ICC2019 Tutorials: Friday, 24 May

Morning: 9:00 – 12:30

1. **Optimization and Economics of Edge-based User-Provided Networks**
   George Iosifidis; Lin Gao; Jianwei Huang; Leandros Tassiulas
2. **Physical Layer Authentication and Location Verification: A Machine-Learning Perspective**
   Stefano Tomasin; Xianbin Wang
3. **One Step Closer Towards Intelligent Wireless Network: Spatiotemporal Models, Learning, and Control**
   Howard Yang; Tony Q. S. Quek
4. **Machine Learning and Stochastic Geometry: Statistical Frameworks Against Uncertainty in Wireless LANs**
   Koji Yamamoto; Takayuki Nishio
5. **Machine Learning for AI-Driven Wireless Networks: Challenges and Opportunities**
   Walid Saad; Mehdi Bennis
6. **Molecular Communications: Theory, Practice and Challenges**
   Lie-Liang Yang
7. **Wireless Communications with Unmanned Aerial Vehicles**
   Evgenii Vinogradov; Sofie Pollin
8. **5G for Vehicle-to-Everything (V2X) Communication**
   Robert Heath; Nuria González-Prelcic
9. **Integrated Aerial/Terrestrial 6G Networks for 2030s**
   Halim Yanikomeroglu

Afternoon: 14:00 – 17:30

1. **Rate-Splitting and Robust Interference Management: Theory and Applications**
   Bruno Clerckx
2. **Safeguarding the 5G Era and Beyond with Physical Layer Wireless Security**
   Nan Yang; Xiangyun Zhou; Jemin Lee
3. **Fog-Radio Access Networks: Principles, Key Techniques, and Applications**
   Zhongyuan Zhao; Haijun Zhang; Chonggang Wang; Mugen Peng
4. **Unlocking new Dimensions in Radio-based Positioning "5G Localization"**
   Henk Wymeersch; Gonzalo Seco-Granados
5. **Machine Learning for Wireless Networks: Basics, Applications, and Trends**
   Ekram Hossain
6. **Orthogonal Time Frequency Space (OTFS) Modulation**
   Emanuele Viterbo; Yi Hong; A. Chockalingam
7. **Orbital Angular Momentum for Wireless Communications: Theory, Challenges, and Future Trends**
   Wenchi Cheng
8. **Wireless Channel Measurements and Models for 5G and Beyond**
   Cheng-Xiang Wang; Zaichen Zhang; Haiming Wang

Tutorial Proposal for IEEE ICC 2019

A. Basic information

Title: Optimization and Economics of Edge-based User-Provided Networks

Length and format: half-day lecture style

B. Speaker Information and Bio

George Iosifidis: Assistant Professor, School of Computer Science and Statistics, Trinity College Dublin, the University of Dublin, Ireland

George Iosifidis received the Diploma degree in electronics and communications from the Greek Air Force Academy, Athens, in 2000; and the Ph.D. degree in 2012 from the Department of Electrical and Computer Engineering, University of Thessaly, Greece. He was a Post-Doctoral Researcher with CERTH-ITI, Greece, from 2012 to 2014, and a Post-Doctoral/Associate Research Scientist with Yale University from 2014 to 2017. He is currently the Ussher Assistant Professor in Future Networks with the School of Computer Science and Statistics, Trinity College Dublin, and a Funded Investigator with the research center CONNECT. He was a co-recipient of the Best Paper Awards in WiOPT 2013 and the IEEE INFOCOM 2017 conferences, a guest editor for the IEEE JSAC Special Issue on Caching, and has received an SFI Career Development Award in 2018. His research interests lie in the area of network optimization and economics, with a recent focus on edge computing, sharing economy, and the Internet of Things.

Lin Gao: Associate Professor, School of Electronic and Information Engineering, Harbin Institute of Technology, Shenzhen, China

Lin Gao is an IEEE Senior Member. He received the Ph.D. degree in Electronic Engineering from Shanghai Jiao Tong University in 2010, and worked as a Postdoc Researcher in the Network Communications and Economics Lab at The Chinese University of Hong Kong during 2010-2015. He received the IEEE ComSoc Asia-Pacific Outstanding Young Researcher Award in 2016. His main research interests are in the area of network economics and games, with applications in wireless communications and networking. He has published more than 80 papers in leading international journals and conference proceedings of communications and networking, and co-authored 3 books in prestigious publishers including Morgan & Claypool and Springer. He is the co-recipient of 3 Best Paper Awards from WiOpt 2013, 2014, 2015, and 1 Best Paper Award Finalist from IEEE INFOCOM 2016. He has been serving as a Co-Chair of the 7th IEEE Workshop on Smart Data Pricing (SDP'18), a TPC Vice Chair of the 16th International Symposium on Modeling and Optimization in Mobile, Ad Hoc, and Wireless Networks (WiOpt'18), a Symposium Chair of the 5th International Conference on Game Theory for Networks (GameNets'14), and a Publicity Chair of the 4th IEEE SDP Workshop. He has been serving as Technical Program Committee (TPC) Members for many leading IEEE conferences including INFOCOM, GLOBECOM, and ICC. He is currently an Associate Editor of the Journal of China Communications and the Journal of Communications and Information Networks.

Jianwei Huang, Professor, IEEE Fellow, IEEE ComSoc Distinguished Lecturer, Department of Information Engineering, Chinese University of Hong Kong, China

Jianwei Huang is a Professor in the Department of Information Engineering at the Chinese University of Hong Kong. He is an IEEE Fellow, a Distinguished Lecturer of IEEE Communications Society, and a Clarivate Analytics Highly Cited Researcher in Computer

Science. He is the co-author of 9 Best Paper Awards, including IEEE Marconi Prize Paper Award in Wireless Communications in 2011. He has co-authored six books, including the textbook on "Wireless Network Pricing." He received the CUHK Young Researcher Award in 2014 and IEEE ComSoc Asia-Pacific Outstanding Young Researcher Award in 2009. He has served as an Associate Editor of IEEE Transactions on Mobile Computing, IEEE/ACM Transactions on Networking, IEEE Transactions on Network Science and Engineering, IEEE Transactions on Wireless Communications, IEEE Journal on Selected Areas in Communications - Cognitive Radio Series, and IEEE Transactions on Cognitive Communications and Networking. He has served as an Editor of Wiley Information and Communication Technology Series, Springer Encyclopedia of Wireless Networks, and Springer Handbook of Cognitive Radio. He has served as the Chair of IEEE ComSoc Cognitive Network Technical Committee and Multimedia Communications Technical Committee. He is the recipient of IEEE ComSoc Multimedia Communications Technical Committee Distinguished Service Award in 2015 and IEEE GLOBECOM Outstanding Service Award in 2010.

Leandros Tassiulas, John C. Malone Professor of Electrical Engineering and Department Chair, Department of Electrical Engineering, Yale University, USA

Leandros Tassiulas is the John C. Malone Professor of Electrical Engineering at Yale University. His research interests are in the field of computer and communication networks with emphasis on fundamental mathematical models and algorithms of complex networks, architectures and protocols of wireless systems, sensor networks, novel internet architectures and experimental platforms for network research. His most notable contributions include the max-weight scheduling algorithm and the back-pressure network control policy, opportunistic scheduling in wireless, the maximum lifetime approach for wireless network energy management, and the consideration of joint access control and antenna transmission management in multiple antenna wireless systems. Dr. Tassiulas has been a Fellow of IEEE (2007) while his research has been recognized by several awards including the inaugural INFOCOM 2007 Achievement Award “for fundamental contributions to resource allocation in communication networks,” the INFOCOM 1994 and 2017 best paper awards, an NSF Research Initiation Award (1992), an NSF CAREER Award (1995), an Office of Naval Research Young Investigator Award (1997) and a Bodossaki award (1999). He holds a Ph.D. in Electrical Engineering from the University of Maryland, College Park (1991). He has held faculty positions at Polytechnic University, New York, University of Maryland, and University of Thessaly, Greece.

C. Abstract

The ever-increasing communication and computing needs of mobile services place the *edge-based user-provided networks* (UPNs) in a conspicuous position for next-generation Internet (of Things) architectures. These systems enable the orchestration of user-owned network, computation and caching resources at the very edge, right next to demand, and hence are scalable and resource-efficient. Today there are numerous proposals for UPN-inspired solutions coming from network operators, over-the-top service providers, or innovative start-ups; and their role is expected to be even more central in the Internet of Things. However, these architectures rely on the availability of resources shared by the end-users, who are inherently self-interested, often risk-averse, and even egotistic. This makes the design of UPNs a multifaceted techno-economic problem, and raises many currently-open challenges that are hindering their large-scale adoption.

This tutorial will provide an overview of UPNs, both in terms of industry practice and academic research. Motivated by novel business models in network sharing solutions, we will focus on mobile UPNs where the energy consumption and data usage costs are critical, while storage and computation resources are limited. Hence, the values of these parameters have large impacts on users’ decisions both for requesting and offering their resources to UPNs. We will first analyze

the technical design challenges of UPNs, discussing possible solutions and presenting results from working prototypes and extensive field tests. Next, we will present different classes of incentive mechanisms aiming to jointly maximize user participation and service performance. We will analyze such mechanisms for different business models, namely self-organizing and operator-controlled wireless networks, and explain the arising trade-offs between performance, efficiency and fairness. The tutorial will discuss cutting-edge UPN design techniques based on cooperative game theory, bargaining theory, auctions, and distributed optimization algorithms; and will conclude by presenting bottleneck issues that must be further addressed in order to unleash the full potential of this promising solution.

D. Importance, Timeliness, and Objective

Today we are witnessing two important socio-technological advances that herald the advent of a new era in communication networks. First, the increasing users needs for ubiquitous Internet connectivity have created an unprecedented volume of mobile data. Second, recent technological developments have resulted in sophisticated user-owned equipment such as advanced Wi-Fi access points (APs), smartphones supporting multi-RAT/path connections, and various edge IoT nodes that can directly communicate with each other. These devices not only can satisfy the communication or computation needs of their owners, but also can be employed to provide related services to other users. In this context, each user is transformed to a micro-service provider (or, a host) who may offer Internet access or other communication, computing, or data storage services to nearby users, giving rise to the concept of user-provided networks (UPNs).

One early commercial UPN example is the Wi-Fi sharing service FON, where users offer Internet connectivity through their residential Wi-Fi APs to other (mobile) users, in exchange for receiving such services when they need them. Since then, many similar models have been proposed, where a user may host other users (clients) by acting as an Internet gateway or as a relay connecting them to users-gateways. This UPN paradigm has recently attracted the focus of academia, and has also inspired many business models employed by either small startups or major network operators (Karma, OpenGarden, BeWiFi, just to name a few). This interest is not surprising, though, as UPNs have substantial performance and economic benefits for users, network operators, and the various over-the-top service providers.

Furthermore, in the emerging era of fog computing, this architecture paradigm offers more opportunities but also becomes more challenging. Users can share network connectivity, storage resources and computing power, or even their devices' battery energy. For example, a device that needs to execute a computation-heavy task can use the idle processor of a nearby device, or its storage resources for caching raw data. Hence the dimension of the sharing problem increases from single-resource to multi-resource problem, but on the other hand there are more collaboration opportunities. For instance, bandwidth can be exchanged with storage or computation capacity, and this creates further opportunities for synergistic interactions among users at the network edge. Several important tasks in fog computing require the orchestration of different resource types, and hence UPNs need to be extended beyond network sharing.

Currently, there are several UPN models that differ in the architectures and services they offer to users. However, one common aspect of these models is that users must agree to serve each other. This is a central issue in UPNs, as both demand (clients' requests) and provision (hosts' availability) depend on users' participation. Nevertheless, more often than not, the participants have conflicting interests. For example, clients would prefer to receive services at low cost, while hosts would prefer to charge high prices. Similarly, an operator's incentive to support UPNs would be high if she can directly gain from such services. Clearly, it is of paramount importance to design incentive mechanisms for reconciling the objectives of all participants. Such mechanisms need to effectively tackle the following questions:

- How much should a host be compensated through payment (directly) or through service exchange (indirectly) for offering UPN services to clients?
- Which combinations of charged prices and offered services render UPNs more attractive than conventional infrastructure-based communication services?
- If a network operator or a service provider enables the UPN service, how much should he charge the clients and reimburse the hosts?

The objective of this tutorial is to provide the audience a comprehensive understanding of the history, the current status, and the future of UPNs for traditional communication services but also for emerging fog-computing applications. We will discuss existing commercial UPNs in terms of their strengths and deficiencies, and the technical challenges of designing future UPNs. Then we will focus on the incentive issues in UPNs and introduce the latest results on the incentive mechanism designs. We will cover both fixed and mobile UPNs, and discuss various important issues such as usage-based pricing, quota-reward mechanisms, membership selection, market evolution, and hybrid cloud/fog-based UPNs for supporting computation services.

E. Target Audience and Assumed Background of Attendees

The target audience of this tutorial will be researchers, engineers, and regulators in the wireless industry, Internet of Things and Fog computing domains, who are interested in understanding the economics-technology interactions of user-provided networks. The audience is expected to have a basic understanding of wireless communications and networking.

F. Tutorial Outline

- Introduction of User-Provided Networks (UPN)
  - Commercial examples of UPN
  - The importance and future of UPN for IoT and Fog Computing
  - Classification of UPN
- Technical challenges of UPN design
  - UPN Security
  - Performance impacts on the consumers and providers in UPN
  - Energy consumption of mobile UPN
  - Computation, communications, and caching resource sharing
- Incentive mechanism design of UPN
  - Membership selection and user interaction in fixed UPNs
  - Two-stage pricing and market evolutions of fixed UPNs
  - Hybrid pricing strategy and market evolution in mobile UPNs
  - Cooperative resource sharing in mobile UPNs
  - Crowdsourced video streaming in mobile UPNs
  - Cloud-based SDN assisted mobile UPNs
- User behavior and network constraints in UPNs
  - Cooperative and competitive equilibriums in service exchange models

- Network cooperation motifs and trust in credit-based platforms
- User behavior and strategies in resource sharing games.

E. Key References (Speaker names in bold)

(1) R. Sofia and P. Mendes, "User-Provided Networks: Consumer as Provider", *IEEE Communications Magazine*, vol. 46, no. 12, 2008.

(2) **G. Iosifidis, L. Gao, J. Huang,** and **L. Tassiulas**, "Incentive Mechanisms for User-Provided Networks*,"* *IEEE Communications Magazine*, vol. 52, no. 9, August 2014.

(3) M. Tang, **L. Gao,** and **J. Huang**, "Enabling Edge Cooperation in Tactile Internet via 3C Resource Sharing," *IEEE JSAC*, IEEE Early Access Article, 2018.

(4) A. G. Saavedra, **G. Iosifidis**, X. C. Perez, D. Leith, "Joint Optimization of Edge Computing Architectures and Radio Access Networks," *IEEE JSAC*, IEEE Early Access Article, 2018.

(5) **L. Gao**, M. Tang†, H. Pang, **J. Huang**, L. Sun, "Multi-User Cooperative Mobile Video Streaming: Performance Analysis and Online Mechanism Design," *IEEE Transactions on Mobile Computing*, IEEE Early Access Article, 2018.

(6) **G. Iosifidis, L. Gao, J. Huang,** and **L. Tassiulas**, "Efficient and Fair Collaborative Mobile Internet Access," *IEEE/ACM Transactions on Networking*, vol. 25, no. 3, pp. 1386 - 1400, June 2017.

(7) K. Poularakis, **G. Iosifidis,** and **L. Tassiulas**, "SDN-Enabled Tactical Ad Hoc Networks: Extending Programmable Control to the Edge*,"* *IEEE Communications Magazine*, vol. 56, no. 7, pp. 132-138, 2018.

(8) M. Tang, H. Pang, S. Wang, **L. Gao, J. Huang**, and L. Sun, "Multi-Dimensional Auction Mechanisms for Crowdsourced Mobile Video Streaming," *IEEE/ACM Transactions on Networking*, vol. 26, no. 5, 2018.

(9) Q. Ma, **L. Gao**, Y. Liu, and **J. Huang**, "Incentivizing Wi-Fi Network Crowdsourcing: A Contract Theoretic Approach," *IEEE/ACM Transactions on Networking*, vol. 26, no. 3, pp. 1035 - 1048, June 2018.

(10) Q. Ma, **L. Gao**, Y. Liu, and **J. Huang**, "Economic Analysis of Crowdsourced Wireless Community Networks," *IEEE Transactions on Mobile Computing*, vol. 16, no. 7, pp. 1856 - 1869, July 2017.

(11) M. Afrasiabi and R. Guérin. "Pricing Strategies for User-Provided Connectivity services," *IEEE INFOCOM*, 2012.

(12) D. Syrivelis, **G. Iosifidis**, D. Delimpasis, K. Chounos, T. Korakis, **Leandros Tassiulas**, "Bits and Coins: Supporting Collaborative Consumption of Mobile Internet", *IEEE INFOCOM*, 2015.

(13) Q. Qin, K. Poularakis, **G. Iosifidis, L. Tassiulas**, "SDN Controller Placement at the Edge: Optimizing Delay and Overheads" *IEEE INFOCOM*, 2018.

(14) Y. Luo, N. B. Shah, **J. Huang,** and J. C. Walrand, "Parametric Prediction from Parametric Agents*,"* *Operations Research*, vol. 66, no. 2, pp. 313-326, 2018.

(15) L. Georgiadis, **G. Iosifidis,** and **L. Tassiulas**, "Exchange of Services in Networks: Competition, Cooperation, and Fairness,", *ACM SIGMETRICS, 2015*.

(16) **G. Iosifidis,** Y. Charette, E. Airoldi, G. Littera, **L. Tassiulas**, and N. Christakis, "Cyclic Motifs in the Sardex Monetary Network," *Nature Human Behavior,* 2018.

(17) J. S. Judd, and M. Kearns, "Behavioral Experiments in Networked Trade*", in Proc. of ACM Electronic Commerce (EC)*, 2008.

G. Related Past Teaching/Presentation History

- Prof. Huang and Prof. Tassiulas have delivered a **tutorial on User-Provided Networks** at IEEE GLOBECOM 2015 (http://globecom2015.ieee-globecom.org/content/tutorials#TT-13), which is a preliminary version of the current proposal. This tutorial is a significantly updated and expanded version of the tutorial, and more than half of the materials are based on publications after 2018 (as shown in the Key Reference section).
- Prof. Huang (and sometimes together with Prof Gao) have been giving various tutorials at ICC/GLOBECOM/ICCC/DySPAN, on topics such as "Optimization and Economics of Mobile Crowd Sensing," "Fog Computing and Networking: A New Paradigm for 5G and IoT Applications," "Economics of TV White Space Networks," "Mobile Data Offloading," and "Wireless Network Economics and Games." These tutorials were well attended and received by the audience.
- Prof. Huang has given invited/keynote/distinguished talks on **"Incentive Mechanisms for User-Provided Networks"** at Osaka Institute of Technology, University of Tsukuba, University of Houston, University of Science and Technology of China, Shanghai Jiaotong University, Shanghai, Asia-US Forum on Fog Networking for 5G and IoT, Taipei, Cambridge University, Academia Sinica, Southeast University, Jiangsu Provincial Collaborative Innovation Center on Satellite Communications, IEEE International Conference on Communications China , National Tsing Hua University, and Sun Yat-Sen University. During the past 7 years, Prof. Huang has given more than 110 invited seminars in universities and companies word-wide on topics related to wireless network optimization/economics.
- Prof. Tassiulas gave over 20 keynote and plenary lectures in conferences and workshops over the past 15 years on topics related to resource allocation and spectrum management in wireless networks; and **over 5 keynotes related to UPNs** in the last 2 years at MIT, University of Maryland, New York University, Nokia Bell Labs Murray Hill, KAUST, etc.
- Dr. Iosifidis has given several recent talks about 5G networks and edge computing in universities such as TU Berlin, Chinese University of Hong Kong, and University of Sorbonne/CNRS-LIP6; and in industry labs such as Huawei Research Paris, Nokia Bell Labs Dublin, and NEC Research Heidelberg. Dr. Iosifidis has also delivered invited talks at the IEEE WiOPT/CCDWN workshop and at the IEEE 5G Summit (Greece/Oct. 18). Finally, Dr. Iosifidis has developed and is teaching the class "Optimization for Data Analysis" in the Data Science M.Sc. at Trinity College Dublin.
- Dr. Gao has given several invited talks about UPNs, mobile crowdsensing, and edge computing in universities such as The University of Macau, The Chinese University of Hong Kong, Shanghai Jiao Tong University, and Tongji University. Dr. Gao has also delivered invited talks at various conference proceedings such as IEEE workshop on smart data pricing, IEEE ICCC, and IEEE WiOpt.

Physical Layer Authentication and Location Verification: A Machine-Learning Perspective

Stefano Tomasin and Xianbin Wang

Title of the tutorial

Physical Layer Authentication and Location Verification: A Machine-Learning Perspective

Abstract

The problem of user and device authentication has been typically approached by cryptographic techniques, while more recently features of the physical transmission channel have been considered as new authentication tags. Since the channel features are typically associated with the specific position of both the transmitter and the receiver, the physical layer user authentication can also be seen as a way to authenticate the position of the user at a single spot or in an area, in what is known as location verification process. However, the channel feature estimates used for authentication are affected by noise, interference and time-varying phenomena, whose statistics are required for an effective authentication. Since these statistics strongly depend on the environment, new approaches based on machine learning are needed. This is particularly relevant when fusing multiple heterogeneous features to make the authentication more robust. Similarly, learning becomes pivotal with location verification, where feature statistics must be known for an entire area rather than for a single position. Indeed, by a proper design, the machine learning solution directly learns the whole decision process behind authentication in the specific use context, exploiting at best the potentials of artificial intelligence (AI). The tutorial will give an overview of physical layer user authentication and location verification techniques, outlining potentials and shortcomings, and indicating practical solutions. An important part of the tutorial will focus on machine learning approaches for fusing multiple channel features in both user authentication and location verification, also establishing the connection with optimal authentication when statistics are perfectly known.

Objectives and Motivation

The general objective of the tutorial is to provide an overview of the problem of user authentication and location verification applying machine-learning approaches to physical layer security techniques. It will cover the theory behind the authentication process at the physical layer, the machine learning and AI enabled solutions to adapt to various contexts and fusing multiple features, and a description of practical solutions that have been developed recently.

In details, the teaching objectives of the tutorial are:

- Formulating the user authentication and location verification problem as an hypothesis testing problem

- Deriving optimal techniques for hypothesis testing (Neyman-Pearson theorem and theoretical performance bounds) and their application to physical layer authentication
- Integrating differentiated channel features for user authentication and location verification purposes using machine learning solutions
- Understanding machine learning approaches to physical layer authentication: connection to Neyman-Pearson theorem, performance results and implementation issues
- Exploring potentials and shortcomings of physical layer authentication in both 5G and IoT scenarios
- Looking into the new research directions ahead on automated physical layer authentication

The motivation to attend the tutorial is to know more on the issue of authentication, a very sensitive topic for any communication system, which may find innovative solutions tailored to the communication scenario (in particular for wireless communications) by physical layer techniques. The increasing number of very differentiated devices also for IoT and machine-to-machine communications calls for simpler and at the same time efficient solutions that could either replace or integrate cryptographic approaches that require long transmission with significant communication overhead. In some cases [Lora-2017] the physical layer has already been used to provide security features, however in a naïve fashion, paving the way to new security issues: therefore a rigorous approach to the use of physical layer techniques for authentication must be pursued. In this context, assumptions on the knowledge of the channel feature statistics are not realistic and must be replaced by automatic solutions: still, understanding their functionalities and connection with theoretic solutions confirm their effectiveness and security.

Timeliness and intended audience

Physical layer security has seen increasing interest and initiatives only in 2018 include:

- Survey papers advocating its application to both cellular 5G [Wu-2018] and IoT scenarios [Sun-2018, Soni-2017];
- Special issues [Hindawi-2018, Hindawi-2-2018];
- Best reading paper collection of IEEE Com. Soc. https://www.comsoc.org/best-readings/physical-layer-security;
- Specific workshops on the topic at GLOBECOM [The 6th IEEE GLOBECOM Workshop on Trusted Communications with Physical Layer Security (TCPLS2018)] and ICC [1st IEEE Workshop on 5G Wireless Security (5G-Security)].

