in general an exponential complexity to be solved. In this context, sequential fractional programming is a recently proposed approach that merges the theories of fractional programming, generalized concavity, and sequential programming, to provide performing resource allocations with affordable complexity, in situations in which the problem to solve does not lend itself to being tackled by standard optimization theory methods. These frameworks will be explained in detail, and then it will be shown how they can be merged to solve many relevant resource allocation problems in realistic wireless network setups, to maximize common performance measures, such as the network spectral and energy efficiency. Fairness issues among the network users will also be taken into account when solving resource allocation problems.

C. *Embedding expert knowledge into deep learning*

After describing the main data-driven and model-based approaches for wireless network design, the tutorial will focus on how these two seemingly separate paradigms can be merged to obtain better performance, thus motivating why, rather than being seen as mutually exclusive competitors, future research should explore the co-existence of model-based and data-driven techniques. Several methods of implementing this cross-fertilization will be discussed: 1) it will be shown how an artificial neural network can learn to optimize, i.e. solve resource allocation problems with a much lower complexity compared to standard optimization methods; 2) it will be shown how transfer learning methodologies applied to (possibly inaccurate) theoretical wireless models lead to significant complexity reductions compared to fully data-driven approaches; 3) it will be shown how traditional reinforcement learning algorithms can be more efficiently implemented through deep learning, leading to the deep reinforcement learning framework.

Applications. Next, the tutorial will describe many relevant applications to show and quantify the advantages of embedding expert knowledge into data-driven methods, considering diverse system scenarios, such as dense heterogeneous cellular networks, energy-efficient networks, network-slicing systems, and chemical-based communication systems. At first, the applications will be tackled taking a model-based approach. In particular, it will be shown how the frameworks of stochastic geometry and sequential fractional programming can be used together to enable system-level modeling and optimization of wireless networks, allowing the optimization of the system energy efficiency, spectral efficiency, throughput, as well as the characterization of the system energy-rate trade-off.

Next, the same applications will be tackled from a data-driven perspective, starting with the description of how a fully-data driven approach would operate, and then highlighting the limitations of fully-data driven methodologies and the benefits represented by the integration of expert knowledge into the design process. For each application, a numerical analysis will be presented to quantify the gains granted by the joint use of model-based and data-driven methodologies.

Finally, concluding remarks are provided to summarize the take-home points of the tutorial.

Primary Audience. Students, academic researchers, industry affiliates and individuals working for government, military, science and technology institutions who are interested in studying emerging tools for wireless network design, understanding the connection and trade-off between model-based and data-driven approaches, enabling to model and optimize candidate network architectures, transmission technologies and communication protocols towards the maximization of multiple performance functions. The tutorial is unique of its kind, as it tackles both the most sophisticated model-based approaches for network design, and the use of fully data-driven approaches, exploring possible cross-fertilization among these two seemingly separate worlds. Therefore, the audience will receive a unique training experience.

D. Detailed Outline

The detailed outline of the tutorial is as follows:

- **Introduction**
  1) Overview on model-based wireless networks design
  2) Overview on data-driven wireless networks design
- **Fundamentals of machine learning for communications**
  1) A definition of machine learning
  2) Supervised vs. unsupervised learning
  3) Underfitting, overfitting, and capacity
- **Deep learning vs. Machine learning**
  1) Artificial neural networks
  2) Feedforward, convolutional, recurrent neural networks
  3) Training artificial neural networks
- **Model-based approaches for wireless network design**
  1) Performance metrics definition and motivation
  2) Stochastic geometry for network planning
  3) Optimization methods for resource allocation
- **Embedding models into deep learning**
  1) Model-based or data-driven?
  2) Expert knowledge into artificial neural networks
  3) Learning to optimize
  4) Transfer learning
  5) Deep reinforcement learning
- **Applications**
  1) Resource allocation in dense heterogeneous cellular networks
  2) Resource allocation in network-slicing systems
  3) Resource allocation in energy-efficient cellular networks
  4) Optimization of beyond-RF wireless networks
- **Concluding remarks**

IV. Tutorial Speakers

- **Dr. Alessio Zappone** - Paris-Saclay University – Laboratory of Signals and Systems (CNRS - CentraleSupelec - Univ. Paris-Sud), Paris, France; alessio.zappone@l2s.centralesupelec.fr, https://scholar.google.com/citations?user=gjdjPu4AAAAJ&hl=it&oi=ao.
- **Dr. Marco Di Renzo** - Paris-Saclay University – Laboratory of Signals and Systems (CNRS - CentraleSupelec - Univ. Paris-Sud), Paris, France; marco.direnzo@l2s.centralesupelec.fr, http://scholar.google.fr/citations?user=5dRt0OoAAAAJ&hl=en&oi=ao.
- **Prof. Merouane Debbah** - Paris-Saclay University – Laboratory of Signals and Systems (CNRS - CentraleSupelec - Univ. Paris-Sud), Paris, France; merouane.debbah@centralesupelec.fr, https://scholar.google.fr/citations?user=HU5I0X4AAAAJ&hl=fr.

V. Short CVs of the Tutorial Speakers

Dr. Alessio Zappone obtained his Ph.D. degree in electrical engineering in 2011 from the University of Cassino and Southern Lazio, Cassino, Italy. His Ph.D. studies were focused on distributed algorithms for energy-efficient resource allocation in wireless networks. After obtaining his Ph.D. Alessio worked as a Post-doc researcher with CNIT (Consorzio Nazionale Interuniversitario per le Telecomunicazioni) until 2012, working on both centralized and distributed energy efficiency optimization in the framework of the FP7 EU-funded project TREND. Afterwards, Alessio has been with the Technische Universität Dresden, Germany, managing the project CEMRIN on energy-efficient resource allocation in wireless networks, funded by the German Research Foundation. Since 2016 he is adjunct professor at the University of Cassino and Southern Lazio. In 2017 he was the recipient of the Marie Curie Individual Fellowship for experienced researchers BESMART, carried out with the LANEAS group of CentraleSupelec.

Dr. Zappone is an IEEE Senior Member, an Associate Editor of the IEEE Signal Processing Letters, and has been a Guest Editor of the IEEE JSAC Special issue on "Energy-Efficient Techniques for 5G Wireless Communication Systems". He was appointed *exemplary reviewer* for both the *IEEE Transactions on Communications* and *IEEE Transactions on Wireless Communications* in 2017.

Dr. Marco Di Renzo received the Ph.D. degree in Electrical and Information Engineering from the University of L'Aquila, Italy, in 2007. In 2013, he received the Habilitation à Diriger des Recherches (Doctor of Science) degree from the University Paris-Sud, Paris, France. He held various research and academic positions at the University of L'Aquila (Italy), at Virginia Tech (USA), at CTTC (Spain), at The University of Edinburgh (UK). Since 2010, he is Associate Professor with the Laboratory of Signals and Systems of Paris-Saclay University – CNRS, CentraleSupélec, Univ Paris Sud, France. He is a Distinguished Visiting Fellow of the Royal Academy of Engineering (UK), and co-founder of the university spin-off company WEST Aquila s.r.l., Italy.

Dr. Di Renzo received a special mention for the outstanding five-year (1997-2003) academic career, University of L'Aquila, Italy; the THALES Communications fellowship (2003-2006), University of L'Aquila, Italy; the 2004 Best Spin-Off Company Award, Abruzzo Province, Italy; the 2008 Torres Quevedo Award, Spain; the "Dérogation pour l'Encadrement de Thèse" (2010), University of Paris-Sud, France; the 2012 IEEE CAMAD, 2014 IEEE CAMAD, 2014 IEEE ATC, 2015 IEEE ComManTel Best Paper Awards; the 2012 and 2014 IEEE WIRELESS COMMUNICATIONS LETTERS Exemplary Reviewer Certificate; the 2013 IEEE VTC-Fall Best Student Paper Award; the 2013 Network of Excellence NEWCOM# Best Paper Award; the 2013 IEEE TRANSACTIONS ON VEHICULAR TECHNOLOGY Top Reviewer Award; the 2013 IEEE-COMSOC Best Young Researcher Award for Europe, Middle East and Africa (EMEA Region); the 2014 Royal Academy of Engineering Distinguished Visiting Fellowship, UK; the 2014 IEEE CAMAD Best Demo Award; and the 2015-2018 CNRS Award for Excellence in Research and in Advising Doctoral Students; and the 2017 IEEE-SEE Alain Glavieux Award.

He serves as Editor of the IEEE COMMUNICATIONS LETTERS and IEEE TRANSACTIONS ON COMMUNICATIONS (Heterogeneous Networks Modeling and Analysis). He is an IEEE Senior Member and a EURACON Member, and a **Distinguished Lecturer of the IEEE Communications and IEEE Vehicular Technology Societies**.

Prof. M. Debbah Mérouane Debbah entered the Ecole Normale Suprieure Paris-Saclay (France) in 1996 where he received his M.Sc and Ph.D. degrees respectively. He worked for Motorola Labs (Saclay, France) from 1999-2002 and the Vienna Research Center for Telecommunications (Vienna, Austria) until 2003. From 2003 to 2007, he joined the Mobile Communications department of the Institut Eurecom (Sophia Antipolis, France) as an Assistant Professor. Since 2007, he is a Full Professor at CentraleSupelec (Gif-sur-Yvette, France). From 2007 to 2014, he was the director of the Alcatel-Lucent Chair on Flexible Radio. Since 2014, he is Vice-President of the Huawei France R&D center and director of the Mathematical and Algorithmic Sciences Lab. His research interests lie in fundamental mathematics, algorithms, statistics, information and communication sciences research. He is an Associate Editor in Chief of the journal Random Matrix: Theory and Applications and was an associate and senior area editor for IEEE Transactions on Signal Processing respectively in 2011-2013 and 2013-2014. Mrouane Debbah is a recipient of the ERC grant MORE (Advanced Mathematical Tools for Complex Network Engineering). He is a IEEE Fellow, a WWRF Fellow and a member of the academic senate of Paris-Saclay. He has managed 8 EU projects and more than 24 national and international projects. He received

19 best paper awards, among which the 2007 IEEE GLOBECOM best paper award, the Wi-Opt 2009 best paper award, the 2010 Newcom++ best paper award, the WUN CogCom Best Paper 2012 and 2013 Award, the 2014 WCNC best paper award, the 2015 ICC best paper award, the 2015 IEEE Communications Society Leonard G. Abraham Prize, the 2015 IEEE Communications Society Fred W. Ellersick Prize, the 2016 IEEE Communications Society Best Tutorial paper award, the 2016 European Wireless Best Paper Award, the 2017 Eurasip Best Paper Award and the 2018 IEEE Marconi Prize Paper Award as well as the Valuetools 2007, Valuetools 2008, CrownCom2009, Valuetools 2012, SAM 2014 and 2017 IEEE Sweden VT-COM-IT Joint Chapter Best Student paper awards. He is the recipient of the Mario Boella award in 2005, the IEEE Glavieux Prize Award in 2011 and the Qualcomm Innovation Prize Award in 2012. He is the co-founder of Ximinds and Ulanta.

VI. Relation to Past Tutorials

To the best of our knowledge, the only tutorial dealing with deep learning methods for application to wireless communications is:

[T.1] S. ten Brink, J. Hoydis, S. Cammerer, and S. Dörner, "Deep Learning for Communications", presented at the 2018 IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC), September 2018, Bologna, Italy.

Nevertheless, a fundamental difference between our proposed tutorial and the above tutorial [T.1] is that, while [T.1] focused specifically on deep learning aspects, our tutorial considers the cross-fertilization between data-driven methods and model-based approaches. Several methods are discussed that show how deep learning methods can be made more effective when used in conjunction with model-based methods which exploit expert knowledge about the problem at hand. Our tutorial will present advanced frameworks like transfer learning and deep reinforcement learning, which are not discussed by [T.1].

Moreover, the above tutorial [T.1] presented applications related to physical-layer problems like data encoding and decoding. Instead, our tutorial is more focused on cross-layer aspects like resource management for system design. Also, all applications will quantitatively show the benefit obtained by merging deep learning with theoretical modeling approaches.

VII. Previous Lecture and Tutorial Experience of the Speakers

Dr. Alessio Zappone has given the tutorials: *Vertical-Oriented End-to-End Orchestration in 5G Networks: Modeling, Optimization, Implementation, and Verification*, (EUSPICO 2018, EuCNC 2018), *Energy-Neutral System-Level Analysis and Optimization of 5G Wireless Networks*, (IEEE PIMRC 2016, EUSIPCO 2016, IEEE GLOBECOM 2016, IEEE ISWCS 2016, EuWireless 2016); *Energy Efficiency in 5G Heterogeneous and Small-Cell Wireless Networks* (IEEE ISWCS 2014), *Energy-Efficient Resource Allocation for 5G Wireless Networks* (IEEE ICASSP 2016), *Energy-efficient design of (5G and beyond 5G) wireless networks*, (2016 Tyrrhenian Workshop on Digital Communications), as well as the keynote *Fractional programming for Energy Efficiency in 5G Wireless Networks*, at the workshop "Physical and Mathematical Foundations of next-generation Wireless Networks", (ISWCS 2015). In addition, he has given several lectures and seminars on energy efficiency at different international institutions, such as Politecnico di Torino (Torino, Italy, 2013), Beihang University (Beijing, 2013), TU Dresden (Dresden, 2014 and 2016), Universitá di Napoli Federico II (Naples, 2014), Beijing University of Posts and Telecommunications (Beijing, 2016). In addition, Dr. Zappone has regularly taught courses on resource allocation for undergraduate and graduate students.

Dr. Marco Di Renzo is a frequent tutorial/keynote speaker and lecturer at IEEE international conferences. During the last five years, he has presented 20+ tutorials on "Spatial Modulation for MIMO Systems" (WCNC 2013, EW 2013, ICC 2013, VTC-Spring 2013 VTC-Fall 2013, CAMAD 2013, WCCN 2014, EW 2014, EUSIPCO 2014, PIMRC 2014, VTC-Fall 2014, ATC 2014), 7 tutorials on "Energy-Efficient Wireless Networks" (MASCOTS 2014, VTC-Fall 2014, CCNC 2014, CCNC 2015, GLOBECOM 2015, WCNC 2016, IEEE ICC 2016), and 20+ tutorials on "Stochastic Geometry Modeling and Analysis of Wireless Networks" (VTC-Spring 2015, EW 2015, ICC 2015, ICCC 2015, ICUWB 2015, ComManTel 2015, CCNC 2016, VTC-Spring 2016). He was: Invited Lecturer on "Stochastic Geometry Modeling" at IEEE ICNC 2016; Invited Plenary Speaker on "Stochastic Geometry Modeling" at the 2015 GTTI Meeting; Invited Distinguished Lecturer on "Stochastic Geometry Modeling" and "Spatial Modulation" at the 2015 IEEE Italy Section Summer Ph.D. School; Invited Distinguished Lecturer on "Stochastic Geometry Modeling” and “Spatial Modulation” at the 2015 Graduate School of the University of Malaga; Invited Distinguished Speaker on “Stochastic Geometry Modeling” and “Spatial Modulation” at the 2015 NICT Japan - US Network Opportunity (JUNO) Workshop on “Future Energy- and Spectral-Efficient Ultra-Dense Networks”; 2015 Royal Academy of Engineering Distinguished Visiting Lecturer on “Stochastic Geometry Modeling for Self-Powered Networks Design” at 10 British Universities; Invited Distinguished Lecturer on “Stochastic Geometry Modeling” and “Spatial Modulation” at the National Key Laboratory of Science and Technology on Communications (UESTC/China); Invited Speaker on “Stochastic Geometry Modeling” and “Spatial Modulation” at the IEEE Austria Section, Johanned Kepler University; Invited Speaker on “Stochastic Geometry Modeling for Millimeter-Wave Networks” at the 2014 NEWCOM# Emerging Topics Workshop on D2D and mmWave - New Paradigms for 5G”; Invited Distinguished Lecturer on “Stochastic Geometry Modeling” and “Spatial Modulation” at the 2014 IEEE Summer School on “5G Emerging Technologies for Circuits and Systems: Beyond 4G Mobile Systems”; Invited panelist on “Spatial Modulation for Green Networks” at IEEE WCNC 2013. In 2017 and 2018, in addition, he has given 10+ Distinguished Lectures in the USA, Europe, the UK, Asia, etc.

Prof. Mérouane Debbah is a frequent tutorial/keynote speaker at international conferences, where he gave more than 50 lecture talks. Examples of recent speeches by Prof. Debbah include: Catalonia Distinguished Lectureship Program, 2009; Plenary at the Femtocell workshop at Globecom 2010; Newcom++ Spring School on Cognitive Wireless Communication Networks, 2010; Indoor and Outdoor Femto Cells workshop at PIMRC 2010; VTC 2011 BeFEMTO keynote WORKSHOP speaker; Keynote speaker at ICASSP 2011; Tutorial ”Random Matrix Theory for Advanced Communication Systems” at IEEE WCNC 2012; Tutorial ”Random Matrix Advances in Signal Processing” at SPAWC 2013; Plenary speaker at ISWCS 2014; Plenary speaker at Valuetools 2014; Plenary speaker at the International School on Small Cells and 5G, 2015; Tutorial Speaker ”Massive MIMO for 5G” at ISWCS 2015; Plenary speaker at EUSIPCO 2015; Plenary speaker at IEEE BlackSeaCom 2015; Keynote speaker at EuCNC 2015; keynote speaker at the inauguration of the Center for Information and Communication Research at Imperial College in 2015; invited Speaker at CTW 2015; Keynote speaker at CTW 2016; Tutorial ”Wireless Proactive Caching for 5G”, at PIMRC 2016 and at Globecom 2016; Keynote Speaker at LIDS Smart Urban Infrastructure Workshop, MIT, USA and at NSF Workshop on Low-Latency Wireless Random-Access, MIT, USA, 2017; ICC 2017 5G UDN workshop; ISWCS 2017; ISWCS 2018; NextGwin 2018; BalkanCom 2018.

VIII. Material to be Distributed to the Audience

We will provide the audience with the complete set of tutorial slides used during the tutorial presentation. The slides will be provided to the attendees at least one week before the tutorial is held, in order to allow them to make notes during the tutorial presentation. The slides will contain a list of key papers that the attendees will be able to use for their research. The reference list will be organized per thematic area and will provide both survey papers and more advanced material. Furthermore, we will provide the audience with a set of preprint papers (submitted for journal publication and currently under review) that are used to develop part of the tutorial presentation. These papers will be uploaded in a secure website and the audience will have access to them.

Furthermore, we will make available to the audience an electronic copy of the following article:

A. Zappone, M. Di Renzo, and M. Debbah, “From Model-Based to Data-Driven Wireless Communications. When is Deep Learning the answer?”, invited paper at *IEEE Transactions on Communications*, submitted, October 2018,

which provides a comprehensive treatment of deep learning for wireless communications, and represents the basis of the content of the proposed tutorial.

In addition, we will provide a supplementary and unpublished document that summarizes the step-by-step procedure to extract empirical data from OFCOM and Ordnance Survey websites in order to use it for other research activities based on stochastic geometry modeling. Finally, a more comprehensive list of free databases that provide data for the locations of cellular base stations and for the footprints of buildings in urban environments will be provided as well. This includes information on several cities in Europe, USA, Canada, etc.

1) MIMO Transmission with Finite Input Signals

Speakers:
Chengshan Xiao, Lehigh University, USA
Yongpeng Wu, Shanghai Jiao Tong University, China

2) Short CV of Each Tutorial Speaker

Chengshan Xiao (M'99, SM'02, F'10) received a Bachelor of Science degree in electronic engineering from the University of Electronic Science and Technology of China in 1987, a Master of Science degree in electronic engineering from Tsinghua University in 1989, and a Ph.D. in electrical engineering from the University of Sydney in 1997.

Dr. Xiao is the Chandler Weaver Professor and Chair of the Department of Electrical and Computer Engineering at Lehigh University. He is a Fellow of the IEEE and a Fellow of the Canadian Academy of Engineering. Previously, he served as a Program Director with the Division of Electrical, Communications and Cyber Systems at the USA National Science Foundation. He was a senior member of scientific staff with Nortel Networks, Ottawa, Canada, a faculty member at Tsinghua University, Beijing, China, the University of Alberta, Edmonton, Canada, the University of Missouri - Columbia, MO, and Missouri University of Science and Technology, Rolla, MO. He also held visiting professor positions in Germany and Hong Kong. His research interests include wireless communications, signal processing, and underwater acoustic communications. He is the holder of several patents granted in USA, Canada, China and Europe. His invented algorithms have been implemented into Nortel's base station radio products after successful technical field trials and network integration.

Dr. Xiao is the Awards Committee Chair of IEEE Communications Society. Previously, he served as an elected member of Board of Governors, a member of Fellow Evaluation Committee, Director of Conference Publications, Distinguished Lecturer of the IEEE Communications Society, and Distinguished Lecturer of the IEEE Vehicular Technology. He also served as an Editor, Area Editor and the Editor-in-Chief of the IEEE Transactions on Wireless Communications, an Associate Editor of the IEEE Transactions on Vehicular Technology, and of the IEEE Transactions on Circuits and Systems-I. He was the Technical Program Chair of the 2010 IEEE International Conference on Communications, Cape Town, South Africa, a Technical Program Co-Chair of the 2017 IEEE Global Communications Conference, Singapore. He served as the founding Chair of the IEEE Wireless Communications Technical Committee. He received several distinguished awards including 2014 Humboldt Research Award, 2014 IEEE Communications Society Joseph LoCicero Award, 2015 IEEE Wireless Communications Technical Committee Recognition Award, and 2017 IEEE Communications Society Harold Sobol Award.

Yongpeng Wu received the B.S. degree in telecommunication engineering from Wuhan University, Wuhan, China, in July 2007, the Ph.D. degree in communication and signal processing with the National Mobile Communications Research Laboratory, Southeast

University, Nanjing, China, in November 2013.

Dr. Wu is currently a Tenure-Track Associate Professor with the Department of Electronic Engineering, Shanghai Jiao Tong University, China. Previously, he was senior research fellow with Institute for Communications Engineering, Technical University of Munich, Germany and the Humboldt research fellow and the senior research fellow with Institute for Digital Communications, University Erlangen-Nurnberg, Germany. During his doctoral studies, he conducted cooperative research at the Department of Electrical Engineering, Missouri University of Science and Technology, USA. His research interests include massive MIMO/MIMO systems, physical layer security, signal processing for wireless communications, and multivariate statistical theory.

Dr. Wu was awarded the IEEE Student Travel Grants for IEEE International Conference on Communications (ICC) 2010, the Alexander von Humboldt Fellowship in 2014, the Travel Grants for IEEE Communication Theory Workshop 2016, the Excellent Doctoral Thesis Awards of China Communications Society 2016, the Exemplary Editor Award of IEEE Communication Letters 2017, and Young Elite Scientist Sponsorship Program by CAST 2017. He was an Exemplary Reviewer of the IEEE Transactions on Communications in 2015, 2016. He was the lead guest editor for the special issue "Physical Layer Security for 5G Wireless Networks" of the IEEE Journal on Selected Areas in Communications. He is currently an editor of the IEEE Access and IEEE Communications Letters. He has been a TPC member of various conferences, including Globecom, ICC, VTC, and PIMRC, etc.

3) Abstract:

Multiple antennas have played an essential role in spatial multiplexing and diversity transmission for a wide range of communication applications. Most advances in the design of high-speed wireless MIMO systems have been based on information-theoretic principles that demonstrate how to efficiently transmit signals conforming to Gaussian distribution. However, although the Gaussian signal is capacity-achieving, practical systems transmit signals belonging to finite and discrete constellations. Therefore, capacity-achieving transceiver processing based on a Gaussian input signal can be quite suboptimal for practical MIMO systems with discrete constellation input signals. To address this shortcoming, this tutorial aims to provide a comprehensive overview of MIMO transmission design with finite input signals. We first summarize existing fundamental results for MIMO systems with finite input signals. Next, focusing on basic point-to-point MIMO systems, we introduce transmission schemes based on the three most important criteria for communication systems: mutual-information-driven designs, mean-square-error-driven designs, and diversity-driven designs. Furthermore, adaptive transmission designs are proposed that switch among these criteria based on channel conditions to formulate the best transmission strategy. A survey is then given of transmission designs with finite input signals for multiuser MIMO scenarios, including MIMO uplink transmission, MIMO downlink transmission, MIMO interference channel, and MIMO wiretap channel. Additionally, transmission designs with finite input signals are discussed for other multi-antenna systems. Finally, a number of technical challenges that remain unresolved currently are highlighted, and future trends in transmission design with finite input signals are discussed.

4) Brief Description:

The unprecedented growth in the number of mobile data and connected machines continues to push the limits of modern wireless network capacity to accommodate the enormous data demand. Also, emerging new services such as ultra-high-definition multimedia streaming and cloud computing, storage, and retrieval require high cell capacity/end-user data rates and extremely low latency, respectively. It is becoming evident that current 4G technologies will be soon be stretched to near breaking point and will struggle to cope with these emerging demands. Therefore, the development of 5G wireless communication technologies is essential for the deployment of future wireless communication networks.

A 5G air interface incorporates three basic technologies: massive MIMO, millimeter-wave, and small-cell. For millimeter-wave transmission, beamforming achieved with the use of large antenna arrays, including both analog and digital beamforming, can reduce propagation losses. Cell shrinking also requires the deployment of large conformal antenna arrays, the cost of which depends inversely on infrastructure density. Therefore, MIMO technology will continue to play an important role in upcoming 5G and other future wireless networks.

From the information-theoretic point of view, a Gaussian-distributed source signal achieves the fundamental limit of MIMO communication. However, Gaussian transmit signals are rarely used in practical communication systems, mainly for two reasons: (i) the amplitude of a Gaussian transmit signal is unbounded, which may result in substantial distortion for power-limited transmitters; (ii) the probability distribution function of a Gaussian transmit signal is continuous, which will significantly complicate the task of signal detection at the receiver. Therefore, in practice, transmit signals are non-Gaussian input signals taken from finite discrete constellations, such as pulse amplitude modulation (PAM) and/or quadrature amplitude modulation (QAM). Transceivers designed for finite input signals will normally be quite different from those for Gaussian signals. One cannot simply use a design optimized for Gaussian input signals to replace the optimization that needs to be performed for finite input signals.

This tutorial will present a comprehensive review of MIMO transmission design with finite input signals with respect to various design criteria. The tutorial will introduce fundamental research results on finite input signals, discuss precoder designs with finite input signals for point-to-point MIMO systems, outline transmission designs for multiuser MIMO systems under finite alphabet input constraints, and provide a future outlook for transmission designs with finite alphabet input signals.

5) Outline

Part I: Fundamental Research Results on Finite Input Signals

- Fundamental Link between Information Theory and Estimation Theory
- Asymptotic Results in the Low- and High-SNR Regimes
- Asymptotic Results in the Large-System Limit
- Numerical Algorithms for Finite Input Signals

Part II: Precoder Designs for Point-to-Point MIMO Systems with Finite Input Signals

- Designs Based on Mutual Information including Mutual Information Maximization Designs and Low Complexity Designs.
- Design Based on MSE including Linear Transmission Design and Non-linear Transmission Design
- Diversity-Driven Designs including Early Research on Open-Loop Systems, Recent Advances for Open-Loop Systems, and Closed-Loop Systems.
- Adaptive MIMO Transmission for Uncoded Systems and Coded Systems.

Part III: Transmission Designs for Multiuser MIMO Systems Under Finite Alphabet Input Constraints

- MIMO Uplink Transmission
- MIMO Downlink Transmission
- MIMO Interference Channel
- MIMO Wiretap Channel

Part IV: Technical Challenges and Future Trends

- Transmission Designs with Finite Input Signals for Massive MIMO Systems
- Fundamental Analysis for Random Access Users with Finite Input Signals
- Adaptive Transmission for Massive-Connectivity MIMO Systems with Finite Input Signals

6) Potential Participants

The half-day tutorial is intended for the generally knowledgeable individual working in the field of wireless communications and networking with some background in information theory, random matrix theory, optimization theory, and communication system designs. It is also suitable for students and researchers who are interested to learn about channel capacity analysis, channel coding design, multiple antenna technologies, convex optimization, robust transceiver designs, adaptive transmission, secure communication, 5G, etc.

7) Prior History of Tutorial

State if a similar tutorial has been offered in recent IEEE ICC or GLOBECOM (last two years) and how your tutorial differs.

To the best of our knowledge, there is no previous tutorial on this topic in the last two years.

8) Lecture Experience of Tutorial Speaker

Prof. Chengshan Xiao and Prof. Yongpeng Wu have given a series of invited talks and lectures on MIMO transmission design with finite alphabet inputs at several universities, public and private research institutions in North America, Asia, and Europe. In addition, they have been delivering courses and lectures on wireless communications and networking at Lehigh University, Missouri University of Science and Technology, SJTU, and overseas universities on a regularly basis.

9) Selected Publications of the Speakers Related to the Tutorial

Selected Publications of Chengshan Xiao

[1] X. Liang, Z. Ding, and **C. Xiao**, "On linear precoding of non-regenerative MIMO relay networks for finite-alphabet source," *IEEE Transactions on Vehicular Technology*, vol. 66, no. 11, pp. 9761-9775, November 2017.

[2] X. Zhu, W. Zeng, and **C. Xiao**, "Precoder design for simultaneous wireless information and power transfer systems with finite-alphabet inputs," *IEEE Transactions on Vehicular Technology*, vol. 66, no. 10, pp. 9085-9097, October 2017.

[3] J. Jin, Y. R. Zheng, W. Chen, and **C. Xiao**, "Generalized quadratic matrix programming: a unified framework for linear precoding with arbitrary input distributions," *IEEE Transactions on Signal Processing*, vol. 65, no. 18, pp. 4887-4901, September 2017.

[4] A. Lu, X. Gao, Y. R. Zheng, and **C. Xiao**, "Linear precoder design for SWIPT in MIMO broadcasting systems with discrete input signals: manifold optimization approach," *IEEE Transactions on Communications*, vol. 65, no. 7, pp. 2877-2888, July 2017.

[5] J. Jin, **C. Xiao**, M. Tao, and W. Chen, "Linear precoding for fading cognitive multiple access wiretap channel with finite-alphabet inputs," *IEEE Transactions on Vehicular Technology*, vol. 66, no. 4, pp. 3059-3070, April 2017.

[6] W. Zeng, Y. R. Zheng, and **C. Xiao**, "Online precoding for energy harvesting transmitter with finite-alphabet inputs and statistical CSI," *IEEE Transactions on Vehicular Technology*, vol. 65, no. 7, pp. 5287-5302, July 2016.

[7] X. Zhu, W. Zeng, and **C. Xiao**, "Throughput optimisation for energy harvesting transmitter with partial instantaneous channel state information and finite-alphabet inputs," *IET Communications*, vol. 10, no. 4, pp. 435-442, April 2016.

[8] W. Wu, K. Wang, W. Zeng, Z. Ding, and **C. Xiao**, "Cooperative multi-cell MIMO downlink precoding with finite-alphabet inputs," *IEEE Transactions on Communications*, vol. 63, no. 3, pp. 766-779, March 2015.

[9] Y. R. Zheng, M. Wang, W. Zeng, and **C. Xiao**, "Practical linear precoder design for finite alphabet multiple-input multiple-output orthogonal frequency division multiplexing with experiment validation," *IET Communications*, vol. 7, no. 9, pp. 836-847, June 2013.

[10] S. Bashar, Z. Ding, and **C. Xiao**, "On secrecy rate analysis of MIMO wiretap channels driven by finite-alphabet input," *IEEE Transactions on Communications*, vol. 60, no. 12, pp. 3816-3825, Dec. 2012.

[11] W. Zeng, **C. Xiao**, J. Lu, and K. B. Letaief, "Globally optimal precoder design with finite-alphabet inputs for cognitive radio networks," *IEEE Journal on Selected Areas in Communications*, vol. 30, no. 10, pp. 1861-1874, Nov. 2012.

[12] X. Liang, Z. Ding, and **C. Xiao,** "Optimized power allocation for packet retransmissions of non-Gaussian inputs through sequential AWGN channels," *IEEE Transactions on Communications*, vol. 60, no. 7, pp. 1889-1902, July 2012.

[13] W. Zeng, **C. Xiao,** M. Wang, and J. Lu, "Linear precoding for finite-alphabet inputs over MIMO fading channels with statistical CSI," *IEEE Transactions on Signal Processing*, vol. 60, no. 6, pp. 3134-3148, June 2012.

[14] W. Zeng, **C. Xiao**, and J. Lu, "A low-complexity design of linear precoding for MIMO channels with finite-alphabet inputs," *IEEE Wireless Communications Letters*, vol. 1, no. 1, pp. 38-41, Feb. 2012.

[15] M. Wang, W. Zeng, and **C. Xiao**, "Linear precoding for MIMO multiple access channels with finite discrete inputs," *IEEE Transactions on Wireless Communications*, vol. 10, no. 11, pp. 3934-3942, Nov. 2011.

[16] S. Bashar, Z. Ding, and **C. Xiao**, "On the secrecy rate of multi-antenna wiretap channel

under finite-alphabet input," *IEEE Communications Letters*, vol. 15, no. 5, pp. 527-529, May 2011
[17] **C. Xiao,** Y. R. Zheng, and Z. Ding, "Globally optimal linear precoders for finite alphabet signals over complex vector Gaussian channels," *IEEE Transactions on Signal Processing*, vol. 59, no. 7, pp. 3301-3314, July 2011.
[18] J. Jin, Y. R. Zheng, W. Chen, and **C. Xiao**, "Hybrid precoding for millimeter wave MIMO systems: a matrix factorization approach," *IEEE Transactions on Wireless Communications*, accepted for publication, 2018

Selected Publications of Yongpeng Wu

[1] **Y. Wu**, C. Xiao, Z. Ding, X. Gao, and S. Jin, "MIMO transmission with discrete input signals: Technical challenges, advances, and future trends," *Proceeding of IEEE*, vol. 106, pp. 1779-1833, Oct. 2018.
[2] K. Cao, Y. Cai, **Y. Wu**, and W. Yang, "Secure communication for amplify-and-forward relay networks with finite alphabet input, " *IEEE Trans. Inf. Foresics Security,* vol. 13, pp. 2269-2278, Sep. 2018.
[3] K. Cao, Y. Cai, **Y. Wu**, and W. Yang, "Secure transmission for MISOME wiretap channels with finite alphabet inputs, " *IEEE Wireless Commun. Lett.,* vol. 7, pp. 570-573, Aug. 2018.
[4] K. Cao, Y. Cai, **Y. Wu**, W. Yang, and X. Guan, "Secure communication for MISO secrecy channel with multiple multiantenna eavesdroppers having finite alphabet inputs," *IEEE Access,* vol. 6, pp. 7402-7411, Dec. 2018
[5] K. Cao, Y. Cai, **Y. Wu,** W. Yang, "Cooperative jamming for secure communication with finite alphabet inputs," *IEEE Commun. Lett.,* vol. 9, pp. 2025-2028, Sep. 2017
[6] K. Cao, **Y. Wu**, Y. Cai, and W. Yang, "Secure transmission with aid of a helper for MIMOME network having finite alphabet inputs," *IEEE Access,* vol. 5, pp. 3698-3708, Dec. 2017.
[7] **Y. Wu,** J.-B. Wang, J. Wang, R. Schober, and C. Xiao, "Secure transmission with large numbers of antennas and finite alphabet inputs," *IEEE Trans. Commun*. vol. 65, pp. 3614-3628, Aug. 2017.
[8] **Y. Wu**, C.-K. Wen, D. W. K. Ng, R. Schober, and A. Lozano, "Low complexity MIMO precoding for finite alphabet signaling," *IEEE Trans. Wireless Commun*. vol. 16, pp. 4571-4584, Jul. 2017
[9] K. Cao, **Y. Wu**, W. Yang, and Y. Cai, "Low-complexity precoding for MIMO channels with finite alphabet input," *Electronics Letters,* vol. 53, pp. 160-162, Feb. 2017.
[10] **Y. Wu**, C.-K. Wen, C. Xiao, X. Gao, and R. Schober, "Linear precoding for the MIMO multiple access channel with finite alphabet inputs and statistical CSI," *IEEE Trans. Wireless Commun.,* vol. 14, pp. 983-997, Feb. 2015.
[11] **Y. Wu**, C. Xiao, X. Gao, J. D. Matyjas, and Z. Ding, "Linear precoder design for MIMO interference channels with finite-alphabet signaling," *IEEE Trans. Commun.,* vol. 61, pp. 3766–3780, Sep. 2013.
[12] **Y. Wu**, M. Wang, C. Xiao, Z. Ding, and X. Gao, "Linear precoding for MIMO broadcast channels with finite-alphabet constraints," *IEEE Trans. Wireless Commun.,* vol. 11, pp. 2906–2920, Aug. 2012.
[13] **Y. Wu**, C. Xiao, Z. Ding, X. Gao, and S. Jin, "Linear precoding for finite alphabet signaling over MIMOME wiretap channels," *IEEE Trans. Veh. Technol.,* vol. 61, pp. 2599–2612, July 2012.

ICC 2019 Tutorial Proposal

1. Title of the tutorial (Half day)

"Accessing from the Sky: UAV Communications for 5G and Beyond"

2. Abstract, objectives and motivation

Unmanned aerial vehicles (UAVs) have found a wide range of applications. Integrating UAVs into cellular systems is a promising technology to practically realize the numerous UAV applications. On one hand, those UAVs with their own missions could be connected into cellular networks as aerial users, which we term as **cellular-connected UAVs**. Thanks to the almost ubiquitous accessibility and high authentication mechanisms of today's LTE and the future 5G-and-beyond networks, cellular-connected UAVs are expected to achieve orders-of-magnitude performance improvement for UAV command and control (C&C) over the existing direct ground-to-UAV communications, in terms of reliability, security, operation range, and throughput. On the other hand, dedicated UAVs including drones, helikite, balloons, could also be dispatched as aerial base stations (BSs), access points (APs), or relays, to further assist the terrestrial communications in 5G, which we term as **UAV-assisted wireless communications**.

The integration of UAVs into existing (4G) and future (5G and beyond) cellular networks calls for a paradigm shift on the design of both cellular and UAV systems. In particular, both paradigms of cellular-connected UAV communications and UAV-assisted terrestrial communications are significantly different from the conventional terrestrial-only communications, due to the high altitude and mobility of UAVs, the unique channel characteristics of UAV-ground links, the asymmetric quality of service (QoS) requirements for downlink C&C and uplink mission-related data transmission, the stringent constraints imposed by the size, weight, and power (SWAP) limitations of UAVs, as well as the additional design degrees of freedom with joint UAV movement control and communication resource allocation. Significant research efforts from both academia and industry have been devoted to exploring this exciting new field, with remarkable progress made, especially in the past couple of years. This tutorial thus aims to provide a comprehensive overview of the state-of-the-art results on UAV-cellular integration, with a particular emphasis on the latest research findings on interference management and trajectory optimization in cellular-connected UAV communications. Open challenges and promising directions for future research will also be highlighted.

3. Timeliness and intended audience

Historically, UAVs have been primarily used in military applications to be deployed in hostile territory to reduce pilot losses. The enthusiasm for using UAVs in civilian and commercial applications has been boosted drastically in recent years due to their countless practical applications. Both frameworks of cellular-connected UAV and UAV-assisted wireless communications have received significant interests from industry and academia, especially in the past couple of years.

Cellular-connected UAV communications have attracted an upsurge of interests in wireless industry since early 2016. For instance, Intel and AT&T demonstrated the world's first LTE-connected drone at the 2016 Mobile World Congress. In August 2016, Ericsson and China Mobile conducted what they called world's first 5G-enabled drone prototype field trial in WuXi of China. In September 2016, Qualcomm tested the drone operation over commercial LTE networks for altitude up to 400 feet, and a trial report was released in May 2017. In 2017, 3GPP also started the work item for the study on enhanced support for aerial vehicles using LTE. On the other hand, UAV-assisted wireless communication has also drawn significant interests. Early efforts mainly focused on providing wireless connectivity via various high-altitude platforms (HAPs). These include the Project Loon by Google aiming to provide internet access in remote areas using balloons, as well as the Project Skybender by Google and Aquila by Facebook, which both use solar-powered drones to beam down internet data from the skies. In October 2016, Verizon launched its Airborne LTE Operations (ALO) initiative, which envisions using drones to help first responders in disaster recovery efforts. In February 2017, AT&T completes its first “flying COW”(Cell On Wings) drone to enhance cell coverage. Under the FP7 framework, European Commission has sponsored an ambitious project known as ABSOLUTE (Aerial Base Stations with Opportunistic Links for Unexpected & Temporary Events), which “combines aerial, terrestrial and satellite communications links for broadband applications during large scale emergency recovery or temporary events”.

In academia, the research on UAV communications has also received growing interests recently, as evident from the steady increase on the number of related publications on IEEE Xplore, arXiv and others. In particular, the article entitled "Wireless communications with unmanned aerial vehicles: opportunities and challenges", which was published by the tutorial speakers in IEEE Communications Magazine in May 2016, has attracted 7928 downloads in IEEE Xplore and 436 citations based on Google Scholar. It has been listed as an ESI highly hot paper (top 0.1% in citations). These all evidently show the great efforts dedicated to this important research area and demonstrate the timeliness of the proposed tutorial.

The targeting audiences of the proposed tutorial include all academic researchers and industry practitioners who are working on or interested in UAV and cellular communications. Except some very preliminary background on wireless communications, no other prerequisite knowledge is specially required from the audience. Due to the fast-growing interests in UAV communications, this tutorial is expected to attract a large number of attendees.

4. Name, affiliation, and biography of tutorial speakers

Rui Zhang, National University of Singapore, Singapore (email: elezhang@nus.edu.sg)
Yong Zeng, The University of Sydney (email: yong.zeng@sydney.edu.au)

Rui Zhang (IEEE Fellow) received the B.Eng. (First-Class Hons.) and M.Eng. degrees from National University of Singapore, and the Ph.D. degree from Stanford University, Stanford, CA USA, all in electrical engineering. From 2007 to 2009, he worked as a Research Scientist at the Institute for Infocomm Research, ASTAR, Singapore. Since 2010, he has joined the Department of Electrical and Computer Engineering of National University of Singapore, where he is now an Associate Professor and Dean’s Chair Professor in the Faculty of Engineering. His current research interests include UAV communications, wireless information and power transfer, MIMO communications, etc. He has published over 270 papers, which have been cited more than 17,000 times. . He has been listed as a Highly Cited Researcher by Thomson Reuters since 2015. He was the recipient of the 6th IEEE Communications Society Asia-Pacific Region Best Young Researcher Award in 2011, and the Young Researcher Award of National University of Singapore in 2015. He was the co-recipient of the IEEE Marconi Prize Paper Award in Wireless Communications in 2015, the IEEE Communications Society

Asia-Pacific Region Best Paper Award in 2016, the IEEE Signal Processing Society Best Paper Award in 2016, and the IEEE Communications Society Heinrich Hertz Prize Paper Award in 2017. He served for over 30 international conferences as TPC Co-Chair or Organizing Committee Members, and as the guest editor for 8 special issues in IEEE and other international journals. He served as an elected member of the IEEE Signal Processing Society SPCOM and SAM Technical Committees, and the Vice Chair of the IEEE Communications Society Asia-Pacific Board Technical Affairs Committee. He served as an editor for the IEEE Transactions on Wireless Communications and the IEEE Journal on Selected Areas in Communications (Green Communications and Networking Series). He is now an editor for the IEEE Transactions on Communications, the IEEE Transactions on Signal Processing, and the IEEE Transactions on Green Communications and Networking.

Yong Zeng is a Lecturer at the School of Electrical and Information Engineering, The University of Sydney, Australia. He received the Bachelor of Engineering (First-Class Honours) and Ph.D. degrees from the Nanyang Technological University, Singapore, in 2009 and 2014, respectively. From 2013 to 2018, he was a Research Fellow and Senior Research Fellow at the Department of Electrical and Computer Engineering, National University of Singapore. His research interest includes UAV communications, wireless power transfer, massive MIMO and millimeter wave communications, and multi-user MIMO communications. He has published over 70 IEEE top-tier journal and conference papers, which have attracted more than 2400 Google Scholar citations, with H-index 22. He is the recipient of the 2018 IEEE Communications Society Asia-Pacific Outstanding Young Researcher Award, 2017 IEEE Communications Society Heinrich Hertz Prize Paper Award, 2017 IEEE Transactions on Wireless Communications Best Reviewer, 2015 and 2017 IEEE Wireless Communications Letters Exemplary Reviewer, and the Best Paper Award for the 10th International Conference on Information, Communications and Signal Processing. He serves as an Associate Editor of IEEE Access, Leading Guest Editor of IEEE Wireless Communications on ``Integrating UAVs into 5G and Beyond'' and China Communications on ``Network-Connected UAV Communications''. He is the workshop organizer for UAV communications workshops in ICC2019, ICC2018, and ICCC2018.

5. Description of the technical issues that the tutorial will address, emphasizing its timeliness

This tutorial aims to address the various technical issues for integrating UAVs into 5G and beyond.

For the first framework of integrating UAVs as aerial users, or cellular-connected UAVs, the main design challenges include, but not limited to: i) Spectrum-efficient techniques for ultra-reliable and secure downlink C&C, and high-capacity uplink payload data transmission; ii) Energy-efficient UAV mobility with minimum UAV energy consumption while satisfying the communication QoS requirements; and iii) Efficient coexisting with terrestrial users with interference management. On the other hand, for the second framework of integrating UAVs as aerial communication platforms, or UAV-assisted 5G communications, some key design challenges are: i) Spectrum-efficient UAV-enabled wireless communications with joint resource allocation and UAV deployment/mobility optimization; ii) Energy-efficient UAV-enabled wireless communications with joint resource allocation and UAV deployment/mobility optimization. For both frameworks, we will discuss the key enabling technologies to address the corresponding design challenges, by exploiting the unique characteristics of UAV communication systems. A systematic research on cellular UAV communications is still in its infancy, and all the above proposed research problems are timely and not yet solved.

6. An outline of the tutorial content, including its tentative schedule

The tutorial consists of four parts. Part I gives an overview of the UAVs and their key communication requirements and main design challenges. Part II introduces the concepts of integrating UAVs into 5G. The two frameworks of cellular-connected UAVs and UAV-assisted 5G will be introduced, including their respective networking architectures, typical use cases, preliminary industrial activities. The related channel model and UAV energy consumption model will also be introduced in this part. Part III focuses on cellular-connected UAV communications, with the main design objectives firstly introduced, followed by the major industrial findings. The various key-enabling technologies will be introduced in great detail and the open issues and future work directions will be discussed. Part IV discusses the UAV-assisted 5G communications. We will start with the main design objectives and the preliminary industrial experiment results, followed by the key enabling technologies and four case studies. Lastly, we will present the open issues and future research directions. The tentative schedule of the proposed tutorial is given as follows.