The intended audience are researchers in both the academia, the industry and government agencies that are interested in the new frontier of physical layer authentication and its potential applications to product and standards.

Tutorial Speakers

Stefano Tomasin, IEEE Senior Member – http://www.dei.unipd.it/ ~tomasin

Stefano Tomasin received the Ph.D. degree in Telecommunications Engineering from the University of Padova, Italy, in 2003. In 2002 he joined University of Padova where he is now associate Professor. He has been on leave at Philips Research (Eindhoven, Netherlands) in 2002, Qualcomm Research Laboratories (San Diego, California) in 2004, Polytechnic University (Brooklyn, New York) in 2007 and Huawei Mathematical and Algorithmic Sciences Laboratory (Boulogne-Billancourt, France) in 2014. His current research interests include physical layer security and signal processing for wireless communications, with application to the 5th generation of cellular systems. In 2011-2017 he has been Editor of the IEEE Transactions of Vehicular

Technologies and since 2016 he is Editor of IEEE Transactions on Signal Processing. Since 2011 he is also Editor of EURASIP Journal of Wireless Communications and Networking.

Xianbin Wang, IEEE Fellow - https://www.eng.uwo.ca/electrical/faculty/wang_x/

Xianbin Wang is a Professor and Tier-I Canada Research Chair at Western University, Canada. He received his Ph.D. degree in electrical and computer engineering from National University of Singapore in 2001. Prior to joining Western, he was with Communications Research Centre Canada (CRC) as a Research Scientist/Senior Research Scientist between July 2002 and Dec. 2007. From Jan. 2001 to July 2002, he was a system designer at STMicroelectronics, where he was responsible for the system design of DSL and Gigabit Ethernet chipsets. His current research interests include 5G technologies, Internet-of-Things, communications security, machine learning and locationing technologies. Dr. Wang has over 300 peer-reviewed journal and conference papers, in addition to 26 granted and pending patents and several standard contributions. Dr. Wang is a Fellow of Canadian Academy of Engineering, a Fellow of IEEE and an IEEE Distinguished Lecturer. He has received many awards and recognitions, including Canada Research Chair, CRC Presidents Excellence Award, Canadian Federal Government Public Service Award, Ontario Early Researcher Award and five IEEE Best Paper Awards. He currently serves as an Editor/Associate Editor for IEEE Transactions on Communications, IEEE Transactions on Broadcasting, and IEEE Transactions on Vehicular Technology and He was also an Associate Editor for IEEE Transactions on Wireless Communications between 2007 and 2011, and IEEE Wireless Communications Letters between 2011 and 2016. Dr. Wang was involved in many IEEE conferences including GLOBECOM, ICC, VTC, PIMRC, WCNC and CWIT, in different roles such as symposium chair, tutorial instructor, track chair, session chair and TPC co-chair.

Addressed Technical Issues

The technical problem at the center of the tutorial is how to confirm the identity of the author of a message (user authentication) or how to ensure that the device of interest is in a given location or area (location verification), using the characteristics of the channels over which the communication occurs. In order to solve this problem a number of associated technical issues are addressed:

- Hypothesis testing when partial information is available: as authentication is a hypothesis testing problem, its optimal solution requires the knowledge of the statistics of the observed channel features in both hypotheses (legitimate transmission and attack). However, statistics of both cases are not immediately available as they strongly depend on the propagation environment and on the attacker transmission capabilities. The tutorial will directly address these issues showing how to both merge different information for authentication and obtaining related statistics (or better, directly an adaptive hypothesis testing procedure) using machine learning approaches.
- Architecture and training of machine learning solutions: among the various machine learning solutions presented in the literature we will identify those that are more suitable for the authentication problem. The tutorial will focus on security issues of the machine learning approach, that is not an issue for most existing solutions in other domains. Indeed, in our context the attacks of an adversarial can be tailored to the authentication process, thus the tutorial will discuss alternatives and present machine learning solutions designed to be robust to new kinds of attacks.
- Estimation of channel features for authentication purposes: the channel characteristics used for authentication may vary over time due to user mobility and environment variations, as well as due to random variations in the transmitting and receiving devices (e.g., phase errors). The tutorial will provide a description of various channel features, highlighting their suitability for authentication, together with procedures to estimate them.
- Security of the physical layer authentication: suitable metrics to measure the security and correctness of the obtained authentication techniques must be provided. The tutorial will present relevant metrics and will highlight the relation of physical layer authentication with cryptographic key-based authentication currently used in many systems. In this respect, the shortcomings of

inaccurate application of physical layer security approaches to conventionally cryptography will be highlighted with relevant examples from standards.

Tutorial Outline and Tentative Schedule

The tutorial will have the following outline:

- Basics of user authentication and location verification problems
- Wireless channel features for physical layer authentication
- Performance metrics for physical layer authentication
- Hypothesis testing and Neyman Pearson theorem
- Multiple hypothesis testing and multi-identity verification
- Performance bounds
- Channel statistics and hardware attributes estimation for physical-layer authentication
- Learning approach for physical layer authentication
- Machine learning techniques overview and choice of channel features
- Connection of ML approaches to Neyman Pearson theorem
- Data fusion for multi-attributes based authentication
- Security for the machine design and its training against authentication attacks
- Experiments and prototypes for physical layer authentication
- Physical layer authentication for cellular 5G and IoT scenarios

The tutorial will fit a half-day time slot.

Past/relevant Experience of the Speakers

S. Tomasin has been active in the physical layer security area since many years with various relevant contributions in this field. He has studied in particular the problem of physical layer authentication, by first finding the optimal defense strategy and the best attack strategy, in particular with application to wireless systems using multiple antennas and/or multiple carriers. Then he has investigated the relation of physical layer authentication with key-based authentication, where the random source for the key generation is still the channel. His most relevant activities for the dissemination of research activity in this field have included editorial activities for journals and organization of workshops. In particular, Dr. Tomasin has been guest Editor of the Special issue on Information-Theoretic Security, 2017, Entropy, 2017 and guest Editor of the Special issue on Physical Layer Security and its Applications, 2015, Proceedings of IEEE, Oct. 2015. He has been organizer of the IEEE Workshop on Wireless Physical Layer Security (WPLS) at the IEEE International Conference on Communications June 2015, London, UK and organizer of the Workshop on Communication Security (WCS 2014) within the ESCAPADE project, Sept. 2014, Ancona, Italy.

X. Wang has developed many original physical layer security techniques to improve wireless security and communication confidentiality. His technical contributions on physical layer security have been well-recognized worldwide and highly cited. A number of physical layer authentication techniques based on CIR, IQ imbalance, CFO and new confidentiality enhancement schemes through opportunistic link adaptation have been developed by him. Malicious devices were identified based on the cooperation of friendly users (authenticated devices) through knowledge-sharing of transmission power, signaling, channel profile, and resource usage. He also invented a new method of using continuous adaptation of communications link for security enhancement. He is the Director of NSERC CREATE program in Communication Security, Privacy and

Cyberethics. His research activities on physical layer security have been supported by NSERC, Canada Research Chair, and Defence and Research Development Canada and have led to several DSP/FPGA prototypes. The physical layer authentication technique using carrier frequency offset has won a Best Paper Award from IEEE ICC2012.

Previous Tutorial Experience

S. Tomasin has delivered the tutorial

- "DVB-T2: Key technologies and implementation issues," half-day tutorial at Int. Conf. Commun. (ICC), Jun. 2009. The tutorial has also been recorded and made available online http://dl.comsoc.org/comsocdl/?article=20323121.

S. Tomasin also has given a short invited presentation on "Machine learning approaches for position and user authentication in wireless systems," at the ShanghaiTech Workshop on Information, Learning and Decision (SWILD 2018) in Shanghai, Jun. 2018.

X. Wang has delivered a number of tutorials at major IEEE conferences, including:

- "Physical and Network Layers of 5G: Requirements, Challenges and Enabling Technologies," half-day tutorial at IEEE VTC Spring, 2016.
- "Emerging Green Technologies for 5G Wireless Networks: From Theory to Practice," half-day tutorial at IEEE ICUWB, 2015, Montreal.
- "Advanced Air Interface Techniques for 5G: Emerging Concepts and Research Opportunities," half-day tutorial at IEEE PIMRC, 2015, Hong Kong.
- "Evolution and Future Development of Cognitive Radio Technology," half-day tutorial at IEEE Vehicular Technology Conference, May, 2008, Singapore.

The tutorial of this proposal has not presented before in other venues.

Similar Tutorials in Recent ICC & Globecom (last two years)

Over the last two years there has been no tutorial on physical layer security and in particular on physical layer authentication. The most similar tutorial was given in ICC 2018 by Aziz Mohaisen and Joongheon Kim with title "TUT23: Securing the Internet of Things: A Machine Learning Approach": however, this tutorial was addressing approaches used for performing behavior-based analyses used for engineering (or automatically extracting) features from the behavior of software associated with it use, the characteristics of hardware associated with baselines and behaviors of sensors, and the communication protocol-level artifacts. Thus, the topic of that tutorial is far from our proposal.

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Selected Speakers’ Bibliography

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- E. Jorswieck, S. Tomasin and A. Sezgin, "Broadcasting Into the Uncertainty: Authentication and Confidentiality by Physical-Layer Processing," in Proceedings of the IEEE, vol. 103, no. 10, pp. 1702-1724, Oct. 2015.
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- Xianbin Wang, Peng Hao, and Lajos Hanzo, “Physical-Layer Authentication for Wireless Security Enhancement: Current Challenges and Future Developments”, IEEE Communications Magazine, vol.54, no.6, pp.152-158, June 2016.
- Yulong Zou, Jia Zhu, Xianbin Wang and Lajos Hanzo, “A Survey on Wireless Security: Technical Challenges, Recent Advances, and Future Trends”, Proceedings of the IEEE, vol. 104, no.9, pp. 1727-1765, September 2016.
- Y. Zou, X. Wang, and W. Shen, “Optimal Relay Selection for Physical-Layer Security in Cooperative Wireless Networks”, IEEE Journal on Selected Areas in Communications, vol.31, no. 10, pp.2099-2111, Oct. 2013.
- Xiaoyu Duan and Xianbin Wang, “Authentication Handover and Privacy Protection in 5G HetNet Using Software-Defined Networking”, IEEE Communications Magazine, vol.53, no.4, pp.28-35, April 2015.

1. Title

One Step Closer Towards Intelligent Wireless Network: Spatiotemporal Models, Learning, and Control

2. Abstract

The rapid growth of wireless applications brings new challenges for next generation system, where it is expected to manage a massive number of devices in real time within a highly dynamic environment. Motivated by the burgeoning progress of artificial intelligence and the breakthroughs it led in a variety of domains, the communication society is currently seeking solutions from machine learning for intelligent controls on the physical (PHY) and medium access control (MAC) layers of future network. While many learning based methods, e.g., reinforcement learning, are able to directly devise control policies from the collected data set without an explicit model, such approaches can on the one hand take a long time to converge, and on the other, perform unreliable trial-and-error exploration actions on real network, which degrades the network performance. To guarantee the real time effectiveness and avoid trying potentially wrong solutions, it becomes essential to incorporate an suitable model that captures the fundamental features of a wireless network, i.e., the physical transmission environment and the temporal dynamic of traffic, for the efficient training procedure of machine learning schemes. In this tutorial, we introduce an approach to develop appropriate spatiotemporal models and incorporate them in the design of intelligent wireless networks. Specifically, we first provide a complete survey to the basic spatiotemporal models for wireless networks, follow by a recently developed refined establishment. We then show how these models can be leveraged with machine learning techniques to design various intelligent applications in wireless networks. Finally, we conclude by shedding light on the future works.

3. Type of Tutorial

Half-day

4. Objective and Motivation

The main objective of this tutorial is to introduce the fundamental research and advancements in spatiotemporal modeling of wireless networks and devise revolution to academic and industrial researchers. In particular, we will thoroughly discuss the modern approaches in modelling the spatiotemporal randomness of wireless networks. Through the effective use of such models, we introduce their applications in the design and analysis of intelligent wireless networks.

5. Intended Audience

The tutorial is intended for the generally knowledgeable individual working in the field of wireless communications and networking with some background in probability theory, signal processing, and machine learning. It is also suitable for students and researchers who are interested to learn about models and the subsequent applications in wireless networks.

6. Tutorial Outline

The tutorial is mainly divided into two parts. In the first part, we introduce the necessary background about spatiotemporal wireless network models by exploring the pros and cons of three modelling schemes that were recently proposed, i.e., the bounding approach based on favourable/dominant system argument, light-traffic steady state approximation, and the Geo/PH/1 queue modelling. We then thoroughly elaborate a meta-distribution based modelling method which covers more refined details over the existing results, being the state-of-the-art result. In the second part, by adopting the proposed spatiotemporal model, we discuss several modern applications in wireless networks, including the design of scheduling policy that optimizes the information freshness, the scaling property of mobile edge computing, and incorporating the spatiotemporal model in reinforcement learning for traffic scheduling.

7. Tutorial Speaker

Prof. Tony Q. S. Quek, Ph.D., IEEE Fellow
Associate Professor, Singapore University of Technology and Design, Singapore

Biography:
Tony Q. S. Quek received the B.E. and M.E. degrees in Electrical and Electronics Engineering from Tokyo Institute of Technology, Tokyo, Japan, respectively. At Massachusetts Institute of Technology (MIT), Cambridge, MA, he earned the Ph.D. in Electrical Engineering and Computer Science. Currently, he is a tenured Associate Professor with the Singapore University of Technology and Design (SUTD). He also serves as the Acting Head of ISTD Pillar and the Deputy Director of SUTD-ZJU IDEA. His current research topics include wireless communications and networking, security, big data processing, network intelligence, and IoT.

Dr. Quek has been actively involved in organizing and chairing sessions, and has served as a TPC member in numerous international conferences. He is serving as the Track Co-Chair for IEEE PIMRC 2018, Track Co-Chair for IEEE VTC Spring 2018, and TPC Co-Chair for IEEE WCSP 2018. He is currently an elected member of the IEEE Signal Processing Society SPCOM Technical Committee. He was an Executive Editorial Committee Member of the IEEE Transactions on Wireless Communications, an Editor of the IEEE Transactions on Communications, and an Editor of the IEEE Wireless Communications Letters. He is a co-author of the book “Small Cell Networks: Deployment, PHY Techniques, and Resource Allocation” published by Cambridge University Press in 2013 and the book “Cloud Radio Access Networks: Principles, Technologies, and Applications” by Cambridge University Press in 2016.

Dr. Quek received the 2008 Philip Yeo Prize for Outstanding Achievement in Research, the IEEE Globecom 2010 Best Paper Award, the 2012 IEEE William R. Bennett Prize, the 2016 IEEE Signal Processing Society Young Author Best Paper Award, 2017 CTTC Early Achievement Award, 2017 IEEE ComSoc AP Outstanding Paper Award, and 2016-2018 Clarivate Analytics Highly Cited Researcher. He is a Distinguished Lecturer of the IEEE Communications Society and a Fellow of IEEE.

Howard H. Yang, Ph.D,
Postdoctoral Research Fellow, Singapore University of Technology and Design, Singapore

Biography:
Howard H. Yang received the B.Sc. degree in Communication Engineering from Harbin Institute of Technology (HIT), China, in 2012, and the M.Sc. degree in Electronic Engineering from Hong Kong University of Science and Technology (HKUST), Hong Kong, in 2013. He earned the Ph.D. degree in Electronic Engineering from Singapore University of Technology and Design (SUTD), Singapore, in 2017. From Aug. 2015 to Mar. 2016, he was a visiting student in the WNCG under supervisor of Prof. Jeffrey G. Andrews at the University of Texas at Austin.

Dr. Yang is now a Postdoctoral Research Fellow with Singapore University of Technology and Design in the Wireless Networks and Decision Systems (WNDS) group led by Prof. Tony Q. S. Quek. He is currently a visiting Postdoc Researcher in Princeton University under supervision of Prof. H. Vincent Poor. His research interests cover various aspects of wireless communications, networking, and signal processing, currently focusing on the spatiotemporal modeling of wireless network, machine learning based communication technology, and graph signal processing. He received the IEEE WCSP Best Paper Award in 2014.

8. Tutorial Description

This tutorial mainly contains two parts. In the first part, we will provide the necessary background on the modeling tools for wireless networks, which includes the basics from queuing theory and the Poisson point process (PPP) models from stochastic geometry. We will also introduce three recent approaches for the spatiotemporal modeling of wireless networks, including the favourable/dominant system approach, the Phase-Type (PH) queueing model, and the meta-distribution based spatiotemporal model. In the second part, we will show how to leverage such models to the design of intelligent wireless networks. Particularly, we will show a distributed traffic scheduling policy that accounts the space-time network dynamic and achieves optimal information freshness transmission. We will also use the model to investigate the scaling property in the deployment of mobile edge computing to wireless networks. Finally, we show how to incorporate the model with reinforcement learning to attain an efficient task offloading scheme for devices in wireless networks with mobile edge computing.

Part I: Recent Advances in Spatiotemporal Modeling for Wireless Networks

- ***Favourable/dominant system approach***
- ***Phase type queuing models***
- ***Meta distribution based models***

In the this section, we first provide necessary backgrounds about stochastic geometry and queueing theory, whereas the former describes the location of randomly deployed base stations and often yields a tractable expression for the interference while the latter has long been accepted as a modeling method for the network temporal traffic. We then introduce three recent advances that combines stochastic geometry and queueing theory for the spatiotemporal modeling of wireless networks, i.e., the favourable/dominant system approach, the Phase-Type (PH) queuing models, and the meta-distribution based spatiotemporal model.

The initial attempt to tackle queuing problem in wireless networks is by adopting the argument of favourable/dominant systems. For favourable system, retransmission of failed packet deliveries is ignored, where the transmitters simply drop each packet once sent out, regardless of the status is success or not. This system gives an upper bound for the network SINR distribution, as the total interference is actually underestimated. On the other hand, by considering a dominant system, the transmitters keep transmitting regardless of the queuing status: Even there is no packet to be transmitted, the transmitter simply sends out dummy packets. Such system provides lower bound of the actual system by overestimating the interference. In regard to the actual system, the actual SINR performance is bounded by the favourable/dominant system SINR distributions, and the performance trend can be inferred from the bounds. Such method benefits from a simple migration from the sophisticated results of stochastic geometry, and gives useful insights to certain level, but is accurate only under heavy traffic regime.

One step beyond the favourable/dominant system comes a recently proposed modeling scheme based on the Phase-Type queues. In such model, the queuing status and transmission protocol is modeled via a two-dimensional Markov chain. Specifically, by assuming Bernoulli arrival in temporal domain and base station spatial locations distributed according to PPP, the queuing evolution is captured via Geo/PH/1 queuing model. Through solving a fixed point equation, the spatial, as well as temporal, randomness in wireless networks are jointly accounted. This method will improve the analytical insight about wireless networks as it considers the impact of both spatial base station location and the temporal traffic dynamic via an average manner.

Finally, we introduce a newly developed meta-distribution based spatiotemporal model, which combines queuing theory with stochastic geometry. In its essence, this model is motivated fact that in addition to the conventionally adopted distribution of SINR, the meta distribution gives more precise information about the SINR information from cell to cell in a large-scale wireless network. Hence by leveraging the per-cell SINR distribution, which is equivalently the random service rate, the cell active information can be precisely captured, and further enables the development of a spatiotemporal model. This model takes a complete treatment on the interplay between temporal traffic dynamic, and the spatial base station location, which influence through interference, and allows one to apply into various applications and analysis.

Part II: Model Based Design of Intelligent Wireless Networks

- ***Distributed Space-Time Scheduling Policy***
- ***Scaling Properties in Deployment of Mobile Edge Computing***
- ***Model Based Reinforcement Learning for Mobile Edge Computing***

The spatiotemporal model allows one to perform a more thoroughly design and analysis on various wireless systems. In this part, we mainly explore three applications where the spatiotemporal model can serve as a useful basis in the design of intelligent wireless network: *i*) the design of a space-time scheduling policy in wireless networks, *ii*) the analysis and investigation on the scaling properties of mobile edge computing, and *iii*) the development of a model based reinforcement learning scheme for task offloading in wireless networks with mobile edge computing. We detail the description about these applications in the following.

By nature, the wireless channel is a broadcast medium, thus transmitters share a common spectrum in space can degrade the performance of each other via the interference they cause. Our first application thus concerns how to regulate the transmission of devices in a highly dynamic large network so as to reduce collision while guaranteeing the delivered information not being out-dated. With the help of spatiotemporal model, we are able to design a distributed algorithm at each transmitting device that dynamically learns the geographic location information, as well as the traffic status, of its proximity neighbours, and leverage such information to adaptively control the transmission state at different time slots. The performance and achievable gain of deploying such algorithm in a wireless network can also be analytically evaluated through the developed model.

Next, the network operators are currently empowering the edge, e.g., access nodes, with processing capability to reduce delay and backhaul burden for wireless applications. In this scenario, how much computing power shall be deployed, and how to upgrade the wireless link communication capacity so as to adapt with the edge computing become an important question. Using the spatiotemporal model, we establish a framework that allows one to take into account the effect from the wireless communication channel, including network topology, interference, and filtering scheme, and the computing server, and device the tradeoff between communication and computation. We devise the scaling property of mobile edge computing and provide guidelines for the deployment in large network.

Finally, as future networks will have multiple devices attached to one access point and utilize the mobile edge computing power, the primary issue becomes how to choose between local computing or offloading tasks to the edge. As on the one hand, local computing may have low computing power, and offloading shall be good. On the other, if offloading is performed too frequently, it will not just consume a large communication bandwidth, but also generate additional mutual interference in the spectrum and thus worsen overall network performance. In this regard, by leveraging the reinforcement learning for the design of task offloading policy at each device, and use the spatiotemporal models as side information, we show how such scheme can capture network dynamics and accelerate the convergent rate of reinforcement learning and thus effectively schedule tasks in local and edge aspects.

9. Prior History of Tutorial

- Tony Q. S. Quek, "Recent Advances in Heterogeneous Cellular Networks," IEEE International Conference on Information, Communications and Signal Processing, Tainan, TAIWAN, Dec. 10, 2013.
- Tony Q. S. Quek, "Heterogeneous Cellular Networks Modeling, Analysis, and Design using Stochastic Geometry," IEEE Vehicular Technology Conference Spring, Seoul, KOREA, May 18, 2014.
- Tony Q. S. Quek, "Fundamental Design of Small Cell Networks," IEEE International Conference on Communications in China, Shanghai, CHINA, Oct. 13, 2014.

- Tony Q. S. Quek, "Heterogeneous Cloud Radio Access Networks: Principles and Technologies," IEEE International Symposium on Personal, Indoor and Mobile Radio Communications, Hong Kong, CHINA, Aug. 30, 2015.
- Tony Q. S. Quek, "Small Cells for 5G: Fundamentals and Recent Theory," IEEE International Conference on Advanced Technologies for Communications, Ho Chi Minh, VIETNAM, Oct. 15, 2015.
- Tony Q. S. Quek, "Fog Computing and Networking: A New Paradigm for 5G and IoT Applications," IEEE International Conference on Communications, Paris, FRANCE, May 21, 2017.
- Tony Q. S. Quek, Howard H. Yang, "Spatiotemporal Modeling for the Next Generation Wireless Networks: Analysis and Applications," IEEE International Conference on Communications in China, Beijing, CHINA, Aug. 16, 2018.

10. Lecture Experience of Tutorial Speaker

Prof. Quek has given a series of invited talks and short courses on small cell networks, device-to-device communication, cloud radio access networks, and 5G networks at several universities, public and private research institutions in Asia and Europe. In addition, he has been delivering courses and lectures on wireless communications and networking at SUTD and overseas universities on a regularly basis.

Dr. Yang has the experience to give talks on massive MIMO enabled cellular networks, energy-harvesting based D2D communications, and delay related analysis of wireless systems at several workshops of major research projects, international conferences and universities.

11. Selected Publications of the speakers (related to the tutorial)

[1] T. Q. S. Quek, G. de la Roche, İ. Güvenç, and M. Kountouris (Eds.), "Small-Cell Networks: Deployment, PHY Techniques, and Resource Management," Book published by Cambridge University Press, 2013.

[2] Y. Zhong, T. Q. S. Quek, and X. Ge, "Heterogeneous Cellular Networks with Spatio-Temporal Traffic: Delay Analysis and Scheduling," *IEEE J. Select. Areas Commun*., vol. 35, no. 6, pp. 1373-1386, June 2017.

[3] Y. Zhong, M. Haenggi, T. Q. S. Quek, and W. Zhang, "On the Stability of Static Poisson Networks under Random Access," IEEE Trans. Commun., vol. 64, no. 7, pp. 2985–2998, Jul. 2016.

[4] H. Yang, G. Geraci, Y. Zhong, and T. Q. S. Quek, "Packet Throughput Analysis of Static and Dynamic T DD in Small Cell Networks," *IEEE Wireless Commun. Lett.*, vol. 6, no. 6, pp. 742-745, Dec. 2017.

[5] J. Li, A. Huang, H. Shan, H. H. Yang, and T. Q. S. Quek, "Analysis of Packet Throughput in Small Cell Networks under Dynamic TDD and Clustering," *IEEE Trans. on Wireless Commun.*, vol. 17, no. 9, pp. 5729-5742, Sept. 2018.

[6] H. H. Yang, Y. Wang, and T. Q. S. Quek, "Delay Analysis of Random Scheduling and Round Robin in Small Cell Networks," *IEEE Wireless Commun. Lett.,* Jun. 2018

[7] H. H. Yang, and T. Q. S. Quek, "Spatiotemporal Analysis for SINR Coverage in Small Cell Networks," *IEEE Trans. Commun.*, submitted

Machine Learning and Stochastic Geometry: Statistical Frameworks Against Uncertainty in Wireless LANs

Koji Yamamoto and Takayuki Nishio
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1. Title of the tutorial;

Machine Learning and Stochastic Geometry: Statistical Frameworks Against Uncertainty in Wireless LANs

2. Abstract, objectives and motivation;

This tutorial aims to provide fundamentals of **machine learning** and **stochastic geometry**. For machine learning, **deep supervised learning** and **reinforcement learning** are introduced. One special feature of this tutorial is that it is specialized to **microwave and mmWave wireless LANs (WLANs)**. WLANs are widely used and new technologies including spatial reuse have been implemented; however, their performances are uncertain due to random access and channel variation including human blockages in mmWave.

Predicting and optimizing the performance in WLANs, e.g., received power, throughput, and spectral efficiency, are still open issues since WLAN, in particular mmWave environments change dynamically and variously due to its distributed operations, non-managed access points and stations, and line of sight blockage. The machine learning can be an enabler of the challenge due to its data-driven model adaptation. For example, throughput and received power prediction can be modeled as a supervised learning problem and predictive handover improving the system throughput can be modeled as a reinforcement learning problem. These problems can be solved by recent machine learning algorithms including deep learning. However, for applying machine learning to our own problems, we require to understand how model the problem, which algorithm and techniques should be used, and how obtains dataset.

In this tutorial, fundamentals of supervised learning, deep learning, and reinforcement learning are introduced, and we address how apply the machine learning to challenges in WLANs based on mmWave received power prediction and handover [1], [17]. Also, relations with strategic-form games and its solution concept, Nash equilibrium, are introduced based on the author's survey paper [5]. In addition, we demonstrate how to use deep learning frameworks with using Google Colab, Tensorflow with Keras, and publicly available dataset of RSSI localization.

Performance analysis of WLANs is mainly conducted through network simulations because protocols are complicated. However, from simulation results, it is sometimes hard to grab the impact of parameters on the performance. Stochastic geometry has become a standard tool to analyze the spatial distribution of interference and outage. In this tutorial, fundamentals of stochastic geometry and Matérn hard-core point process, which are used to model simultaneous transmitters in CSMA/CA networks, are introduced based on previous works [13], [14]. Then, the effect of carrier sense threshold management is introduced based on the speakers' paper [6].

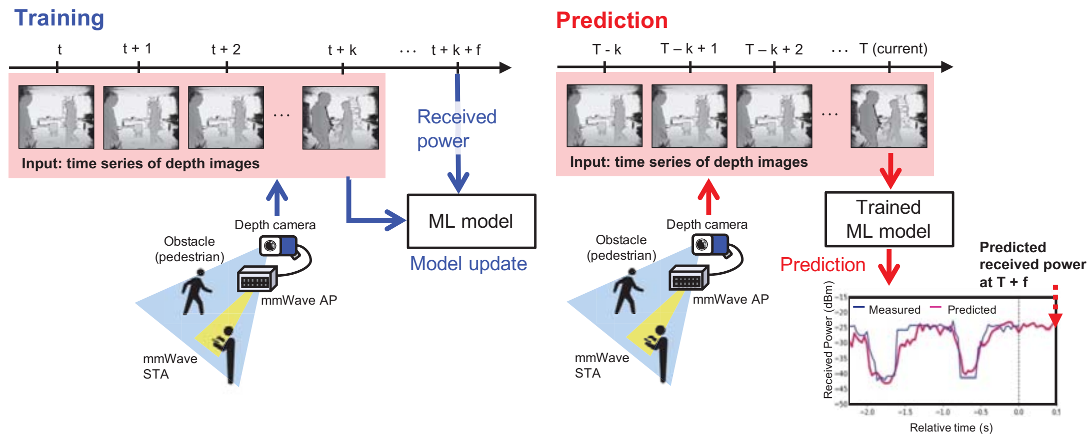

Fig. 1: mmWave Received Power Prediction from Camera Imagery. A mapping from a set of image to received power is

3. Timeliness and intended audience;

Both machine learning and stochastic geometry are recent hot topics. There is a number of related tutorials in recent ICC & Globecom as summarized in Section 9. Also, the standardization of IEEE 802.11ax is scheduled to be completed next year and the discussion of the next generation WLANs has been started.

Machine learning is expected to provide a solution against the huge variety of WLAN environments due to its data-driven adaptation. Especially in WLANs, huge number of data including signal transmission and reception failure are available, which can feed recent deep learning algorithms that are data-hungry but powerful. Moreover, mobile learning algorithms and distributed learning mechanisms have been developed, which enables learning processes in WLANs. Now is the time to apply machine learning to WLANs.

Stochastic geometry enables tractable performance modeling of wireless networks, particularly cellular networks, taking into account uncertainty in locations of transmitters and random fading. Especially for WLANs, Matérn hardcore point process is a frequently assumed model which represent the result of carrier sensing mechanism.

Intended audiences of this tutorial are students, academia, and industries, who are interested in the frameworks but don't know what the frameworks can do in WLANs.

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

Koji Yamamoto, Graduate School of Informatics, Kyoto University

Koji Yamamoto (S'03–M'06) received the B.E. degree in electrical and electronic engineering from Kyoto University in 2002, and the M.E. and Ph.D. degrees in Informatics from Kyoto University in 2004 and 2005, respectively. From 2004 to 2005, he was a research fellow of the Japan Society for the Promotion of Science (JSPS). Since 2005, he has been with the Graduate School of Informatics, Kyoto University, where he is currently an associate professor. From 2008 to 2009, he was a visiting researcher at Wireless@KTH, Royal Institute of Technology (KTH) in Sweden. He serves as an editor of IEEE Wireless Communications Letters from 2017, Vice Chair of IEEE ComSoc Asia Pacific Board Chapters Coordination Committee from 2018, the Track Co-Chairs of APCC 2017, CCNC 2018, APCC 2018, and CCNC 2019, and Technical Committee Member of IEEE Signal Processing and Communications Electronics (SPCE) from 2016. His research interests include radio resource management and applications of game theory. He received the PIMRC 2004 Best Student Paper Award in 2004, the Ericsson Young

Scientist Award in 2006. He also received the Young Researcher's Award, the Paper Award, SUEMATSU-Yasuharu Award from the IEICE of Japan in 2008, 2011, and 2016, respectively, and IEEE Kansai Section GOLD Award in 2012.

Takayuki Nishio, Graduate School of Informatics, Kyoto University

Takayuki Nishio received the B.E. degree in Electrical and Electronic Engineering from Kyoto University in 2010. He received the master and Ph.D. degrees in Communications and Computer Engineering, Graduate School of Informatics from Kyoto University, Kyoto, Japan, in 2012 and 2013, respectively. From 2012 to 2013, he was a research fellow (DC1) of the Japan Society for the Promotion of Science (JSPS). Since 2013, He is an Assistant Professor in Communications and Computer Engineering, Graduate School of Informatics, Kyoto University. From 2016 to 2017, he was a visiting researcher in Wireless Information Network Laboratory (WINLAB), Rutgers University, United States. His current research interests include mmWave networks, wireless local area networks, application of machine learning, and sensor fusion in wireless communications. He received IEEE Kansai Section Student Award in 2011, the Young Researcher's Award from the IEICE of Japan in 2016, and Funai Information Technology Award for Young Researchers in 2016.

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

This tutorial will introduce two statistical frameworks, machine learning and stochastic geometry, which are gathering high attention in industry and research community of wireless networks. Especially, applications of these frameworks to WLANs will be addressed.

As machine learning problems in WLANs, two problems will be addressed, mmWave received power prediction and decision making of mmWave handover. These problems can be modeled as a supervised problem and reinforcement learning, but to model and to solve the problems require know-how of machine learning. Machine learning in WLANs has big potential since the WLANs can generate huge amount of data required for machine learning from their millions of frame transmission and network operations. However, for using machine learning in WLANs, we have to know how model problems as machine learning problems and how process the data. This tutorial will provide such know-how based on the applications of machine learning in WLANs [1], [17]

Stochastic geometry enables the performance analysis of complex wireless networks taking into account randomness in the locations of transmitters and fading. We will introduce solutions to the question, how to model the transmitters in carrier sense-based networks and how to evaluate the impact of carrier sense threshold, which can be adjusted in IEEE 802.11ax WLANs.

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

1) Issues in microwave and mmWave WLANs
   a) Densification
   b) CCA threshold control and spatial reuse
   c) mmWave propagation including human blockage
2) Stochastic geometry and analysis of microwave WLAN taking into account spatial reuse technique in IEEE 802.11ax (45 min)
   a) How to model the locations of transmitters — Poisson point process and Matern hardcore point process
   b) How to derive the distribution of interference and outage probability — Campbell's theorem
   c) How to evaluate the impact of carrier sense threshold control on the performance
3) Reinforcement learning towards spatial reuse technique in IEEE 802.11ax (45 min)

   a) What is the difference between reinforcement learning problem and game-theoretic problem?
   b) What kind of problem should be modeled as reinforcement learning problem?
   c) How can we solve the problem? Is it optimal? — Q-learning and Markov decision process
4) From Basics to Practice: Supervised Learning in WLANs (45 min)
   a) What is Supervised Learning and Deep Learning?
   b) What kind of problem should be modeled as supervised learning problem? — mmWave throughput and received power prediction
5) Deep Learning in/for WLANs (45 min)
   a) What is Deep Learning? What can we use it for?
   b) How can we feed deep learning? — transfer learning and federated learning
   c) How can we use deep learning frameworks?

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

Speakers' research topics related to the tutorial are summarized in Table I.

TABLE I: Past/relevant experience of the speakers on the topic of the tutorial.

	WLANs	Other wireless networks
Supervised learning		Spectrum sharing [21], [23]
Deep supervised learning	Received power prediction [17], [18], [20], [22]	Federated learning [16]
Deep reinforcement learning	Handover to avoid human blockage in mmWave [1]	Vehicle movement control for mmWave VANET [15]
Game theory	Carrier sense threshold management [2], channel allocation [3], [4]	Survey of applications of potential games [5]
Stochastic geometry	Carrier sense threshold management [6], mmWave RAN sharing [7]	Spectrum sharing using spectrum database [8], [9], multi-user scheduling [10]–[12]

They published nine machine-learning related papers and seven stochastic geometry related papers in refereed journals and conferences.

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

K. Yamamoto has provided several tutorial talks related to stochastic geometry and game theory as follows.

- K. Yamamoto, "[Invited talk] Elements of stochastic geometry analysis of cellular networks," (in Japanese) IEICE Tech. Rep., RCS2017-46, May 2017.
- K. Yamamoto, "Elements of stochastic geometry analysis of cellular networks," (in Japanese) IEICE Tech. Rep., ASN2017-55, Jul. 2017.
- K. Yamamoto, "[Invited talk] Elements of stochastic geometry analysis of cellular networks," (in Japanese) IEICE Tech. Rep., CQ2017-57, Aug. 2017.
  Slides: https://speakerdeck.com/kojiyam/ieice-rcs-201705.
- K. Yamamoto, "[Invited talk] Application of game theory for wireless communication systems," (in Japanese) IEICE Tech. Rep., CCS, Mar. 2014.

- K. Yamamoto, "[Invited talk] Game theory and radio resource management," (in Japanese) IEICE Tech. Rep., RCS2012-14, Apr. 2012.
- K. Yamamoto, et al., "[Tutorial] Game theory and distributed resource management," (in Japanese) IEICE Gen. Conf., BT-3-5, Mar. 2010.

T. Nishio has provided seven tutorial talks related to machine learning in these two years, which are listed up as follows. All talks are provided in Japanese. In these tutorials, he introduced a fundamentals of machine learning, especially supervised learning and deep learning and the state of the art techniques in the deep learning, and provided demonstration using deep learning framework and realistic dataset.

- T. Nishio, "[Invited tutorial] Machine Learning From Basics to Practice Toward Wireless Network Control," IEEE AP-S Kansai Joint Chapter Tutorial, Sept. 2018.
- T. Nishio, "[Tutorial] Deep Learning Tutorial," IEICE Tech. Rep., MoNA2018-21, Aug. 2018.
- T. Nishio, "[Invited tutorial] Machine Learning for Wireless Network Management," KEC Wireless Seminar, July 2018.
- T. Nishio, "[Invited talk] Wireless Link Quality Prediction And Wireless Control Through Machine Learning," IEICE Tech. Rep., SR2018-1, May 2018.
- T. Nishio, "[Invited tutorial] Machine Learning Basics and Applications to Wireless Network Management," IEEE AP-S Kansai Joint Chapter Tutorial, Sept. 2017.
- T. Nishio, "[Invited talk] Machine Learning in Wireless Networks," IEICE Tech. Conf., CQ Workshop, Aug. 2017.

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

The followings are related tutorials in recent ICC & Globecom. Thus, we can say that they are hot topics.

1) Machine learning
    - Deep Learning for Communications (GC 2018)
    - Machine Learning and Artificial Intelligence in Wireless Networks: Challenges and Opportunities (GC 2018)
    - Statistical Learning and Online Optimization Reinforcing Network Management in IoT (GC 2018)
    - Securing the Internet of Things: A Machine Learning Approach (ICC 2018)
    - Artificial Intelligence Driven Management of Future Indoor 5G Networks (GC 2017)
2) Stochastic geometry
    - A Crash Course in Stochastic Geometry-Based Modeling and Analysis of 5G Cellular Networks (ICC 2018)
    - Stochastic Geometry-Based Modeling and Analysis of 5G Cellular Networks (GC 2017, ICC 2017)
3) Wireless LANs, radio resource management
    - Unlicensed Spectrum Technologies: From Wi-Fi to 5G and Beyond (ICC 2018)
    - Mechanism Design for Network Allocation Problems (ICC 2018)
    - IEEE 802.11ay: Introduction to the first standard for 100 Gbps Wi-Fi (GC 2017)
    - Resource Allocation in Wireless Networks under Uncertainties: A Stochastic Optimization Framework (ICC 2017)

The aforementioned recent tutorials addressed overview and applications of machine learning in wireless networks. The difference from these tutorials is that the proposed tutorial aims to provide appropriate frameworks for specific problems in microwave and mmWave WLANs, e.g.,

- mmWave propagation including human blockage
- CSMA-based MAC protocol
- packet based transmission

Another difference is that our tutorial will provide instructions on how to use deep learning framework via live-coding with using publicly available dataset of wireless communications and Google Colab. The audience will be able to download dataset and follow the tutorial by themselves, which are valuable for the audience to acquire the skill to use deep learning.

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Title: Machine Learning for AI-Driven Wireless Networks: Challenges and Opportunities

Speakers: Dr. Walid Saad (ECE, Virginia Tech, USA) and Dr. Mehdi Bennis (Center for Wireless Communications, University of Oulu, Finland)

Tutorial Abstract:

Next-generation wireless networks must support ultra-reliable, low-latency communication and intelligently manage a massive number of Internet of Things (IoT) devices in real-time, within a highly dynamic environment. This need for stringent communication quality-of-service (QoS) requirements as well as mobile edge and core intelligence can only be realized by integrating fundamental notions of *artificial intelligence (AI) and machine learning* across the wireless infrastructure and end-user devices. AI is expected to play several roles in the next-generation of wireless networks. First, the most natural application of AI and machine learning is to exploit big data analytics to enhance situational awareness and overall network operation. In this context, AI will provide the wireless network with the ability to parse through massive amounts of data, generated from multiple sources that range from wireless channel measurements and sensor readings to drones and surveillance images, in order to create a comprehensive operational map of the massive number of devices within the network. This map can, in turn, be exploited to optimize various functions, such as fault monitoring and user tracking, across the wireless network. Second, beyond its powerful prediction and data analytics functions, AI will be a major driver of intelligent and data-driven wireless network optimization. For instance, reinforcement learning tools will enable the introduction of intelligent resource management tools, that can be used to address a variety of problems ranging from cell association and radio access technology selection to frequency allocation, spectrum management, power control, and intelligent beamforming. In contrast to conventional distributed optimization technique, that are often done iteratively in an offline or semi-offline manner. AI-guided resource management mechanisms will be able to operate in a fully online manner by learning and predicting, in real time, the states of the wireless environment and the network's users, thus allowing the network to adapt to those predictions. Third, the rapid deployment of highly user-centric wireless services, such as virtual reality strongly motivates the need for wireless networks that can track and adapt to their human user behavior. In this regard, machine learning is perhaps the only tool that is capable to learn and mimic human behavior. Last, but not least, beyond its system-level functions, AI can play a key role at the physical layer of a wireless network, as a tool to enhance channel estimation and encoding/decoding, by leveraging predictions from the physical layer. Given this prominent role that AI and machine learning will play in tomorrow's wireless networks, it is imperative to provide an in-depth overview on their fundamentals as well as their applications in wireless and communication networks.

To this end, the goal of this tutorial is to provide one of the first holistic tutorials on the topic of machine learning for wireless network design. In particular, we will first provide a comprehensive treatment of the fundamentals of machine learning and artificial neural networks, which are one of the most important pillars of machine learning. After providing a substantial introduction to the basics of machine learning, we introduce a classification of the various types of neural networks that include feed-forward neural networks, recurrent neural networks, spiking neural networks, and deep neural networks. For each type, we provide an introduction on their basic components, their training processes, and their use cases with specific example neural networks. Then, we overview a broad range of wireless applications that can make use of neural network designs. This range of applications includes spectrum management, multiple radio access technology cellular networks, wireless virtual reality, mobile edge computing and caching, drone-based communications, the Internet of Things, and vehicular networks. For each application, we first outline the main rationale for applying machine learning while pinpointing illustrative scenarios. Then, we overview the challenges and opportunities brought forward by the use of neural networks in the specific wireless application. We complement this overview with a detailed example drawn from the state-of-the-art. Finally, we conclude by shedding light on the potential future works within each specific area and within the overall area of AI for wireless networks.

Target Audience:

The potential audience includes researchers from both academia and industry (operators, vendors and network engineers), including graduate and undergraduate students who are interested in learning the fundamental science and technology underlying emerging concepts from machine learning and artificial intelligence, and their applications in wireless networking environment. This includes both the fundamentals of machine learning as well as its potential use and deployment in various wireless networking, environments such as heterogeneous cellular networks, Internet of Things, drone-based communications, wireless virtual reality, and mobile edge computing/caching. In particular, this tutorial is expected to attract a large crowd which can include (but not limited to):

- Researchers and networking engineers in both industry and academia looking for a comprehensive introduction on artificial intelligence and machine learning, their inherent features, and the wireless networking domains that can leverage them.
- Researchers and communication engineers interested in learning new network design and analytical tools, based on machine learning, suitable for modeling, analysis, design, and optimization of future wireless networks.
- Graduate students pursuing interdisciplinary wireless and networking research who are interested in studying novel analytical frameworks for intelligent network design.
- Graduate students pursuing research in machine learning and interested in new application domains.
- Researchers interested in an introduction on emerging paradigms in both wireless networking and machine learning.

Tutorial Outline:

- **Introduction to Machine Learning:**

- What is machine learning?
- Machine learning and artificial intelligence.
- Brief overview on the basics of machine learning.

- **Artificial Neural Networks (ANNs) Preliminaries:**

- Brief introduction to machine learning and motivation behind artificial neural networks.
- Introduction to the architecture of artificial neural networks and their training process.

- **Classification of Artificial Neural Networks:**

- Introduction to recurrent neural networks: fundamentals, training, and specific examples such as echo state networks.
- Introduction to spiking neural networks: fundamentals, training, and specific examples such as liquid-state machines.
- Introduction to deep neural networks: fundamentals, training, and specific examples such as long short term memory and convolutional neural networks.
- Brief review of other types of artificial neural networks.
- Collaborative learning and neural networks.

- **Reinforcement Learning:**

- Introduction to reinforcement learning.
- Q-learning: basics and state of the art.
- Boltzmann-Gibbs learning: basics and state of the art.
- Reinforcement learning with artificial neural networks.
- Deep reinforcement learning: basics and state of the art.

- **AI for Spectrum Management in Multi Radio Access Technology (RAT) Networks:**

- Brief overview on the spectrum management challenge in multi-RAT networks.
- Overview on potential applications of machine learning and AI for spectrum management and multi-RAT systems.
- Step-by-step introduction to an example application using deep learning for proactive spectrum management.
- Future works and opportunities of ANNs in the spectrum management application domain.

- **AI for Virtual Reality (VR) over Wireless Networks:**

- Brief introduction to VR and explanation on the role of VR over wireless in future networks.
- Overview of the applications for reinforcement learning and artificial neural networks in wireless VR.
- Step-by-step explanation of an example application that uses recursive neural networks for wireless VR.
- Future works and opportunities for ANNs in the wireless VR application domain.

- **AI for Mobile Edge Caching and Computing:**

- Brief introduction to the basic notions in mobile edge caching and computing.
- Overview on potential applications of AI for mobile edge caching and computing.
- Step-by-step overview on a sample application that uses AI for mobile edge caching.

- Step-by-step overview on an illustrative application that uses AI for mobile edge computing.
- Future works and opportunities for optimizing edge caching and computing using machine learning

  - **AI for Wireless Communications using Drones:**
- Overview on the role of drones in wireless communications and networking.
- Overview on potential applications of AI for drone-based communications.
- Step-by-step overview on a sample application that uses recurrent and spiking neural networks for optimizing the performance of drone-based wireless communications.
- Step-by-step overview on an illustrative application that uses deep reinforcement learning for path planning in cellular-connected drone networks..
- Future works and opportunities for optimizing drone communications using machine learning.

  - **AI for the Internet of Things (IoT):**
- Overview on the Internet of Things and its challenges.
- Overview on potential applications of machine learning and AI within the Internet of Things.
- Step-by-step overview on a sample application that uses machine learning for big data analytics in the IoT.
- Step-by-step overview on an illustrative application that uses reinforcement learning for optimizing IoT communications.
- Step-by-step overview on the use of deep learning for IoT security and authentication.
- Future works and opportunities for optimizing the IoT performance using machine learning.

  - **AI for Vehicular Networks:**
- Overview on vehicular networks and their evolution.
- Overview on potential applications of machine learning and AI within vehicular networks.
- Step-by-step overview on a sample application that uses deep learning for optimized vehicular communications and security.
- Future works and opportunities for using AI in vehicular networks.