I. Introduction (20 mins)
  a. Brief history of UAVs and their contemporary applications
  b. Classification of UAVs
  c. UAV authority regulations
  d. Wireless communications with UAV: key requirement and main design challenges

II. UAV meets Cellular: An Overview (40 mins)
  a. Existing UAV communication technologies and main limitations
  b. Brief overview of cellular networks and their key enabling technologies
  c. Paradigm shift: integrating UAVs into 5G and beyond
    i. Network architectures: cellular-connected UAVs and UAV-assisted 5G communications
    ii. Typical use cases and application scenarios
    iii. Overview of proof-of-concept experiments and main research findings by industry: Intel, AT&T, Ericsson, China Mobile, Qualcomm, Huawei, Google, Facebook, Verizon, Nokia, etc.
  d. Channel model
    i. Ground-to-UAV channel model: LoS, probabilistic LoS, Rician, ground-to-UAV MIMO channel model, etc.
    ii. UAV-UAV channel model
  e. UAV energy consumption model: fixed-wing and rotary-wing

III. Cellular-connected UAVs (60 mins)
  a. Overview of main design objectives:
    i. Spectrum-efficient downlink C&C and uplink information transmission
    ii. Energy-efficient UAV mobility
    iii. Minimal negative impact to existing terrestrial users
  b. Preliminary industrial experimental findings:
    i. coverage hole at high altitude
    ii. number of detected BSs versus altitude

            iii. uplink and downlink interference versus altitude
    c. Key enabling technologies
        i. Aerial-terrestrial user interference mitigation: spectrum allocation, power allocation, non-orthogonal multiple access (NOMA)
        ii. Inter-UAV interference mitigation: BS cooperation, 3D beamforming
        iii. High-capacity uplink transmission: millimeter wave
        iv. Spectrum-efficient joint resource allocation and UAV trajectory design
        v. Energy-efficient joint resource allocation and UAV trajectory design
    d. Open issues and future research directions

IV. UAV-assisted 5G (60 mins)
    a. Overview of main design objectives:
        i. Spectrum-efficient UAV-enabled wireless communications
        ii. Energy-efficient UAV-enabled wireless communications
    b. Preliminary industrial experiments
    c. Key enabling technologies
        i. 3D quasi-stationary aerial BS placement
        ii. Multiple access techniques
        iii. Hybrid aerial-terrestrial networks
        iv. Spectrum-efficient joint resource allocation and UAV trajectory design
        v. Energy-efficient joint resource allocation and UAV trajectory design
    d. Case study
        i. UAV-enabled mobile relaying
        ii. UAV-enabled data collection
        iii. UAV-enabled multiuser network
        iv. Energy-efficient UAV communication
    e. Open issues and future research directions

7. Relevant experience of the speakers on the topic of the tutorial

During the past 3 years, both speakers have extensively worked on UAV communications and significant research contributions have been made. Since 2015, the speakers have authored/co-authored 17 high-quality IEEE journal papers and 8 international conference papers on this topic. Among these papers, 4 of them have been listed as ESI highly cited papers (top 1% in citations), and 3 as ESI hot papers (top 0.1% in citations). Besides, the first speaker was invited to give keynote talks at three UAV communication related workshops in IEEE flagship conferences recently, including VTC2016, Globecom 2017, and ICC 2018.

8. Previous tutorial experience of the speakers and past versions of the tutorial

The first speaker has rich experiences in giving tutorials and keynote talks in major IEEE conferences, including:

1) IEEE WCNC 2018, Tutorial entitled "UAV Meets Wireless Communication in 5G and Beyond: Main Research Challenges and Key Enabling Techniques,"
2) IEEE Globecom 2016: Tutorial entitled "Wireless Powered Communication: From Theory to

Applications"

3) IEEE Globecom 2016, Workshop on Wireless Energy Harvesting, keynote talk entitled "Communications and Signals Design for Wireless Power Transmission"
4) WCSP 2016: keynote talk entitled "Millimeter Wave Lens MIMO: A (Potential) Disruptive Technology for 5G"
5) VTC (Spring) 2016: Workshop on Wireless Communications for High Speed Railways, keynote talk entitled "Wireless Communications with Unmanned Aerial Vehicles: Opportunities and Challenges"
6) IEEE WCNC 2016: Keynote talk entitled "Wireless Powered Communication Networks: An Overview"
7) ICC 2015, Workshop on Green Communications and Networks with Energy Harvesting, Smart Grids, and Renewable Energies, keynote talk entitled "Wireless Communications in the Era of Energism"
8) IEEE OnlineGreenComm, 2014, invited tutorial entitled "Cost-Aware Green Cellular Networks with Energy and Communication Cooperation"
9) IEEE ICC 2014: tutorial entitled "Wireless Powered Communication: Opportunities and Challenges"

Though the second speaker has no prior tutorial experience, he has rich experience in giving technical presentations at IEEE major conferences, including Asilomar'12, ICC'13, ICC'15, ICC'16, ICASSP'16, and ICC'17. He also has rich experience in giving invited talks in many occasions.

Past version of the tutorial:
IEEE Globecom 2018, **"**Integrating UAVs into Cellular: Enabling Technologies and Research Challenges", to be given on December 9, 2018, by both the first and second speakers
IEEE WCNC 2018, "UAV Meets Wireless Communication in 5G and Beyond: Main Research Challenges and Key Enabling Techniques," given by the first speaker. No. of attendees: ~40

9. Similar tutorial in the last two years and the uniqueness of the proposed tutorial

The most relevant tutorial was given at Globecom 2016, which is entitled "Wireless Communications and Networking with Unmanned Aerial Vehicles", but its focus was more on the performance analysis and resource allocation of standalone UAV systems, without integrating them into cellular, as will be focused on in the proposed tutorial. Furthermore, the GC16 tutorial was mainly based on the speakers' academic research findings published about three years ago (by the time when the proposed tutorial is held). As evident from our previous discussion, the relevant research to the proposed tutorial topic has grown significantly during the past three years, where many new promising results, from both industry and academic, have appeared. As a result, the proposed tutorial will provide a comprehensive and timely overview of the latest findings that have not been covered in any previous tutorial on similar topic, which will shed new lights on this exciting and important field. On the other hand, compared to our presented IEEE WCNC 2018 tutorial (see above), we will provide more discussions in this tutorial on the cellular-enabled UAV paradigm, with a particular emphasis on the latest research findings on interference management and trajectory optimization techniques for cellular-connected UAV communications.

Quantum Internet: Wiring the Weirdness

By
Angela Sara Cacciapuoti and Marcello Caleffi

1. Title

Quantum Internet: Wiring the Weirdness

2. Abstract, objectives and motivation

The quantum technologies are finally in the engineering phase, with several tech giants as IBM, Google and Intel entered the quantum race. In November 2017 IBM announced a quantum processor constituted by 50 quantum bits (qubits). In March 2018 Google announced a 72-qubits processor. Meanwhile, in April 2017 the European Commission launched a ten-years 1€-billion flagship project to boost European quantum technologies research. In June 2017 China successfully tested a 1200 km quantum link between satellite Micius and ground stations. In June 2018 the US introduced a bi-partisan legislation authorizing the establishment of a National Quantum Initiative funded with 1.2$-billion over five years. And the market for the quantum computing is forecast to worth more than 10$-billion by 2024.

By oversimplifying, the computing power of a quantum computer scales with the number of qubits that can be embedded and interconnected within. However, the challenges for controlling, interconnecting, and preserving the qubits get harder and harder as the number of qubits increases within a single device. Hence, a path towards scalability for quantum computers is envisioned to be the *Quantum Internet*. Specifically, the idea is to wire multiple quantum devices via a quantum network to build up a virtual quantum computer constituted by a number of qubits that scales with the number of interconnected devices. This, in turn, implies an exponential speed-up of the quantum computing power, by utilizing only a linear amount of physical resources.

But the Quantum Internet is governed by the laws of quantum mechanics. Phenomena with no counterpart in classical networks, such as no-cloning, quantum measurement, entanglement and teleporting, impose very challenging constraints for the network design. Specifically, classical network functionalities, ranging from error-control mechanisms to overhead-control strategies, are based on the assumption that classical information can be safely read and copied. But this assumption does not hold in the Quantum Internet. As a consequence, the design of the Quantum Internet requires a major network-paradigm shift to harness the quantum mechanics specificities.

The goal of this tutorial is to shed light on the challenges and the open problems of the Quantum Internet design from a communication engineering perspective. More in details, this tutorial aims at providing the participants with a wide view about quantum communications and the unique challenges for transmitting quantum information.

3. Timeliness and Intended Audience

Given the novelty of the topic, the tutorial is targeted to audience new to the field. A graduated knowledge on communications theory is assumed.

4. Name, affiliation, and a short biography of each tutorial speaker

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Angela Sara Cacciapuoti (M'10, SM'16) received the Ph.D. degree in Electronic and Telecommunications Engineering in 2009, and the *Laurea summa cum laude* in Telecommunications Engineering in 2005, both from the University of Naples Federico II. Since April 2017, she held the Italian Habilitation as "*Associate Professor*" in Telecommunications Engineering and since July 2018, she held the Italian Habilitation as "*Full Professor*" in Telecommunications Engineering. Currently, she is a Tenure-Track Assistant Professor at the Department of Electrical Engineering and Information Technology, University of Naples Federico II. Prior to that, she was a visiting researcher at the Georgia Institute of Technology (USA) and at the NaNoNetworking Center in Catalunya (N3Cat), School of Electrical Engineering, Universitat Politecnica de Catalunya (Spain). Her work appeared in the first tier IEEE journals and she received different awards including the elevation to the grade of IEEE Senior Member in February 2016, most downloaded article and most cited article awards, and outstanding young faculty/researcher fellowships for conducting research abroad. Angela Sara serves as Editor/Associate Editor for the journals: IEEE Trans. on Communications, IEEE Communications Letters, Computer Networks (Elsevier) Journal and IEEE Access. She was awarded with the 2017 Exemplary Editor Award of IEEE Communications Letters. Since 2016, she is a board member of the IEEE ComSoc Young Professionals (YPs) Standing Committee and, since 2018 of the IEEE ComSoc Women in Communications Engineering (WICE) Standing Committee. In February 2017, she has been appointed Award Co-Chair of the N2Women Board and in July 2017, she has been elected Treasurer of the IEEE Women in Engineering (WIE) Affinity Group (AG) of the IEEE Italy Section.

Marcello Caleffi (M'12, SM'16) received the M.S. degree (summa cum laude) in computer science engineering from the University of Lecce, Lecce, Italy, in 2005, and the Ph.D. degree in electronic and telecommunications engineering from the University of Naples Federico II, Naples, Italy, in 2009. Currently, he is with the DIETI Department, University of Naples Federico II, and with the National Laboratory of Multimedia Communications, National Inter-University Consortium for Telecommunications (CNIT). From 2010 to 2011, he was with the Broadband Wireless Networking Laboratory at Georgia Institute of Technology, Atlanta, as visiting researcher. In 2011, he was also with the NaNoNetworking Center in Catalunya (N3Cat) at the Universitat Politecnica de Catalunya (UPC), Barcelona, as visiting researcher. Since July 2018, he held the *Italian national habilitation* as Full Professor in Telecommunications Engineering. His work appeared in several premier IEEE Transactions and Journals, and he received multiple awards, including *best strategy*, *most downloaded article*, and *most cited article* awards. Currently, he serves as editor/associate technical editor for IEEE Communications Magazine, IEEE Communications Letters, IEEE Access and Elsevier Ad Hoc Networks. He has served as Chair, TPC Chair, Session Chair, and TPC Member for several premier IEEE conferences. In 2016, he was elevated to IEEE Senior Member. In 2017, he has been appointed as elected treasurer of the IEEE ComSoc/VT Italy Chapter, and he has been appointed as Distinguished Lecturer from the IEEE Computer Society.

5. A description of the technical issues that the tutorial will address, emphasizing its timeliness

The tutorial provides an introduction to the Quantum Internet from a communication engineering perspective.

First, the importance of the Quantum Internet will be highlighted, by reviewing the very last efforts, from both Industry and Academia. Then, the physical mechanisms underlying quantum communications, such as entanglement, no-cloning theorem, teleportation, as well as the quantum bra-ket notation will be gently introduced.

Furthermore, the unique implications of these physical mechanisms on quantum communications will be presented and discussed. Moreover, quantum noise phenomena with no counterpart in the classical world, such as decoherence mechanisms, will be described along with their impacts on the transmission of the quantum information in the Quantum Internet.

Finally, a review of the existing open problems and possible research directions for designing the Quantum Internet will conclude the tutorial.

6. Outline of the tutorial content, including its tentative schedule

1. Introduction and Motivations
    a. The Quantum Internet: why do they matter?
        - State-of-the-Art
    b. The dawn of quantum communications
2. Very (basic) quantum mechanics
    a. Superposition
    b. Measurement
    c. Entanglement
    d. No-Copying
    e. Teleportation
3. Communications Models for the Quantum Internet
    a. Closed and Open Quantum Systems
    b. Decoherence Model: the Quantum Noise
    c. Quantum Communication Channels
    d. Open Problems and Research Directions

Scheduling: half-day
8:30 am-12:30 pm
- 8:30 - 9:00: section 1
- 9:00 - 10:00: section 2
- 10:00-12:00: section 3
- 12:15-12:30: discussion and questions

7. Description of the past/relevant experience of the speaker(s) on the topic of the tutorial

Marcello Caleffi has been appointed in 2017 as Distinguished Lecturer from the IEEE Computer Society on quantum computing topic[1]. Furthermore, both the speakers are members of the IEEE ComSoc's Emerging Technical Committee on Quantum Communications and Information Technology (ETC-QCIT).
In the following we report some recent publications we produced with reference to the subject:

- A. S. Cacciapuoti, M. Caleffi, F. Tafuri, F.S. Cataliotti, S. Gherardini, G. Bianchi, "*Quantum Internet: Networking Challenges in Distributed Quantum Computing*", under review, https://arxiv.org/abs/1810.08421, 2018.
- A. S. Cacciapuoti, M. Caleffi (Invited Paper): Toward the Quantum Internet: A Directional-dependent Noise Model for Quantum Signal Processing, under review, 2018.
- M. Caleffi, A. S. Cacciapuoti, G. Bianchi, "*Quantum internet: from communication to distributed computing!*", Invited Paper, Proc. of ACM NANOCOM, 2018.
- M. Caleffi, "*Optimal Routing for Quantum Networks*", IEEE Access, Vol. 5, pp. 22299-22312, October 2017.
- M. Caleffi, "*End-to-end entanglement rate: Toward a quantum route metric*", Proc. of IEEE Globecom Workshops, Dec 2017.

8. Speaker's Tutorial Delivery Experience

As detailed in Sec. 9, the main material of the proposed tutorial is completely new, and it does not overlap with any of the following tutorials or talks.

Tutorials

- IEEE ICC'18 "*Network Design for Distributed Quantum Computing*" [Cacciapuoti, Caleffi]
- IEEE CCNC'18 "*2020: Toward Practical Quantum Networks*" [Cacciapuoti, Caleffi]
- Tyrr2017 "*Toward Practical Quantum Communications*" [Caleffi]
- ICT2017 "Biological Computing: Building Chips with Living Organisms" [Caleffi]

Talks and Invited Talks

- IEEE ComSoc Quantum Communications & Information Technology Emerging Technical Subcommittee (QCIT-ETC) at ICC'18, Invited Talk [Cacciapuoti, Caleffi]
- National Telecommunications and Information Theory Group, Annual Meeting Jun. 27th 2018, "Quantum Internet: from Communication to Distributed Computing!" [Caleffi]
- "Radio Spectrum and 5G: Challenges and Open Problems ", Centro Europeo di Ricerca sui media per la società dell'informazione, Italy, 6 June 2016 [Cacciapuoti]
- University at Buffalo, "Biological Networks: Building Communication Networks with Living Organisms", Apr. 14th 2014 [Caleffi]
- University of Nebraska-Lincoln, "Biological Networks: Building Communication Networks with Living Organisms", Apr. 8th 2014 [Caleffi]
- Universitat Politècnica de Catalunya, "Unexpected Cleverness in Unicellular, Organisms: The Slime Mold Case", Jul. 19th 2011 [Caleffi]

Panels

[1] https://www.computer.org/profiles/marcello-caleffi

- Visions for Future Communications Summit organized by Networld2020 with the support of 5G Infrastructure Association, European Commission, IEEE and National Science Foundation [Caleffi]

IEEE Computer Society Distinguished Lecturer Talks

- Riga Technical University, "2020: Toward Distributed Quantum Computing", Nov. 2018 [Caleffi]
- Tallin University of Technology, "2020: Toward Distributed Quantum Computing", Nov. 2018 [Caleffi]
- Academia Sinica, "2020: Toward Distributed Quantum Computing", Dec. 8th 2017 [Caleffi]
- Singapore Polytechnic, "2020: Toward Distributed Quantum Computing", Dec. 4th 2017 [Caleffi]

9. Previous similar tutorials

At IEEE ICC 2018, the speakers gave a tutorial on quantum networks.
In the following, a short summary of how the previous tutorial differs from the tutorial proposed for IEEE ICC 2019 is given.

- As regards to the introductory material (basic of quantum mechanics), clearly there is some overlapping since both the tutorials target to audience new to the field.
- As regards to the main material, the tutorials do not overlap. Previous talks focused on routing aspects, with emphasis on quantum repeaters and entanglement swapping. Differently, this tutorial focuses on providing a communication engineering perspective on quantum communications. Indeed, the main concepts of this tutorial (quantum networks regarded as open quantum systems, quantum channels, and decoherence models for the quantum noises) are not even mentioned in none of our previous tutorials and talks.

Cognitive Backscatter Network: A New Paradigm of Energy- and Spectrum-Efficient IoT Communications

Title of tutorial:
Cognitive Backscatter Network: A New Paradigm of Energy- and Spectrum-Efficient IoT Communications

Abstract:
Ambient backscatter communication (AmBC) has recently emerged as a promising technology for energy- and spectrum-efficient Internet-of-Things (IoT) communication technology. On the one hand, AmBC enables IoT backscatter devices (BDs) to modulate their information symbols over ambient radio-frequency (RF) carriers (e.g., WiFi, TV, or cellular signals) without using costly and power-hungry RF transmitter. On the other hand, AmBC does not need dedicated radio spectrum which is scarce and expensive, due to the spectrum sharing between the backscatter transmission and the ambient transmission. Since the backscatter transmission depends on the ambient RF signals, there are many challenging problems in both fundamental theory and key techniques waiting to be solved, for example, how to find the communication limits, design a high-rate AmBC transceiver, and allocate resource optimally? In this tutorial, we will introduce the cognitive backscatter network (CBN) architecture based on AmBC, and provide efficient technical solutions for the above questions. In particular, this tutorial includes the basics of IoT communications, AmBC over OFDM carriers, MIMO-CBN, machine learning receiver for AmBC, spectrum sharing for AmBC, as well as future directions.

Objectives and Motivation:
This half-day tutorial is designed to bring together academic and industrial researchers in an effort to introduce the major technical challenges and recent results related to AmBC and CBN.

Timeliness:
Internet of Things (IoT) which is revolutionizing the industry and our lives, is a key application paradigm for the forthcoming fifth-generation (5G) and future wireless communication systems. IoT devices in practice have strict limitations on energy, cost, and complexity, thus it is highly desirable to design energy- and spectrum-efficient communication technologies. AmBC is being recognized as a promising candidate to fulfill such demand. In recent years, there has appeared some progress on AmBC systems, many open questions still need to be addressed to support high-rate transmission and wide area coverage for IoT devices. For example, the Direct-Link-Interference (DLI) is strong and evitable in AmBC, and the ambient RF source may be unstable. To address the above questions, there is a need to investigate the system architecture, transceiver design, and resource allocation schemes to achieve energy- and spectrum-efficient IoT communication system based on AmBC.

Intended audience:
Researchers, students, and engineers in the wide area of IoT, RFID, and wireless communications.

Speaker Name(s): Ying-Chang Liang
Speaker Affiliation: University of Electronic Science and Technology of China (UESTC), China
Speaker Email(s): liangyc@ieee.org

Speaker Name(s): Dusit Niyato
Speaker Affiliation: Nanyang Technological University, Singapore
Speaker Email(s): dniyato@ntu.edu.sg

Biography of speaker:

Ying-Chang Liang is a Professor at University of Electronic Science and Technology of China (UESTC), China, where he leads the Center for Intelligent Networking and Communications (CINC). He was a Professor in University of Sydney, Australia, and a Principal Scientist and Technical Advisor in the Institute for Infocomm Research (I2R), Singapore. His research interest lies in the general area of wireless networking and communications, cognitive radio, dynamic spectrum access, Internet-of-Things, artificial intelligence and machine learning techniques.

Dr Liang was elected a Fellow of the IEEE for contributions to cognitive radio communications, and was also recognized by Thomson Reuters (Now Clarivate Analytics) as a Highly Cited Researcher from 2014-2018. He received the Institute of Engineers Singapore (IES)'s Prestigious Engineering Achievement Award in 2007, and the IEEE Standards Association's Outstanding Contribution Appreciation Award in 2011. He has also received numerous paper awards, with the recent ones including IEEE ICC Best Paper Award in 2017, IEEE ComSoc's TAOS Best Paper Award in 2016, and IEEE Jack Neubauer Memorial Award in 2014.

Dr Liang is Founding Editor-in-Chief of IEEE Journal on Selected Areas in Communications-Cognitive Radio Series, and Editor-in-Chief of IEEE Transactions on Cognitive Communications and Networking. He was the Chair of IEEE Communications Society Technical Committee on Cognitive Networks, and served as Guest/Associate Editor of IEEE Transactions on Wireless Communications, IEEE Journal of Selected Areas in Communications, IEEE Signal Processing Magazine, IEEE Transactions on Vehicular Technology, and IEEE Transactions on Signal and Information Processing over Network. He was also an Associate Editor-in-Chief of the World Scientific Journal on Random Matrices: Theory and Applications. Dr Liang was a Distinguished Lecturer of the IEEE Communications Society and the IEEE Vehicular Technology Society, and served as TPC Chair and Executive Co-Chair of IEEE Globecom'17. He will serve as the general chair of IEEE 2018 International Conference on Communication Systems.

Dusit Niyato is currently a professor in the School of Computer Science and Engineering and, by courtesy, School of Physical & Mathematical Sciences, at the Nanyang Technological University, Singapore. He received B.E. from King Mongkuk's Institute of Technology Ladkrabang (KMITL), Thailand in 1999 and Ph.D. in Electrical and Computer Engineering from the University of Manitoba, Canada in 2008. He has published more than 380 technical papers in the area of wireless and mobile networking, and is an inventor of four US and German patents. He has authored four books including "Game Theory in Wireless and Communication Networks: Theory, Models, and Applications" with Cambridge University Press. He won the Best Young Researcher Award of IEEE Communications Society (ComSoc) Asia Pacific (AP) and The 2011 IEEE Communications Society Fred W. Ellersick Prize Paper Award. Currently, he is serving as a senior editor of IEEE Wireless Communications Letter, an area editor of IEEE Transactions on Wireless Communications (Radio Management and Multiple Access), an area editor of IEEE Communications Surveys and Tutorials (Network and Service Management and Green Communication), an editor of IEEE Transactions on Communications, an associate editor of IEEE Transactions on Mobile Computing, and IEEE Transactions on Cognitive Communications and Networking. He was a guest editor of IEEE Journal on Selected Areas on Communications. He was a Distinguished Lecturer of the IEEE Communications Society for 2016-2017. He was named the 2017, 2018 highly cited researcher in computer science. He is a Fellow of IEEE.

Description of Technical Issues to be Covered:

In the first part, we will start from the background of IoT and the technical challenges of IoT communications, and then we review the existing and emerging IoT communication technologies. We will then provide a contemporary and comprehensive review on fundamentals, applications, challenges, and research efforts/progress of backscatter communications. We will present fundamentals of backscatter communications and briefly review monostatic and bistatic backscatter communications systems. Then, the general architecture, advantages, and solutions to address existing issues and limitations of backscatter communications systems are discussed. Additionally, emerging applications of ambient backscatter communications are highlighted. We will focus on the AmBC system with separated backscatter receiver and ambient transmitter.

In the second part, we will propose a new architecture of CBN, i.e., a cooperative AmBC with co-located backscatter receiver and legacy receiver, and present the information theoretical work on CBN. In particular, we will introduce the modeling of the CBN and rigorously analyze the spread spectrum effect in CBN and AmBC. Then, we will investigate a unique multiplicative multiple access channel (M-MAC), and further characterize the capacity region for both the legacy user(s) and the backscatter devices (BDs). This part explores the communication limits for CBN, providing fundamental information theory for practical CBN/AmBC system design.

In the third part, we will investigate the transceiver design for AmBC systems over ambient OFDM carriers. In particular, we will first present the system model and analyze the DLI. Then, we will introduce the joint design of the BD transmission waveform and the DLI-cancellation based optimal detector receiver. This part provides high-speed transceiver design for AmBC via many practical wireless systems like LTE, WiFi and DVB.

In the fourth part, we will first present the optimal maximum-likelihood (ML) detector, successive-interference-cancellation (SIC) based suboptimal detectors, and machine learning receivers for Single-Input-Multiple-Output (SIMO) CBN. Then, we will introduce the optimal transmit beamforming design for Multiple-Input-Single- Output (MISO) CBN. This part provides efficient transmitter and receiver design for AmBC systems with multiple antennas.