  - **On-device AI:**
- What is on-device AI? why is it different than classical AI?
- Principles of federated and transfer learning, collaborative AI, etc.
- Step-by-step overview of selected use cases (e.g., V2V)

  - **Conclusions and future directions:**
- Brief overview on other applications of AI and machine learning, such as smart cities.
- Discussion of future directions and open opportunities: toward AI-inspired wireless networks.
- Conclusions and summary.

Key Objectives and Importance:

Machine learning has become a significant topic of research in both academic and industrial circles, as evidenced by the significant amount of research papers, startups, and other activities that are centered around the use of machine learning and artificial intellignece techniques. In particular, there has been a recent surge in research that attempts to leverage synergies between machine learning and wireless networking designs. Therefore, a tutorial on the topic of machine learning for wireless networking is extremely timely and much needed. Moreover, in contrast to past tutorials on the topic, which focused on very basic introductions on isolated topics in machine learning and on very limted wireless application domains, this proposed tutorial will provide an in-depth introduction to a plethora of tools from machine learning while providing concrete models and formulations, as well as mathematically rigorous solutions for many pertinent wireless networking applications. In summary, the objectives of this tutorial are summarized as follows:

- Providing a comprehensive overview on a plethora of machine learning tools that range from conventional supervised/unsupervised learning, to different neural networks such as recurrent neural networks, spiking neural networks, and deep neural networks.
- Overviewing the various roles of artificial intelligence in future wireless networks.
- Introducing the fundamentals of reinforcement learning and its use for network optimization.
- Formulating and discussing key research challenges pertaining to the development of machine learning and artificial

intelligence techniques for optimized communications, networking, and security in a variety of wireless networking domains.

- Providing a comprehensive treatment of state-of-the-art research in the field of machine learning for wireless networks by focusing on several pertinent applications: multi-RAT networks, mobile edge caching and computing, virtual reality, UAV/drone systems, Internet of Things, vehicular systems, and physical layer designs.
- Discussing future directions and opportunities for the use of machine learning and artificial intelligence in wireless networks.

Overall the proposed tutorial will provide the attendees with exposure to both emerging machine learning topics as well as emerging wireless networking domains that can be used to address imminent research challenges of global interest to the research community at large.

Instructors Biography and Past Tutorial Experience:

Walid Saad (S'07, M'10, SM'15) received his Ph.D degree from the University of Oslo in 2010. Currently, he is an Associate Professor at the Department of Electrical and Computer Engineering at Virginia Tech, where he leads the Network Science, Wireless, and Security (NetSciWiS) laboratory, within the Wireless@VT research group. His research interests include wireless networks, machine learning, game theory, cybersecurity, unmanned aerial vehicles, and cyber-physical systems. Dr. Saad is the recipient of the NSF CAREER award in 2013, the AFOSR summer faculty fellowship in 2014, and the Young Investigator Award from the Office of Naval Research (ONR) in 2015. He was the author/co-author of six conference best paper awards at WiOpt in 2009, ICIMP in 2010, IEEE WCNC in 2012, IEEE PIMRC in 2015, IEEE SmartGridComm in 2015, and EuCNC in 2017. He is the recipient of the 2015 Fred W. Ellersick Prize from the IEEE Communications Society and of the 2017 IEEE ComSoc Best Young Professional in Academia award. From 2015-2017, Dr. Saad was named the Stephen O. Lane Junior Faculty Fellow at Virginia Tech and, in 2017, he was named College of Engineering Faculty Fellow. He currently serves as an editor for the IEEE Transactions on Wireless Communications, IEEE Transactions on Communications, IEEE Transactions on Mobile Computing, and IEEE Transactions on Information Forensics and Security.

Past Tutorial Experience: Dr. Saad has delivered over 14 tutorials at various international venues such as IEEE WCNC 2010 (Cooperative game theory, about 25 attendeeds, chosen as tutorial of high interest and broadcast via web by IEEE), IEEE SARNOFF 2011 (Cooperative game theory, about 15 attendees), IEEE GLOBECOM 2012 (Small cell networks, about 45 attendees), IEEE ICCIT 2013 (Small cell networks, 15 attendees), IEEE DySpan 2014 (Small cell networks, about 45 attendees), IEEE GLOBECOM 2014 (Small cell netwokrs, about 30 attendees), IEEE ICC 2015 (Game theory, about 15 attendees), IEEE GLOBECOM 2016 (UAV networking, about 45 attendees), and IEEE GLOBECOM 2017 (Internet of Things, about 20 attendees), IEEE MILCOM 2017 (UAVs, about 20 attendees), IEEE ISCC 2017 (UAVs, about 20 attendees), and IEEE PIMRC 2017 (UAVs, about 20 attendees). Dr. Saad was also a Keynote at IEEE GLOBECOM 2011, Workshop on Broadband Wireless Access , a keynote speaker at IEEE VTC-Fall workshop on Backhaul in 2017, a plenary speaker at Virginia APA Conference 2017, and a plenary at the NEXT Workshop on Cooperative Games, May 2014. Dr. Saad has also been a speaker at various seminars at the University of Illinois at Urbana-Champaign, the University of Houston, NJIT, SUPELEC, UCLA IPAM AGT Workshop 2011, the American University of Beirut, UCLA, UC-Irvine, FIU, Thales, USC, and many other institutions. The speaker has several publications on the subject being presented in this tutorial for more information please consult the speaker's personal and group websites:
Personal: http://resume.walid-saad.com Group: http://www.netsciwis.com

In particular, the speaker has published the following papers related to the topic at hand:

- *M. Chen, U. Challita, W. Saad, C. Yin, and M. Debbah, "Machine Learning for Wireless Networks with Artificial Intelligence: A Tutorial on Neural Networks", arXiv:1710.02913, 2017.*
- *T. Park, N. Abuzainab, and W. Saad, "Learning How to Communicate in the Internet of Things: Finite Resources and Heterogeneity", IEEE Access, Special Issue on Optimization for Emerging Wireless Networks: IoT, 5G and Smart Grid Communication Networks, vol. 4, November 2016.*
- *M. Chen, W. Saad, C. Yin, and M. Debbah, "Echo State Networks for Proactive Caching in Cloud-Based Radio Access Networks with Mobile Users", IEEE Transactions on Wireless Communications, vol. 16, no. 6, pp. 3520 - 3535, June 2017.*
- *U. Challita, W. Saad, and C. Bettstetter, "Deep Reinforcement Learning for Interference-Aware Path Planning of Cellular-Connected UAVs", in Proc. of the IEEE International Conference on Communications (ICC), Wireless Networking Symposium, Kansas City, MO, USA, May 2018.*
- *A. Ferdowsi and W. Saad, "Deep Learning-Based Dynamic Watermarking for Secure Signal Authentication in the Internet of Things", in Proc. of the IEEE International Conference on Communications (ICC),*

Communication and Information Systems Security Symposium, Kansas City, MO, USA, May 2018.
- *U. Challita, L. Dong, and W. Saad, "Deep Learning for Proactive Resource Allocation in LTE-U Networks", in Proc. of European Wireless, Dresden, Germany, May 2017.*
- *M. Chen, W. Saad, and C. Lin, "Echo State Networks for Self-Organizing Resource Allocation in LTE-U with Uplink-Downlink Decoupling", IEEE Transactions on Wireless Communications, vol. 16, no. 1, pp. 3-16, January 2017.*
- *M. Chen, W. Saad, and C. Yin, "Liquid State Machine Learning for Resource Allocation in a Network of Cache-Enabled LTE-U UAVs", in Proc. of the IEEE Global Communications Conference (GLOBECOM), Singapore, December 2017.*
- *M. Chen, W. Saad, and C. Yin, "Echo State Learning for Wireless Virtual Reality Resource Allocation in UAV-enabled LTE-U Networks", in Proc. of the IEEE International Conference on Communications (ICC), CRN Symposium, Kansas City, MO, USA, May 2018.*
- *M. Chen, W. Saad, and C. Yin, "Virtual Reality over Wireless Networks: Quality-of-Service Model and Learning-Based Resource Management", arXiv:1703.04209.*
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- *M. Chen, W. Saad, C. Yin, and M. Debbah, "Echo State Transfer Learning for Data Correlation Aware Resource Allocation in Wireless Virtual Reality", in Proc. of the 51st Asilomar Conference on Signals, Systems and Computers, Pacific Grove, CA, USA, November 2017.*
- *A. Hajijamali Arani, A. Mehbodniya, M. J. Omidi, F. Adachi, W. Saad, and I. Guvenc, "Distributed Learning for Energy-Efficient Resource Management in Self-Organizing Heterogeneous Networks", IEEE Trans. on Vehicular Technology, vol. 66, no. 10, pp. 9287 - 9303, Oct. 2017.*
- *A. Talebzadeh, W. Saad, and M. Debbah, "Brain-Aware Wireless Networks: Learning and Resource Management", in Proc. of the 51st Asilomar Conference on Signals, Systems and Computers, Pacific Grove, CA, USA, November 2017.*
- *N. Abuzainab, W. Saad, and B. Maham, "Robust Bayesian Learning for Wireless RF Energy Harvesting Networks", in Proc. of the 15th International Symposium on Modeling and Optimization in Mobile, Ad Hoc, and Wireless Networks (WiOpt), Paris, France, May 2017.*

Mehdi Bennis is an associate professor at the University of Oulu, Finland. He received his M.Sc. degree from the Ecole Polytechnique Federale de Lausanne (EPFL), Switzerland and the Eurecom Institute, France in 2002. He obtained his Ph.D. degree in electrical engineering December 2009 on spectrum sharing for future mobile cellular systems. He was the co-PI of the Broadband Evolved FEMTO (FP7-BeFEMTO) project, and is currently the PI of the European CELTIC project SHARING (2013-2015). His main research interests are in radio resource management, heterogeneous networks, game theory and machine learning. He has published more than 50 research papers in international conferences, journals, book chapters and patents. He is currently an editor for the IEEE Transaction of Wireless Communications. Further, he was a co-chair at the 1st international workshop on small cell wireless networks (SmallNets) in conjunction with IEEE ICC 2012, the 2nd Workshop on Cooperative Heterogeneous Networks (coHetNet) in conjunction with ICCCN 2012, the international workshop on cooperative and heterogeneous cellular networks in conjunction with IEEE PIMRC 2012 (Sydney, Australia), the 2nd international workshop on small cell wireless networks (SmallNets) in conjunction with IEEE ICC 2013, and the forthcoming 3rd workshop on small cell wireless networks (SmallNets) in conjunction with IEEE ICC 2014. Recently, he gave seven tutorial presentations at IEEE PIMRC 2012 (Sydney, Sep. Australia) and IEEE GLOBECOM 2012 (Annaheim, CA, Dec. 2012), IEEE DySPAN (McLean, VA, Apr. 2014), IEEE WCNC (Istanbul, Turkey, Apr. 2014), IEEE GLOBECOM 2014, IEEE ICC (London, UK, Jun. 2015), and IEEE DySPAN (Stockholm, Sweden, Sep. 2015). He was the recipient of the prestigious 2015 Fred W. Ellersick Prize from the IEEE Communications Society, the 2016 IEEE COMSOC Best Tutorial Prize and recently the 2017 EURASIP Best Paper Award for the Journal on Wireless Communications and Networking.

Past Tutorial Experience:

Recently, Dr. Bennis gave tutorial presentations at IEEE PIMRC 2012, IEEE GLOBECOM 2012, IEEE DySPAN 2014, IEEE WCNC 2014, IEEE GLOBECOM 2014, IEEE ICC 2015, and IEEE DySPAN 2015, IEEE GLOBECOM 2017. The speaker has several publications on the subject being presented in this tutorial for more information please consult the speaker's website: http://www.cwc.oulu.fi/~bennis/. Beyond the joint papers with Dr. Saad above, Dr. Bennis published the following full papers that can serve as basis for this tutorial, particularly for the resource allocation aspect:

- *M. Bennis, M. Simsek, W. Saad, S. Valentin, M. Debbah, and A. Czylwik, "When Cellular Meets WiFi in Wireless Small Cell Networks," IEEE Communications Magazine, vol. 51, no. 6, June 2013 (featured among top 10 most accessed online papers in IEEE Comsoc for June 2013 and July 2013).*
- *E. Bastug, M. Bennis, and M. Debbah," Living on The Edge: On the Role of Proactive Caching in 5G Wireless Networks," IEEE Comm. Mag., SI on Context Awareness, 52(8): 82-89, Nov. 2014.*
- *C. Perfecto, J. Del Ser, and Mehdi Bennis, "Millimeter Wave V2V Communications: Distributed Association and Beam Alignment," JSAC SI on mmwave communication for future mobile networks, 2017.*
- *E. Bastug, M. Bennis, and M. Debbah,* "A transfer learning approach for cache-enabled wireless networks", WiOpt 2015: 161-166
- *E. Zeydan, E. Bastug, M. Bennis, M. Abdel Kader, I. Alper Karatepe, A. Salih Er, M. Debbah, "Big data caching for networking: moving from cloud to edge," IEEE Communications Magazine 54(9): 36-42 (2016)*
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- *E. Baştuğ, M. Bennis, M. Médard, and M. Debbah, "Towards Interconnected Virtual Reality: Opportunities, Challenges and Enablers, " IEEE Communications Magazine 55(6): 110-117 (2017)*
- *K. Hamidouche, A. Talebzadeh, W. Saad, M. Bennis, and M. Debbah, "Collaborative Artificial Intelligence (AI) for User-Cell Association in Ultra-Dense Cellular Systems", in Proc. of the IEEE International Conference on Communications (ICC), Workshop on Promises and Challenges of Machine Learning in Communication Networks, Kansas City, MO, USA, May 2018.*
- *S. Samarakoon, M. Bennis, W. Saad, and M. Latva-aho, "Dynamic Clustering and ON/OFF Strategies for Wireless Small Cell Networks," IEEE Transactions on Wireless Communications, vol. 15, no. 3, pp. 2164-2178, March 2016.*
- *X. Chen, Z. Han, H. Zhang, G. Xue, Y. Xiao, and M. Bennis, "Wireless resource scheduling in virtualized radio access networks using stochastic learning,"* IEEE Trans. Mobile Comput., *2017.*
- *M. S. Elbamby, C. Perfecto, M. Bennis, K. Doppler, "Towards Low-Latency and Ultra-Reliable Virtual Reality," IEEE Network, special issue in URLLC, in press, 2018.*

Title: Molecular Communications: Theory, Practice and Challenges

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Subject Area: Molecular Communications

Length of the tutorial: half-day

Abstract, Objectives and Motivation: Molecular communications (MC) has been recognized as an attractive solution for information exchange between nano-machines and in nano-scale networks operated in fluid and gas environments. By taking its potential advantages of bio-compatibility and low energy consumption, MC is expected to find a lot of applications in the areas, where the operation of conventional electromagnetic based communications is inefficient and/or impractical. Potential applications of MC may include health-care, intelligent drug delivery, environment monitoring, industry applications, Internet of Nano Things (IoNT), etc. Owing to these, MC has received an increasing attention in research and development in recent years. In this tutorial, we motivate to provide a comprehensive introduction to the state-of-the-art in MC. We will emphasize the similarity and difference between MC and the conventional electromagnetic based communications. The fundamentals of MC, channel modeling in MC and the transceiver techniques for MC, as well as some advanced MC techniques, including multiple-input multiple-output (MIMO) MC, multiple-access MC, and the error-control coding in MC, will be addressed. Furthermore, some challenges and opportunities of MC will be discussed.

The objectives of the tutorial include:

- to review MC by comparing it with the electromagnetic based communications;
- to discuss the different media for molecule transportation, and the channel models in MC as well as their statistical properties;
- corresponding to the various channel models, to explore the transceiver design and optimization techniques, which include the optional signaling techniques, optimum and sub-optimum detection techniques, low-complexity coding techniques for reliability enhancement of MC systems, etc.

- to explore the theoretical performance limits of some MC systems, and analyze the implementation challenges of MC schemes in practice.
- to survey the mathematical tools for studying the performance of various MC systems;
- to investigate some advanced issues, with the emphasis on the MIMO-MC, multiple-access MC, and the error-control coding in MC;
- to identify some important challenges and opportunities for future research in MC and the development of MC systems.

Intended Audience: People from industries, researchers from research institutions/universities, PhD students, etc., who are interested in this emerging and future-proofing field.

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Biography: Lie-Liang Yang is the professor of wireless communications in the School of Electronics and Computer Science at the University of Southampton. He received his BEng degree from Shanghai TieDao University, Shanghai, China in 1988, and his MEng and PhD degrees from Northern (Beijing) Jiaotong University, Beijing, China in 1991 and 1997, respectively. From June 1997 to December 1997 he was a visiting scientist to the Institute of Radio Engineering and Electronics, Academy of Sciences of the Czech Republic. Since December 1997, he has been with the University of Southampton, UK. He has research interest in a range of areas in wireless communications, wireless networks and signal processing for wireless communications, as well as molecular and nano communications. He has authored/co-authored three books and several book chapters, and published over 360 research papers, which include 150+ journal papers and 210+ conference papers, mainly in IEEE/IET journals and conference proceedings. He is a Fellow of the IEEE in the USA, and a Fellow of the IET (previously IEE) in the UK. He acted as TPC/symposium/area/track/workshop chairs for various conferences and was involved in the teams of Technical Programme Committees (TPC) of many conferences. He served as an associate editor to the *IEEE Transactions on Vehicular Technology*, *Journal of Communications and Networks (JCN)*, etc., and he is currently a subject editor to the *Electronics Letters* of the IET, and an associate editor to the *IEEE Access* and the *Security and Communication Networks (SCN) Journal*. He was one of the guest editors for the special issues in: *IEEE Journal on Selected Areas in Communications* (2013), *IEEE Wireless Communication Magazine* (2013), *IEEE Communication Magazine* (2014), *IEEE Systems Journal* (2015), *EURASIP Journal on Wireless Communications and Networking* (2011).

Outline of Tutorial Contents and Schedules: The tutorial contents as well as their organization are as follows:

- Review of molecular communications (MC) by comparing it with the conventional electromagnetic based communications; (15 minutes)
- MC channel modeling, including the possible media for molecule transportation, channel models in MC, and channel statistical properties; (20 minutes)
- Transceiver design and optimization techniques, including optional signaling techniques, optimum and sub-optimum detection techniques, low-complexity coding techniques for reliability enhancement of molecular communications, etc.; (40 minutes)
- Theoretical performance limits of some MC systems, and practical challenges of MC implementation; (30 minutes)
- Survey of mathematical tools for studying the performance of MC systems; (30 minutes)
- Multiple-input multiple-output (MIMO) MC; (25 minutes)
- Multiple-access MC; (25 minutes)
- Error-control coding in MC; (25 minutes)
- Mobile MC as well as the challenges and benefits resulted from mobility; (20 minutes)
- Challenges and opportunities for research and development of MC, and future research issues. (10 minutes)

Past Experience on The Topic of The Tutorial: The speaker has carried out research in molecular communications for about four years, and has published several journal/conference papers, and several more are in the review process. He provided a tutorial on MC at the IEEE/CIC ICCC'2017 conference held in Qingdao, China. Furthermore, he provided four tutorial lectures on MC at four universities in China in 2017. These tutorial lectures have inspired researchers (in particular, young researchers) to carry out research in molecular communications.

Tutorial Experience: Chinacom'2012, IEEE ICCVE'2012, IEEE/CIC ICCC'2015 and IEEE/CIC ICCC'2017.

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

No similar tutorial has been offered in recent ICC & Globecom.

Wireless Communications with Unmanned Aerial Vehicles

EVGENII VINOGRADOV, SOFIE POLLIN
KU Leuven, Department of Electrical Engineering - ESAT, Leuven Belgium

***Abstract*— The growing use of Unmanned Aerial Vehicles (UAVs) for various applications requires ubiquitous and reliable connectivity for safe control and data exchange between these devices and ground terminals. Depending on the application, UAV-mounted wireless equipment can either be an aerial user equipment (AUE) that co-exists with the terrestrial users, or it can be a part of wireless infrastructure providing a range of services to the ground users. For instance, AUE can be used for real-time search and rescue and Aerial Base Station (ABS) can enhance coverage, capacity, and energy efficiency of wireless networks. We will start with discussing the open challenges of communication with UAVs. To give answers to the posed questions, we will focus on the UAV communication basics, providing the channel modeling background and giving guidelines on how various channel models should be used. Next, theoretical, simulation- and measurement-based approaches to address the key challenges for AUE usage will be presented. Moreover, we will provide a comprehensive overview on how UAV-mounted equipment (e.g. ABS) can be used as a part of the communication network. Based on the theoretical analysis, we will show how various network parameters (for example coverage area of ABSs, power efficiency, or user localization error) can be optimized. Finally, we will discuss how to ensure the safe use of UAVs via various RF-based techniques for detecting the presence of UAVs in the airspace (including Machine Learning and Passive Coherent Location techniques).**

I. TUTORIAL FOCUS

Motivation: One of the ICC goals is to increase the interaction between industry, academia, and government sectors. We believe that UAVs (Unmanned Aerial Vehicles) is the domain where their interests significantly overlap. **We have given a tutorial related to UAV communication to an industry audience, and also authored invited book chapters and tutorials on UAV communication targeted towards an academic audience.** Attendees having an industrial background will be interested in promising use-cases offered by UAVs and our overview on how currently used technologies (designed and optimized for serving ground users) perform while communicating with drones. Wireless communications with UAVs poses many motivating research challenges in front of the academic community: from channel modeling to novel cellular architectures (using aerial base stations) and counter-drone measures (including radar and localization techniques) helping to shape the appropriate regulation rules. The illegal UAV flights detection is of a great interest for the government bodies shaping the UAV-related regulation documents.

Objectives: The main goal of this half-day tutorial is to give a complete overview of the main scenarios (aerial user equipment (AUE) and aerial base station (ABS)), channel and performance models, compare them, and discuss open research points. This tutorial for wireless communication with UAVs will give a comprehensive overview of the research done until now and depicts a comprehensive picture to foster new ideas and solutions while avoiding duplication of past works.

The participants will learn

- the main air-to-ground and air-to-air channel modeling approaches and how to choose the appropriate model according to the targeted goal,
- the theoretical, simulation and measurement based approaches to estimate the performance of UAV-enabled communication networks for multiple frequency bands,
- several efficient ways to address the public concerns on the UAVs safety (early UAV detection in no-fly zones based on passive RF techniques)

The main goal is to gather and systematize the vast, but fragmented state-of-the-art research contributions regarding most important aspects of UAV-enabled wireless communications networks.

Intended audience: Our purpose is to provide an introduction of the UAV wireless communications to the attendee not working in this topic but interested in getting an general introduction to the subject. This tutorial also targets researchers wishing to get a comprehensive background before working on the subject. Practical guidelines on how to optimize existing and future communication networks will be interesting for attendees from the industry. The government sector will be interested by the progress overview of the research in the field of UAV-related safety.

II. OUTLINE AND TENTATIVE SCHEDULE

Total tutorial duration is 3h30.

- Introduction: i) Applications of UAVs ii) wireless communication links for UAV communication iii) main UAV-enabled scenarios and challenges [20 min]
- Channel modelling fundamentals: i) Channel components, ii) Popular models for large and small-scale fading mechanisms iii) future works [1h]
- Performance of LTE and Wi-Fi for aerial users (AUE) estimated via: i) theory, ii) simulations and iii) measurements [50 min]
- Aerial Base stations (ABS) for future cellular networks: i) Motivation and challenges, ii) Network design (power, optimal positioning, coverage, capacity, achievable rates), iii) Localization service iv)Future works [50 min]

- UAV detection: i) Passive RF sensing, ii) Radar, iii) Future works [30 min]

III. Description of the technical issues

Channel modeling: Next generation UAV-enabled networks design (i.e., algorithms development) is impossible without the knowledge of the wireless channel. Consequently, radio channel characterization and modeling in such innovative architectures becomes crucial to evaluate the achievable network performance.

The vast majority of the channel modeling efforts is dedicated to terrestrial radio channels. Unfortunately, wireless communication with UAVs cannot rely on these models. The nature of A2G channels implies a higher probability of LOS propagation. This results in a higher link reliability and lower transmission power. Even for NLOS links, power variations are less severe than in the terrestrial communication networks due to the fact that only the ground-based side of the link is surrounded by the objects that affect the propagation. On the other hand, the UAV mobility causes high rates of change. Modeling of these changes is challenging due to arbitrary mobility patterns and complex operational environment. Doppler shift caused by the UAV motions has to be taken into account as well.

The main challenge in Air-to-Ground (A2G) channel modeling is the complexity of 3D environment and a large set of 3D variant parameters that must be considered: Path Loss (PL), Large-Scale fading (LS-fading, also known as shadowing), and small-scale fading (SS-fading) behavior depends on the environment type (urban, rural, etc.), transmitter (Tx) and receiver (Rx) heights, incident and/or elevation angles, the carrier frequency, Line-of-Sight (LOS) probability, etc.

In this tutorial, we will first provide a *necessary background on channel modeling*. Second, we will give *a comprehensive overview of existing channel models* that can be directly used for practical UAV applications as well as for research. We will draw explicit separation between different propagation slices (or echelons): the ground level (below 10 m and 22.5 m for suburban and urban environments, respectively), obstructed A2G channel (10 - 40 m and 22.5 - 100 m), and high-altitude A2G channel (40 - 300 m and 100 - 300 m). Then we will provide the model parameters for each slice. Finally, we will show *examples of the practical implementation of these models* for simulation based performance estimation of several drone-enabled scenarios.

Aerial user equipment: AUE performance estimation is needed since the popular wireless technologies were not designed to operate in A2G links, so their performance is unpredictable in such peculiar environments. Moreover, the current cellular infrastructure is optimized for ground users. As a result, the performance for aerial users connected to cellular networks has to be studied. It was shown in many research and industrial works that the main issue limiting AUE performance is interference. Consequently, the main challenge is to estimate the performance taking into account a complex propagation channel (see above) and the terrestrial network topology (BS density and location, Tx power, 3D antenna patterns). Coexistence of AUE with ground UE must be investigated as well.

In this tutorial we will give an overview of the theoretical state-of-the-art, mainly concentrating on the the analytical works using the channel models, or, more precisely, we develop our performance analysis framework based on the channel model separating LOS and NLOS propagation cases. First, we will present the *exact expressions for coverage probability, channel capacity, and spectral efficiency*. Several case-studies will be presented to *demonstrate the effect of flight altitude, antenna patterns, environmental impact, and network density.*

Second, we present the *performance estimation* (altitude-dependent coverage) of an LTE and future mmWave cellular networks serving an UAV *based on simulator of a realistic 3-dimensional urban propagation channel* (consisting of a measured 3D map of a Belgian city combined with semi-deterministic channel models).

Finally, we will complete the study by giving an *overview of relevant measurement campaigns* detailing the currently achieved UAV communication for existing communication technologies such as LTE and Wi-Fi.

Summarizing, we will show that all mentioned approaches confirm that by considering the impacts of the altitude, environments, antenna configuration, and network density, the UAV position potentially can be optimized in order to achieve the highest performance.

Aerial base station: UAV-mounted base stations can become an important component of the 5G environment due to the ability of providing on-demand connectivity to the users at little additional cost. Moreover, an ABS can be seen as a part of a robust, fast, and capable emergency communication system enabling effective communications during public safety operations. It is vital to understand whether using ABSs will be beneficial.

We will start with an overview of the state-of-the-art, mainly concentrating on the theoretical works on optimal ABS deployment based on using the channel models presented earlier. The main technical challenge that we will discuss in the tutorial is the *optimal 3D positioning, ABS deployment density, and path-planning* (when the UAV carrying the communication equipment is mobile) maximizing the advantages of ABS over the conventional terrestrial BSs. The complete analysis taking into account the complex propagation channel, antenna patterns, practical limitations (e.g. power consumption, weight or maximum flight altitude) or required network performance metrics will be given.

First, based on the theoretical analysis, we will show *how to optimize the coverage area of ABSs.* The size of this area is a function of several parameters, e.g. UAV height, transmit power and antenna tilt. The presented framework allows to estimate the effect of these parameters on the ABS system and optimal deployment configuration. Moreover, the influence of multiple ABSs will be investigated. Just like with terrestrial BSs, multiple ABSs interfere with each other. Therefore, the density of these ABSs must be optimized to maximize the coverage of the network, while minimizing the interference.

Second, we will indicate how to chose *the ABS deployment parameters to optimize the accuracy of the localization service* that the ABS will provide. For example, we analyze how the height of the UAV influences the positioning error of the localization system.

Detection of non-cooperative UAVs: Safety and security problems can be caused by malicious UAVs at critical locations such as airports, power plants, military zones, densely populated areas and private residences. Another issue is violation of privacy when people operate mini-UAVs equipped with cameras. Next important concern is the abuse of UAVs for protests, criminal acts or even terrorist attacks. A great concern regarding the abuse of UAVs resulted in over-protective regulations that can be relaxed if the UAV-detection techniques will demonstrate their efficiency.

We believe that the Latin principle *similia similibus curentur* (i.e. *let similar things be taken care of by similar things*) should be applied to the UAV detection: intruder UAVs detection and localization systems mounted on another UAV have demonstrated several advantages over the terrestrial competitors due to their scalability and favorable propagation conditions.

In the tutorial, we will present several techniques for drone detection and localization. First, we will present a *Machine Learning (ML)-based technique for the detection of a UAV communicating with its operator*: continuous passive radio spectrum monitoring should be enabled to allow effective detection of UAVs. Accurate technology classification can be achieved by using state-of-the-art (SoA) machine learning classifier models (convolutional neural networks (CNN) and long short term memory (LSTM) units). The deep learning models take IQ samples as input giving out the probability of the data belonging to a particular technology class. Next, we will show that RSS-based techniques are successfully used to estimate the distance between the surveillance and intruder UAVs.

Second, we will demonstrate how a *UAV-mounted passive radar can be used to detect an intruder UAV,* which is operating in a ”silent mode” (i.e. autonomously). We will point out the appropriate signal processing techniques (recovery of the reference signal, suppression of the interfering direct signal, cross-ambiguity function calculation and analysis). Detection of different UAV types will be estimated and analyzed.

IV. Biography of the speakers

Biography

Evgenii Vinogradov received the Dipl. Engineer degree in Radio Engineering and Telecommunications from Saint-Petersburg Electrotechnical University (Russia), in 2009. After several years of working in the field of mobile communications, he joined UCL (Belgium) in 2013, where he obtained his Ph.D. degree in 2017. His doctoral research interests focused on multidimensional radio propagation channel modeling. In 2017, Evgenii joined the electrical engineering department at KU Leuven (Belgium) where he is working on wireless communications with UAVs and UAV detection.

Sofie Pollin obtained her PhD at KU Leuven in 2006. She continued her research on wireless communication at UC Berkeley. In November 2008 she returned to imec to become a principal scientist in the green radio team. Since 2012, she is professor at the electrical engineering department at KU Leuven. Her research centers around Networked Systems that require networks that are ever more dense, heterogeneous, battery powered and spectrum constrained. She has been working on drone communication since 2012, and given various invited talks on the topic, and authored invited book chapters, journals and tutorials related to UAV communication. She is also co-founder of the ACM workshop DroNET, focusing on drone communication and networks. Prof. Pollin has experience with tutorials at academic conferences such as ICC or Crowncom, or mixed industry/academic fora such as Embedded Silicon West or the SDR forum.

Tutorials and invited talks:

1) E. Vinogradov et al, ”Tutorial on Wireless Communications with Unmanned Aerial Vehicles: from Wi-Fi and LTE to 5G”, *OmniDrone Industry Advisory Committee meeting, Leuven, 2018. approx. 20 attendees.*
2) E. Vinogradov ”Autonomous drones will be there before autonomous cars”, *ComTech for Drones - IEEE - FITCE, Leuven 2018*
3) E.Vinogradov ”Intelligent wireless communication for future autonomous aerial vehicles”, *LICT workshop on Autonomous Systems, Leuven, 2018*
4) E. Vinogradov ”Drones in the air: broadcasting dreams and realities”, *ComTech for Drones - IEEE - FITCE, Ghent, 2018*
5) E. Vinogradov et al, ”Drones and Research in KU Leuven”, *Drones and research at the university: state of play in Belgium, Louvain-la-Neuve, 2017*
6) S. Pollin, ”Aerial capacity and interference: 4G facts”, *Drone Convention 2016.*
7) S. Pollin, ”Energy-efficient Internet of Things and Internet of Mobile Things”, *NextGWIN conference, 2016, Dublin*
8) S. Pollin., ”Aerial capacity and interference: 5G to the rescue”, *workshop on UAVs for civilian use (October 29/30 2015), Vienna*
9) S. Pollin., ”Aerial capacity and interference: 5G to the rescue”, *LICT workshop on ICT for UAVs, Nov 27 2015.*
10) S. Pollin , ”5G and context awareness for MAV communication”, *FLYNET (Micro and Nano Aerial Vehicle Networks for Civilian Use), Zurich, November 3-5, 2014.*

Related papers:

1) A. Colpaert, E. Vinogradov, and S. Pollin, Aerial

coverage analysis of cellular systems at LTE and mmWave frequencies using 3D city models *submitted as an Invited Paper for IEEE Sensors, Special Issue "UAV Networks, Systems and Applications"*

2) M.M. Azari, F. Rosas, and S. Pollin. Cellular connectivity for UAVs: Network modeling, performance analysis and design guidelines. *submitted to IEEE Transactions on Wireless Communications.*
3) E. Vinogradov, H. Sallouha, S. De Bast, M. M. Azari, and S. Pollin Tutorial on UAVs: A Blue Sky View on Wireless Communication *submitted as an Invited Paper for Journal of Mobile Multimedia*
4) E. Vinogradov, D. Kovalev, and S. Pollin. Simulation and detection performance evaluation of a UAV-mounted passive radar. *In 2018 IEEE PIMRC, 2018.*
5) H. Sallouha, M. M. Azari, A. Chiumento, and S. Pollin. Aerial anchors positioning for reliable RSS-based outdoor localization in urban environments. *IEEE Wireless Communications Letters, 2018.*
6) M.M. Azari, F. Rosas, and S. Pollin. Reshaping cellular networks for the sky: Major factors and feasibility. *In IEEE ICC, 2018.*
7) M. M. Azari, F. Rosas, K.C. Chen, and S. Pollin. Ultra Reliable UAV Communication Using Altitude and Cooperation Diversity. *IEEE Transactions on Communications, 2018.*
8) M. M. Azari, H. Sallouha, A. Chiumento, S. Rajendran, E. Vinogradov, and S. Pollin. Key technologies and system trade-offs for detection and localization of amateur drones. *IEEE Communications Magazine, 2018.*
9) B. Van den Bergh and S. Pollin, Air-to-Ground and Air-to-Air Data Link Communication, *invited book chapter for UAV Networks and Communications. Cambridge University Press, 2017.*
10) M. M. Azari, F. Rosas, A. Chiumento, and S. Pollin. Coexistence of terrestrial and aerial users in cellular networks. *In 2017 IEEE Globecom Workshops, 2017.*
11) M.M. Azari, Y. Murillo, O. Amin, F. Rosas, M.-S. Alouini, and S. Pollin. Coverage maximization for a poisson field of drone cells. *In IEEE PIMRC, 2017.*
12) H. Sallouha, A. Chiumento, and S. Pollin. Localization in Long-range Ultra Narrow Band IoT Networks using RSSI. *In IEEE ICC, 2017.*
13) B. Van den Bergh, A. Chiumento, and S. Pollin. LTE in the sky: trading of propagation benefits with interference costs for aerial nodes. *IEEE Communications Magazine, May 2016.*
14) M. M. Azari, F. Rosas, K. Chen, and S. Pollin. Optimal UAV Positioning for Terrestrial-Aerial Communication in Presence of Fading. *In 2016 IEEE GLOBECOM, 2016.*

5G for Vehicle-to-Everything (V2X) Communication

Abstract, Objectives, and Motivation

Vehicles are becoming more intelligent and automated. To achieve higher automation levels, vehicles are being equipped with more and more sensors. High data rate connectivity seems critical to allow vehicles and road infrastructure exchanging all these sensor data to enlarge their sensing range and make better safety related decisions. Connectivity also enables other applications such as infotainment or high levels of traffic coordination. Current solutions for vehicular communications though do not support the gigabit-per-second data rates. This presentation makes the case for 5G as the solution for the next generation of V2X. First, the motivation and challenges associated with vehicle-to-vehicle and vehicle-to-infrastructure applications are highlighted. Second, the key uses cases for V2X in 5G are summarized including raw sensor data sharing, platooning, collision avoidance, see-through, and mapping are reviewed. Finally, specific technical challenges in realizing 5G V2X are identified, with an emphasis on solutions that make use of millimeter wave spectrum.

Name, affiliation, and short biography of each tutorial speaker

Robert W. Heath Jr.
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Nuria González Prelcic
The University of Texas at Austin / University of Vigo, Spain
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Robert W. Heath Jr. received the Ph.D. in EE from Stanford University. He is a Cullen Trust for Higher Education Endowed Professor in the Department of Electrical and Computer Engineering at The University of Texas at Austin and a Member of the Wireless Networking and Communications Group. He is also the President and CEO of MIMO Wireless Inc and Chief Innovation Officer at Kuma Signals LLC. Prof. Heath is a recipient of the 2012 Signal Processing Magazine Best Paper award, a 2013 Signal Processing Society best paper award, the 2014 EURASIP Journal on Advances in Signal Processing best paper award, and the 2014 Journal of Communications and Networks best paper award, the 2016 IEEE Communications Society Fred W. Ellersick Prize, the 2016 IEEE Communications Society and Information Theory Society Joint Paper Award, 2017 IEEE Marconi Prize Paper Award, and the 2017 EURASIP Technical Achievement Award. He authored "Introduction to Wireless Digital Communication" (Prentice Hall in 2017) and "Digital Wireless Communication: Physical Layer Exploration Lab Using the NI USRP" (National Technology and Science Press in 2012). He co-authored "Millimeter Wave Wireless Communications" (Prentice Hall in 2014). He is a licensed Amateur Radio Operator, a registered Professional Engineer in Texas, a Fellow of the National Academy of Inventors, and a Fellow of the IEEE.

Nuria González Prelcic is a Senior Research Scientist at The University of Texas at Austin and (on leave) an Associate Professor in the Signal Theory and Communications Department, University of Vigo, Spain. She received her Ph.D. in Electrical Engineering in 1998. She has held visiting positions with the University of New Mexico (2012), and The University of Texas at Austin (2014 -2017). Her main research interests include signal processing theory and signal processing for wireless communications: filter banks, compressive sampling and estimation, multicarrier modulation, channel estimation and MIMO processing for millimeter wave communications, including V2X at millimeter wave. She has published around 80 papers in the topic of signal processing for communications, including a tutorial on millimeter wave communication published in the IEEE Journal of Selected Topics in Signal Processing. She has also served as guest editor for the special issue of this journal on signal processing for mmWave wireless communications. She is and Editor for IEEE Transactions on Wireless Communications. She has co-organized several special sessions on mmWave communications at SPAWC 2015, Asilomar 2016 and CAMSAP 2017. She has been the founder director of the Atlantic Research Center for Information and Communication Technologies (AtlantTIC) at the University of Vigo.

Description of the technical content of the tutorial

Fifth generation (5G) is the next evolution of cellular systems. The first versions of 5G have now been released. Most of the initial enthusiasm around 5G has been applications to fixed wireless access. Other applications are envisioned for pedestrian use in stadiums with low mobility. The next release of 5G will feature more support for vehicular communication, both vehicle-to-infrastructure and vehicle-to-vehicle that we collectively call V2X.

We will begin this tutorial with an introduction to V2X communication. In particular, we will review two main prior solutions to V2X communication. The first one, dedicated short range communication (DSRC), uses a WiFi-like waveform in dedicated automotive spectrum. The second one, LTE C-V2X, is a recent release of LTE (pre-5G) that includes additional support for low latency safety messaging. We will also review the general objectives of V2X communication as it relates to the different levels of vehicle automation.

In the second part of the tutorial, we will focus on use cases for 5G V2X. Some of these use cases can also work with the older standards while others make use of the higher data rates and/or lower latency of 5G. We will talk extensively about sensor data sharing as a major application of 5G. This application provides enhanced situational awareness by allowing vehicles to exchange raw sensor data with each other and with the infrastructure. The fusion of the data can be done on each vehicle or can be done at the edge and forwarded to the vehicles. We will also describe other important applications of connectivity including collision warnings, platooning, and of course high-speed mobile Internet access.

In the final part of the tutorial, which will be the longest part, we will focus on specific design challenges related to 5G V2X communication. Most of this section will focus specifically on challenges related to millimeter wave for V2X as the large spectral channels at mmWave frequencies provide a means of achieving much higher data rates in vehicular communication systems. We will start by explaining how the current beam training paradigm used in 5G is not well suited to support mobility. Then we will review the state-of-the-art in vehicular channel modeling both at lower frequencies and millimeter wave. In the duration of the tutorial, we will talk about specific challenges at the physical and MAC layers like adaptive beam training, adaptive compressive channel information, and exploiting sensor information for beam and channel tracking, handoff, and blockage mitigations. Mathematical tools such as compressive sensing and machine learning will be highlighted as needed. The main objective is to summarize key findings in each area, with special attention paid to identifying important topics of future research. While we will talk about several of our own results, we will also summarize the literature and activities in the field more broadly to give coverage on many aspects of 5G.

Potential outline and schedule (assuming 3.5 hours)

Introduction (45 minutes)

- V2X communication
- DSRC and its limitations
- LTE V2X and its limitations
- Fundamental features of 5G

Use cases powered by 5G (45 minutes)

- High data rate sensor data sharing
- Platooning
- Situational awareness: See-through and birds-eye-view
- Remote driving and automated intersections
- Wireless Internet access for passengers
- High resolution mapping

Technical challenges in going to V2X (150 minutes)

- Limitations of the initial release of 5G
- Millimeter wave communication for 5G V2X
- Vehicular channel models
- PHY design for V2X, including beam training and tracking
- MAC design for V2X including the V2V side link

Past experience on the topic of this tutorial

The tutorial presenters have significant experience on 5G V2X. Together, they run a center at UT Austin called SAVES (situation aware vehicular engineering systems) see e.g. http://www.utsaves.org. This center is supported by Honda, Toyota, Qualcomm, AT&T, Huawei, Fujitsu, and Samsung. As a result, they have substantial experience in working with both automotive equipment vendors (Honda and Toyota) as well as with cellular equipment providers (Qualcomm, Huawei, Fujitsu, and Samsung), as well as with a carrier that is interested in V2X. They will bring their insights to provide a tutorial that is meaningful for students, faculty, and members of industry. Some relevant evidence in terms of past publications include:

J. Choi, Vutha Va, N. González Prelcic, R. Daniels, C. R. Bhat, and R. W. Heath, Jr., ``Millimeter Wave Vehicular Communication to Support Massive Automotive Sensing," IEEE Communications Magazine, vol. 54, no. 12, pp. 160-167, December 2016.

J. P. González-Coma, J. Rodríguez-Fernández, N. González-Prelcic, L. Castedo and R. W. Heath, "Channel Estimation and Hybrid Precoding for Frequency Selective Multiuser mmWave MIMO Systems," in IEEE Journal of Selected Topics in Signal Processing, vol. 12, no. 2, pp. 353-367, May 2018.

Takayuki Shimizu, Vutha Va, Gaurav Bansal, and R. W. Heath, Jr., "Millimeter Wave V2X Communications: Use Cases and Design Considerations of Beam Management," in the Proc. of the 2018 Asia-Pacific Microwave Conference, Kyoto, Japan, Nov. 6-9, 2018.

P. Kumari, J. Choi, N. González Prelcic and R. W. Heath, Jr., `` IEEE 802.11ad-based Radar: An Approach to Joint Vehicular Communication-Radar System," IEEE Trans. on Veh. Tech vol. 67, no. 4, pp. 3012-3027, April 2018.

R. W. Heath, Jr., N. González Prelcic, S. Rangan, Wonil Roh, and A. Sayeed, `` An Overview of Signal Processing Techniques for Millimeter Wave MIMO Systems ," IEEE Journal on Sel. Topics in Sig. Proc. (special issue on Millimeter Wave MIMO), vol. 10, no. 3, pp. 436-453, April 2016.

Vutha Va,Takayuki Shimizu, Gaurav Bansal, and R. W. Heath, Jr., "Millimeter Wave Vehicular Communications: A Survey" Foundations and Trends in Networking: Vol. 10: No. 1, pp 1-113, 2015.

Recent tutorial experience by either speaker

For ICC 2019, we are crafting a new tutorial, which draws on our past experience with V2X for millimeter wave, as well as signal processing for vehicular systems. A list of our recent tutorials (given by Heath, Gonzalez-Prelcic, or both) are listed below. The most relevant one is "Millimeter Wave communication for connected vehicles" presented at VTC 2016. That tutorial, given with a colleague from Toyota ITC, focused on the challenges of millimeter wave communication for V2X. As 5G was still developing, it did not have 5G as a theme. We may reuse some content (probably 10 slides) of background material especially relating to the motivation for millimeter waves and background on dedicated short range communications (DSRC). We may also reuse some content (around 10 slides) related to channel models from our other tutorials. Most of the content will be completely new (90%).

Signal Processing for Millimeter Wave Wireless Communications, June 8, 2017, IEEE BlackSeaCom

Fundamentals of mmWave Communication I, May 30, 2017, Joint IEEE SPS and EURASIP Summer School on Signal Processing for 5G Wireless Access

Fundamentals of mmWave Communication II, May 30, 2017, Joint IEEE SPS and EURASIP Summer School on Signal Processing for 5G Wireless Access

Signal Processing for Millimeter Wave Wireless Communications, March 19, 2017, IEEE Wireless Communications and Networking Conference

Sparse signal processing in MIMO systems with large arrays, March 5, 2017, IEEE International Conference on Acoustics, Speech, and Signal Processing,

Millimeter Wave MIMO Communications, February 6, 2017, 11th International ITG Conference on Systems, Communications and Coding

Signal Processing for Millimeter Wave Wireless Communications, December 8, 2016, IEEE GLOBECOM

Millimeter Wave communication for connected vehicles, September 18, 2016, IEEE Vehicular Technology Conference

Perspectives on 5G: Beamforming, MIMO, and more, July 14, 2016, IEEE Spectrum Tech Insiders Webinar Series

Millimeter Wave Wireless Communications, March 20, 2016, International Conference on Acoustics, Speech, and Signal Processing

Relation to other related tutorials that have been given

We have not attended any related tutorials. We are basing our review on tutorials that have been advertised at recent conferences. The only related tutorial being presented at GLOBECOM 2018 is

> TUT23: Connected Vehicles in the 5G Era
> Presenters: Claudio E. Casetti (Politecnico di Torino, Italy)
>
> This tutorial will cover both the state-of-the-art of vehicular communication and networking, from the point of view of protocols and regulations, as well as the most recent proposals in the context of C-V2X along with the requirements for the novel use cases they are ushering. Overall, the tutorial will provide a comprehensive view of how inter-vehicular communication will fit into the broader 5G landscape.

As you can see from the description, the emphasis is on protocols and regulations. Our tutorial focuses more on the physical layer especially the signal processing challenges. We also have a substantial emphasis on millimeter wave communication.