In the fifth part, we will investigate the AmBC systems from a spectrum sharing perspective. After analyzing the interference between the AmBC and the legacy communication, we will obtain the closed-form capacity based on interference analysis. Then, we will present the optimal power control scheme for maximizing the ergodic capacity of AmBC. This part benefits to understand how the AmBC systems can optimally co-exist with legacy communication systems.

In the sixth part, we will first present the optimal resource allocation for ambient backscatter assisted cognitive radio networks, wireless powered communications, backscatter relay communications, and then analyze the performance for device-to-device communications with ambient backscattering. This part will provides design guidelines for resource allocation for typical wireless networks assisted by AmBC.

In the seventh part, we outline some open issues and future research directions such as emerging heterogeneity of ambient signals, interference management, security and jamming issues, and full-duplex based backscatter communication.

Outline of Tutorial Contents:

Part 1: Basics of IoT Communications (30 mins)
1. Introduction of IoT
2. Overview of IoT Communication Technologies
    a) Existing techniques with active radios
    b) Monostatic backscatter communications
    c) Bistatic backscatter communications
    d) Ambient backscatter communication (AmBC)

Part 2: Cognitive Backscatter Communication (30 mins)
1. System model of CBN
2. Spread spectrum analysis
3. Multiplicative MAC versus Conventional MAC
4. Capacity region of CBN

Part 3: AmBC over OFDM Carriers (30 mins)
1. System model for AmBC over OFDM carriers
2. Direct-Link-Interference (DLI) analysis
3. Transceiver design for DLI cancellation
    a) Transmission waveform
    b) DLI-cancellation based optimal detector
4. BER analysis

Part 4: MIMO-CBN (30 mins)
1. Single-Input-Multiple-Output (SIMO) CBN/AmBC
   a) Low-complexity ML detector for CBN
   b) SIC-based detector for CBN
   c) Receive-beamforming based detector for AmBC
   d) Machine learning receiver
2. Multiple-Input-Single-Output (MISO) CBN
   a) Transmit beamforming
   b) Rate performance analysis

Part 5: Spectrum Sharing for AmBC (20 mins)
1. Spectrum Sharing Perspective for AmBC
2. Interference Analysis
3. Ergodic capacity maximization
4. Power control

Part 6: Resource Allocation for AmBC Assisted Wireless Networks (30 mins)
1. Ambient backscatter assisted cognitive radio networks
2. Ambient backscatter assisted wireless powered communications
3. Backscatter relay communications networks
4. Device-to-device communications with ambient backscattering

Part 7: Future Directions (45 mins)
1. Management of heterogeneity of ambient signals
2. Interference management
3. Security and jamming issues
4. Full-duplex based backscatter communication

Past experiences of the speaker on the tutorial topic:

1. **Conference Keynote**: Y.-C. Liang, Modulation in the Air: A New Paradigm of Wireless Communications for Green Internet of Things, 12th EAI International Conference on Communications and Networking in China (CHINACOM), Xi'An, Oct. 2017.
2. **Conference Keynote**: Y.-C. Liang, Modulation in the Air: A New Paradigm of Wireless Communications for Green Internet of Things, IEEE VTC-Spring Workshop on Wireless Access Technologies and Architectures for Internet of Things Applications, Sydney, Australia, Jun. 2017.

Past versions of the tutorial: None

Previous tutorial experience of the speaker(s):
1. **Y.-C. Liang**, S. Sun, X. Peng and F. Chin, Emerging Wireless Standards for WRAN, WiFi, WiMedia and ZigBee, IEEE 2006 International Conference on Communication Systems, 30 October 2006.
2. **Y.-C. Liang**, Cognitive Radio Technologies for Dynamic Spectrum Access, IEEE 2008 International Conference on Communication Systems, 19-21 November 2008, Guangzhou, China
3. **Y.-C. Liang**, Cognitive Radio Networking and Communications, the 12th International Symposium on Wireless Personal Multimedia Communications, 7-10 September 2009, Sendai, Japan.
4. **D. Niyato** and D. I. Kim, "Wireless Powered Communication Networks: Architectures, Protocols, and Applications," half-day tutorial in IEEE International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC), Hong Kong, 30 August 2015.
5. **D. Niyato** and E. Hossain, "A Crash Course on Mobile Cloud Computing," half-day tutorial in IEEE Wireless Communications and Networking Conference (WCNC), Paris, France, 1 April 2012.
6. **D. Niyato**, Rose Q. Hu, E. Hossain, and Y. Qian "Communications and Networking for Smart

Grid Systems," half-day tutorial in IEEE Global Communications Conference (GLOBECOM), Houston, Texas, USA, 5-9 December 2011.
7. **D. Niyato** and E. Hossain "Game Theory for Multiple Access and Resource Allocation in Wireless Networks," half-day tutorial in IEEE Wireless Communications and Networking Conference (WCNC), Cancun, Mexico, 28-31 March 2011.

Similar tutorial in recent ICC & Globecom (last two years):
There is no similar tutorial offered in recent ICC & Globecom.

Related Publications

1. G. Yang, **Y.-C. Liang**, R. Zhang, and Y. Pei, Modulation in the Air: Backscatter Communications over Ambient OFDM Signals, IEEE Trans Communications, vol.66, No.3, pp.1219-1233, March 2018.
2. G. Yang, Q. Zhang, and **Y.-C. Liang**, Cooperative Ambient Backscatter Communication Systems for Future Internet-of-Things, IEEE Internet of Things Journal, vol.5, No.2, pp.1116-1130, April 2018.
3. W. Liu, **Y.-C. Liang**, Y. Li, and B. Vucetic, Backscatter Multiplicative Multiple-Access Systems: Fundamental Limits and Practical Design, IEEE Trans on Wireless Communications, vol.17, No.9, pp.5713-5728, Sept 2018.
4. H. Guo, Q. Zhang, S. Xiao, and **Y.-C. Liang**, Exploiting Multiple Antennas for Cognitive Ambient Backscatter Communications, IEEE Internet of Things Journal, doi: 10.1109/JIOT.2018.2856633, 2018.
5. X. Kang, **Y.-C. Liang**, and J. Yang, Riding on the Primary: A New Spectrum Sharing Paradigm for Wireless-Powered IoT Devices, IEEE Trans on Wireless Communications, vol.17, No.9, pp.vol.6335-6347, Sept 2018.
6. D. Li, W. Peng, and **Y.-C. Liang**, Hybrid Ambient Backscatter Communication Systems with Harvest-Then-Transmit Protocols, IEEE Access, vol.6, No.1, pp.45288-45298, Dec. 2018.
7. L. Zhang, M. Xiao, G. Wu, M. Alam, and **Y.-C. Liang**, and S. Li, “A survey of advanced techniques for spectrum sharing in 5G networks,” IEEE Wireless Communication Magazine, vol. 24, no. 5, pp. 44-51, Oct. 2017.
8. Q. Zhang, H. Guo, **Y.-C. Liang**, and X. Yuan, Constellation Learning based Signal Detection for Ambient Backscatter Communication Systems, IEEE Journal on Selected Areas in Communications, doi: 10.1109/JSAC.2018.2872382, 2018.
9. D. Li, and **Y.-C. Liang**, Adaptive Ambient Backscatter Communication Systems with MRC, IEEE Transactions on Vehicular Technology, DOI 10.1109/TVT.2018.2871154, 2018.
10. G. Yang, D. Yuan, **Y.-C. Liang**, R. Zhang, and V. C.M. Leung, Optimal Resource Allocation in Full-Duplex Ambient Backscatter Communication Networks for Green Internet-of-Things, IEEE Internet of Things Journal, doi: 10.1109/JIOT.2018.2799848, 2018.
11. L. Zhang, **Y.-C. Liang**, and M. Xiao, “Spectrum Sharing for Internet of Things: A Survey,” to appear in IEEE Wireless Communications Magazine, 2018.
12. L. Zhang and **Y.-C. Liang**, “Average Throughput Analysis and Optimization in Cooperative IoT Networks with Short Packet Communication,” IEEE Transaction on Vehicular Technology, Early Access, 2018.
13. L. Zhang, J. Liu, M. Xiao, G. Wu, Y.-C. Liang, and S. Li, “Performance Analysis and Optimization in Downlink NOMA Systems with Cooperative Full-duplex Relaying,” IEEE Journal on Selected Areas in Communications, vol. 35, no. 10, pp. 2398-2412, Oct. 2017.
14. X. Kang, **Y.-C. Liang**, and J. Yang, “Riding on the primary: A new spectrum sharing paradigm for wireless-powered IoT devices,” in Proc. of IEEE Conf. Commun. (ICC), Paris, France, May 2017, pp. 1-6. (**IEEE ICC’17 Best Paper Award**)
15. G. Yang, **Y.-C. Liang**, “Backscatter Communications over Ambient OFDM Signals: Transceiver Design and Performance Analysis”, IEEE GLOBECOM, 2016. (**IEEE ComSoc TAOS Best Paper Award**)
16. N. V. Huynh, D. T. Hoang, X. Lu, **D. Niyato**, P. Wang, and D. I. Kim, "Ambient backscatter communications: A contemporary survey," IEEE Communications Surveys and Tutorials, accepted.
17. W. Wang, D. T. Hoang, **D. Niyato**, P. Wang and D. I. Kim, "Stackelberg game for distributed time scheduling in RF-powered backscatter cognitive radio networks," IEEE Transactions on Wireless Communications, vol. 17, no. 8, pp. 5606-5622, August 2018.

18. S. Gong, X. Huang, J. Xu, W. Liu, P. Wang, and **D. Niyato**, "Backscatter relay communications powered by wireless energy beamforming," IEEE Transactions on Communications, vol. 66, no. 7, pp. 3187-3200, July 2018.
19. X. Lu, **D. Niyato**, H. Jiang, D. I. Kim, Y. Xiao and Z. Han, "Ambient backscatter assisted wireless powered communications," IEEE Wireless Communications, vol. 25, no. 2, pp. 170-177, April 2018.
20. X. Lu, H. Jiang, **D. Niyato**, D. I. Kim, and Z. Han, "Wireless-powered device-to-device communications with ambient backscattering: Performance modeling and analysis," IEEE Transactions on Wireless Communications, vol. 17, no. 3, pp. 1528-1544, March 2018.
21. D. T. Hoang, **D. Niyato**, P. Wang, D. I. Kim, and Z. Han, "Ambient backscatter: A new approach to improve network performance for RF-powered cognitive radio networks," IEEE Transactions on Communications, vol. 65, no. 9, pp. 3659-3674, September 2017.
22. D. T. Hoang, **D. Niyato**, P. Wang, D. I. Kim, and L. B. Le, "Optimal data scheduling and admission control for backscatter sensor networks," IEEE Transactions on Communications, vol. 65, no. 5, pp. 2062-2077, May 2017.
23. N. V. Huynh, D. T. Hoang, **D. Niyato**, P. Wang, and D. I. Kim, "Optimal time scheduling for wireless-powered backscatter communication networks," IEEE Wireless Communications Letters, accepted.
24. H. V. Nguyen, D. T. Hoang, D. N. Nguyen, E. Dutkiewicz, **D. Niyato**, and P. Wang, "Reinforcement learning approach for RF-powered cognitive radio network with ambient backscatter," to be presented in IEEE GLOBECOM, Abu Dhabi, UAE, 10-13 December 2018.
25. J. Li, J. Xu, S. Gong, C. Li, and **D. Niyato**, "A game theoretic approach for backscatter-aided relay communications in hybrid radio networks," to be presented in IEEE GLOBECOM, Abu Dhabi, UAE, 10-13 December 2018.
26. X. Gao, P. Wang, **D. Niyato**, K. Yang, and J. An, "An auction-based time scheduling mechanism for backscatter-aided RF-powered cognitive radio networks," to be presented in IEEE International Conference on Green Computing and Communications (GreenCom), Halifax, 30 July - 03 August 2018.
27. X. Lu, G. Li, H. Jiang, **D. Niyato**, and P. Wang, "Performance analysis of wireless-powered relaying with ambient backscattering," in Proceedings of IEEE ICC, Kansas City, MO, USA, 20-24 May 2018.
28. X. Lu, H. Jiang, **D. Niyato**, D. I. Kim, and P. Wang, "Analysis of wireless-powered device-to-device communications with ambient backscattering," in Proceedings of IEEE VTC-Fall, Toronto, Canada, 24-27 September 2017.
29. D. T. Hoang, **D. Niyato**, P. Wang, and D. I. Kim, "Optimal time sharing in RF-powered backscatter cognitive radio networks," in Proceedings of IEEE ICC, Paris, France, 21-25 May 2017.
30. D. T. Hoang, **D. Niyato**, P. Wang, D. I. Kim, and L. B. Le, "Overlay RF-powered backscatter cognitive radio networks: A game theoretic approach," in Proceedings of IEEE ICC, Paris, France, 21-25 May 2017.
31. D. T. Hoang, **D. Niyato**, P. Wang, D. I. Kim, and Z. Han, "The tradeoff analysis in RF-powered backscatter cognitive radio networks," in Proceedings of IEEE GLOBECOM, Washington, DC USA, 4-8 December 2016.

ICC 2019 Tutorial Proposal:

Tactile Internet with Human-in-the-Loop

1 TITLE OF THE TUTORIAL

The title of the proposal is „Tactile Internet with Human-in-the-Loop".

2 NAMES, ADDRESSES, AND A SHORT BIOGRAPHY (UP TO 200 WORDS) OF THE INSTRUCTORS

Frank Fitzek
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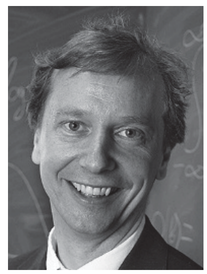

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Frank H. P. Fitzek is a Professor and chair of the communication networks group at Technische Universität Dresden coordinating the 5G Lab Germany. He received his diploma (Dipl.-Ing.) degree in electrical engineering from the University of Technology - Rheinisch-Westfälische Technische Hochschule (RWTH) - Aachen, Germany, in 1997 and his Ph.D. (Dr.-Ing.) in Electrical Engineering from the Technical University Berlin, Germany in 2002 and became Adjunct Professor at the University of Ferrara, Italy in the same year. In 2003 he joined Aalborg University as Associate Professor and later became Professor. He co-founded several start-up companies starting with acticom GmbH in Berlin in 1999. He has visited various research institutes including Massachusetts Institute of Technology (MIT), VTT, and Arizona State University. In 2005 he won the YRP award for the work on MIMO MDC and received the Young Elite Researcher Award of Denmark. He was selected to receive the NOKIA Champion Award several times in a row from 2007 to 2011. In 2008 he was awarded the Nokia Achievement Award for his work on cooperative networks. In 2011 he received the SAPERE AUDE research grant from the Danish government and in 2012 he received the Vodafone Innovation price. His current research interests are in the areas of wireless and mobile 5G communication networks, mobile phone programming, network coding, cross layer as well as energy efficient protocol design and cooperative networking.

Gerhard Fettweis Gerhard P. Fettweis earned his Ph.D. under H. Meyr's supervision from RWTH Aachen in 1990. After one year at IBM Research in San Jose, CA, he moved to TCSI Inc., Berkeley, CA. Since 1994 he is Vodafone Chair Professor at TU Dresden, Germany, with 20 companies from Asia/Europe/US sponsoring his research on wireless transmission and chip design. He coordinates 2 DFG centers at TU Dresden, namely cfaed and HAEC. Gerhard is IEEE Fellow, member of the German academy acatech, and his most recent award is the Stuart

Meyer Memorial Award from IEEE VTS. In Dresden he has spun-out eleven start-ups, and setup funded projects in volume of close to EUR 1/2 billion. He has helped organizing IEEE conferences, most notably as TPC Chair of ICC 2009 and of TTM 2012, and as General Chair of VTC Spring 2013 and DATE 2014.

3 A DESCRIPTION OF THE TECHNICAL ISSUES THAT THE TUTORIAL WILL ADDRESS, EMPHASIZING ITS TIMELINESS

ABSTRACT:

A big step lies ahead, when moving from today’s 4G cellular networks to tomorrows 5G network. Today, the network is used for content delivery, e.g. voice, video, data. Tomorrow, the 5G network will provide a ubiquitous Tactile Internet infrastructure for controlling and steering real and virtual objects. For this we must create a control processing and a control communications infrastructure. For enabling the former, distributed mobile edge cloud computing will be created at a level, unheard of today. For enabling the latter, latency and resilience requirements must be met by designing networks along new paradigms. The resulting Tactile Internet will shape our future and our society, touching almost every part of life.

TIMELINESS:

The topic is clearly timely and is the first of its kind that tries to build up a holistic understanding of the 5G technologies. Currently IEEE has started the own research group on Tactile Internet.

EXPECTED AUDIENCE:

The audience that will attend the tutorial is:

- Researchers in the field of 5G and Tactile Internet
- Network operators with interest in the field of 5G
- Service providers with interest in the field of 5G
- Hardware manufactures
- Students and PhD students looking for interesting topics with a horizon of 2020

DESCRITPION:

The tutorial will start to lay out the 5G use case with respect to control and steering. The use cases are broad, comprising transport, smart grids, Industry 4.0, eHealth and others, as given in Figure 1. The tutorial will advocate that most of the examples require massively reduced delays, some of the latency values of 1ms.

Figure 1: Use cases for the 5G Tactile Internet

In order to support the 1ms delay requirements, the tutorial will introduce the need for advances in:

- The design of chip and antenna design
- Novel techniques for the wireless links (protocol design and link level)
- Fusion of transport and cloud services with the backhaul (software defined networks, content centric networks, etc)
- Description of new use case within for the tactile Internet

4 AN OUTLINE OF THE TUTORIAL CONTENT, INCLUDING ITS TENTATIVE SCHEDULE

09.00-09.30	Introduction to 5G and motivating the tactile Internet by use cases (see above for nine different use cases)
09.30-10.00	Derivation of technical requirements (latency, throughput, security, safety, resilience, massive, heterogeneity)
10.00-10.30	Holistic approach comprising the cloud services, networks, wireless links, silicon design, and tactile use case.
10.30-10.45	Pause
10.45-11.15	Demo Session and Hands-on
	 *Tactile Internet Goggles:* Here the audience can experience the impact of latency by catching physical objects or interact with the real world by introduced delays. We will give out cardboard to the audience to understand the impact of latency.
	 Tactile Video Distribution: Here the audience can experience a large number of devices receiving multimedia content or controlling information in a reliable and synchronous way.
	 Human Robot Coworking: A demo for telepresence is shown as a result from a demonstration with Deutsche Telekom AG.
11.15-11.45	Wireless Tactile Support
11.45-12.30	Mobile Edge Cloud/Computing and Transport for 5G Network

5 Planned format of the tutorial, such as lecture or hands-on

The tutorial is planned to comprise lectures and hands-on or demo sessions to illustrate the future 5G technologies or use cases. Several videos will help to understand the need for Tactile Internet and its potential impact on the market. The two presenters will share the task to train the audience.

6 If appropriate, a description of past versions of the tutorial, including number of attendees, etc.

The tutorial was given at ICC 2018 and Globecom 2015 with great success.

Both speakers have a long record of speaker engagements.

Gerhard Fettweis's record (selected list):

- Several keynote talks at IEEE conferences: ICC, GlobeCom, VTC, etc
- More than 30 keynotes in 2014
- World famous for his visionary talks

Frank Fitzek's record (selected list):

- Tutorial at ICC 2018, June 2018, Fitzek/Medard: Network Coding: From Theory to Practice (40+ attendees)
- Tutorial at ICC 2018, June 2018, Fitzek/Fettweis: 5G Tactile Internet (40+ attendees)
- Tutorial at ICC 2014, June 2014, Fitzek/Medard: Network Coding: From Theory to Practice (90+ attendees)
- Tutorial at European Wireless 2014, May 2014, Fitzek/Medard, Network Coding: Theory and Implementation (10 attendees)
- Tutorial at GlobeCom 2013, December 2013, Fitzek/Pedersen: Implementing Network Coding (15 attendees)
- Tutorial at ICC 2013, June 2013, Medard/Fitzek: Network Coding: From Theory to Practice (100+ attendees)
- Tutorial at COST IC 1004 Training School, 20th May 2013, Fitzek: Green Mobile Clouds: Network Coding and User Cooperation for Improved Energy Eficiency (60+ attendees)

Audience @ ICC 2013: Medard/Fitzek: Network Coding: From Theory to Practice (100+ attendees)

DEEP LEARNING FOR COMMUNICATIONS: A HANDS-ON EXPERIENCE

STEPHAN TEN BRINK, JAKOB HOYDIS, SEBASTIAN CAMMERER, SEBASTIAN DÖRNER

Tutorial Proposal: Deep Learning for Communications: A Hands-On Experience

Tutorial Lecturers

Prof. Dr. Stephan ten Brink – University of Stuttgart, Germany
Dr. Jakob Hoydis – Nokia Bell Labs, France
Sebastian Cammerer – University of Stuttgart, Germany
Sebastian Dörner – University of Stuttgart, Germany

Abstract

In the last decade, deep learning has led to many breakthroughs in various domains, such as computer vision, natural language processing, and speech recognition. Motivated by these successes, researchers all over the world have recently started to investigate applications of this tool to their respective domain of expertise, with communications being one of them. The goal of this tutorial is to provide an introduction to deep learning that will enable the attendees to identify potential applications in their own research field. We give an overview of the very rapidly growing body of literature, explain state-of-the-art neural network architectures and training methods, and go through several promising applications and concepts, such as neural decoding, deep MIMO detection and autoencoders. In the second part of this tutorial, we aim to lower the barrier-to-entry for ML-newcomers to enable the implementation of own applications. Therefore, a practical hands-on coding session introduces a state-of-the-art deep learning toolchain by implementing, training and evaluating an autoencoder system in Tensorflow. The attendees receive tutorial slides and Jupyter notebooks containing code examples, which allows them to quickly get up to speed with this new and exciting field. During the break, we demonstrate the world's first fully neural network-based communications system.

Objectives and Motivation

Artificial intelligence and machine learning are currently considered as the most important universal technology of our era, similar to electricity and the combustion engine; their applications now extend into almost every industry and research domain. Although researchers have tried to address communications-related problems with machine learning in the past, it did not have a fundamental impact on the way we design and implement communications systems today. At first glance, machine learning techniques do not appear to be a good match to physical layer problems, with 50 years of tremendous progress based on "classic" signal processing, communication and information theory, approaching close-to-optimal Shannon limit performance on many channels.

However, several open problems remain, e.g., pertaining adaptivity and complexity of joint processing, where first results using machine learning-based approaches are promising (e.g., as shown by one of the lecturers J. Hoydis in "An Introduction to Deep Learning for the Physical Layer", TCCN'17). We believe that the key importance of machine learning for communications is not necessarily found in (potential) performance gains, but rather in a possible paradigm shift in how we design and implement future communication systems. It promises a communications system that can learn to communicate over any type of channel without the need for detailed prior mathematical abstraction of the channel model, breaking up restrictions commonplace in conventional block-based signal processing by moving away from handcrafted, carefully optimized sub-blocks towards adaptive and flexible (artificial) neural networks. The benefits of machine learning approaches may include more flexible hardware, highly adaptive systems, and less overall complexity. For now, this field is still in its infancy and offers many attractive interdisciplinary research questions at the interface between information theory, communications engineering, and machine learning. For these reasons, we believe that it is important and timely to provide a tutorial on deep learning for the physical layer. One important aspect of this tutorial is to pave the way for further research on the topic of deep learning from the perspective of communications and, consequently, to provide tools, analysis, and definitions for simplifying such activities.

Timeliness and Intended Audience

We believe this tutorial will attract researches from academia as well as from industry. The intended audience for this tutorial are domain experts in the field of communications (particularly the physical layer) without prior knowledge of deep learning. The planned tutorial does not require any particular background in machine learning and we will cover the content in a self-contained manner.

The huge interest from academia and industry in machine learning is mirrored by the amount of upcoming special sessions, special issues and workshops around this emerging topic at many flagship conferences and journals. To mention only a few, these are the IZS'18 ("Invited Session on Machine Learning for Communications: Theory and Applications", organized by the instructor Stephan ten Brink), ICC'18 Workshop (two of the instructors serve as TCP), the upcoming JSAC special issue'18 on "Machine Learning for Cognition in Radio Communications and Radar" and many more (e.g., SPAWC and Asilomar 2018).

Finally, the recent "**COMSOC Emerging Technology Initiative (ETI) – Machine Learning for Communications**" (mainly driven by one of the instructors Jakob Hoydis) emphasizes the timeliness of this topic for the Communications Society.

Addressed Technical Issues

Although a huge amount of literature and tutorials on deep learning are freely accessible, only little information is available in the specific context of communications where many new questions arise. These range from "how to deal with complex numbers?" over suitable loss-functions supported by information theoretical considerations, to the optimal neural network architectures, and many more.

The key target of this tutorial is not solving a specific technical problem, but rather explaining general concepts of how deep learning can be applied to a wide variety of tasks in communications. We choose the following two general issues:

1. How can existing (mostly iterative) algorithms be enhanced through deep learning-techniques?
2. How can completely new algorithms based on neural network structures be designed?

The first issue deals with defining a gradient of each step in the existing algorithm and the question where to inject trainable parameters. From a more practical perspective, it turns out that the implementation of existing algorithms in state-of-the-art machine-learning software libraries is often demanding and time consuming. We provide the basic techniques known in literature such as iterative loop-unrolling and suitable multi-loss functions.

The second issue relates to a simple but rather effective data-driven design of new algorithms. However, this approach turns out to be limited by scalability and training complexity (e.g., as shown by the lecturers in "On Deep Learning-based Channel Decoding", CISS'17). Thus, hierarchical net structures in combination with deterministic layers turn out to be much more efficient (e.g., see lecturers article "Deep learning-based communications over the air", JSTSP'18).

All these issues will be addressed by recent examples such as belief propagation decoding, MIMO detection and the autoencoder as end-to-end learning approach.

Outline

1. Introduction (15 min) – S. ten Brink
    - Hype around artificial intelligence and deep learning
    - Some historical remarks
    - Role of machine learning for future communications systems
2. A primer on Deep Learning (30 min) – J. Hoydis, S. Cammerer
    - Activation functions
    - Universal approximation theorem & Approximation and estimation bound
    - Wide versus deep
    - Stochastic gradient descent (SGD)
    - Backpropagation algorithm
    - Gradient descent optimization algorithms
    - Capacity, overfitting and underfitting
    - Regularization
3. Overview of Applications (45 min) – J. Hoydis, S. ten Brink, S. Cammerer, S. Dörner
    - Algorithm learning:
        - i. Deep MIMO Detection
        - ii. Neural channel decoding & Deep Unfolding
    - Autoencoders
    - Physical Channels: Approaches for the missing channel gradient

Break: Demo of "Deep learning-based communications over the air" – S. Dörner (as presented in the corresponding journal article in J-STSP'18)

4. A Hands-on Experience (75 min) – S. Cammerer, S. Dörner
    - Tensorflow and Jupyter-Notebooks
    - Implementing an Autoencoder in Tensorflow
    - Tips & tricks for training
    - Implementing Deep Unfolding / iterative loop unrolling
5. Future research directions (15 min) – J. Hoydis, S. ten Brink
    - Overview of the current status regarding the "COMSOC Emerging Technology Initiative – Machine Learning for Communications

DEEP LEARNING FOR COMMUNICATIONS:
A HANDS-ON EXPERIENCE

STEPHAN TEN BRINK, JAKOB HOYDIS, SEBASTIAN CAMMERER, SEBASTIAN DÖRNER

Prior history of the tutorial presentation and number of past attendees, if applicable

"Deep Learning for Communications" (3h), PIMRC 2018, around 70 attendees (no more seats available)

"Deep Learning for Communications" (3h), Globecom 2018, number of attendees not yet known

Similar tutorials in recent ICC & Globecom and how it differs

We would like to point out that a similar tutorial has been offered at PIMRC 2018 (& Globecom 2018) attracting more than 70 attendees, spurring most interesting discussions. However, no Tensorflow program code has been shown as the PIMRC/Globecom tutorial aimed to provide a broad overview and present different conceptual approaches. Based on the experience from previous tutorials and the fact that more and more researchers are, in principle, familiar with (and interested in) the fundamentals of deep learning techniques, we aim to lower the barrier-to-entry for practically implementing own networks and own ideas. For this, we particularly focus on giving the attendees a true "hands on" experience: Taking attractive problems from physical layer communications and showing, in detail, how to get down to neural network structures that can solve those problems. Thus, this tutorial also provides new aspects for attendees (non-exclusively) of our Globecom tutorial.

Further, this tutorial may also advertise and present the recent status regarding the « COMSOC Emerging Technology Initiative – Machine Learning for Communications ».

CVs & Previous lecture and tutorial expertise

Stephan ten Brink is a faculty member at the University of Stuttgart, Germany, since July 2013, where he is head of the Institute of Telecommunications. From 1995 to 1997 and 2000 to 2003, Dr. ten Brink was with Bell Laboratories in Holmdel, New Jersey, conducting research on multiple antenna systems. From July 2003 to March 2010, he was with Realtek Semiconductor Corp., Irvine, California, as Director of the wireless ASIC department, developing WLAN and UWB single chip MAC/PHY CMOS solutions. In April 2010, he returned to Bell Laboratories as Department Head of the Wireless Physical Layer Research Department in Stuttgart, Germany. Dr. ten Brink is a recipient and co-recipient of several awards, including the Vodafone Innovation award, the IEEE Stephen O. Rice Paper Prize, and the IEEE Communications Society Leonard G. Abraham Prize for contributions to channel coding and signal detection for multiple-antenna systems. He is best known for his work on iterative decoding (EXIT charts) and MIMO communications (soft sphere detection, massive MIMO).

Previous lecture and tutorial experience:

Two undergraduate and three graduate courses on wireless, optical and fundamentals of communications at University of Stuttgart, summing up to **115 hours** of teaching **per year** (since 2013)

Tutorial on Iterative Detection and Decoding in Communications (4 hours), IEEE European School of Information Theory (ESIT), Zaandvoort aan Zee, April 2015, by invitation of Prof. Frans Willems

Tutorial on Massive MIMO (4 hours), summer course (Ferienakademie), University of Stuttgart, University of Erlangen/Nuremberg and Technical University of Munich, Sarntal, Italy, 2016

Tutorial on Iterative Detection (4 hours), summer course (Ferienakademie), University of Stuttgart, University of Erlangen/Nuremberg and Technical University of Munich, Sarntal, Italy, 2015

Tutorial on Multicarrier Modulation (4 hours), summer course (Ferienakademie), University of Stuttgart, University of Erlangen/Nuremberg and Technical University of Munich, Sarntal, Italy, 2014

Tutorial on coding for the optical channel, "FEC and Soft Decision: Concept and Directions" (2 hours), S. ten Brink, A. Leven; Optical Fiber Conference (OFC) 2012, Anaheim, CA, USA

Tutorial on Ultra-Wideband System Design (12 hours), industry short course, with Dr. V. Rajendran, University of California, Los Angeles (UCLA), Department of Engineering and Information Systems, 2007

Tutorial on Low-Density Parity Check-Codes (12 hours), industry short course, UCLA Extension; with Prof. R. Wesel, Prof. W. Stark, Dr. D. Divsalar/JPL-NASA Pasadena; four courses summer 2004/05/06/07

"Algebraic Coding Theory: Classic and Modern Aspects", lecture at Columbia University, New York, winter term 2002/2003, with Dr. G. Kramer; by invitation of Prof. X. Wang

Jakob Hoydis is a member of technical staff at Nokia Bell Labs, France, where he is investigating since several years applications of deep learning for the physical layer. Before this position he was co-founder and CTO of the social network SPRAED and worked for Alcatel-Lucent Bell Labs in Stuttgart, Germany. He received the diploma degree (Dipl.-Ing.) in electrical engineering and information technology from RWTH Aachen University, Germany, and the Ph.D. degree from Supélec, Gif-sur-Yvette, France, in 2008 and 2012, respectively. His research interests are in the areas of machine learning, cloud computing, SDR, large random matrix theory, information theory, signal processing and their applications to wireless communications. He is recipient of the 2012 Publication Prize of the Supélec Foundation, the 2013 VDE ITG Förderpreis, and the 2015 Leonard G. Abraham Prize of the IEEE COMSOC. He received the WCNC'2014 best paper award and has been nominated as an Exemplary Reviewer 2012 for the IEEE Communication letters. He has co-authored the textbook *Massive MIMO Networks: Spectral, Energy, and Hardware Efficiency* in 2017.

Previous lecture and tutorial experience:

"Deep Learning Applications for Communications" (21h), undergraduate course at University of Stuttgart, Apr.-Jul. 2018

"Deep Learning for Communications" (3h), PIMRC, Sept. 2018, around 70 attendees

"Machine learning for future communications systems" (6h), invited lecture, ITN Scavange Training School 2017, Bristol

"Machine learning for future communications systems", invited lecture, DNAC Conference 2017, Paris

"Machine learning for future communications systems", Nokia Lecture 2017, University of Stuttgart

"Machine Learning for Communications" (4h), lecture at INSA Lyon, Nov. 2017

"Massive MIMO" (21h), undergraduate course at University of Stuttgart, Apr.-Jul. 2017

"Machine Learning for Communications" (4h), lecture at INSA Lyon, Dec. 2016

Tutorial on Massive MIMO and HetNets: Benefits and Challenges (3h), Newcom# Summer School on Interference Management at EURECOM, France, May 2014, around 100 attendees

Tutorial on Random matrix theory for advanced communication systems (3h), IEEE WCNC, Paris, France, Apr. 2012, with Prof. Merouane Debbah, around 50 attendees

Tutorial on Massive MIMO – Fundamentals and State-of-the-Art (3h), IEEE WCNC, Barcelona, Apr. 2018, with Emil Björnson and Luca Sanguinetti

Sebastian Cammerer is a member of research staff at Institute of Telecommunications, University of Stuttgart, and is pursuing his Ph.D. He received the B.Sc. and M.Sc. degree (with distinction) in electrical engineering and information technology from University of Stuttgart, Germany, in 2013 and 2015, respectively. During his years of study, he worked as a research assistant at multiple institutes of University of Stuttgart. His research topics are channel coding and machine learning for communications. Further research interests are in the areas of modulation, parallelized computing for signal processing and information theory. He is recipient of the Anton- und Klara Röser Preis 2016, the Rohde&Schwarz Best Bachelor Award 2015 and the VDE-Preis 2016 for his master thesis.

Previous lecture and tutorial experience:

"Deep Learning Applications for Communications" (21h), together with Jakob Hoydis, undergraduate course at University of Stuttgart, Apr.-Jul. 2018

"On Deep Learning-based Channel Decoding", invited presentation, Donnersbachtal, Austria, Mar. 2017, around 30 attendees

"Machine Learning for Communications" (2h), guest lecture at TUM Munich, Jan. 2018, together with Sebastian Dörner and Stephan ten Brink, around 55 attendees

Sebastian Dörner is a member of research staff at Institute of Telecommunications, University of Stuttgart, and is pursuing his Ph.D. He received the B.Sc. and M.Sc. degree in electrical engineering and information technology from University of Stuttgart, Germany, in 2014 and 2017, respectively. During his years of study, he worked as a research assistant at multiple institutes of University of Stuttgart and as GLT operator at Hawk-Eye Innovations, Sony Europe. His main research topic is applying machine learning techniques to different areas of communication systems. Further research interests include machine learning in general, parallelized GPU computing, channel coding, SDR and signal processing with machine learning tools. He is recipient of the Günther Woysch Award for his master thesis.

Previous lecture and tutorial experience:

"Deep Learning Applications for Communications" (21h), together with Jakob Hoydis, undergraduate course at University of Stuttgart, Apr.-Jul. 2018

"Machine Learning for Communications" (2h), guest lecture at TUM Munich, Jan. 2018, together with Sebastian Cammerer and Stephan ten Brink, around 55 attendees

"Deep Learning for Communications" (3h), PIMRC, Sept. 2018, together with Jakob Hoydis, around 70 attendees

1. Title: Cyber-Security Solutions for Internet of Things based on Hardware Security Primitives

2. Abstract, Objectives and Motivation: The Internet of Things (IoT) represents a paradigm shift in the connectivity between people, information, and things, and is envisioned as the enabling technology for a wide range of application domains such as smart cities, power grids, health care, and control systems for critical installments and public infrastructure. This diversity, increased control and interaction of devices, and the fact that IoT systems use public networks to transfer large amounts of data make them a prime target for cyber attacks. IoT security and human safety are often tied to each other, and security breaches can lead to loss of service, damage to equipment, economic losses, and even loss of human lives. IoT devices are usually small, low cost and have limited resources, which makes them vulnerable to a wide range of physical, side-channel, and cloning attacks. This tutorial will start with an introduction and in-depth coverage of the security challenges associated with IoT systems and highlight the common methods to address these challenges. Next, the tutorial will address the shortcomings of current solutions, specially in the context of physical and side-channel attacks. The tutorial will then motivate the use of hardware based security primitives for solving these security issues, followed by an in-depth description of the current state-of-the-art in this area. Physically unclonable function (PUFs) and nano-enabled security primitives will be the two main focus technologies that will be covered in detail. Next, security protocols for authentication, confidentiality, and message integrity for IoT devices based on hardware security primitives will be introduced. Finally, the tutorial will conclude with a discussion on open research issues in this area.

3. Timeliness and intended audience: The IoT is emerging as an important technological development that will bring about significant transformational changes in the society. The IoT is expected to grow to tens of billions of devices in the forthcoming years, resulting in a market opportunity of US$14 trillion by the year 2020, as estimated by IBM and Cisco Corporation. However, cyber-security for IoT devices is a growing concern for both practitioners and academia. Recent research shows that nearly half of firms using an IoT networks in USA have been hit by security breaches, which can cost up to 13% of the annual revenue of small companies. Thus, this tutorial on cyber-security issues for IoT is timely and expected to be of interest to a wide audience. The intended audience for this tutorial are members of both the academia and the industry who want to get a detailed introduction to the cyber-security challenges in the IoT and their solutions.

4. Name, affiliation, and short biography: Biplab Sikdar received the B. Tech degree in electronics and communication engineering from North Eastern Hill University, Shillong, India, M. Tech degree in electrical engineering from Indian Institute of Technology, Kanpur and Ph.D in electrical engineering from Rensselaer Polytechnic Institute, Troy, NY, USA in 1996, 1998 and 2001, respectively. He is currently an Associate Professor in the Department of Electrical and Computer Engineering of National University of Singapore where he serves and the Director of the Communication and Networking research group. His current research interest is primarily in the area of cyber-security for the Internet of Things and cyber-physical systems. Biplab is a recipient of the NSF CAREER award, faculty fellowships from the Japan

Society for the Promotion of Science, Norwegian Research Foundation and the Tan Chin Tuan Fellowship. He currently serves as an Associate Editor for the IEEE Transactions on Mobile Computing and has previously served on the editorial board of the IEEE Transactions on Communications. Biplab is a member of Eta Kappa Nu, Tau Beta Pi and a senior member of IEEE.

5. Description of technical issues that the tutorial will address: The tutorial will cover the following topics:

    a. Introduction to cyber-security issues in IoT systems: This part of the will highlight various threats and vulnerabilities in IoT systems. Examples and case studies of recent attacks will be provided.
    b. Security solutions: This part of the tutorial will present the state-of-the-art in security solutions for IoT devices. The strengths and weaknesses of these solutions will be described.
    c. Physical and side-channel attacks on IoT devices: This part of the tutorial will describe the state-of-the-art in physical and side channel attacks, with particular emphasis on how they relate to IoT devices.
    d. Hardware security primitives: This part of the tutorial will introduce hardware security primitives that can be used in IoT systems. Particular emphasis will be placed on Physically Unclonable Functions and nano-enabled security primitives.
    e. Security protocols and solutions based on hardware security primitives: This part of the tutorial will describe the state-of-the-art in security protocols that use hardware security primitives, in particular for IoT devices, and how they address the drawbacks of traditional security solutions.
    f. Open research directions: The tutorial will conclude with open problems and challenges in the area of security for IoT systems.

6. Outline of tutorial content, including its tentative schedule: The duration of the tutorial is 3 hours. The topics covered and their schedule is given below.

    a. Introduction to cyber-security issues in IoT systems: 15 minutes
    b. Security solutions: 30 minutes
    c. Physical and side-channel attacks on IoT devices: 30 minutes
    d. Hardware security primitives: 40 minutes
    e. Security protocols and solutions based on hardware security primitives: 45 minutes
    f. Open research directions: 15 minutes
    g. Question and answers: 5 minutes

7. Past/relevant experience of the speaker(s) on the topic of the tutorial: The speaker has previously presented keynotes and invited talks in a number of conferences on the topic of security for IoT and cyber-physical systems. The recent ones include:

    a. IEEE IoT World Forum 2018 (Singapore): Title: Security Solutions for the Internet of Things
    b. IEEE MICC 2017 (Malaysia): Title: Cyber Security Challenges and Solutions for the Internet of Things
    c. INFORMS Annual Meeting 2017 (USA): Title: Smart Grid Security through Synchrophasor Data: Real-time Detection of Attacks on AC State Estimation
    d. NSF Smart Grids Big Data Workshop 2017 (USA): Title: Security for Synchrophasor Data
    e. IEEE WIOT 2017 (India): Title: Cyber-security for the IoT and Cyber-physical Systems: Challenges and Some Solutions

8. Description of previous tutorial experience of the speaker(s), and past versions of the tutorial: The speaker has not presented this tutorial in the past. The speaker has previously presented a tutorial on "Network Infrastructure for the Internet of Things and M2M Communications" in IEEE BlackSeaCom 2015 and NCC (India) 2015.

9. Similar tutorials in recent IEEE ICC or GLOBECOM (last two years): None

Cellular-based V2X Communications

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***Abstract* - A wide variety of work has been down in vehicle-to-everything (V2X) communications to enable various applications for road safety, traffic efficiency and passenger infotainment. Although IEEE 802.11p used to be considered as the main technology for V2X, new research trends nowadays are considering cellular technology as the future of V2X due to its rapid development and ubiquitous presence. This tutorial surveys the recent development and challenges on 4G LTE and 5G mobile wireless networks to support efficient V2X communications. In the first part, we highlight the technical motivations of 4G LTE for V2X communications. In the second part, we explore the LTE V2X architecture and operating scenarios being considered. In the third part, we discuss the challenges and the new trends in 4G and 5G for supporting V2X communications such as physical layer structure, synchronization, resource allocation, security, multimedia broadcast multicast services (MBMS), as well as possible solutions to these challenges. Finally, we discuss some open research issues for future 5G based V2X communications.**

***Keywords* - V2X communications, intelligent transportations, 4G, LTE, 5G wireless networks.**

I. A SHORT BIO OF THE TUTORIAL SPEAKER

Yi Qian is a professor in the Department of Electrical and Computer Engineering, University of Nebraska-Lincoln (UNL). Prior to joining UNL, he worked in the telecommunications industry, academia, and the government. His research interests include information assurance and network security, network design, network modeling, simulation and performance analysis for next generation wireless networks, wireless ad-hoc and sensor networks, vehicular networks, smart grid communication networks, broadband satellite networks, optical networks, high-speed networks and the Internet. He is serving on the editorial board for several international journals and magazines, including serving as the Associate Editor-in-Chief for IEEE Wireless Communications Magazine. He was the Chair of IEEE Communications Society Technical Committee for Communications and Information Security 2014-2015. He is the Technical Program Committee Chair for IEEE ICC 2018. He is a Distinguished Lecturer for IEEE Vehicular Technology Society & a Distinguished Lecturer for IEEE Communications Society.

Prof. Qian received the Henry Y. Kleinkauf Family Distinguished New Faculty Teaching Award in 2011, the Holling Family Distinguished Teaching Award in 2012, the Holling Family Distinguished Teaching/Advising/Mentoring Award in 2018, and the Holling Family Distinguished Teaching Award for Innovative Use of Instructional Technology in 2018, all from University of Nebraska-Lincoln. In the recent years, he has been a frequent speaker on many topics in his research areas in various venues and forums, as a keynote speaker, a tutorial presenter, and an invited lecturer.

II. OBJECTIVES AND MOTIVATION

There have been many recent research activities to address the communication capabilities in vehicles and transportation infrastructure, which mainly include vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), vehicle-to-pedestrian (V2P) and vehicle-to-network (V2N) communications collectively termed as vehicle-to-everything (V2X) communications. This V2X communications can improve the efficiency and safety of transportation systems. V2X communications together with existing vehicle sensing capabilities provide support for enhanced safety use cases, passenger infotainment and vehicle traffic optimization. V2X communications should support variety of use cases like forward collision warning, do not pass warning, queue warning, parking discovery, optimal speed advisory, curve speed warning, etc.

Currently there exists two main technologies to support V2X communications: dedicated short-range communications (DSRC) and cellular network technologies. DSRC technology is mainly considered to support intelligent transportation system (ITS) applications in V2V scenarios. DSRC technology supports short exchange of information among DSRC devices for automotive and ITS. DSRC devices include onboard units (OBU), roadside units (RSU) and hand held devices carried by pedestrians. U.S. Federal Communication Commission (FCC) has allocated 75 MHz of spectrum in 5.9 GHz frequency band to be exclusively used for DSRC based applications. Set of services and interfaces have already been defined by IEEE 802.11p and IEEE 1609 standards, for Wireless Access for Vehicular Environment (WAVE), to be used in DSRC based applications. U.S. National Highway Traffic Safety Administration (NHTSA) worked with U.S. Department of Transportation to enable vehicular communication capabilities in new light vehicles by 2017. However, lack of infrastructure and other limiting feature of IEEE 802.11p diverted some researchers to look for other access technologies. Introduction of device-to-device (D2D) communications improved spectrum utilization efficiency and system capacity in cellular system. The limitations of DSRC and recent advancements in cellular technologies like D2D communications motivated research communities to investigate 4G LTE based V2X communications.

LTE based V2X communications can make use of high capacity, large cell coverage range and widely deployed infrastructure to support vehicular communications. Due to which the 3rd Generation Partnership Project (3GPP) is currently working on cellular technology based V2X service and aims to provide a variety of V2X services. 3GPP has already completed its Release 14 with LTE based V2X service as one of the main features including other features like license assisted access, machine type communications, massive MIMO. Cellular-V2X Release 14 provides highly reliable, real time communications for automotive safety use cases. It will continue to evolve to Release 15 along with 5G to provide complementary and new capabilities like sensor sharing while maintaining backward compatibility. The technical organizations like 3GPP and Qualcomm have already prepared the roadmap towards 5G based V2X services. There is also active research being conducted in interworking between DSRC and cellular technology to support efficient V2X communications.

In this tutorial, we provide a comprehensive survey on state-of-the-art of various works on 4G LTE and 5G to support V2X communications. We illustrate that how strengths of LTE such as high capacity, wide coverage, high penetration to complement the drawbacks of 802.11p. We also show that several challenges lie ahead before LTE can be massively deployed in vehicular environment. The main challenge identified in supporting V2X services will be high relative mobility causing Doppler Effect and dense UEs. LTE systems need to be enhanced especially physical layer structure to address the problem of this Doppler Effect. Resource allocation will be another challenge where resources being used by the vehicular system should not conflict with the resources being used by cellular users. Interference from vehicular user to the existing cellular user need to be taken care while assigning resources. Another main challenge will be the security. As V2X network will be controlled by operator, operator can easily track the vehicular users. Several solutions have been proposed in 3GPP to address this problem. Broadcast system MBMS should be enhanced in order to better support the safety message dissemination.

3GPP has already completed work for Release 14 and is currently working for further LTE evolution and new air interface design to support vehicular communication based on 5G.

III. PROPOSED DURATION

Half day

3.5 hours of instruction

IV. INTENDED AUDIENCE

Graduate students, professors, researchers, scientists, practitioners, engineers, industry managers, consultants, and government agencies.