We did not find any related tutorials at ICC 2018, only a few about 5G or millimeter wave (without a vehicular emphasis). At GLOBECOM 2017 there was one related tutorial

> Tut04: Vehicular Communications and Networking: Where Benz Meets Marconi
> Presenters: Liuqing Yang (Colorado State University, USA), Xiang Cheng (Peking University, P.R. China)
> Recently, we are witnessing the overwhelming research and development in automobile technology, energy research as well as artificial intelligence towards an era of transportation involving smart vehicles, automatic driving, and electric vehicles. All these urgently call for advanced vehicular communications capable of supporting massive data exchanges at highly stringent latency requirements. 130 years since Karl Benz invented motor cars, and 120 years since Marconi's first demonstration of wireless, time eventually seems to come for the two great human inventions to integrate to revolutionize today's transportation. As such, it is not surprising that this area is gaining significant attention from both industry and academia for its essential role in, and great potential of bringing to reality, the intelligent transportation revolution envisioned in the coming decade. Vehicular environments are inherently challenging with doubly selective physical channels, constrained radio spectrum bandwidth resources, and constantly changing network connectivity and topology. Hence, research in this area is essential for bringing to reality the many demanding vehicular applications that consist of the gateway towards the ultimate connected mobility. In this tutorial, fundamentals of vehicular channels will be comprehensively analyzed, based on which various practical communications and networking techniques will be introduced. Challenges and opportunities in this field will also be discussed to stimulate future research and development from various industry and academia sectors.

From the abstract, we understand that this tutorial focused on vehicular propagation channels, and also included some discussion about communication techniques and protocols. We do not see any mention of 5G nor millimeter wave communication. While we will discuss the vehicular channel, it will not be the main focus of our tutorial.

Integrated Aerial/Terrestrial 6G Networks for 2030s

1. Objectives and Motivation

The 5G standards are currently being developed with a scheduled completion date of late-2019; the 5G wireless networks are expected to be deployed globally throughout 2020s. As such, it is time to reinitiate a brainstorming endeavour followed by the technical groundwork towards the subsequent generation (6G) wireless networks of 2030s.

2. Abstract

One reasonable starting point in this new 6G discussion is to reflect on the possible shortcomings of the 5G networks to-be-deployed. 5G promises to provide connectivity for a broad range of use-cases in a variety of vertical industries; after all, this rich set of scenarios is indeed what distinguishes 5G from the previous four generations. Many of the envisioned 5G use-cases require challenging target values for one or more of the key QoS elements, such as high rate, high reliability, low latency, and high energy efficiency; we refer to the presence of such demanding links as the super-connectivity.

However, the very fundamental principles of digital and wireless communications reveal that the provision of ubiquitous super-connectivity in the global scale – i.e., beyond indoors, dense downtown or campus-type areas – is infeasible with the legacy terrestrial network architecture as this would require prohibitively expensive gross over-provisioning. The problem will only exacerbate with even more demanding 6G use-cases such as UAVs requiring connectivity (ex: delivery drones), thus the 3D super-connectivity.

In this talk, we will present a 5-layer vertical architecture composed of fully integrated terrestrial and non-terrestrial layers for 6G networks of 2030s:

- Terrestrial HetNets with macro-, micro-, and pico-BSs
- Flying-BSs (aerial-/UAV-/drone-BSs); altitude: up to several 100 m
- High Altitude Platforms (HAPs) (floating-BSs); altitude: 20 km
- Very Low Earth Orbit (VLEO) satellites; altitude: 200-1,000 km
- Geostationary Orbit (GEO) satellites; altitude: 35,786 km

In the absence of a clear technology roadmap for the 2030s, the talk has, to a certain extent, an exploratory view point to stimulate further thinking and creativity. We are certainly at the dawn of a new era in wireless research and innovation; the next twenty years will be very interesting.

3. Timeliness and Intended Audience

This is the first tutorial on 6G wireless. The presentation was originally prepared as a one-hour talk in Spring 2018. Since then it has been offered a number of times; in its each offering, it has been received very well. The presentation is scheduled to be made in various forms in the coming months as well:

- Invited Talk
  Huawei Wireless Research Advisory Board Inaugural Meeting
  Ottawa, 01 May 2018

- IEEE Communications Society Distinguished Lecture, ACT Chapter
  Australian National University
  Canberra, ACT, Australia, 09 July 2018

- Invited Seminar (videoconference)
  Intel, USA
  02 October 2018

- Keynote Speech
  The 21st ACM International Conference on Modeling, Analysis and Simulation of Wireless and Mobile Systems
  Montreal, 30 October 2018

- Keynote Speech
  The 10th International Congress on Ultra Modern Telecommunications and Control Systems
  5G Summit R&D Russia
  Moscow, Russia, 05 November 2018

- IEEE Kingston Chapter Distinguished Lecture
  Queen's University, Kingston, Canada

- IEEE Communications Society Jordan Chapter Distinguished Lecture Tour
  Jordan Tour
  Amman, 20 November 2018; Irbid, 21 November 2018; Ma'an, 22 November 2018

- Keynote Speech
  IEEE GLOBECOM 2018 Wireless Networking and Control for Unmanned Autonomous Vehicles Workshop
  Abu Dhabi, UAE, 09 December 2018

- Tutorial
  IEEE Consumer Communications & Networking Conference
  Las Vegas, 14 January 2019

No specialized knowledge is expected from the audience. Researchers, engineers, and policy makers from government, industry, and academia (including graduate students and 4th year undergraduate students) will benefit from this visionary tutorial.

5) Prior History of Tutorial Presentation

Dr. Yanikomeroglu

- has delivered a total of 79 invited seminars + tutorials + keynotes + panels since 2012;

- has given 29 tutorials in leading conferences including the major IEEE conferences such as ICCs, Globecoms, Wireless Communications and Networking Conferences (WCNCs), and Vehicular Technology Conferences (VTCs); for instance,

  - Globecom 2017 – Singapore, 04 December 2017
  - ICC 2016 – Kuala Lumpur, Malaysia, 27 May 2016
  - WCNC 2016 – Doha, Qatar, 03 April 2016
  - Globecom 2015 – San Diego, CA, USA, 10 December 2015

- VTC 2015-Fall – Boston, MA, USA, 06 September 2015
- ICC 2015 – London, UK, 12 June 2015
- Globecom 2014 – Austin, Texas, USA, 12 December 2014
- Globecom 2013 – Atlanta, Georgia, USA, 13 December 2013
- ICC 2013 – Budapest, Hungary, 13 June 2013

- received several teaching awards (in addition to research awards), including

  - IEEE Ottawa Section Outstanding Educator Award in 2014
  - Carleton University Faculty Graduate Mentoring Award in 2010
  - Carleton University Graduate Students Association Excellence Award in Graduate Teaching in 2010.

Dr. Yanikomeroglu's tutorials have always attracted strong attendance. Attendance numbers can be obtained from IEEE Communications Society and IEEE Vehicular Technology Society

6) Detailed Outline of the Tutorial

- Brief introduction to the fundamental dynamics of cellular and wireless communications
- 3GPP operation
- Key technologies in 4G LTE and 5G
- Cellular generations: Use-cases and timelines
- 5G timeline
- Do we need 6G?
- Possible bottleneck problems in 5G networks
- Future congestion scenarios
- Ubiquitous high rate coverage
- Possible 6G timeline
- Aerial networks
- Relevant 3GPP documents:
  - TR38.913 – Study on Scenarios and Requirements for Next Generation Access Technologies
  - TS22.261 – Service Requirements for Next-Generation New Services and Markets; Stage 1
  - TR38.811 – Study on NR to Support Non-Terrestrial Networks (NTN)
  - TR36.777 – Enhanced LTE Support for Aerial Vehicles
  - TR22.822 – Study on Using Satellite Access in 5G; Stage 1
  - TR22.829 – Enhancements for UAVs

- Aerial (flying and/or floating) base stations (BSs)
- Comparison between aerial BSs and terrestrial BSs
- High-altitude platforms (HAPs)
- Very low earth-orbit (VLEO) satellites
- Research topics
    - Interference dynamics
    - Aerial BS placement – a 3D optimization problem
    - Cost analysis
    - PHY for aerial networks
    - Free-space optical (FSO) communications in aerial networks
    - Antenna architectures
    - Vertical fronthaul/backhaul
    - Integrated terrestrial / aerial operation
    - HAPs for V2X
    - User-in-the-loop
    - Machine learning & data analytics in aerial networks
    - Energy
    - UAV-enabled backscatter communications
    - Vertical RAN
- Conclusions and key take-away messages

7) Author's Publications on the Tutorial Topic (last two years)

IEEE Journal Papers

- C.T. Cicek, T. Kutlu, H. Gultekin, B. Tavli, H. Yanikomeroglu, "Backhaul-aware placement of a UAV-BS with bandwidth allocation for user-centric operation and profit maximization", under review in *IEEE Transactions on Vehicular Technology*.
- M. Gapeyenko, V. Petrov, D. Moltchanov, S. Andreev, Y. Koucheryavy, M. Valmaka, H. Yanikomeroglu, "Mission-critical UAV applications over integrated terrestrial and non-terrestrial 5G/5G+ networks", under review in *IEEE Vehicular Technology Magazine*.
- Azizi, S. Parsaeefard, M.R. Javan, N. Mokhari, H. Yanikomeroglu, "Profit maximization in beyond-5G with heterogeneous aerial and ground base stations", under review in *IEEE Transactions on Mobile Computing*.

- S. Enayati, H. Saeedi, H. Pishro-Nik, H. Yanikomeroglu, "Moving aerial base station networks: Stochastic geometry analysis and design perspectives", under review in *IEEE Transactions on Wireless Commun*.
- S. Andreev, V. Petrov, M. Dohler, H. Yanikomeroglu, "Future of ultra-dense mmWave networks beyond 5G: Harnessing heterogeneous moving cells", under review in *IEEE Communications Magazine*.
- X. Zhou, J. Guo, S. Durrani, H. Yanikomeroglu, "Underlay drone cell for temporary events: Impact of drone height and aerial channel environments", to appear in *IEEE Internet of Things Journal*.
- I. Bor-Yaliniz, M. Salem, G. Senerath, H. Yanikomeroglu, "Is 5G ready for drones?: A look into contemporary and prospective wireless networks from a standardization perspective", to appear in *IEEE Wireless Communications Magazine*.
- I. Bor-Yaliniz, A. El-Keyi, H. Yanikomeroglu, "Spatial configuration of agile wireless networks with drone-BSs and user-in-the-loop", to appear in *IEEE Transactions on Wireless Communications*.
- X. Cao, P. Yang, M. Alzenad, X. Xi, D. Wu, H. Yanikomeroglu, "Airborne communication networks: A survey", to appear in *IEEE Journal on Selected Areas in Communications*.
- F. Lagum, I. Bor-Yaliniz, H. Yanikomeroglu, "Strategic densification with UAV-BSs for cellular networks", *IEEE Wireless Communications Letters,* June 2018.
- I. Bor-Yaliniz, S.S. Szyszkowicz, H. Yanikomeroglu, "Environment aware drone-base-station placements in modern metropolitans", *IEEE Wireless Communications Letters,* June 2018.
- M. Alzenad, A. El-Keyi, H. Yanikomeroglu, "3D placement of an unmanned aerial vehicle BS for maximum coverage of users with different QoS requirements", *IEEE Wireless Commun. Letters,* Feb. 2018.
- M. Alzenad, M.Z. Shakir, H. Yanikomeroglu, M.-S. Alouini, "FSO-based vertical backhaul/fronthaul framework for 5G+ wireless networks", *IEEE Communications Magazine,* January 2018.
- M. Alzenad, A. El-Keyi, F. Lagum, H. Yanikomeroglu, "3D placement of unmanned aerial vehicle base station (UAV-BS) for energy-efficient maximal coverage", *IEEE Wireless Commun. Letters,* Aug. 2017.
- I. Bor-Yaliniz, H. Yanikomeroglu, "The new frontier in RAN heterogeneity: Multi-tier drone-cells", *IEEE Communications Magazine,* November 2016.

IEEE Conference Papers

- A. Farajzadeh, O. Ercetin, H. Yanikomeroglu, "UAV data collection over NOMA backscatter networks: UAV altitude and trajectory optimization", under review in *IEEE ICC 2019*
- M. Khoshkholgh, K. Navaie, H. Yanikomeroglu, V.C.M. Leung, K.G. Shin, "How do non-ideal UAV antennas affect air-to-ground communications?", under review in *IEEE ICC 2019*.
- M. Khoshkholgh, K. Navaie, H. Yanikomeroglu, V.C.M. Leung, K.G. Shin, "Coverage performance in aerial-terrestrial HetNets", under review in *IEEE VTC2019-Spring*.
- M. Khoshkholgh, K. Navaie, V.C.M. Leung, H. Yanikomeroglu, "Cooperative edge caching in UAV-enabled fog-RAN", under review in *IEEE WCNC 2019*.
- C.T. Cicek, H. Gultekin, B. Tavli, H. Yanikomeroglu, "UAV Base station location optimization for next generation wireless networks: Overview and future research directions", under review in *IEEE UVS-Oman 2019*.
- M. Alzenad, H. Yanikomeroglu, "Coverage and rate analysis for downlink unmanned aerial vehicles base stations with LoS/NLoS propagation", *IEEE Globecom Workshops 2018*. (01)
- X. Zhou, J. Guo, S. Durrani, H. Yanikomeroglu, "Uplink coverage performance of an underlay drone cell for temporary events", Invited Paper, *IEEE Int'l Conf. in Communications Workshops (ICCW) 2018*. (04)
- M. Gapeyenko, I. Bor-Yaliniz, S. Andreev, H. Yanikomeroglu, Y. Koucheryavy, "Effect of blockage in deploying mmWave drone base stations for beyond-5G networks", Invited Paper, *IEEE Int'l Conf. in Communications Workshops (ICCW) 2018*.
- R. Ghanavi, E. Kalantari, M. Sabbaghian, H. Yanikomeroglu, A. Yongacoglu, "Efficient 3D aerial base station considering users mobility by reinforcement learning", *IEEE WCNC 2018*.
- E. Kalantari, I. Bor-Yaliniz, A. Yongacoglu, H. Yanikomeroglu, "User association and bandwidth allocation for terrestrial and aerial base stations with backhaul considerations", *IEEE PIMRC 2017*.
- E. Kalantari, M.Z. Shakir, H. Yanikomeroglu, A. Yongacoglu, "Backhaul-aware robust 3D drone placement in 5G+ wireless networks", *IEEE Int'l Conf. in Commun. Workshops (ICCW) 2017*.
- E. Kalantari, H. Yanikomeroglu, A. Yongacoglu, "On the number and 3D placement of drone base stations in wireless cellular networks", *IEEE Vehicular Technology Conference (VTC2016-Fall)*.
- I. Bor Yaliniz, A. El-Keyi, H. Yanikomeroglu, "Efficient 3-D placement of an aerial base station in next generation cellular networks", *IEEE Int'l Conf. in Communications (ICC) 2016*.

8) Instructor Biography

Dr. Yanikomeroglu is a full professor in the Department of Systems and Computer Engineering at Carleton University, Canada. He has made substantial contributions to wireless research, innovation, and education. He has been a very active and exemplary member of IEEE, ComSoc, and Wireless Communications Technical Committee; he has served in these platforms in almost every capacity.

Research & Innovation: Dr. Yanikomeroglu has had extensive collaboration with industry and led large-scale research projects. His collaborative research resulted in 25 granted patents (plus about a dozen applied). In the previous decade, he participated in the EU WINNER Project, which was at the time world's largest collaborative research project in wireless with 40 partners from academia and industry. The WINNER Project (including Dr. Yanikomeroglu's work on wireless relaying and intercell interference coordination technologies) had substantial impact to the **4G** LTE standardization. More recently, he led a 5-year project which was one of the largest pre-standards **5G** research projects, sponsored by the industry and the Ontario government. In 2019, Dr. Yanikomeroglu plans to initiate another large-scale project with the theme "integrated aerial-terrestrial **6G** network architecture for 2030s". Dr. Yanikomeroglu has coauthored 360+ peer-reviewed research papers including 125 in the IEEE journals; these publications have received 11,000+ citations including very many in patent applications.

Education & Training: Dr. Yanikomeroglu has supervised 20 PhD and 28 MASc students (all completed with theses) and 12 PDFs; 9 of these researchers became faculty members, and several of them received various medals for their PhD theses. In addition, he has hosted and supervised 11 visiting professors, 6 visiting PDFs, and 22 visiting graduate students. Dr. Yanikomeroglu is a Distinguished Lecturer for IEEE ComSoc and a Distinguished Speaker for IEEE VTS. He is one of the most frequent tutorial presenters in the leading international IEEE conferences including ICCs and Globecoms (29 times). He has delivered a total of 79 invited seminars + tutorials + keynotes + panels since 2012. He has served in the editorial boards of IEEE Communications Surveys & Tutorials, IEEE Trans. on Wireless Communications, and IEEE Transactions on Communications. He guest co-edited two IEEE journal special issues in 2018 (in JSAC and ITPro Magazine).

Service: Dr. Yanikomeroglu served as the General Chair of the IEEE VTS's flagship conference VTC twice: VTC 2010-Fall Ottawa and VTC 2017-Fall Toronto (possibly, the only colleague who chaired VTCs twice). He has been involved in ComSoc's flagship wireless conference WCNC from its inception in 1998 in almost every capacity including serving as the Steering Committee member for a decade, and the Technical Program Chair/Co-Chair for three times: WCNC 2004 Atlanta, WCNC 2008 Las Vegas, and WCNC 2014 Istanbul (the only colleague who served as WCNC TP Chair for three times). Dr. Yanikomeroglu served as the Chair of one of the largest and most influential technical committees in IEEE, Technical Committee on Personal Communications (now called Wireless Communications Technical Committee with 1,700+ members). He was involved in this technical committee as chair (2 years), vice-chair (2 years), secretary (2 years), awards committee chair (2 years), and awards committee member (2 years), spanning a full decade of service. Dr. Yanikomeroglu has been involved in a large number of IEEE conferences as a member of the Organizing or Executive Committee (ex: IEEE Globecom 2018, Publicity Co-Chair), and in around 100 conferences as a TPC member. For the last seven years, Dr. Yanikomeroglu organized (with a number of colleagues) the International Workshop on Emerging Technologies for 5G and Beyond Wireless Networks (ET5GB) collocated with IEEE Globecom; in each edition of this event, he served either as a General Co-Chair or Technical Program Co-Chair.

Awards & Recognition: Dr. Yanikomeroglu is a Fellow of the IEEE with the citation "for contributions to wireless access architectures in cellular networks". He is a recipient of the IEEE Ottawa Section Outstanding Service Award in 2018, IEEE Ottawa Section Outstanding Educator Award in 2014, Carleton University Research Achievement Awards in 2018 and 2009, Carleton University Faculty Graduate Mentoring Award in 2010, and Carleton University Graduate Students Association Excellence Award in Graduate Teaching in 2010.

Tutorial Proposal (IEEE ICC 2019)

Tutorial Title

Rate-Splitting and Robust Interference Management: Theory and Applications

Presenter

Bruno Clerckx, Reader (Associate Professor),
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Bruno Clerckx is a Reader (Associate Professor) in the Electrical and Electronic Engineering Department at Imperial College London (London, United Kingdom). He received his M.S. and Ph.D. degree in applied science from the Université catholique de Louvain (Louvain-la-Neuve, Belgium) in 2000 and 2005, respectively. From 2006 to 2011, he was with Samsung Electronics (Suwon, South Korea) where he actively contributed to 3GPP LTE/LTE-A and IEEE 802.16m and acted as the rapporteur for the 3GPP Coordinated Multi-Point (CoMP) Study Item. Since 2011, he has been with Imperial College London, first as a Lecturer (2011-2015), then as a Senior Lecturer (2015-2017), and now as a Reader. From March 2014 to March 2016, he also occupied an Associate Professor position at Korea University, Seoul, Korea. He also held visiting research appointments at Stanford University, EURECOM, National University of Singapore and The University of Hong Kong.
He is the author of 2 books, 150 peer-reviewed international research papers, 150 standard contributions and the inventor of 75 issued or pending patents among which 15 have been adopted in the specifications of 4G (3GPP LTE/LTE-A and IEEE 802.16m) standards. Dr. Clerckx served as an editor for IEEE TRANSACTIONS ON COMMUNICATIONS from 2011-2015 and is currently an editor for IEEE TRANSACTIONS ON WIRELESS COMMUNICATIONS and IEEE TRANSACTIONS ON SIGNAL PROCESSING. He has been TPC member, symposium chair, TPC chair of many symposia on communication theory, signal processing for communication and wireless communication for several leading international IEEE conferences. He has also been (lead) guest editor for EURASIP Journal on Wireless Communications and Networking, IEEE Access and IEEE Journal on Selected Areas in Communications. He was the editor for 3GPP LTE-Advanced standard technical report on CoMP. He is an Elected Member of the IEEE Signal Processing Society SPCOM Technical Committee. His research area is communication theory and signal processing for wireless networks.

Presenter's previous tutorial delivery experience:
Here is a list of tutorials I have given at conferences in the last three years:

1. Bruno Clerckx and Hamdi Joudeh, "Rate Splitting for MIMO Wireless Networks: A Promising PHY-Layer Strategy for 5G," IEEE VTC Fall 2016, Montreal, Canada.
2. Bruno Clerckx, "Rate Splitting for MIMO Wireless Networks: A Promising PHY-Layer Strategy for 5G," IEEE ISWCS 2016, Posnan, Poland.
3. Bruno Clerckx and Hamdi Joudeh, "Rate Splitting for MIMO Wireless Networks: A Promising PHY-Layer Strategy for 5G," IEEE ICC 2017, Paris, France.
4. Bruno Clerckx, "Emerging Topics in 5G Networks: Simultaneous Wireless Information and Energy Transfer" European Signal Processing Conference EUSIPCO 2017, Greece.
5. Bruno Clerckx, "Rate Splitting for MIMO Wireless Networks: A Promising PHY-Layer Strategy for 5G and Beyond," IEEE/CIC International Conference on Communications in China (ICCC) 2017, Qingdao, China.

6. Bruno Clerckx, “Communication and Signal Processing Advances in Wireless Power Transmission,” IEEE/CIC International Conference on Communications in China (ICCC) 2017, Qingdao, China.
7. Marco di Renzo, Samir M. Perlaza and Bruno Clerckx, “Emerging Topics in 5G Networks: Simultaneous Wireless Information and Energy Transfer” IEEE Globecom 2017, Singapore.
8. Bruno Clerckx and Paul Mitcheson, “Far-Field wireless power transmission: RF, signal and system designs,” European Conference on Antennas and Propagation (EUCAP) 2018.
9. Bruno Clerckx, “Rate Splitting for MIMO Wireless Networks: A Promising PHY-Layer Strategy for 5G and Beyond,” IEEE International Symposium on Wireless Communication Systems (ISWCS) 2018
10. Bruno Clerckx, “Rate-Splitting and Robust Interference Management: Theory and Applications” in IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC) 2018
11. Bruno Clerckx, “Rate-Splitting Multiple Access for Next Generation Wireless Networks: Bridging the Extremes,” IEEE Globecom 2018.

Motivation and Background

<u>Abstract and Motivation</u>

MIMO has grown beyond the original point-to-point channel and nowadays refers to a diverse range of centralized and distributed deployments. Numerous techniques have been developed in the last decade for MIMO wireless networks, including among others MU-MIMO, CoMP, Massive MIMO, Non-Orthogonal Multiple Access (NOMA), millimetre wave MIMO. All those techniques rely on two extreme interference management strategies, namely fully decode interference and treat interference as noise. Indeed, while NOMA based on superposition coding with successive interference cancellation relies on strong users to fully decode and cancel interference created by weaker users, MU-MIMO/Massive MIMO/CoMP/millimetre wave MIMO based on linear precoding rely on fully treating any multi-user interference as noise. In the presence of imperfect channel state information at the transmitter (CSIT), CSIT inaccuracy results in additional multi-user interference that is treated as noise by all those techniques.

To efficiently cope with the high throughput, reliability, heterogeneity of Quality-of-Service (QoS), and massive connectivity requirements of future multi-antenna wireless networks, multiple access and multiuser communication system design need to depart from two conventional and extreme interference management strategies, namely fully treat interference as noise (as commonly used in 4G, MU-MIMO, CoMP, Massive MIMO, millimetre wave MIMO) and fully decode interference (as in NonOrthogonal Multiple Access - NOMA).