V. A DESCRIPTION OF THE TECHNICAL ISSUES THAT THE TUTORIAL WILL ADDRESS

There have been many recent research activities to address the communication capabilities in vehicles and transportation infrastructure, which mainly include vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), vehicle-to-pedestrian (V2P) and vehicle-to-network (V2N) communications collectively termed as vehicle-to-everything (V2X) communications. This V2X communications can improve the efficiency and safety of transportation systems. V2X communications together with existing vehicle sensing capabilities provide support for enhanced safety use cases, passenger infotainment and vehicle traffic optimization. V2X communications should support variety of use cases like forward collision warning, do not pass warning, queue warning, parking discovery, optimal speed advisory, curve speed warning, etc.

The proposed tutorial not only covers the current research and development on V2X communications for 4G LTE mobile wireless networks, but also the latest development on V2X communications for 5G mobile systems, and the unique discussions on the challenges and open research issues in the area, based on the tutorial speaker's own research experience and comprehensive surveys on the subject.

VI. OUTLINE OF THE TUTORIAL CONTENT & TENTATIVE SCHEDULE

1. Motivation for 4G LTE based V2X Communications
   (20 minutes)
   a. DSRC based V2X communications
   b. LTE based V2X communications and new trends
2. LTE V2X infrastructure and operating scenarios
   (75 minutes)
   a. 4G LTE V2X communication model
   b. 3GPP LTE V2X communication architecture
   c. Operating scenarios
      - Multiple operators for a given area with each UE using spectrum of its own operator
      - Multiple operators for a given area with dedicated spectrum for V2X
      - Single operator for a given area
      - Out of cellular coverage
3. Challenges and solutions in 4G and 5G for supporting V2X communications
   (75 minutes)
   a. Physical layer structure
   b. Synchronization
   c. Resource allocation
   d. Security and privacy
   e. Multimedia broadcast multicast services
4. Open research issues for future 5G based V2X communications
   (30 minutes)
   a. Emerging 5G technologies and V2X communications
   b. Vehicular cloud computing
   c. Vehicular fog computing
   d. Security and privacy in 5G V2X communications

5. Conclusion
   (10 minutes)

VII. PREVIOUS TUTORIAL DELIVERY OF THE SPEAKER

***The proposed tutorial has not been offered in recent ICC or GLOBECOM yet*.**

Yi Qian has given several tutorials in various IEEE conferences recently:

1. Yi Qian, "4G and 5G based V2X Communications", IEEE VTC 2018-Fall, 9:00 am – 12:30 pm, August 27, 2018, Chicago, USA
2. Yi Qian, "Challenges and Solutions for LTE and 5G based V2X Communications", IEEE/CIC 2018, 9:00 am – 12:30 pm, August 16, 2018, Beijing, China.
3. Yi Qian, "Challenges and Development for 5G Wireless Network Security", IEEE GLOBECOM 2017, Singapore, 2:00 pm - 5:30 pm, December 8, 2017.
4. Yi Qian, "Security for 5G Wireless Communication Systems - Recent Development and Challenges", IEEE LATINCOM 2017, Guatemala City, Guatemala, 10:45 am – 17:30 pm (5 hours) November 8, 2017.
5. Yi Qian, "Security in 4G & 5G Mobile Wireless Networks", IWCMC 2017, Valencia, Spain, 9:00 am - 12:00 noon, June 26, 2017. The classroom was full, with about 30 registered attendees.
6. Yi Qian, "Security for 5G Wireless Network Systems", IEEE VTC 2017-Spring, Sydney, Australia, 8:30 am - 12:00 noon, June 4, 2017. With 20 registered attendees.
7. Yi Qian, "Security for 5G Wireless Network Systems", IEEE ICC 2017, Paris, France, 2:00 pm - 5:30 pm, May 25, 2017. With 8 registered attendees.
8. Yi Qian, "Security for Next Generation Mobile Wireless Networks", IEEE VTC 2016 Spring, Nanjing, China, 8:30 am - 12:00 noon, May 15, 2016. The classroom was full, with about 25 registered attendees.
9. Rose Qingyang Hu and Yi Qian, "Recent Advances in Communication Infrastructures for Smart Grid", IEEE ICC 2014. The classroom was full with the attendees.
10. Rose Qingyang Hu, Yi Qian, Qian Li, "Towards Spectrum and Energy Efficient Heterogeneous Wireless Networks", IEEE WCNC 2013. The classroom was full with the attendees.
11. Dusit Niyato, Rose Qingyang Hu, Ekram Hossain, Yi Qian, "Communications and Networking for Smart Grid Systems", IEEE GLOBECOM 2011. With more than 100 attendees.
12. Yi Qian, and David Tipper, "Security and Dependability of Networked Information Systems", IEEE ICC 2008. With 10 registered attendees.
13. Yi Qian, "Security and Survivability and Their Interactions for Wireless Networks", IEEE VTC 2008-Spring. With 8 registered attendees.

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Channel measurement and modeling for fifth-generation (5G) system

Andreas F. Molisch
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Jianhua Zhang
Beijing University of Posts and Telecommunications

Abstract, objectives, and motivation

Research in fifth-generation wireless communications (5G) communications systems has attracted worldwide attention in recent years. Compared with existing mobile communication systems, 5G is expected to include new requirements, applications and scenarios, e.g., enhanced mobile broadband (eMBB), massive machine type communications (mMTC) and ultra-reliable and low latency communications (URLLC). To meet the high spectrum efficiency and growing capacity targets, 5G will need massive and three-dimensional (3D) MIMO, and increased spectrum via the use of millimeter (mm) wave frequency bands due to the enormous amount of available bandwidth in this frequency range.

For the design, performance assessment, and deployment planning of wireless systems, understanding of the propagation mechanisms and creation of suitable channel models is a *conditio sine qua non*. For 5G systems, measurement and modeling of the corresponding propagation channels is thus of the utmost interest. This is particularly relevant since the emerging massive or 3D MIMO bring a new domain, i.e., vertical plane while currently 4G standard channel model only including azimuth plane. Thus channel properties in the vertical domain are vital for the full utilization of novel MIMO schemes. Secondly, many of the dominant propagation effects of mm wave are significantly different from those at the traditional cm-wave frequencies. It is therefore clear that more efforts are needed to understand propagation characteristics especially in mm wave bands and to demonstrate their impact on system design and deployment.

Due to the complexity of 5G systems, also the channel models have to correctly account for a variety of channel parameters. Pathloss and shadowing are of obvious importance, since they determine range and interference level. Spatial modulation, beamforming, etc. are important techniques for 5G systems and they are highly depending on the angular dispersion, that is, the spatial correlation of channel. Thus, the angular dispersion needs to be characterized. Not only the angular spread, but also the temporal changes of the angular dispersion have to be described, so that it can be judged how fast beamformers need to adapt. Due to the wideband nature of 5G systems, delay dispersion needs to be characterized, both with respect to delay spread, and the number of multipath components. Frequency correlation within the

mm-wave band, and between this band and the microwave band is vital for assessing the potential and performance of multi band systems.

Timeliness, Intended audience and learning objectives:

The importance of channel model for 5G, and thus the future of wireless, does not need any further elaboration – a fundament and deep area of research in the communications community is dedicated to this. The current tutorial is intended both for experts in 5G channel modeling, and for communications engineers that want to apply channel models and gain an understanding of how channel characteristics impact system design.

For the non-expert in channel modeling, the main goal of the tutorial is to provide a broad overview of the state of the art. The participants should have a good overview on when which channel sounding method is appropriate, when ray tracing can give them reliable results, what channel parameters are known with reasonable confidence from previous measurements, and where there are gaps in our knowledge. Experts in the field will profit from the aggregation of the many measurement results, and from the insights that the presenter can offer into the standardized channel models, including the contributed 3GPP and ITU 5G channel model standards.

Biographical information of the tutorial speakers:

Andreas F. Molisch is the *Solomon Golomb – Andrew and Erna Viterbi* Chair Professor at the University of Southern California. He previously was at TU Vienna, AT&T (Bell) Labs, Lund University, and Mitsubishi Electric Research Labs. His research interest is wireless communications, with emphasis on wireless propagation channels, multi-antenna systems, ultrawideband signaling and localization, novel modulation methods, and caching for wireless content distribution. He is the author of four books, 18 book chapters, more than 200 journal papers, 280 conference papers, as well as 80 patents and 70 standards contributions. He is a Fellow of the National Academy of Inventors, IEEE, AAAS, and IET, as well as Member of the Austrian Academy of Sciences and recipient of numerous awards. He has been the chair or major contributor in many channel measurement and modeling groups, including the channel measurement/modeling groups of COST 259 (co-chair), COST 273 (chair), IEEE 802.15.3a, IEEE 802.15.4a (chair), IEEE 802.11n, 3GPP SCM, 5GSCM, NIST 5G mmWave Alliance (channel model subgroup chair).

Jianhua Zhang is the professor of information and engineering college, Beijing University of Posts and Telecommunications (BUPT). She received B.S. from the North China University of Technology in 1994 and Ph.D. degrees from the in 2003. Her research interests are massive MIMO and millimeter wave channel modeling and channel estimation, synchronization transmission techniques, data mining or machine learning applied in channel research etc. She has published more than 70 journal papers and 150 conference papers, received 3 best paper awards, as well as 40 patents and 50 standards contributions, main contributors from ITU-R M.2135 to

3GPP 36.814, 873,900/901 and ITU-R M. 2412 (She was the Drafting Group Chairwoman of ITU-R IMT-2020 channel model). She received two national novelty awards for her contribution to the research and development of Beyond 3G TDD and 1 Gbps system, respectively. She received the second prize from the Chinese Communication Standards Association for her contributions to 4G channel model and the first prize from Radio Association for China for her contribution to 5G channel model.

Technical issues to be addressed

This tutorial aims to give a comprehensive overview of 5G channel measurements and models, including the following aspects:

- Channel measurement techniques: the first step for any channel investigation has to be an accurate measurement. We will review different types of channel sounders, including narrowband, wideband, and directional (MIMO) sounding techniques, with special attention to the unique challenges that arise at mm-wave frequencies and massive antenna size.
- We will also discuss ray tracing and its challenges arising from the fact that most surface structures are larger than a wavelength.
- Channel measurement results in the literature: the tutorial will next give an overview of the measurement results in the literature. We have recently performed an extensive literature review of hundreds of papers and will present a concise summary of the main observed trends.
- Channel models: in order to serve for system design and testing, the measurement results have to be turned into suitable models. We will review the main classes of channel models, namely tapped delay line, geometry-based stochastic, and quasi-deterministic, and discuss the pros and cons of these approaches for mm-wave systems. An assessment of existing standardized models such as the 3GPP and ITU 5G model will also be included.

Tutorial outline and schedule

1. Background of 5G systems and the tendency of 5G channel model (15min)

2. Channel sounding (60 min)
2.1 Narrowband sounders
2.2 Vector Network Analyzer based sounders
2.3 Correlation based sounders
2.4 Rotating horn antennas for directional resolution
2.5 Virtual antenna arrays (including massive elements) and switched beams
2.6 Fourier-based analysis and high resolution techniques
2.7 Ray tracing

3. Measurement results and channel characteristics in the literature (45 min)

3.1 Pathloss and shadowing
3.2 Delay dispersion
3.3 Angular dispersion (massive favorable propagation and mm wave)
3.4 Wideband K factor estimation
3.5 Special scenarios (Industrial, car or body networks etc.)

4. Channel models (60 min)
4.1 Tapped delay line models
4.2 Geometry-based stochastic channel models
4.3 Quasi-deterministic and map-based models
4.4 Standardized channel models and advanced feature of 5G channel model
4.5 Machine learning application in channel models
4.6 Future research topics

Relevant experience of the speakers on the topic of research

The presenters, Prof. Molisch and Prof. Jianhua Zhang, both have several ten years' experience in channel measurement and modeling. Prof. Molisch has authored some of the most widely cited papers in the field, and has received numerous awards for this work. In terms of mm-wave channel measurement and modeling, he has been performing numerous measurement campaigns, was the first to apply high-resolution algorithms to the evaluation of mm-wave channels, and has recently built a first of its kind phased-array channel sounder. Prof. Jianhua Zhang has two of the earliest 3D MIMO channel model publications and first observed the favorable propagation with 256 antenna measurement campaigns. As for machine learning, she has one best paper award in 2016 China Comms for the novel idea to use machine learning in channel models. They were both participants in the 3GPP SIG that developed the basis for the 3GPP mm-wave channel model and Prof. Molisch is chairperson of the channel modeling group in the 5G mm-wave channel modeling alliance. Prof. Jianhua Zhang is the chairwoman of channel model draft group of ITU-R 5G channel model, ITU-R M. 2412 and now was widely used for 5G research and evaluation.

Relevant tutorial experience
The speaker Prof. Molisch has given more than 20 tutorials over the past 20 years at a variety of IEEE conferences. The speaker Prof. Jianhua Zhang has a lot experiencing in presentation and invited talks. In 2017 ICC, Prof. Molisch gave a tutorial about channel research on mm wave. In the current proposal, he and Prof. Jianhua Zhang jointly extend the topic from mm wave to the general 5G channel model, both including massive MIMO and mm wave, as well as machine learning and more scenarios of 5G, including industrial etc. Those also are a part of undergoing work of academia and standards.

Ultra-Low Latency and Machine-Learning Based Mobile Networking

Abstract

Autonomous (or unmanned) vehicles (AVs) emerge as one major technological paradigm shift of the industry and human society, while introducing more technological challenges in wireless networks. As the technology for single AV/robot becoming mature, the real challenge comes from reliable, safe, real-time operation of AVs/robots in massive scale. To achieve such multi-scale management and control, effective cloud computing, edge computing, and on-board computing, networking and computing in real-time to interact with environments and other agents such as vehicles and individuals. Ultra-low latency mobile networking is inevitably wanted to ensure successful control and services in this most challenging Internet of Things and robotics. Considering high reliability and safety, various innovative networking technologies would be needed. This tutorial will present key and emerging technological aspects of ultra-low latency mobile networking based on machine learning (ML) network architecture: uplink and downlink air-interface, ultra reliable and ultra-low latency communication (uRLLC) for 5G and beyond, network function virtualization (NFV) of network resources, ML enabled anticipatory mobility management, channel estimation and radio resource allocation based on ML, software defined networking architecture and realization, network security, and machine-learning based network architecture under new development by the ITU-T, toward future ultra-low latency and ML based mobile networking.

Objectives and motivation

Massive operation of autonomous vehicles and service robots requires ultra-low latency mobile networking to enable complicated cloud computing for management and control, edge computing for real-time control and information exchange, and on-board computing for each AV's (or robot's) smooth and safe maneuvering based on collected information. Such a goal demands uRLLC and ultra-low latency mobile networking for 5G and beyond, by satisfying latency requirements of tactile Internet and high mobility at the same time. This tutorial wishes to achieve the multi-fold goal to let audience (1) understand the important role of ultra-low latency networking in this complicated and AI-enabled IoT that requires reliability and safety (2) comprehend state-of-the-art uRLLC and wireless networking technology to assist the operation of AVs and robots (3) get familiar with innovative network architecture (particularly, machine-learning based future network architecture under initial development by ITU-T) and novel SDN implementation to satisfy ultra-low latency and then to accomplish the ultimate goal of autonomous real-time actions for AVs and robots in a reliable and safe way. Ultra-low latency mobile networking is not just a driving force for vehicular networking, but also for tactile Internet, AR/VR, smart manufacturing, and much more IoT services in future digital society.

Timeliness and intended audience

Artificial intelligence and machine learning realize the dream of single autonomous vehicle (AV) and robotic operation, as one of the most important technological achievements in recent years. However, massive operation of AVs and robots, and consequent new service industry remains on the horizon due to lacking of ultra-low latency mobile networking that might be one of the most wanted technologies into digital society. Although autonomous vehicles and robots have attracted tremendous industrial attention, the critical role of ultra-low latency mobile networking to ensure safety and reliability of massive operation has been overlooked and only limited research on uRLLC are available in literature. This newly developed tutorial presents newly developed aspects for wireless and vehicular technology in uRLLC, SDN and machine-learning based networking, as a unique and important subject for IEEE ICC audience.

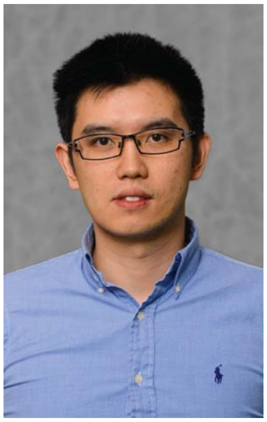
Target audience includes researchers, graduate students, and practice engineers in intelligent transportation, AVs and robotics, wireless networks, mobile communication systems, and professionals in vehicular transportation industrial and wireless/networking industry. General IoT professionals who want to understand the role of networking in massive AVs and robots to develop further services in digital society shall be potential audience.

Name, affiliation, and a short biography of each tutorial speaker

Tutorial Speaker: Prof. Kwang-Cheng Chen, IEEE Fellow
Affiliation: University of South Florida
Email: kwangcheng@usf.edu Phone: (813) 974-1023

Kwang-Cheng Chen received the B.S. from the National Taiwan University in 1983, and the M.S. and Ph.D from the University of Maryland, College Park, United States, in 1987 and 1989, all in electrical engineering. From 1987 to 1998, Dr. Chen worked with SSE, COMSAT, IBM Thomas J. Watson Research Center, and National Tsing Hua University in mobile communications and networks. During 1998-2016, he was with National Taiwan University, Taipei, Taiwan, as the *Distinguished Professor* in the College of Electrical Engineering & Computer Science, National Taiwan University. Since 2016, Dr. Chen is a Professor at the Department of Electrical Engineering, University of South Florida, Tampa, USA. Dr. Chen founded a wireless IC design company in 2001, which was acquired by MediaTek Inc. in 2004. He has been actively involving in the organization of various IEEE conferences as General/TPC chair/co-chair (2002 IEEE Globecom, 2010 IEEE VTC-Spring, and 2020 IEEE Globecom), serving editorships with a few IEEE journals, and various IEEE volunteer services with IEEE Fellow Committee, IEEE VTS Fellow Evaluation Committee, IEEE VTS Distinguished Lecturer, IEEE COMSOC NEC, Emerging Technology Committee, etc. He founds and chairs the Technical Committee on Social Networks in the IEEE Communications Society. Dr. Chen also has contributed essential technology to various international standards like IEEE 802 wireless LANs, Bluetooth, LTE and LTE-A. He has authored and co-authored over 300 IEEE publications and more than 23 granted US patents. He co-edited (with R. DeMarca) the book *Mobile WiMAX* published by Wiley, and authored the book *Principles of Communications* published by River, and co-authored (with R. Prasad) another book *Cognitive Radio Networks* published by Wiley. Dr. Chen is an IEEE Fellow and has received a number of awards including *2011 IEEE COMSOC WTC Recognition Award*, *2014 IEEE Jack Neubauer Memorial Award, 2014 IEEE COMSOC AP Outstanding Paper Award*. He also serves the series editor for "Data Science and AI for Communications", in the *IEEE Communications Magazine*, and is heavily devoting to ITU-T FG on ML5G standard efforts. Dr. Chen's current research interests include wireless networks, artificial intelligence and machine learning, IoT/CPS, social networks and data analytics, and cybersecurity.

Tutorial Speaker: Professor Shih-Chun Lin
Affiliation: North Carolina State University
Email: slin23@ncsu.edu Phone: (919) 515-5128



Dr. Shih-Chun Lin received the B.S. degree in electrical engineering and the M.S. degree in communication engineering from National Taiwan University, Taiwan, in 2008 and 2010, respectively, and the Ph.D. degree in electrical and computer engineering from Georgia Institute of Technology, Atlanta, USA, in 2017. Currently, he is a tenure-track Assistant Professor with the Department of Electrical and Computer Engineering at the North Carolina State University. His research interests include 5G and beyond wireless systems, software-defined networking, Internet of Things, cyber-physical systems, big-data analytic and machine learning, wireless sensor networks in changed environment, statistical scheduling and mathematical optimization.

Technical issues that the tutorial will address, emphasizing its timeliness

Different from traditional textbook approach, the technical issues to be address in this tutorial on ultra-low latency and machine-learning based mobile networking cover timely technological components and system architecture as follows.

- State-of-the-art V2X/V2V networking and ultra reliable and low-latency communication (uRLLC).
- Disruptive open-loop wireless communication and implementation techniques as the air-interface technology with the assistance of asynchronous multiuser detection
- Heterogeneous networks by mobile edge computing to facilitate ultra-reliable and ultra-low latency communication via proactive network association, radio slicing and network slicing, radio resource allocation in physical networks
- Network function virtualization (NFV) of network resources, software defined networking architecture and realization, and network security
- Machine learning enabled anticipatory mobility management, channel estimation and radio resource allocation based on machine learning, and machine-learning based network architecture under new development by the ITU-T

An outline of the tutorial content, including its tentative schedule

The proposed tutorial consists of the following technical scope, with totally 210 minutes 3.5 hours) to present, which can be adjust to 180 minutes subject to the requirements.

1. State-of-the-art V2X/5G networking for connected vehicles [30 minutes]
   Wireless networking like dedicated short-range communications (DRSC) and IEEE 802.11 family standards facilitates information exchange between road-side units and on-board units. Under the requirements from US DoT, for many real-time safety concerns, inter-vehicle multi-hop networking that does not require infrastructure will be presented to resolve technological challenges in ad hoc networking in high dynamic operating environments. 5G networks can also supply in-time information to vehicles to assist human driving in a more comfortable and safe way.
2. Open-Loop Wireless Communications and Error Control [30 minutes]
   Leveraging large bandwidth of mmWave frequency bands, open-loop wireless communication to significantly reduce end-to-end latency. LTE-U and further migration on unlicensed bands

supplies alternatives to achieve ultra-low latency. To ensure end-to-end service quality, error control techniques will be introduced for open-loop wireless communications by the path-time codes (PTC). Further integral FEC and PTC can be developed to effectively achieve reliability.

3. Proactive Network Association, Proactive Radio Resource Allocation, and Uplink/Downlink Air-Interface to Achieve Ultra-Low Latency [30 minutes]
   Each AV can be viewed as a virtual cell with the aid of cooperative networking via CoMP and proactive network association with open-loop communication. Network function virtualization (NFV) and proactive methodology can be adopted to network/radio resource allocation. Multiuser detection (MUD) and computational efficient implementations will be introduced to resolve these technological challenges.
4. Anticipatory Mobility Management and Interference Management Using Channel Estimation by Machine Learning [30 minutes]
   Proactive network association gives birth a new technology challenge about ultra-low latency downlink communication. Using machine learning and artificial intelligence, prediction of access points to fog networking can be realized by big data analytics. After quick orientation of machine learning techniques, data-drive anticipatory mobility management will be introduced. Further channel estimation and user mobility patterns can be obtained by machine learning techniques, such that interference management and radio resource allocation for air-interface can be innovated to form machine learning based cross-layer design.
5. NFV/SDN Realization of uRLLC [40 minutes]
   Software-defined networking (SDN) has been recently introduced to facilitate system design and management flexibility, which potentially solves the challenges in vehicular edge computing and 5G. The main ideas of SDN are (i) to separate the data forwarding plane from the network control plane and (ii) to introduce novel network control functionalities based on a network abstraction. Hence, SDN provides the upper-running applications with a centralized view of distributed network states. This in turn can dramatically improve network resource utilization, simplify network management, reduce operating cost, and promote innovation and evolution. However, current SDN realizations only focus on the programmability of networking functions, e.g., packet forwarding, via flow tables and wildcard rules and do not support any of distributed data processing. A computing-based SDN vehicle-centric networking architecture for uRLLC will be suggested, while self-organizing distributed network realization of flexibility and resilience requiring further novel and simplified SDN/NFV will be introduced.
6. Security in heterogeneous networks for AVs [20 minutes]
   To achieve ultra-low latency, distributed computing/networking on the edge of the heterogeneous networks is inevitable, which creates new treats to security and reliability of the entire system of AVs. New attacks and new light-weight security methods will be oriented.
7. uRLLC machine-learning based network architecture for 5G and beyond [30 minutes]
   Ultra-reliable and low-latency communications (uRLLC) have been envisioned to support new applications in the fifth generation (5G) wireless communications, such as autonomous vehicles that perform cooperation and safety functions, monitoring and control in smart grids, tactile feedback in remote medical procedures, control and coordination of unmanned aviation vehicles, robotics, and industrial automation. The current 3GPP requirement for uRLLC includes 1ms hard latency over the air interface and 99.999% system reliability. However, it is very challenging to satisfy these strict requirements, due to complicated propagation environments in terrestrial wireless networks. We will introduce network architecture for

uRLLC and many machine-learning techniques, which connects ITU-T's new standard effort of machine learning for future network architecture (5G and beyond).

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[22] S.C. Hung, S.Y. Lien, K.C. Chen (2015). Low Latency Communication for Internet of Things. *IEEE International Conference on Communications in China.*

[23] E. Ko, K.-C. Chen, "Wireless Communications Meets Artificial Intelligence: An Illustration by Autonomous Vehicles on Manhattan Streets", *IEEE Globecom*, 2018.
[24] L. Zhao, K.-C. Chen, "The Game Theoretic Consensus in A Multi-Agent System", *IEEE Globecom*, 2018.
[25] G. Zhou, L. Zhao, Q. Shi, G. Zheng, K.-C. Chen, "Rate-Delay Analysis of Radio Access Network Slices", *IEEE Globecom*, 2018.
[26] C.-H. Zeng, K.-C. Chen, "Low Complexity Multiuser Detection in the Downlink of Ultra-Low Latency Virtual-Cell Based Vehicular Networks", *IEEE Vehicular Technology Conference – Fall*, 2018.
[27] C.-H. Zeng, K.-C. Chen, "Downlink Multiuser Detection of Ultra-Low Latency Virtual-Cell Vehicular Networks", *IEEE Vehicular Technology Conference – Fall*, 2018.
[28] C.-Y. Lin, K.-C. Chen, D. Wickramasuriya, S.-Y. Lien, R.D. Gitlin, "Anticipatory Mobility Management by Big Data Analytics for Ultra-Low Latency Mobile Networking", *IEEE International Conference on Communications*, 2018.
[29] **S.-C. Lin**, H. Narasimhan, "Towards Software-Defined Massive MIMO for 5G&B Spectral-Efficient Networks", *IEEE International Conference on Communications*, 2018.

Past/relevant experience of the speaker(s) on the topic of the tutorial;

This emerging subject has been presented in different occasions as invited talks at

- INTEL Research Wireless Communication Laboratory, Santa Clara (2 hours, June 2017)
- Beijing University of Post and Telecommunications, Beijing (1.5 hours, June 2017)
- Princeton-PKU Joint Laboratory on Advanced Communication Technology, Beijing (September, 2017)
- Keynotes, 2017 IEEE International Conference on Wireless and Mobile Computing, Rome (October, 2017)
- Tutorial, *IEEE International Conference on Communications*, Kansas City, August 2018.
- Keynote, 2018 ITU Workshop Machine Learning for 5G and Beyond (August 2018)
- Invited Talk, *2018 IEEE International Conference on Communications in China*, Beijing (August 2018)

Previous tutorial experience of the speaker(s), and past versions of the tutorial

The first speaker has presented many well-attended tutorials in the IEEE ICC/GC, IEEE PIMRC, IEEE WCNC on different subjects (Socially Enabled Wireless Networks; Cognitive Radio Networks; Wireless LANs, etc.), while the second speaker as an expert in NFV/SDN has published extensively in IEEE journals and conferences. In last year IEEE ICC 2018, the first speaker presented a tutorial on "Ultra-Low Latency Mobile Networking", and this current proposal has been evolved from ICC 2018, but include roughly 50+% of new materials such as more on uRLLC in 5G, much more machine learning techniques in much wider range, much deeper in NFV/SDN (thanks to the second speaker), and new efforts to (uRLLC and machine learning based) network architecture and ITU's new network architecture efforts.

State if a similar tutorial has been offered in recent ICC & Globecom (last two years) and how your tutorial differs

Tutorial "Ultra-Low Latency Mobile Networking" in the IEEE ICC 2018 by the first speaker but this tutorial is newly evolved with more than half of new materials to comfortably say a new tutorial. In the meantime, we realize colleagues at UC Berkeley are planning a tutorial about uRLLC, but focusing on different aspects of this proposal. This proposal primarily presents networking, cross-layer communication technology, and uRLLC/ML based network architecture.

Sparse Signal Processing in Intelligent Communications: from Theory to Practice

A Proposal for IEEE ICC 2019

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1. Abstract, Objectives and Motivation

Sparse representation can efficiently model signals in different applications to facilitate processing. In this tutorial, we will discuss the sparse representations in wireless communications, with focus on the most recent machine learning and compressive sensing enabled approaches. With the help of the sparsity property, compressive sensing is able to enhance the spectrum efficiency and energy efficiency for the fifth generation (5G) networks and Internet of Things (IoT) networks. This tutorial starts from a comprehensive overview of compressive sensing principles and different sparse domains potentially used in 5G and IoT networks. Then recent research progress on applying compressive sensing to address the major opportunities and challenges in 5G and IoT networks will be introduced, in which the wideband spectrum sensing is provided as an example. Particularly, both the latest theory contributions and the implementation platform will be discussed. Moreover, other potential applications and research challenges on sparse representation for 5G and IoT networks are discussed. This tutorial will provide readers a clear picture of how to exploit the sparsity properties to process wireless signals in different applications.

- The first objective is to provide a general introduction to different tools used for sparse representation in wireless communications, such as machine learning and compressive sensing. We will demonstrate the theory background of sparse representation and the research challenges faced by wireless communications in 5G networks and IoT networks.
- The seconde objective is to demonstrate the basic framework of compressive spectrum sensing, which is used to reduce the sampling cost and improve the spectrum utilization in order to support massive connectivity in 5G and IoT networks. The most advanced developments of compressive spectrum sensing will be included, from theory to practice.
- The third objective is to illustrate the potential of applying compressive sensing in practice. A series of in-field test conducted by us will be presented and the collected real-world data will be provided in open access. The research challenges, opportunities and potential solutions will also be identified.

2. Intended Audience

Whilst this overview is ambitious in terms of providing a research-oriented outlook, potential attendees require only a modest background in signal processing and wireless 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. The participants will receive the set of slides as supporting material and they may find the detailed mathematical analysis from the papers and books listed in the slides.

Course Notes: a copy of the slides will be made available for the participants. Furthermore, related book chapters will also be made available;

3. Speaker Biography

- Yue Gao: Reader from Queen Mary University of London

  Yue Gao (S'03, M'07, SM'13) is a Reader in Antennas and Signal Processing, and Director of Whitespace Machine Communication (WMC) Lab in the School of Electronic Engineering and Computer Science at at Queen Mary University of London (QMUL). He worked as Research Assistant, Lecturer (Assistant Professor) and Senior Lecturer (Associate Professor) at QMUL after his PhD degree obtained from QMUL in 2007. He is currently leading a team developing fundamental research into practice in the interdisciplinary area of embedded artificial intelligence by using smart antennas and sparse signal processing techniques for spectrum sharing, internet of things (IoT) and millimetre-wave systems. He has published over 150 peer-reviewed journal and conference papers, 2 patents, 1 book and 5 book chapters. He is an EPSRC Early Career Fellow (2018-2023) and a co-recipient of the EU Horizon Prize Award on Collaborative Spectrum Sharing in 2016, and has obtained the Research Performance Award from Faulty of Science and Engineering at QMUL in 2017. He is an Editor for the IEEE Transactions on Vehicular Technology, IEEE Wireless Communication Letter and China Communications. He have been served as Cognitive Radio Symposium Co-Chair of the IEEE Globecom 2017, the Signal Processing for Communications Symposium Co-Chair for IEEE ICCC 2016, Publicity Co-Chair for IEEE Globecom 2016, and General Chair of the IEEE WoWMoM and iWEM 2017. He is a Secretary of the IEEE Technical Committee on Cognitive Networks, and an IEEE Vehicular Technology Society Distinguished Lecturer.

- Zhijin Qin: Lecturer (Assistant Professor) from Queen Mary University of London

  Zhijin Qin (S'13, M'16) received her Ph.D. degree from Queen Mary University of London in U.K. in 2016, and her B.S. degree from Beijing University of Posts, China, in 2012. She was with Imperial College London as a postdoctoral Research Associate from May 2016 to July 2017. After that, she was Lancaster University in U.K. as a Lecturer (Assistant Professor). Since August 2018, she has joint Queen Mary University of London as a Lecturer. Her research interests include machine learning and compressive sensing wireless signal processing, low-power wide-area network for Internet of Things applications, and non-orthogonal multiple access for 5G networks. She is an Editor of IEEE Communication Letter. She has served as the co-chair of IEEE WoWMoM CORAL Workshop 2017, track co-chair of IEEE ICPADS 2018, and a TPC member for many IEEE conferences such as Globecom, ICC, and VTC. She won the best paper award at IEEE Globecom 2017.

- **Geoffrey Ye Li**: Professor from Georgia Institute of Technology

  Geoffrey Ye Li (S'93-M'95-SM'97-F'06) is a Professor with Georgia Tech. His general research is in signal processing and machine learning for wireless communications. In these areas, he has published over 400 articles with around 33,000 citations and been listed as a Highly-Cited Researcher by Thomson Reuters all except one year. He has been an IEEE Fellow since 2006. He won IEEE ComSoc Stephen O. Rice Prize Paper Award and Award for Advances in Communication, IEEE VTS James Evans Avant Garde Award and Jack Neubauer Memorial Award, IEEE SPS Donald G. Fink Overview Paper Award, and Distinguished ECE Faculty Achievement Award from Georgia Tech. He has been involved in editorial activities for about 20 technical journals for the IEEE Communications and Signal Processing Societies including founding Editor-in-Chief of IEEE 5G Tech Focus. He organized and chaired many international conferences, including technical program vice-chair of IEEE ICC'03, technical program co-chair of IEEE SPAWC'11, general chair of IEEE GlobalSIP'14 and technical program co-chair of IEEE VTC'16 (Spring).

4. Addressed Technical Issues

Sparse representation expresses some signals as a linear combination of a few atoms from a prespecified and over-complete dictionary. This form of sparse (or compressible) structure arises naturally in many applications. For example, audio signals are sparse in frequency domain, especially for the sounds representing tones. Image processing can exploit a sparsity property in the discrete cosine domain, i.e. many discrete cosine transform coefficients of images are zero or small enough to be regarded as zero. This type of sparsity property has enabled intensive research on signal and data processing, such as dimension reduction in data science, wideband sensing in cognitive radio networks, data collection in large-scale wireless sensor networks, and channel estimation and feedback in massive MIMO.

Traditionally, signal acquisition and transmission adopt the procedure with sampling and compression. While for wideband spectrum sensing, signal processing has been confronted with challenges on high sampling rates for data acquisition and large amount of data for storage and transmission. Except for developing advanced sampling and compression techniques, it is natural to ask whether there is an approach to achieve signal sampling and compression simultaneously. As an appealing approach employing sparse representations, compressive sensing technique has been proposed to reduce data acquisition costs by enabling sub-Nyqusit sampling.

At the time of the writing of this proposal, the massive connectivity has been one of the most important and challenging issues to be solved as the huge amount of devices are to be connected in the 5G and Internet of Things (IoT) networks. Spectrum scarcity limits the number of connected devices. Therefore, how to find more spectrum holes effectively and efficiently attracts extensive research interest. The compressive spectrum sensing provides a low-cost sampling method for fast and efficient sensing so that more access opportunities can be identified. Moreover, the secure blockchain based dynamic spectrum allocation has been regarded as a promising solution for the sixth generation (6G). This gives us confidence that the hybrid framework with low-cost compressive spectrum sensing and geo-location database is of great interest for both industry and academia. However, realizing the full potential of compressive spectrum sensing in practical communication scenarios is challenging, and there are still many important open problems that have not been solved.

The aim of this tutorial is to discuss the applications of spare representation in wireless communications, with particular focus on the most recent developed compressive sensing enabled approaches from theory to practice. With the help of sparsity property, sub-Nyquist sampling can be achieved in wideband cognitive radio networks by adopting compressive sensing. This tutorial starts from a comprehensive overview of compressive sensing principles. Subsequently, we will present a framework for compressive spectrum sensing, which is able to provide guarantee on noise robustness, low-complexity, and security. Particularly, robust compressive spectrum sensing, data-driven compressive spectrum sensing, and secure compressive sensing based malicious user detection are proposed to address the various issues in wideband cognitive radio networks. Moreover, the real-world signals and data collected by the in-field tests carried out during TV white space pilot trial will be presented to verify the algorithm designs and provide significant insights on the potential of bring compressive spectrum sensing from theory to practice. All the real-world data will be open access for the audiences and researchers to test their designs. Finally, this tutorial will identify promising research opportunities for the future. We believe this tutorial will provide readers a clear picture on how to exploit the compressive sensing to process wireless signals.

5. Detailed Outline

- Background and Basics for Wireless Communications - present the basics, challenges, recent progress, and open issues for wireless communication systems.
    1) Challenges: present new requests, open issues and research challenges for wireless communications;
    2) Key solutions: low-cost sampling based on compressive sensing from antenna design to signal processing.
- Sparse Signal Recovery
    1) Compressive Sensing Basics - discuss the basic principles of sparse signal recovery and the applications.
        a) Signal acquisition and sparse representation
        b) Measurement matrix design in compressive sensing
        c) Sparse signal recovery
        d) Compressive spectrum sensing framework
    2) Robust Compressive Spectrum Sensing - present promising compressive spectrum sensing with robustness to channel noise and low complexity during sparse signal recovery.
        a) Single user compressive spectrum sensing using sparsity property from low spectrum utilization
        b) Collaborative compressive spectrum sensing utilizing joint sparsity property
    3) Data-Driven Compressive Spectrum Sensing - present promising compressive spectrum sensing by utilizing prior information from geo-location database for performance enhancement.
        a) Hybrid sensing aided by prior information of TV white space
        b) Low-cost sparse signal detection
        c) Multi-coset sampling based sparse support detection

4) Secure Compressive Spectrum Sensing - present malicious user detection in compressive spectrum sensing to enhance network security.
   a) Framework of low-matrix completion with outliers
   b) Malicious user detection in compressive spectrum sensing

- Implementation Challenges of Sparse Signal Processing - identify some implementation approaches and issues
  1) Measurement setup for real-world signal collection
  2) In-field test for real-world signal collection and algorithm verification
- Research Outlook - identify some research directions in sparse signal processing
  1) Deep learning based sparse signal recovery
  2) Embedded artificial intelligence

6. Past Experience on the Addressed Topic

Dr. Yue Gao has rich experience on signal processing in wireless communication and the hardware system implementation over the past 15 years. Dr Gao is leading a team developing fundamental research into practice in the interdisciplinary area of embedded artificial intelligence by using smart antennas, sparse signal processing for spectrum sharing, Internet of Things and millimetre-wave systems. He is an Engineering and Physical Sciences Research Council Fellow from 2018 to 2023. He was a co-recipient of the EU Horizon Prize Award on Collaborative Spectrum Sharing in 2016.

Dr. Zhijin Qin has been working on sparse signal recovery, with particular focus on compressive sensing and matrix completion in wireless communications, for more than six years since her PhD. She has carried out extensive research work in the related areas from theory to practice. Many of her published journal papers in this area have been ranked as one of the most popular articles in the related journal and four of them have been ranked as the ESI highly cited paper.

Dr. Geoffrey Li has performed research in machine learning and statistical signal processing for wireless communications in the past two decades. His recent work includes sparse signal compression for channel estimation and feedback in massive MIMO networks.

7. Prior History of the Tutorial Presentation

Dr. Yue Gao has provided invited talks over 20 times at IEEE ICCC, ICCS, VTC, research institutions and companies like Sony Mobile, Huawei Technologies for spectrum sharing, sub-Nyquist sampling, smart antennas, IoT and millimetre-wave systems.

Dr. Zhijin Qin has provided invited talks over 10 times at various research institutions and companies like Intel, Huawei Technologies for sub-Nyquist sampling and IoT networks.

Dr. Geoffrey Ye Li has provided tutorials 24 times at IEEE Globecom, ICC, PIMRC, WCNC, and VTC in the areas of OFDM for wireless communications, spectral and energy efficiency networks, and big data signal processing.

8. Similar Tutorial in Recent ICC & Globecom

- "Sparse Signal Processing: Recent Advances and Applications in Wireless Communications", presented by Zhi Tian and Yue Wang in IEEE ICC'18.

  This tutorial focused on employing sparse signal processing principles and techniques in various wireless applications, such as sparse channel estimation and noncoherent transmission for large-antenna arrays in both millimeter-wave communication systems. Particular focus has been put on the theory development of the structure-based compressive sensing beyond sparsity, compressive covariance sensing and super-resolution gridless compressive sensing. While our tutorial will focus more on the implementable and configurable sparse signal processing. Moreover, the in-field tests carried out in London as part of the Ofcom TVWS trial will be introduced. Moreover, the collected real-world data will be released for open access to boom the sparse signal processing in wireless communications.

- "Bayesian-Inspired Methods for Sparse Signal Recovery-Brand New Theoretical Insights and Applications to Wireless Communications", presented by Chandra R. Murthy in IEEE ICC'18.

  This tutorial examined the more recent developments and a complementary set of tools based on a Bayesian framework to address the general problem of sparse signal recovery and the challenges associated with it. Different from the above tutorial and our tutorial, this one is more focused on the new theory and the insights that can be obtained from the theory to facilitate the wireless communications. Again, our tutorial will attract researchers with background on both theory and hardware implementation. Real-world sensing data over TVWS will be released for algorithm verification and analysis, which will bring great benefits to the researchers in this area.

- **Title**

  A Unifying Data-Oriented Approach to Wireless Transmission of Big and Small Data

- **Abstract**

  Wireless communication systems will play an essential role in the data transmission for future big data and Internet of Things (IoT) applications. The data generated by these applications will have variable sizes and dramatically different quality of service requirements. Therefore, the design and optimization of wireless transmission strategies for diverse traffic types are of critical current interest. In the proposed tutorial, we present a unique data-oriented approach for the design and analysis of wireless transmission strategies, targeting an integrated common physical transmission infrastructure for both big and small data. Unlike conventional channel-oriented approach, which emphasizes on improving the quality of the wireless channels with various transmission technologies, the data-oriented approach designs transmission strategies for individual data transmission sessions, with consideration of traffic properties and operating environment. After introducing the key idea and example designs, we present novel data-oriented performance metrics and apply them to the analysis of wireless transmission strategies in information theoretical and practical transmission settings. We also develop analytical frameworks to accurately characterize the data transmission time in both cognitive and non-cognitive environments. Compared to conventional analytical approach, the data-oriented approach offers important new insights and leads to interesting new research directions. Through this tutorial, the attendees will obtain a brand new perspective to wireless transmission technology design.

- **Motivation and Objective**

  Data is becoming one of the most essential resource of modern society. The timely processing, delivery, and analysis of relevant data will bring huge social and economic benefit. With the growing popularity of big data and Internet of Things (IoT) applications, data will be generated and collected at an accelerating rate. Big data applications, such as video surveillance, AR/VR gaming, and medical imaging, generate data of large sizes. The ever-growing IoT devices typically transmit and exchange small data packets in a sporadic fashion. The data from different applications will have dramatically different quality of service requirements. For example, factory automation applications require a packet loss rate of less than 10^{-9} with a end-to-end delay smaller than one ms, whereas remote sensing nodes are expected to operate for 10 years on very compact battery. Future wireless communication systems must optimize their transmission strategies to efficiently support a large variety of data.

  There have been significant developments in digital wireless transmission technologies over the past three decades. Various advanced transmission technologies, including multiple antenna (MIMO) transmission, channel adaptive transmission, cooperative relay transmission, and cognitive radio transmission, are developed and deployed to meet the growing demand for high data rate wireless services. These technological development have successfully enabled the mass offering of mobile broadband (MBB) service and even paved the path to future enhanced MBB (eMBB) service. Meanwhile, the efficient transmission of data traffics with diverse size and dramatically different quality of service requirements presents new technical challenges. In particular, it is unclear how to effectively support the physical transmission of these diverse data traffics over a common physical infrastructure.

Most existing wireless transmission technologies were designed with the goal of enhancing or approaching the capacity limits of wireless channels, usually characterized by ergodic capacity and outage capacity. The rationale of such channel oriented approach is that enhancing the average quality of wireless channels will necessarily improve the average quality of service experienced by individual transmission session. Meanwhile, this channel oriented approach is ignorant of the specifics of individual data transmission session, such as the channel state, the data property, and the network conditions, and apply the same transmission strategy for all transmission sessions over the channel. Typically, the quality of services experienced by individual transmission sessions may vary dramatically with the operating environment. The transmission solution based on channel-oriented approach will become insufficient and/or inefficient for certain application scenarios. To further improve the efficiency and effectiveness of wireless transmission systems in supporting diverse data transmission, we need to study them from a new perspective.

In this proposed, we propose a novel data-oriented approach for wireless transmission system design. Specifically, we consider the optimal design of transmission strategy for individual data transmission session according to the operating environment. In particular, when a certain amount of data is available for transmission, the transmission strategy will be determined in an optimal fashion. For a given data packet from mission-critical application, a transmission strategy that minimizes the latency while satisfying the reliability requirement should be applied. Meanwhile, strategies that minimizes energy consumption under a certain delay requirement will be used for massive IoT applications. For example, we will determine whether power adaptation need to apply together with rate adaptation or not, should the relay be activated, and what MIMO structure should be adopted, etc. The transmission strategy will be adjusted for each data transmission session. The rationale of such data oriented approach is that optimizing the transmission strategy for individual data session will directly satisfy the reliability and efficiency requirement, which will in turn enhance the performance of overall transmission system.

There are many challenges to be addressed for the new data-oriented approach. We need to define suitable metrics to quantify the quality of service experienced by individual data transmission session. We also need to establish the performance limits from data transmission perspective and use them as guideline to optimize transmission strategies. In this tutorial, we present several interesting research findings following this data-oriented approach. After presenting the general design principle and selected illustrative examples, we develop novel data-oriented performance metrics to effectively characterize the quality of individual data transmission session. These novel characterizations help develop new insights on wireless transmission strategies and serve as guidelines for practical transmission strategy design. We also develop analytical frameworks to investigate the transmission time performance with practical wireless transmission technologies in both non-cognitive and cognitive environments. These analytically results are readily applicable to the energy consumption analysis and queuing analysis for wireless transmission.

The objective of the tutorial is to bring new insights to the analysis and design of wireless transmission strategies. We adopt a unique and unifying data-oriented approach by targeting at the performance and efficiency of individual data transmission sessions. Through this tutorial, the attendees can obtain a brand new perspective on the analysis and optimization of wireless transmission strategy for big data and IoT applications. The tutorial will best prepare the attendees to further explore the potential of the data-oriented approach in wireless communication system design and analysis.

- **Target Audience**

  The tutorial coverage is sufficiently broad as to have strong appeal to MS and PhD students, instructors/lecturers, and researchers currently working in the field of wireless communications, as well as a large cross-section of practicing engineers who are responsible for the design, development, and performance evaluation of wireless communication systems for big data and IoT applications. It is our sincere wish that this tutorial will best prepare participants to further investigate the efficient design of wireless transmission technologies.

- **Presenter information**

  Hong-Chuan Yang, Professor, SMIEEE, P.Eng., University of Victoria, Canada

  Dr. Hong-Chuan Yang (*Senior Member IEEE*) received the Ph.D. degree in electrical engineering from the University of Minnesota in 2003. He is a professor of the Department of Electrical and Computer Engineering at the University of Victoria, Canada. From 1995 to 1998, He was a Research Associate at the Science and Technology Information Center (STIC) of the Ministry of Posts & Telecomm. (MPT), Beijing, China. His current work mainly focuses on different aspects of wireless communications, with special emphasis on channel modeling, diversity techniques, system performance evaluation, cross-layer design, and energy efficient communications. He has published over 200 journal and conference papers. He is the author of the book *Introduction to Digital Wireless Communications* by IET Press and the co-author of the book *Order Statistics in Wireless Communications* by Cambridge University Press. He is a registered professional engineer (P.Eng) in British Columbia, Canada.