In this tutorial, we depart from those two extremes and introduce the audience to a more general, more robust, and more powerful transmission framework based on Rate-Splitting (RS) that consists in decoding part of the interference and in treating the remaining part of the interference as noise. This capability of RS to partially decode interference and partially treat interference as noise enables to softly bridge and therefore reconcile the two extreme strategies of fully decode interference and treat interference as noise.

In order to partially decode interference and partially treat interference as noise, RS splits messages into common (degraded) messages decoded by multiple users, and private (nondegraded) messages decoded by their corresponding users. As a result, RS pushes multiuser transmission away from conventional unicast-only transmission to superimposed unicast multicast transmission and leads to a more general class/framework of strategies. For instance, in a MISO Broadcast Channel, RS is shown to encompass NOMA and MU-MIMO/SDMA with linear precoding as special cases.

Through information and communication theoretic analysis, RS is shown to be optimal (from a Degrees-of-Freedom region perspective) in a number of scenarios and provide significant benefits in terms of spectral efficiencies, reliability and CSI feedback overhead reduction over conventional strategies used/envisioned in LTE-A/5G that rely on fully treat interference as noise or fully decode interference.

Rate-Splitting (RS) has emerged in the last few years as a powerful transmission strategy for robust interference management and a key enabler of novel multiple access, with applications in a wide range of scenarios (multi-user MIMO, massive MIMO, multi-cell MIMO/CoMP, overloaded systems, NOMA, multigroup multicasting, mmwave communications, communications in the presence of RF impairments and superimposed unicast and multicast transmission, relay,…) and systems (terrestrial, cellular, satellite, ...). The tutorial will demonstrate the benefits of RS in this wide range of scenarios and systems, and will present and elaborate on the signal processing and optimization techniques used to achieve the fundamentally promised gains. Open problems and challenges will also be discussed.

Importance and Timeliness

Rate-Splitting is an emerging paradigm in wireless networks that is in its infancy. Rate-Splitting relies on the transmission of common (degraded) messages decoded by multiple users, and private (nondegraded) messages decoded by their corresponding users. Through rate-splitting and the transmission of common and private messages, MIMO networks move away from conventional unicast-only transmission to superimposed unicast multicast transmission and enables to bridge extremes of fully decode interference and fully treat interference as noise. Rate splitting has the potential to radically change the design of the PHY layer of communication system.

This tutorial is dedicated to the theory, design, optimization and applications of rate splitting in many different scenarios relevant to wireless communications and signal processing. It is unique and its content is not available in any other tutorials. It focuses on a key communication theoretic idea and highlights its potential in a wide range of very popular scenarios and applications. Hence in contrast with many tutorials that focus on particular technologies like massive MIMO, mmwave communications, multi-cell cooperation, etc, this tutorial introduces the audience to a fundamental technique and shows how it can tackle numerous problems that all those technologies are currently facing.

The tutorial is given by an expert with a diverse range of expertise, including years of research experience in academia and in industry and familiar with latest advances in academic and industrial research.

Previous experience

Earlier versions of this tutorial were given at IEEE VTC Fall 2016, IEEE ISWCS 2016, IEEE ICC 2017, IEEE/CIC ICCC 2017, IEEE ISWCS 2018, IEEE PIMRC 2018, IEEE Globecom 2018 and received excellent feedback from the audience (15 to 50 attendees at each session). It is aimed at PhD students, researchers and engineers in academia and industry interested in the lower layers of wireless communication systems and in particular the design of 5G physical layer. The tutorial is designed to be accessible to anyone with a background in at least one of the following areas: (wireless) communication theory, MIMO, interference management, signal processing and optimization for communications. The tutorial has been updated compared to versions given last year with the addition of several new results: RS as an enabler of a new multiple access called Rate-Splitting Multiple Access (RSMA), comparisons with NOMA and confirmation that NOMA and SDMA are subsets of RSMA, energy efficiency of RSMA, RS for superimposed unicast and multicast transmissions.

Structure and Content

1. Introduction to MIMO networks, interference management and 4G design (**10min**)
    a. Point to point MIMO
    b. Multi-user SISO/MIMO
    c. Multi-cell MIMO and HetNets
    d. Massive MIMO
    e. Interference Management
    f. Non-Orthogonal Multiple Access
2. Problem of current 4G and emerging 5G architecture (**10min**)
    a. LTE-A performance and limitations: NOMA, MU-MIMO, CoMP, HetNets
    b. Motivation for a new physical layer
3. Fundamentals of Rate-Splitting (**50min**)
    a. Interference Channel
    b. Broadcast Channel with perfect and imperfect CSIT
    c. Performance Limits and Degrees of Freedom
    d. Sum-Rate Enhancement and CSI Feedback Reduction
4. Transceiver Optimization of Rate-Splitting (**20min**)
    a. Problem formulation
    b. Robust beamforming (sum-rate maximization, max-min fairness)
5. Applications and Extensions of Rate Splitting (**70min**)
    a. Multiple receive antennas
    b. Massive MIMO
    c. Multi-Cell MIMO
    d. Overloaded systems
    e. Rate-Splitting Multiple Access: Generalization of SDMA and NOMA
    f. Multigroup Multicast
    g. Communications in the presence of RF impairments
    h. Millimeter Wave Communications
    i. Superimposed Unicast and Multicast transmissions
6. Rate-Splitting in 5G and beyond (**10min**)
    a. Standardization issues and efforts
7. Future Challenges (**10min**)

Material to be delivered
The presentation material (slides) used during the tutorial presentation will be provided to the audience before the tutorial is held, in order to allow them to prepare and take notes during the tutorial presentation. The material will include a detailed list of relevant papers to facilitate the audience to jump onto this research area.

Specific Promotion
The tutorial will be advertised using the usual IEEE email lists and through researchgate.

Safeguarding the 5G Era and Beyond with Physical Layer Wireless Security

Nan Yang, Xiangyun (Sean) Zhou, and Jemin Lee

1. Title of the Tutorial

Safeguarding the 5G Era and Beyond with Physical Layer Wireless Security

2. Abstract, Objectives and Motivation

Abstract: Wireless everything—this is the goal that the digital society is marching towards. Looking 10—20 years ahead, the ubiquitous wireless world aims at building ultra-high-quality wireless networks that connect a massive number of human- and machine-type devices and enable fully interoperable information exchange among them. Security is one of the pivotal issues that need to be carefully addressed in the design and implementation of such wireless networks, since wireless transmissions are inherently vulnerable to security breaches. This tutorial focuses on physical layer security, which has been recognized as a promising paradigm to protect data confidentiality by exploiting the intrinsic randomness of the communications medium. In particular, this tutorial places an emphasis on leveraging disruptive wireless technologies to secure data transmission from the physical layer. First, this tutorial provides a high-level overview of the security methods for the previous and current mobile networks. Then, this tutorial introduces the state-of-the-art fundamental research of physical layer security, such as the evolution of secrecy performance evaluation and physical layer key generation. After this, the tutorial presents a structured and comprehensive survey of the security solutions enabled by cutting-edge wireless techniques, such as massive multiple-input multiple-output (MIMO), millimeter wave (mmWave) and terahertz (THz) communications, machine-to-machine (M2M) communication, energy-efficient communication, full-duplex (FD) communication, unmanned aerial vehicle (UAV) communication, and software defined radio-based prototype. Finally, this tutorial identifies and discusses the outstanding barriers that future wireless security designers must tackle to unlock the full benefits of the three pillar scenarios in the 5G era and beyond.

Objectives: The overarching objective of this tutorial is to provide a physical layer perspective on the security design of future wireless networks in the 5G era and beyond. At the end of this tutorial the participants will be able to:

- Gain a fundamental understanding of the traditional security methods used in the previous and current wireless mobile networks and the security requirements of futuristic wireless networks.
- Obtain critical comprehension of the state-of-the-art theoretical advancement of physical layer security.
- Understand the concepts and underlying principles in cutting-edge physical layer security solutions and explore the role of disruptive wireless technologies in such solutions.
- Analyse the benefits brought by physical layer security in supporting the deployment of safety-critical wireless networks in the not distant future.

Motivation: As a promising low-complexity strategy to securing wireless communications, physical layer security has attracted numerous research efforts from both the information theoretical perspective and the practical design perspective over the past decade. Despite such efforts stand on their own merit, the role that physical layer security plays in the 5G era and beyond has not been clearly identified. Indeed, how to harness the full benefits offered by physical layer security for three pillar scenarios, namely, enhanced mobile broadband, massive Internet of Things, and mission-critical communications, has not been explicitly answered in the literature.

To meet the requirements mandated by the three scenarios, innovative changes in both wireless technologies and core networks have been under development over the past few years, such as massive MIMO, mmWave and THz, FD, non-orthogonal multiple access (NOMA), M2M, massive Internet of Things (IoT), mobile edge computing (MEC), fog networks, and short-packet communications (SPC). Considering the great potential of physical layer security and the diverse usage scenarios of 5G, the design of future communications techniques with "built-in" physical layer security requires a cogent and insightful discussion beyond what the community has done so far. Thus, this tutorial will trigger this discussion among the researchers in both academia and industry from diverse backgrounds to advance the physical layer security techniques for wireless networks in the 5G era and beyond.

3. Timeliness and Intended Audience

Timeliness: The speaker team believes that the proposed tutorial is very timely. By carefully reviewed all the tutorials delivered in recent IEEE ICC (2016—2018) and IEEE GlobeCOM (2016—2018), there is no dedicated tutorial which has directly addressed physical layer security for 5G and beyond networks. Specifically, there are only four recent tutorials which have targeted on the general security for 5G cellular networks, but not on the exploration of physical layer security for the three pillar scenarios in 5G and beyond networks. Despite that 5G research is already overwhelming and its first version of implementation is already underway, it is still very unclear how physical-layer security can make the full use of the new features of 5G and beyond networks to realize its full potential for securing the wireless network. More importantly, the possible paths that physical layer security can eventually reach practical implementation in the next 10 years or so still remain unanswered.

Against this background, the proposed tutorial will provide a *first* look at cutting-edge wireless physical layer technologies that enable secure communications in 5G and beyond networks. In particular, the proposed tutorial will offer pivotal guidance for the secure design and implementation of 5G and beyond networks which is beneficial for a wide range of people across the academic, industry, and professional communities. Ultimately, the proposed tutorial will allow relevant stakeholders to thoroughly understand the role of physical layer security in safeguarding wireless communications in the 5G era and beyond and help them to fully unlock its potential for the benefit of the future networked society.

Intended Audience: This tutorial will be of interest to graduate students, junior and senior researchers, and engineers from the communications, signal processing, and networking communities who are interested in the secure design of the next-generation wireless networks (e.g., multi-tier/HetNets, massive MIMO and mmWave systems, D2D communication, massive IoT, and mission-critical communication). It will be also of interest to commercial and government security sectors who are interested in regulating and framing the use of physical layer security techniques in future.

4. Name, Affiliation, and A Short Biography of Each Tutorial Speaker

Nan Yang, Australian National University

Dr. Yang received his Ph.D. degree in Electronic Engineering from Beijing Institute of Technology in 2011. Since July 2014, he has been with the Australian National University, Canberra, Australia, where he is currently a Senior Lecturer and a Future Engineering Research Leadership Fellow at the Research

School of Electrical, Energy and Materials Engineering. He received the Top Editor Award from the Transactions on Emerging Telecommunications Technologies in 2017, the Exemplary Reviewer Certificate of the IEEE Transactions on Communications in 2016 and 2015, the Top Reviewer Award from the IEEE Transactions on Vehicular Technology in 2015, the IEEE ComSoc Asia-Pacific Outstanding Young Researcher Award and the Exemplary Reviewer Certificate of the IEEE Wireless Communications Letters in 2014, and the Exemplary Reviewer Certificate of the IEEE Communications Letters in 2013 and 2012. Also, he is the co-recipient of Best Paper Awards at the IEEE GlobeCOM 2016 and the IEEE VTC Spring 2013. He is currently serving on the Editorial Board of the IEEE Transactions on Wireless Communications, IEEE Transactions on Vehicular Technology, and Transactions on Emerging Telecommunications Technologies. His research interests include massive multiple-antenna systems, millimetre wave and terahertz communications, heterogeneous wireless networks, ultra-reliable and low-latency communications, cyber-physical security, collaborative and distributed signal processing, and molecular communications.

Xiangyun (Sean) Zhou, Australian National University

Sean Zhou is a Senior Lecturer at the Australian National University (ANU). He received the Ph.D. degree from ANU in 2010. His research interests are in the fields of communication theory and wireless networks. Sean is a senior member of IEEE. He was awarded as the Best Young Researcher in the Asia-Pacific Region in 2017 by IEEE ComSoc Asia-Pacific Board for his research impact and leadership in physical layer security. Currently, Sean serves as an Editor for IEEE Transactions on Wireless Communications and IEEE Wireless Communication Letters. He was a co-organizer of two ICC and GlobeCOM workshop series, one on wireless physical layer security from 2014 to 2016 and the other on wireless energy harvesting communications from 2016 to 2018. He is a recipient of the Best Paper Award at IEEE ICC 2011 and IEEE ComSoc Asia-Pacific Outstanding Paper Award in 2016.

Jemin Lee, Daegu Gyeongbuk Institute of Science and Technology

Jemin Lee is an Associate Professor at the Department of Information and Communication Engineering, Daegu Gyeongbuk Institute of Science and Technology (DGIST), Daegu, Korea. She received the Ph.D. degrees in Electrical and Electronic Engineering from Yonsei University, Seoul, Korea, in 2010. Her current research interests include wireless communications, wireless security, intelligent networking, and machine-type communications. She is currently an Editor for the IEEE Transactions on Wireless Communications and the IEEE Communications Letters, and served as a Guest Editor for the IEEE Wireless Communications, special issue on LTE in Unlicensed Spectrum, in 2016. She serves as a Secretary (2017—2018) for the IEEE ComSoc Radio Communications Technical Committee (RCC) and a Secretary (2018—2019) for IEEE ComSoc Asia-Pacific Board. She received the IEEE ComSoc AP Outstanding Paper Award in 2017, the IEEE ComSoc AP Outstanding Young Researcher Award in 2014, the Temasek Research Fellowship in 2013, the Chun-Gang Outstanding Research Award in 2011, and the IEEE WCSP Best Paper Award in 2014.

5. A Description of the Technical Issues that the Tutorial will Address, Emphasizing its Timeliness

The proposed tutorial will address some technical issues that are necessary to enable a comprehensive understanding of physical layer security. These technical issues are:

1. The fundamental knowledge of wiretap coding and commonly-used performance metrics in physical layer security;

2. The evolvement of physical layer security performance metrics from perfect secrecy to partial secrecy, based on He's work published in 2016;
3. The principle and performance metrics used for physical layer key generation, based on Zhang's and Lee's work published in 2016, 2017, and 2018;
4. The most up-to-date theoretical research progress in cutting-edge physical layer security solutions, based on various authors' work published in 2016, 2017, and 2018;
5. Experimental results on physical layer security, based on Thai's work which will be published in 2019;
6. Emerging topics on physical-layer security beyond content secrecy and the cross-layer security approach, based on various authors' work published in 2017 and 2018.

Based on the aforementioned information, the speaker team believes that the technical issues addressed in the proposed tutorial have great timeliness, since they are based on very recent publications.

6. An Outline of the Tutorial Content, Including its Tentative Schedule

The proposed tutorial covers four sections, namely, (1) security in mobile communication networks, (2) theoretical advancement in physical layer security, (3) cutting-edge physical layer security solutions, and (4) challenges and open issues in the 5G era and beyond. Specifically, the tutorial is planned to deliver according to the following schedule:

1) **Security in Mobile Communication Networks** (approximately 30 minutes)
   a) Evolution of cellular networks
   b) Security issues in cellular networks
   c) Re-shape security design in 5G wireless networks
2) **Theoretical Advancement in Physical Layer Security** (approximately 50 minutes)
   a) Information-theoretical foundation of physical layer security
   b) Evolution of secrecy performance metrics
   c) Secure physical layer key generation
3) **Cutting-Edge Physical Layer Security Solutions** (approximately 90 minutes)
   a) Heterogeneous secure communication
   b) Full-duplex secure communication
   c) Massive MIMO-aided secure communication
   d) Secure communication over mmWave channels
   e) Machine type secure communication
   f) Energy-efficient secure communication
   g) Ultra-reliable and low-latency secure communication
   h) Unmanned aerial vehicle secure communication
   i) Software defined radio-based prototyping and experimental outcomes
4) **Challenges and Open Issues in the 5G Era and Beyond** (approximately 40 minutes)
   a) Physical layer security beyond content secrecy

b) Cross-layer security design

c) Challenges imposed by future wireless world

7. If Appropriate, a Description of the Past/Relevant Experience of the Speaker(S) on the Topic of the Tutorial

Nan Yang

Dr. Yang received the IEEE ComSoc Asia-Pacific Outstanding Young Researcher Award in recognition of his contributions in wireless security. Over the past years, he has published 1 book chapter and over 40 journal and conference papers on physical layer security. He was the TPC Chair of the 2015—2018 IEEE GLOBECOM Workshops on *Trusted Communications with Physical Layer Security* and will be the TPC Chair of the 2019 IEEE ICC Workshop on *Wireless Physical Layer Security*. He is currently serving as the Lead Guest Editor of a special issue on *Safeguarding 5G-and-Beyond Networks with Physical Layer Security* in the IEEE Wireless Communications. In addition, he served as the Lead Guest Editor of a special issue on *Physical Layer Security for Emerging Wireless Networks: From Theory to Practice* in the Physical Communication.

Xiangyun (Sean) Zhou

Sean is well known by peers as an international leading researcher in physical layer security, having more than 60 publications over the last 10 years of research in this particular area. He was awarded as the Best Young Researcher in the Asia-Pacific Region in 2017 by IEEE ComSoc Asia-Pacific Board for his research impact and leadership in physical layer security. He recently contributed the publication of the IEEE ComSoc Best Readings in physical layer security. He previously served as a Guest Editor for IEEE Communications Magazine's feature topic on wireless physical layer security in 2015. He was a co-organizer of ICC workshop series on wireless physical layer security from 2014 to 2016 and he delivered a keynote speech on this topic at a GlobeCOM workshop in 2017. The Best Paper Award he received at the IEEE ICC 2011 was for his early work on wireless security attack.

Jemin Lee

Jemin is known as a wireless security expert, having more than 40 publications in the areas of physical layer security and network security. She received the IEEE ComSoc Asia-Pacific Outstanding Young Researcher Award in 2014 for her contributions to communication security. She was a Co-chair of IEEE ICC workshop on Wireless Physical Layer Security in 2016, and will also organize this workshop in IEEE ICC 2019. In addition, she organized special sessions for physical layer security in various conferences including IEEE SPAWC 2017. She served as a Guest Editor of a special issue on *Physical Layer Security for Emerging Wireless Networks: From Theory to Practice* in the Physical Communication.

8. A Description of Previous Tutorial Experience of the Speaker(s), and Past Versions of the Tutorial

Nan Yang

Dr. Yang delivered a tutorial on physical layer security together with Dr. Zhou in IEEE VTC Spring 2017. Compared to the tutorial in IEEE VTC Spring 2017, the proposed tutorial will put a stronger emphasis on cutting-edge physical layer security solutions for the massive Internet of Things scenario and the mission-critical communications scenario. Also, the proposed tutorial will provide an updated statement regarding some new physical layer security concepts, e.g., covert communications and cross-layer security design.

Xiangyun (Sean) Zhou

Dr. Zhou delivered a tutorial on physical layer security together with Dr. Yang in IEEE VTC Spring 2017.

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

Not available, since this tutorial has not been delivered at the IEEE ICC or GlobeCOM.

Fog-Radio Access Networks: Principles, Key Techniques, and Applications

1. Abstract, Objectives and Motivation

To satisfy the explosively increasing demands of diverse mobile services and massive access requirements of various Internet-of-thing (IoT) devices, a framework of fog-radio access networks (F-RANs) has emerged as a promising evolution path for the network architecture. In F-RANs, the principles and the key techniques should be studied to take full advantages of distributed caching and centralized processing, which can provide great flexibility to satisfy quality-of-service requirements of various application scenarios. In this tutorial, we will provide a comprehensive overview of F-RANs, and the following topics are included:

1) An introduction of F-RANs is provided, including the background and the motivation, the network architecture, and the coordination mechanisms between the cloud computing layer and the fog computing layer.
2) The information-theoretical performance of F-RANs is analyzed. We focus on the content caching and the computation offloading of F-RANs to evaluate the performance gains achieved by the collaboration of communication, computing, and caching (3C). The tractable analytical results are presented to provide some insights with respect to the bottleneck of F-RANs and keeping a sophisticated balance of 3C capability.
3) The network orchestration schemes of F-RANs are introduced. The existing orchestration frameworks in F-RANs are first presented, which are based on the multi-dimension virtualized resources. Then an information-aware orchestration scheme is introduced to improve the resource utilization efficiency and satisfy diverse QoS requirements simultaneously, and the joint optimization of resource allocation is designed.
4) The network intellectualization of F-RANs are presented. We introduce some application scenarios of artificial intelligence in F-RANs, i.e., deep-learning based network management and intent-driven networking. To fully explore the potential of hierarchically centralized architecture of F-RANs, a federated learning-based paradigm of network intellectualization is introduced, which are suitable for processing the privacy-sensitive wireless data with non-independent identically distributed and dynamic features.
5) The future trends and some open issues of F-RANs are discussed, such as the fundamental limits of artificial intelligence in F-RANs, data-driven intelligent network orchestration, and the evolution path of network architecture to fully implement intent-oriented F-RANs.

In summary, the objective of this tutorial is to provide a solid guidelines of F-RAN to the audience, which can present the most recent research progress comprehensively,

by clarifying the key problems, by introducing the research methodologies, as well as by explaining the main results. Moreover, we share our points of view with respect to the possible future research directions.

2. Timeliness and Intended Audience

The paradigm of F-RANs is a cutting-edge research area in the fields of communication and computer science, and has great application potential in the future wireless networks, especially in the beyond 5G/6G systems. Moreover, the collaboration of 3C is an important issue for F-RANs, as well as for other evolved network architectures. Therefore, this tutorial will attract the researchers from both academia and industry working the network architecture, the collaboration of 3C, and the network intellectualization.

3. Information of Tutorial Speakers

1) Zhongyuan Zhao, Beijing University of Posts and Telecommunications, China

Biography: Zhongyuan Zhao received the B.S. degree in applied mathematics and the Ph.D. degree in communication and information systems from Beijing University of Posts and Telecommunications (BUPT), Beijing, China, in 2009 and 2014, respectively. He is currently an associate professor with BUPT. His research interests include cloud and fog computing-based radio access networks, content caching, and advanced wireless signal processing and transmission technologies.

Dr. Zhao serves as an editor of IEEE Communications Letters (since 2016), and a guest editor of the IEEE Access special section entitled “Fog Radio Access Networks (F-RANs) for 5G: Recent Advances and Future Trends.” He was the recipient of the Best Paper Awards at the IEEE CIT 2014 and WASA 2015. He was also the recipient of Exemplary Reviewers-2017 of IEEE Transactions on Communications, and Exemplary Editor Award 2017 of IEEE Communication Letters.

2) Haijun Zhang, University of Science and Technology Beijing, China

Biography: Haijun Zhang is currently a Full Professor in University of Science and Technology Beijing, China. He was a Postdoctoral Research Fellow in Department of Electrical and Computer Engineering, the University of British Columbia (UBC), Vancouver Campus, Canada. He serves as Editor of IEEE Transactions on Communications, IEEE Transactions on Green Communications and Networking, IEEE 5G Tech Focus. He serves/served as General Co-Chair of GameNets'16, Symposium Chair of Globecom'19, TPC Co-Chair of INFOCOM'18 Workshop IECCO, General Co-Chair of ICC'18/ICC'17/Globecom'17 Workshop on UDN, and General Co-Chair of Globecom'17 Workshop on LTE-U. He received the IEEE CSIM Technical Committee Best Journal Paper Award in 2018 and IEEE ComSoc Young Author Best Paper Award in 2017.