  Mohamed-Slim Alouini, Professor, FIEEE, King Abdullah University of Science and Technology (KAUST), Saudi Arabia

  Dr. Mohamed-Slim Alouini (*Fellow IEEE*) received the Ph.D. degree in electrical engineering from the California Institute of Technology (Caltech) in 1998. He also received the Habilitation degree from the Universitè Pierre et Marie Curie in 2003. Dr. Alouini started his academic career at the University of Minnesota in 1998. In 2005, he joined Texas A&M University at Qatar, Doha, and in 2009, he was appointed as Professor of Electrical Engineering at KAUST, Thuwal, Mekkah Province, Saudi Arabia, where he is responsible for research and teaching in the areas of Communication Theory and Applied Probability. More specifically, his research interests include design and performance analysis of diversity combining techniques, MIMO techniques, multi-hop/cooperative communications systems, cognitive radio systems, and multi-resolution, hierarchical and adaptive modulation schemes. Dr. Alouini has published several papers on the above subjects, and he is co-author of the textbook Digital Communication over Fading Channels published by Wiley Interscience. He is a Fellow of the IEEE, a member of the Thomson ISI Web of Knowledge list of Highly Cited Researchers, and a co-recipient of best paper awards in eight IEEE conferences (including ICC, GLOBECOM, VTC, and PIMRC).

- **Scope and Timeliness**

  In this proposed tutorial, we will present a data-oriented analysis and design of wireless transmission strategies, targeting the transmission of data with different size and quality of service requirements over a common physical infrastructure. We first review the recent development of digital wireless transmissions and motivate the proposed data-oriented approach. Then the design principle of the proposed approach is introduced and illustrated with selected design examples. After introducing the general design procedures of the data oriented approach, we present two novel data-oriented performance limits for arbitrary data transmission over fading channels. As an immediate application of these metrics, we study the transmission strategies for the channel state information at the transmitter (CSIT) scenario: namely rate adaptation only and optimal power and rate adaptation. We then investigate the practical data transmission over fading channels with channel adaptation. In particular, we present an analytical framework to derive the statistics of transmission time over block and Markov fading channels. These results are applied to the energy consumption analysis of wireless transmission system. After that, we move on to study the cognitive transmission of big and small data with interweave implementation. Specifically, we presents novel performance metrics to quantify temporal spectrum opportunity. We investigate the statistics of the total delivery time of big data, including both transmission time and waiting time. The resulting extended delivery time is essential to the queuing/throughput analysis of secondary transmission. The effects of data transmission strategies and spectrum sensing strategies, including sensing errors, are investigated through theoretical derivation and numerical results. We conclude the tutorial with some remarks on open research topics. We strive to achieve an ideal balance between theory and practice. Special emphasis will be placed on the accurate quantification of the performance versus complexity tradeoff throughout the presentation.

  Wireless communication systems will play an essential role in the data transmission for big data and IoT applications. The design and optimization of wireless transmission strategies for data with diverse sizes and various quality of service requirement are of critical current interest. The data-oriented approach will provide important new insights to the analysis and design of wireless transmission strategies. The tutorial will coherently cover the most recent research findings of the presenters that were accepted or published in IEEE journals within the past three years. Through the tutorial, the attendees will be best prepared to further explore the potential of the data-oriented approach in their own research.

- **Tutorial Outline**

  I. Data transmission over fading channels

  II. Data oriented approach for wireless transmission design

  - II.1 Design principle
  - II.2 Illustrating examples

  III. Data oriented performance limits

  - III.1 Minimum transmission time
  - III.2 Maximum entropy throughput
  - III.3 Application: rate adaptation only vs optimal power and rate adaptation

  IV. Channel adaptive transmission of big and small data

  - IV.1 Transmission time analysis for block fading channel
  - IV.2 Transmission time analysis for Markov channel
  - IV.3 Application: energy consumption analysis

  V. Cognitive transmission of big and small data

  - V.1 Characterization for temporal spectral opportunities
  - V.2 Extended delivery time analysis
  - V.3 Work-preserving vs non-work-preserving strategies
  - V.4 Effect of sensing imperfection
  - V.5 Application: secondary queuing performance analysis

  VI. Conclusion and future research directions

- **Presentation History**

  The proposed tutorial is based on the on-going joint research of the presenters. The presenters have jointly published multiple journal papers within the past three years on the related topics. The tutorial will cover the results in these papers in a coherent fashion under the umbrella of data oriented analysis and design.

  The presenters have jointly presented two tutorials on the topic of "Order Statistics in Wireless Communications" at IEEE conferences, namely IEEE VTC Fall 2008 and IEEE VTC Fall 2011.

  The proposed tutorial is an extended version of the one presented at IEEE VTC Fall 2018 by the presenters. No similar tutorial has ever been offered in IEEE ICC and Globecom.

Energy and Spectral Efficiency Tradeoffs in Future Communication Networks

1. Abstract, Objectives, and Motivation

The future success of communication networks hinges on the ability to overcome the mismatch between requested quality of service and limited network resources. Spectrum is a natural resource that cannot be replenished and therefore must be used efficiently. This makes spectrum efficiency to be very important for communication systems. Communications engineers have developed many techniques to maximize spectral efficiency. Accompanying this great success is also the significant energy consumption that is generating growing environmental and economical concerns. The sustainable development calls for solutions to reduce network energy consumption and improve network energy efficiency. It is particularly important to consider energy efficiency as the key performance metric designing future communication networks.

We will then concentrate on mobile data networks. With the upcoming Fifth Generation (5G) cellular standard and the expected tremendous increase in network traffic, these networks will become even more important than today. It is already known that today's cellular networks are not energy-efficient. After revealing the causes of energy inefficiency in today's networks, we will introduce a large number of techniques, applicable across several layers of the communications hierarchy, that have demonstrated substantial improvement in energy and spectral efficiency. We will discuss techniques to jointly optimize spectral and energy efficiency in such networks.

Finally, we will discuss energy efficiency in future data centers. Data centers are where most of the future Internet services will originate from and where the biggest challenges to energy efficiency exist. Currently, data centers provide about 4% of the total energy consumption, with today's 5 billion devices connected to the Internet. Yet, Internet-of-Things is expected to bring about 50 billion devices connected to the Internet, with much more intelligence expected to take place in data centers, for example, via extensive simulations of the data provided by sensors. Resulting energy consumption figures are very high. Therefore, new approaches to data center energy efficiency are needed. We will discuss such existing approaches.

2. Timeliness and Intended Audience

Since conventional communication networks, such as the cellular wireless networks, have been designed only with considerations of throughput or capacity maximization, they can be highly energy- inefficient. It is expected that the demand for throughput will increase tremendously, and it is important that the next generation communication networks be designed with a major consideration for energy efficiency. As an example, this tutorial will explain the sources of energy inefficiency in cellular wireless networks and offer a number of solutions in different layers of the communications hierarchy. It will also describe how much gain is possible by adapting judicious choices for running cellular wireless networks as well-designed cyber-physical systems. With the coming era of Internet-of-Things, cyber-physical systems will be introduced at an extremely grand scale. In this vision, about 50 billion devices are expected to be connected to the Internet, most via wireless. This is an order of magnitude increase in the number of devices connected to the Internet as compared to today. In addition, most experts expect there will be a tremendous increase in traffic demand in wireless networks. Many believe this will be of three orders of magnitude, or 1000 times. Such an increase requires special attention to be paid to both spectral and energy efficiency. In addition, this attempt requires an approach across layers of communications hierarchy.

The subject of green communications is very active. Many major conferences in the field of communications have had special sessions dedicated to the topic. There are in fact specialized conferences dedicated to this topic. A number of journals and magazines have published and continue to publish papers on the subject. In particular, *IEEE ComSoc* has introduced a new journal, *IEEE Transactions on Green Communications and Networks*, recently. Several companies have well-publicized programs on the subject, and there have been consortia formed internationally to attack the subject. Examples of such consortia are the Greentouch Consortium, led by Bell Labs, and the EARTH project, funded by the European Commission Framework Programme 7. The National Science Foundation has a research grant program that pays special attention to the combination of spectral efficiency and energy efficiency in wireless networks, known as SpecEES. For the reasons quoted above, this tutorial is highly timely.

The intended audience of this tutorial is researchers, students, and practicing engineers who want to understand the issues involved and the solutions proposed on the subject of green communications and networking. The instructors will pay a special attention on quantifying the potential gains as well as pointing out major areas of significant research potential so that the participants can fully appreciate the breadth and depth of the subject and concentrate on those areas for advancing their research when applicable.

Practicing engineers and researchers who are interested in understanding and doing research in wireless communications and related topics, particularly those who desire to design spectral and energy efficient wireless systems, will be very much interested in this tutorial. Green wireless system design that achieves high network performance is currently a very hot topic in both the academic and industrial communities and it is anticipated that this tutorial will be very well attended.

3. Name, Affiliation, and Biography of Speakers

Guowang Miao	KTH
Zhisheng Niu	Tsinghua University
Ender Ayanoglu	University of California, Irvine

Guowang Miao is an associate professor at KTH. He once worked in Intel Labs as a research engineer and in Samsung Research America as a senior standard engineer and a 3GPP LTE RAN 1 delegate. In 2011, he won the Individual Gold Award from Samsung Research America for his contributions in LTE standardization. His research interest is in the design of networking systems and is well known for his original contributions in building a set of fundamental energy-efficient communications and networking theories, which are widely accepted nowadays. For example, he is the main inventor of energy-efficient scheduling and capacity-approaching transmission (United States Patent 7782829). He has delivered many tutorials on energy-efficient design related topics at flagship conferences. He is the lead author of the graduate textbook entitled Fundamentals of Mobile Data Networks (Cambridge University Press), and the book entitled Energy and Spectrum Efficient Wireless Network Design (Cambridge University Press). He has authored over 100 research papers in premier journals or conferences. So far 42% of his first-author journal papers are ESI highly cited. He has more than a dozen patents granted and many more filed. Several of his patented technologies were adopted as essential in 4G and 5G standards and are being used globally. He received B.S., M.S., and Ph.D. degrees from Tsinghua University and Georgia Institute of Technology respectively.

Zhisheng Niu graduated from Beijing Jiaotong University, China, in 1985, and got his master and PhD degrees from Toyohashi University of Technology, Japan, in 1989 and 1992, respectively. During 1992-94, he worked for Fujitsu Laboratories Ltd., Japan, and in 1994 joined with Tsinghua University, Beijing, China. He is now a professor at the Department of Electronic Engineering and director of Tsinghua-Hitachi Joint Lab on Environment-Harmonious ICT. His major research interests include queueing theory, traffic engineering, mobile Internet, radio resource management of wireless networks, and green communication and networks. Dr. Niu has been an active volunteer for IEEE and IEICE, including Director for Asia-Pacific Board (2008-09), Director for Conference Publications (2010-11), Chair of Emerging Technology Committee (2014-15), and currently Director for Online Contents (2018-19) of IEEE Communication Society. He has served as associate editor-in-chief of IEEE/CIC joint publication *China Communications* (2012-16) and editor of *IEEE Wireless Communication* (2009-13), and currently serving as area editor of *IEEE Trans. Green Commun. & Networks*. He has also been selected as a distinguished lecturer (2012-15) of IEEE Communication Society and a distinguished lecturer (2014-18) of IEEE Vehicular Technologies Society. Dr. Niu received the Outstanding Young Researcher Award from Natural Science Foundation of China in 2009 and the Best Paper Award from IEEE Communication Society Asia-Pacific Board in 2013. He was also the Chief Scientist of the National Basic Research Program (so called "973 Project") of China on "*Fundamental Research on the Energy and Resource Optimized Hyper-Cellular Mobile Communication System*" (2012-2016). He is a fellow of both IEEE and IEICE.

Ender Ayanoglu received the M.S. and Ph.D. degrees from Stanford University 1982 and 1986. He was with Bell Laboratories until 1999. During 1999-2002, he was a Systems Architect at Cisco Systems, Inc. Since 2002, he has been a Professor in the Department of Electrical Engineering and Computer Science, University of California, Irvine, where he served as the Director of the Center for Pervasive Communications and Computing and held the Conexant-Broadcom Endowed Chair during 2002-2010. During 2000-2001, he served as the founding chair of the IEEE-ISTO Broadband Wireless Internet Forum (BWIF), an industry standards organization which developed a broadband wireless system employing Orthogonal Frequency Division Multiplexing (OFDM) and a Medium Access Control (MAC) algorithm that provides Quality-of-Service (QoS) guarantees, a precursor of today's Fourth Generation (4G) cellular wireless systems. During 1993-2014 he was an Editor, and since January 2014 is a Senior Editor, of the *IEEE Transactions on Communications.* He served as the Editor-in-Chief of the *IEEE Transactions on Communications during* 2004-2007. During 1990-2001, he served on the Executive Committee of the IEEE Communications Society Communication Theory Committee, and during 1999-2001, was its Chair. Dr. Ayanoglu is currently serving as the Founding Editor-in-Chief of *IEEE Transactions on Green Communications and Networking.* Dr. Ayanoglu is the recipient of the IEEE Communications Society Stephen O. Rice Prize Paper Award in 1995 and the IEEE Communications Society Best Tutorial Paper Award in 1997. He has been an IEEE Fellow since 1998.

4. Technical Issues the Tutorial Will Address

Energy efficiency is becoming increasingly important. From the perspective of user experiences, small form factor mobile devices are getting more and more energy hungry as battery technology has not kept up with the growing requirements stemming from ubiquitous multimedia applications. On the other hand, from a global perspective, we are confronted with severe challenges of environment protection and prevention of climate changes. This tutorial introduces cross-layer technologies to improve both spectral and energy efficiencies of wireless systems, which are affected by all layers of system design, ranging from silicon to applications. The traditional layer-wise approach leads to independent design of different layers and results in high design margins. Cross-layer approaches exploit interactions among different layers and can significantly improve system performance as well as adaptability to service, traffic, and environment dynamics. The physical (PHY) layer plays a very important role in wireless communications due to the challenging nature of the communication medium. The medium access control (MAC) layer ensures that wireless resources are efficiently allocated to maximize network-wide performance metrics while maintaining user quality-of-service requirements. In this tutorial, we will emphasize joint MAC and PHY techniques. Note that spectral efficiency and energy efficiency are two different metrics. Some design criteria optimized for improving one metric may not necessarily improve the other. We can see there is an urgent need to address spectral efficiency and energy efficiency in a joint way. Especially, new metrics that are completely distinct from existing ones in literature will be necessary to address the need. This will be the focus of this tutorial.

As indicated before, the conventional communication networks have been designed with the purpose of providing high throughput for the user and high capacity for the service provider, without any provisions of energy efficiency. As a result, these networks have an enormous carbon footprint. For example, only in the United States, the carbon footprint of the cellular wireless industry is equal to that of about 3/4 million cars. In addition, the cellular network is highly inefficient and therefore a large part of the energy dissipated is wasted.

In this tutorial, we will analyze the energy dissipation in cellular wireless networks and point to sources of major inefficiency. We also discuss how much more mobile traffic is expected to increase so that this carbon footprint will increase tremendously more. We then discuss potential sources of improvement at the physical layer as well as at higher layers of the communication protocol hierarchy. For the physical layer, we discuss new modulation formats and new device technologies and what they may bring in terms of energy efficiency gain. At higher layers, considering that most of the energy inefficiency in cellular wireless networks is at the base stations, we will address multi-tier networks and point to the potential of exploiting mobility patterns in order to use base station energy judiciously. We will investigate link adaptation and point to why energy efficiency, rather than power efficiency, should be pursued and what it means for the choice of link rates. We show how much gain is possible by energy-efficient link rate adaptation. We will also describe the gains by exploiting non-uniform traffic in space, relays and cooperation, device-to-device communications, multiple antenna techniques, and in particular coordinated multipoint and massive MIMO, sleeping modes for the base stations, the techniques of cell breathing and cell zooming, the energy trap problem for the mobile terminals, and the potential approaches for video that provide energy efficiency. We also provide several survey papers and books published on this topic.

By a consideration of the combination of all potential gains, we conclude that an improvement in energy consumption in communication networks by orders of magnitude is possible. The tutorial will present in detail where to concentrate research to achieve the largest gains.

5. Outline and Schedule of the Tutorial

1. Introduction
   a. Motivation
   b. Challenges and opportunities
   c. Methodologies
2. Wireless channel properties
   a. Single-user perspective
   b. Multi-user perspective
3. Basic concepts
   a. Wireless PHY layer
   b. Fundamental wireless resources
   c. Traditional Medium Access Control (MAC) for wireless resource management
4. Cross-layer optimization for spectral efficiency improvement
   a. Centralized adaptive spectral efficient MAC
   b. Distributed adaptive spectral efficient MAC
5. Channel-aware distributed MAC
   a. Energy-efficient adaptive link transmission
   b. Centralized adaptive energy-efficient MAC
   c. Distributed adaptive energy-efficient MAC
   d. Energy-efficient wireless network design
6. Fundamental tradeoffs in wireless resource utilization
   a. Four fundamental tradeoffs in cellular networks
   b. Spectral efficiency-energy efficiency tradeoff in interference-free and –limited networks
7. Brief history of computing and communications in six decades
8. Predictions of wireless traffic in the next decade
9. Sources of energy inefficiency in cellular networks
   a. OFDM and power backoff
   b. Weekly and daily variations in cellular traffic
   c. Base station energy consumption
   d. What it means for the service provider
10. Methods for energy efficiency in wireless networks
    a. Constant-envelope modulation
    b. Class J power amplifiers
    c. Link adaptation and energy-efficient transmission modes
    d. Exploiting distribution of traffic in space and load balancing
    e. Relays and cooperation
    f. Device-to-device communications
    g. Multiple antenna techniques: MIMO, coordinated multipoint, massive MIMO
    h. Sleeping mode for the base station
    i. Hierarchical and small cells
    j. Energy efficiency of mobile units: The energy trap problem
    k. Techniques for energy-efficient video transmission
11. An example of a joint spectral and energy efficient cellular network design
12. Energy efficiency in data centers

a. The role of data centers in today's and the future Internet
b. Energy consumption in a typical data center
c. Employing renewable energy for data centers
d. Architectures of today's data centers
e. Methods to improve energy efficiency in data centers
f. Fog computing vs. cloud computing for energy efficiency

13. Conclusion

6. Past Experience of the Speakers on the Topic of the Tutorial

Dr. Guowang Miao's key research interest in the past ten years has been in the energy-efficient design of mobile communications and networking and he has been well known for his original contributions in building a set of fundamental energy-efficient communications theories, which are widely accepted nowadays. For example he is the main inventor of energy efficient scheduling and capacity-approaching transmission (United States Patent 7782829). He is also the lead author of the graduate textbook entitled Fundamentals of Mobile Data Networks (Cambridge University Press), and the book entitled Energy and Spectrum Efficient Wireless Network Design (Cambridge University Press). Fundamentals of Mobile Data Networks is the first graduate textbook that has a dedicated chapter on energy-efficient network design. In addition to his academic work, he has also successfully pushed several of his key energy-efficient techniques into 4G standards. He has delivered many tutorials on energy-efficient related topics at major conferences.

Dr. Zhisheng Niu has been working on green communications for nearly 10 years. His very early paper entitled "Green mobile access network with dynamic base station energy saving" published at ACM MobiCom'09 has been listed as one of the pioneer papers on green communications. Another early paper entitled "Cell zooming for cost-efficient green cellular networks" published at IEEE ComMag in 2010 has attracted 700+ Google citations and selected as the IEEE ComSoc Asia-Pacific Board Best Paper Award in 2013. He was also the Principal Investigator (PI) and Chief Scientist of the very first national project on green communications in China entitled "Fundamental Research on the Energy and Resource Optimized Hyper-Cellular Mobile Communication System" (2012-2016) funded by the Ministry of Science and Technology of China. He has delivered more than 10 keynote/plenary speeches in major international conferences or workshops. He is now serving as an area editor of IEEE Trans. Green Comm. Networking (TGCN).

Dr. Ender Ayanoglu is the recipient of an NSF grant titled "Achieving two orders of magnitude reduction in cellular network energy inefficiency" and is the author of the survey and tutorial paper titled "Quantifying potential energy efficiency gain in green cellular wireless networks" which is published in the journal *IEEE Communications Surveys and Tutorials*. The paper is available on IEEE Xplore. The proposed tutorial will employ material from this paper as well as research papers. In addition, Dr. Ayanoglu formerly served as the Editor-in-Chief of the *IEEE Journal on Selcted Areas in Communications – Series on Green Communications and Networking* and is currently serving as the Founding Editor-in-Chief of the *IEEE Transactions on Green Communications and Networking.* In addition to his own experience in the field, he will bring his expertise developed in observing this new field.

7. Previous Tutorial Experience of the Speakers and Past Versions of the Tutorial

Guowang Miao has taught seven tutorials in IEEE conferences. A number of these tutorials are as follows.

1. "Spectrum and Energy Efficiency in 5G Mobile Data Networks," *IEEE International Conference on Communications (ICC),"* Kansas City, Missouri, May 2018.
2. "Joint PHY-MAC Design for Spectral- and Energy-Efficient Wireless Networks," *IEEE Global Communications Conference (GLOBECOM),* Anaheim, California, Dec. 2012.
3. "Joint PHY-MAC Design for Spectral- and Energy-Efficient Wireless Networks," *IEEE Personal, Indoor, and Mobile Communications (PIMRC*), Sydney, Australia, Sep. 2012.

Zhisheng Niu has taught four tutorials in conferences in the past, including flagship conferences of the IEEE Communications Society.

1. "Revisit the Cellular: A Hyper-cellular Framework for Green and Smart (5G) Mobile Communication Systems", *IEEE International Conference on Communications (ICC2014)*, Sydney, Australia, June 2014.
2. "Advances in Green Communications and Networking", Tutorial at *2013 Malaysia International Conference on Communications (MICC2013)*, Kuala Lumpur, Malaysia, Nov. 2013.
3. "Paradigm Shift to Globally Resource-optimized and Energy-Efficient Networks (GREEN)", Tutorial at *2012 IEEE International Conference on Communication Systems (ICCS2012)*, Singapore, Nov. 2012.
4. "Advances in Green Communications and Networks", Tutorial at *2012 IEEE 75th Vehicular Technology Conference (VTC2012-Spring),* Yokohama, Japan, May 2012.

Ender Ayanoglu has taught nine tutorials in conferences in the past, including several flagship conferences of the IEEE Communications Society.

1. "Spectrum and Energy Efficiency in 5G Mobile Data Networks," *IEEE International Conference on Communications (ICC),"* Kansas City, Missouri, May 2018.
2. "Optimizing Spectral and Energy Efficiency in Next-Generation Cellular Networks" *International Conference on Computing, Networking, and Communications (ICNC),* Maui, Hawaii, Mar.2018.
3. "Green Cellular Communications: What Are the Potential Gains and How to Achieve Them?" *IEEE Wireless Communications and Networking Conference (WCNC),* New Orleans, Lousiana, Mar. 2015.

8. Similar Tutorials in ICC/GLOBECOMs Last Two Years and How This Tutorial Differs

In GLOBECOM 2016 and ICC 2017, there were not any tutorials on spectral or energy efficiency or cross-layer investigation of these two measures.

In GLOBECOM 2017, there were a number of tutorials that are somewhat related. The first is titled "Massive MIMO - Spectral, Energy, and Hardware Efficiency." The main topic of this tutorial was Massive MIMO, which is only one of the topics considered in the tutorial being proposed. A second related tutorial is titled "Energy Informatics: Communications, Learning and Optimization." This tutorial had its focus on edge computing and software defined networks for the smart grid, machine and deep learning for reliable smart grid operation, and a new scenario for V2G mobile energy networks where mobile vehicles serve as both data and energy sharing nodes. As such, this tutorial targeted mainly machine and deep learning for the smart grid. Note that this is fundamentally different than the focus of the proposed tutorial, which is making networks inherently more energy efficient by analytically identifying their weaknesses and improving them. A third related tutorial is called "Greening Cloud and Virtualised Communication Networks." This tutorial concentrated on the cloud and provided a number of approaches for optimizing the energy use in the cloud. Whereas, the proposed tutorial covers wireless networks as a major topic, in addition to data centers.

In ICC 2018, Guowang Miao, Geoffrey Li, and Ender Ayanoglu taught a tutorial titled "Energy Efficiency in 5G Mobile Data Networks."

In GLOBECOM 2018, there are no tutorials on energy or spectral efficiency.