3) Chonggang Wang, InterDigital Communications, USA, IEEE Fellow

Biography: Chonggang Wang received the Ph.D. degree from Beijing University of Posts and Telecommunications, Beijing, China, in 2002. He is currently a Member of Technical Staff with InterDigital Communications. His R&D focuses on: Internet of Things (IoT), Machine-toMachine (M2M) communications, Heterogeneous Networks, and Future Internet, including technology development and standardization. He (co-)authored more than 100 journal/conference articles and book chapters. He is on the editorial board for several journals including IEEE Communications Magazine, IEEE Wireless Communications Magazine, and IEEE Transactions on Network and Service Management.

Dr. Wang is the founding Editor-in-Chief of IEEE Internet of Things Journal. He is serving and served in the organization committee for conferences/ workshops including IEEE WCNC 2013, IEEE INFOCOM 2012, IEEE Globecom 2010–2012, IEEE CCNC 2012, and IEEE SmartGridComm 2012. He has also served as a TPC member for numerous conferences such as IEEE ICNP (2010–2011), IEEE INFOCOM (2008–2014), IEEE GLOBECOM (2006–2014), IEEE ICC (2007–2013), IEEE WCNC (2008–2012), and IEEE PIMRC (2012–2013). He is a corecipient of National Award for Science and Technology Achievement in Telecommunications in 2004 on IP QoS from China Institute of Communications. He is the recipient of the Outstanding Leadership Award from IEEE GLOBECOM 2010 and InterDigital's 2012 and 2013 Innovation Award. He served as an NSF panelist in wireless networks in 2012. He is the Vice Chair of IEEE ComSoc Multimedia Technical Committee (MMTC) (2012–2014).

4) Mugen Peng, Beijing University of Posts and Telecommunications, China

Biography: Mugen Peng received the Ph.D. degree in communication and information systems from the Beijing University of Posts and Telecommunications (BUPT), Beijing, China, in 2005. Afterward, he joined BUPT, where he has been a Full Professor with the School of Information and Communication Engineering since 2012. During 2014 he was also an academic visiting fellow at Princeton University, USA. He leads a Research Group focusing on wireless transmission and networking technologies in BUPT. He has authored and coauthored over 90 refereed IEEE journal papers and over 300 conference proceeding papers. His main research areas include wireless communication theory, radio signal processing, cooperative communication, self-organization networking, heterogeneous networking, cloud communication, and Internet of Things.

Dr. Peng was a recipient of the 2018 Heinrich Hertz Prize Paper Award, the 2014 IEEE ComSoc AP Outstanding Young Researcher Award, and the Best Paper Award in the JCN 2016, IEEE WCNC 2015, IEEE GameNets 2014, IEEE CIT 2014, ICCTA 2011, IC-BNMT 2010, and IET CCWMC 2009. He is currently or have been on the Editorial/Associate Editorial Board of the IEEE Communications Magazine, IEEE

ACCESS, IEEE Internet of Things Journal, IET Communications, and China Communications. He received the First Grade Award of Technological Invention Award three times in China.

4. A Description of the Technical Issues That the Tutorial Will Address

As clarified in the abstract, the following technical issues will be addressed:

1) The performance limits of F-RANs are analyzed. In this tutorial, we focus on the content caching and the computation offloading, which are typical scenarios of 3C collaboration, and the analytical results are provided to show some insights.
2) The possible schemes to enable the collaboration of 3C are provided in this tutorial. In particular, the network orchestration of F-RANs is introduced, which provide feasible solutions of integrating 3C in F-RANs, and fully explore the computing and the caching capability.
3) The intellectualization of F-RANs is discussed, which is based on the full integration of 3C. We introduce the possible application scenarios of implementing network intellectualization in F-RANs, and provide suitable methods (such as federated learning).
4) The future trends and some open issues are introduced to provide potential research directions.

5. An Outline of the Tutorial Content

The content of this tutorial is initially organized as follows:

- Part 1. An introduction of F-RANs (about 30 mins)
- Part 2. Information-theoretical performance limits of F-RANs (about 60 mins)
- Part 3. Network orchestration of F-RANs (about 60 mins)
- Part 4. Network intellectualization of F-RANs (about 60 mins)
- Part 5. Future trends and open issues (about 30 mins)

6. A Description of Previous Tutorial Experience of the Speakers

1) Hierarchical content caching: Performance analysis and algorithm design, by Zhongyuan Zhao, in Shanghai Jiao Tong University, Nov. 6th, 2015.
2) Haijun Zhang, et al, “Ultra Dense Networks: Principles and Technologies,” IEEE International Conference on Communications (ICC 2018), Kansas City, MO, USA, 2018.
3) Haijun Zhang “Ultra Dense Networks,” WiOpt 2018, Shanghai, China, 2018.

4) Haijun Zhang “Ultra Dense Networks: Principles and Technologies,” IEEE International Conference on Hot Topics in Information-centric Networking (IEEE HotICN 2018), Shenzhen, China, Aug 15th-17th, 2018.
5) Haijun Zhang, David Lopez-Perez, and Ming Ding, “Ultra Dense Networks: Principles and Technologies,” PIMRC 2017, Montreal, QC, Canada, 08-13 Oct. 2017.
6) Haijun Zhang “Heterogeneous Ultra Dense Networks: Principles and Technologies,” IEEE/CIC International Conference on Communications in China (ICCC 2017), Qingdao, China, Oct. 2017.
7) Haijun Zhang, et al, "Ultra Dense Heterogeneous Small Cell Networks in 5G: Principles and Technologies”, The 19th International Symposium on Wireless Personal Multi-media Communications (WPMC 2016), Shenzhen, China, Nov. 16, 2016.

7. Differences with the Similar Tutorials in Recent ICC & GlobeCom (Last Two Years)

1) Fog Services and Enabling Technologies, in IEEE ICC 2018

This tutorial mainly focus on the fog computing-enabled services, while our tutorial focus on the fog computing-based wireless network architecture.

2) Fog Computing and Networking: A New Paradigm for 5G and IoT Applications, in IEEE ICC 2017

This tutorial introduces the networking technologies of fog computing-based networking, and focus on the 5G and IoT application scenarios. Different from this tutorial, we discuss the performance limits of F-RANs, and the network intellectualization is introduced as well, which are not included in the previous tutorials.

3) Fog as a Service Technology (FA2ST): a New Approach for the Development of 5G Applications, in IEEE GlobeCom 2017

This tutorial mainly focus on the fog computing-enabled services in 5G systems, while our tutorial focus on the fog computing-based wireless network architecture.

Unlocking new Dimensions in Radio-based Positioning "5G Localization"

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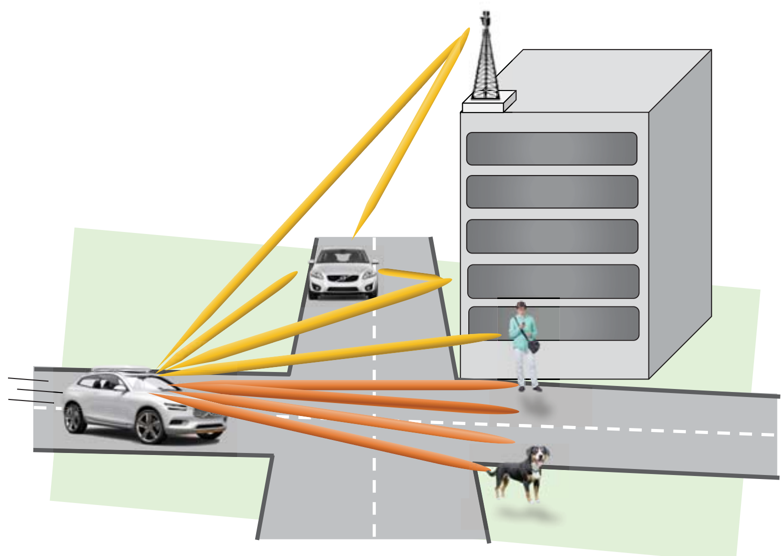

Figure 1. *5G will provide accurate positioning for individuals and vehicles, and can also support mapping of the environment as well as discovery of vulnerable road users. This tutorial will cover models, bounds, and algorithms to provide attendees an overview of this new research topic.*

1. Tutorial Title

Unlocking new Dimensions in Radio-based Positioning - 5G Localization

2. Abstract, objectives and motivation

Abstract: 5G will be characterized by increased data rates, higher density of devices, and a wide variety of use cases. The use mmWave technology is one of the novel elements in 5G systems, and it offers the potential to satisfy the rate requirements is mmWave thanks to the large available bandwidth and directional interference-free transmissions. As a side-effect, mmWave signals are useful for inter-device ranging as well as inter-device angle estimation. In turn, this leads to a potential new positioning technology: 5G localization. This tutorial will cover the basics of the new area 5G localization, covering models; performance bounds; algorithms for localization, tracking, and mapping; and applications. The tutorial presumes basic knowledge on wireless communication and statistical signal processing.

Motivation: The tutorial intends to provide wireless communication engineers with the necessary tools to include the positioning functionality in the design and analysis of communication systems. The objective of the tutorial is to describe models, theoretical bounds, and algorithms that serve to exploit the 5G technologies also for positioning services.

Objective: Positioning of devices using radio-frequency signals is a long-standing topic, and many systems have been used or specifically designed for this objective. Examples include LORAN-C and GPS for outdoor positioning, as well as ultra-wide band and WiFi for indoor positioning. Even though cellular systems could have had the advantage of offering a low-cost localization solution, up to the current generation (4G), they have never been an attractive solution for positioning due to their low accuracy. Consequently, their main application has been limited to the (mandatory) localization of emergency calls. The situation can change drastically with 5G. Thanks to 5G proposed technologies (use of large carrier frequencies, large antenna arrays and network densification), and if the localization functionality is considered at due time in the design, 5G systems can be the first generation offering high-accuracy localization and orientation, together with high coverage while maintaining low cost because the communication infrastructure is used. Hence, it is important for communication researchers to be aware of this opportunity.

Moreover, 5G systems will offer a natural and tight connection between localization and communication, where each of two functionalities will benefit from the other. This tutorial will also contribute to creating links between a broad spectrum of topics, from those more related to communications such as throughput, beam alignment, channel estimation, etc. to those closer signal processing and positioning such as channel modeling for positioning, compressed sensing, estimation bounds for positioning, tracking and mapping.

3. Timelines and audience

Timeliness: The standardization process of the second release (3GPP rel.16) of 5G has just been initiated, and positioning has been included in a number of study items. Given this is still an area with few publications, it is the right time to raise awareness on this topic so a larger number of researchers can focus their efforts on 5G localization and make key research contributions. The standardization process will last at least until March 2020, which is the expected finalization date of release 16, so exactly from this moment on there is an excellent window of opportunity to train researchers that can make directly or indirectly contributions to the standard, and eventually that come up with new 5G localization techniques that respond to use cases that are nowadays unimaginable. It is also worth mentioning that the inclusion of positioning into 5G systems has not been specifically addressed in previous tutorials.

Audience: The targeted audience includes researchers in wireless communications that want to learn about positioning opportunities in 5G. Furthermore, it also includes researchers in signal processing interested in learning about 5G localization, tracking and mapping techniques, as well as about the synergies between communication and localization. Researchers on GPS also form part of the target audience since they may be interested to understand the possibilities of 5G positioning since its hybridization with GPS gives rises to a practically ubiquitous localization solution. The level of the tutorial will make it accessible to first year PhD students with a basic knowledge of statistical signal processing. The emphasis of the tutorial is to provide insights as well as hands-on experience through small exercises.

4. Presenters

Henk Wymeersch is a Professor in Communication Systems with the Department of Electrical Engineering at Chalmers University of Technology, Sweden. He is also affiliated with the FORCE research center on fiber-optic communication, and was the PI of COOPNET, an ERC project on cooperative networks. Prior to joining Chalmers, he was a Postdoctoral Associate during 2006-2009 with the Laboratory for Information and Decision Systems (LIDS) at the Massachusetts Institute of Technology (MIT). Henk Wymeersch obtained the Ph.D. degree in Electrical Engineering/Applied sciences in 2005 from Ghent University, Belgium. For his thesis, he received the 2006 Alcatel Bell Scientific Award. He received a fellowship from the Belgian American Educational Foundation in 2005-2006. He is a member of the IEEE, and served as Associate Editor for IEEE Transactions on Communications (2016-present), IEEE Transactions on Wireless Communications (2013-2018), for IEEE Communication Letters (2009-2013). He served as Guest Editor for IEEE Journal on Selected Areas in Communications (JSAC, special issue on Location-aware Radios and Networks), EURASIP Journal on Wireless Communications and Networking (special issue on Localization in Mobile Wireless and Sensor Networks), and for EURASIP Journal on Advances in Signal Processing (special Issue on Signal Processing Techniques for Anywhere, anytime positioning). In 2015, he served as General Chair of the International Conference on Localization and GNSS.

Gonzalo Seco-Granados received the Ph.D. degree in telecommunications engineering from the Universitat Politecnica de Catalunya, Spain, in 2000. His PhD received the award from Spanish Association of Electrical

Engineers. From 2002 to 2005, he was member of the technical staff at European Space Agency, involved in the design of the Galileo System. He did some of the seminal work on the application of antenna arrays in GPS receivers, and he is inventor of patented techniques that are widely used in Galileo receivers. Since 2006, he is with Universitat Autonoma de Barcelona, Spain, where is a Professor. He has been a principal investigator of more than 30 research projects, and he has co-authored over 230 contributions in journals and international conferences. He is senior member of the IEEE. In 2016, he served as General Co-Chair of the International Conference on Localization and GNSS, and as Executive Co-Chair of the 8th Advanced Satellite Multimedia Systems Conference and the 14th Signal Processing for Space Communications Workshop (ASMS/ SPSC). He has been co-organizer of Special Sessions dealing with localization at IEEE CAMSAP 2017 and Asilomar Conference on Signals, Systems, and Computers 2018. In 2015, he was a Fulbright Visiting Professor with the University of California at Irvine, CA, USA.

5. Technical issues

The tutorial will start with stating the "5G Positioning Challenge":

- How can a user, from the downlink signal of a single base station, estimate its position, orientation, as well as clock bias, even the presence of an unknown propagation environment?
- How can the user additionally build up a map of the environment?
- And how can the above be achieved even when the line-of-sight path is blocked?

These questions will be addressed interactively with the audience, using also small exercises revealing fundamental concepts.

Answering these questions relies on the application of several timely techniques from signal processing, and communication theory, including beamforming design, sparse channel estimation, data association, and simultaneous localization and mapping. In addition, we describe novel positioning and mapping methods, tailored to the 5G scenario.

6. Outline

The half-day tutorial comprises 8 parts and will contain hands-on examples that participants will solve during the tutorial. The tutorial comprises a set of over 150 slides, of which only a part will be covered in detail. Items 1-4 comprise the first 1.5 hours, while items 5-8 comprise the second 1.5 hours.

1. *Radio-based positioning:* We will give an overview of measurements derived from radio signals that can convey position-related information. These include signal strength, time or arrival, angle of arrival and departure, and Doppler shifts. For these measurements, we will provide insights into how they contribute to positioning, through the tool of Fisher information, which will itself be detailed in a tutorial manner. Techniques for fusing measurements and providing snapshot positioning will be covered (including optimization-based methods, geometric methods, and inference-based methods). The integration of measurements into tracking filters ((extended) Kalman filter and particle filter) will be mentioned. Finally, weaknesses of each type of measurement will be highlighted and the relative performance will be compared.
2. *5G key technologies:* Before transitioning into 5G localization, we will provide a brief summary of 5G scenarios, requirements, technologies and their properties. These technologies include mmWave, massive MIMO, network densifications, and device-to-device (D2D) communications. Aspects related to internet of things will not be covered in this tutorial.
3. *5G selling points of 5G localization:* Now that the attendee has a knowledge of positioning and 5G, we are ready to present the potential of 5G technologies for positioning. In particular, we will describe, both qualitatively and quantitatively, how large bandwidths, high carrier frequencies, large arrays, and D2D are each individually beneficial for positioning. Each aspect will be supported with mathematical analysis and indicative performance results.
4. *5G localization below 6 GHz:* In the sub-6 GHz band, massive MIMO and network densification are the main technologies to be harnessed. Based on recent papers in the technical literature, we utilize tools from compressive sensing to perform localization. We also show how well-known techniques (such as the extended Kalman filter) can be used to develop powerful localization methods in the

massive MIMO regime.

5. *5G localization above 28 GHz:* Above 28 GHz, the large bandwidth and the presence of few specular reflections in the channel lead to fundamentally different localization opportunities. This forms the core of the tutorial. We cover fundamental performance bounds (based on Fisher information, already covered in part 1), positioning algorithms (based on compressive sensing, already covered in part 3), as well as methods for radio mapping the environment for simultaneous localization and mapping (SLAM). Aspects related to beamforming and hybrid precoding will be included.
6. *5G cooperative positioning:* Through D2D communication, cooperative localization can be harnessed to improve both coverage and accuracy. The concept of cooperative localization for 5G will be derived, again in terms of performance bounds and algorithms.
7. *Joint positioning and communication:* In 5G mmWave, location information has been shown to be useful for initial access, beam tracking, and scheduling. We will provide an overview of results in this area, and highlight the benefit of in-band location information with respect to out-of-band location information (e.g., from GPS).
8. *Research challenges, conclusions, list of references:* We will conclude the tutorial with a list of research challenges, useful for researchers wishing to embark on this topic. Finally, we will also deliver the overall conclusions and an extensive list of references from the technical literature.

7. Experience of the speakers

As seen from the CVs, the speakers have extensive experience in the area of radio-based localization. To exemplify their technical knowledge, below a list of recent related publications:

- Bernhard Etzlinger and **Henk Wymeersch** (2018), "Synchronization and Localization in Wireless Networks", *Foundations and Trends® in Signal Processing*: Vol. 12: No. 1, pp 1-106.
- R. M. Buehrer, **H. Wymeersch** and R. M. Vaghefi, "Collaborative Sensor Network Localization: Algorithms and Practical Issues," in *Proceedings of the IEEE*, vol. 106, no. 6, pp. 1089-1114, June 2018.
- G. E. Garcia, **G. Seco-Granados**, E. Karipidis, **H. Wymeersch**, "Transmitter Beam Selection in Millimeter-Wave MIMO with In-Band Position-Aiding", *IEEE Transactions on Wireless Communications*, vol. 17, no. 9, pp. 6082-6092, September 2018.
- Z. Abu-Shaban, Xiangyun Zhou, T. Abhayapala, **G. Seco-Granados, H. Wymeersch**, "Error Bounds for Uplink and Downlink 3D Localization in 5G mmWave Systems", *IEEE Transactions on Wireless Communications*, vol. 17, no. 8, pp. 4939-2018, August 2018.
- A. Shahmansoori, G. E. Garcia, G. Destino, **G. Seco-Granados** and **H. Wymeersch**, "Position and Orientation Estimation Through Millimeter-Wave MIMO in 5G Systems," in *IEEE Transactions on Wireless Communications*, vol. 17, no. 3, pp. 1822-1835, March 2018.
- **H**. **Wymeersch, G. Seco-Granados**, G. Destino, D. Dardari, and F. Tufvesson, "5G mm-Wave Positioning for Vehicular Networks", in *IEEE Wireless Communications Magazine*, Dec. 2017.
- J. A. del Peral-Rosado, R. Raulefs, J. A. Lopez-Salcedo, **G. Seco-Granados**, "Survey of Cellular Mobile Radio Localization Methods: from 1G to 5G", *IEEE Communications Surveys and Tutorials*, vol. 20, no. 2, pp. 1124-1148, Apr 2018,
- A. Shahmansoori, **G. Seco-Granados, H. Wymeersch**, "Survey on 5G Positioning", chapter in *Multi-technology Positioning, Springer*, pp. 165 - 196, Jan 01 2017.

8. Previous tutorial experience

The presenters have extensive experience in tutorials at IEEE communication conferences:

- 2007: IEEE International Symposium on Personal, Indoor and Mobile Radio Communications
- (PIMRC), IEEE Military Comm. Conference (MILCOM)
- 2008: IEEE Vehicular Technology Conference (VTC), IEEE Sarnoff Symposium, IEEE MILCOM
- 2009: IEEE Wireless Comm. and networking conference (WCNC), IEEE VTC, IEEE International Conference on Communications (ICC)

- 2010: IEEE PIMRC
- 2011: IEEE Swedish Communication Technologies Workshop
- 2012: IEEE WCNC
- 2013: IEEE WCNC, IEEE ICC
- 2014: IEEE International Symposium on Wireless Communication Systems
- 2015: IEEE International Conference on Systems, Communications and Coding
- 2016: International Summer School of Automatic Control, Grenoble

In addition, the presenters have presented variations on the current tutorial on 5G positioning at a number of venues in 2017 and 2018.

- 1.5-hour tutorial at 5GCAR summer school 2018 (attendance 70)
- 1.5-hour tutorial at INSURE/DELTA Summer School 2018 on “Cybersecurity in Localization”, Finland, (attendance 30)
- 3-hour tutorial at IEEE PIMRC 2018 (attendance 25)
- 3-hour lecture at the 2017 Joint IEEE SPS and EURASIP Summer School on Signal Processing for 5G Wireless Access, Sweden (attendance 100)
- 2-hour lecture at Ericsson AB, Sweden (attendance 20)
- 1-hour lecture at CEA-LETI, France (attendance 70)
- 1-hour lecture at IRACON workshop on dependable wireless communication and Localization, Austria, 2017 (attendance 80)
- 2-hour lecture at École Nationale Supérieure de l'Electronique et de ses Applications (ENSEA), Cergy, France, 2017 (attendance 10)
- 1.5-hour lecture at e-KnoT project school, Poland (attendance 15)
- 3-hour youtube video https://www.youtube.com/watch?v=VKF-Xgn0O6A

8. Related tutorials

Venue	Title	Relation
Globecom 2018	--	--
ICC 2018	“Network Localization and Navigation: Fundamental Limits, Cooperative Algorithms, and Network Experimentation” by Moe Z. Win and Andrea Conti	This tutorial is focused on general radio positioning as well as on cooperative positioning. In our tutorial, we only focus on 5G, so we are narrower but deeper in the specific area of 5G. We have a small topic on cooperative localization, since 5G will have device-to-device communication so that cooperation is relevant.
Globecom 2017	--	--
ICC 2017	“Cellular localization: principles, evolution and new trends towards 5G” by Ronald Raulefs, German Aerospace Center, Germany, and José A. del Peral-Rosado, Universitat Autònoma de Barcelona, Spain	This tutorial provides an overview of cellular localization across different generations (1G, 2G, 3G, 4G), with a short discussion on the promise of 5G. Thus, our tutorial complements this, as we consider how to fulfill this promise in practice.

Title: Machine Learning for Wireless Networks: Basics, Applications, and Trends

Abstract, objectives, and motivation:

Abstract: This tutorial will provide a friendly introduction to the different machine learning (ML) techniques with their applications to design and optimization of wireless communications networks. After motivating the potential applications of machine learning for the evolving future cellular networks (e.g. 5G and beyond 5G [B5G] cellular networks), it will introduce the basics of machine learning (ML) tools and the related mathematical preliminaries. In particular, the basics of supervised, unsupervised, and reinforcement learning techniques as well as artificial neural networks will be discussed. The basics of deep learning and deep reinforcement learning will be also provided. Then, applications of ML techniques to different "wireless" problems including resource allocation, mobility prediction, channel estimation, as well as coverage and capacity optimization will be discussed and the current state-of-the-art will be reviewed. This will be followed by three case studies on using (i) supervised and unsupervised learning for cooperative spectrum sensing, (ii) a deep supervised learning technique for resource allocation, and (iii) reinforcement learning techniques for mobile computation offloading in cellular networks. Finally, the current trends, open research challenges and future research directions on using ML techniques in wireless networks will be discussed.

Objectives: The objective of this tutorial is to provide a friendly introduction of different ML techniques to the wireless communications engineers and researchers. This will be achieved through discussing the mathematical preliminaries for the different ML methods, the existing literature on the use of these ML techniques in wireless systems, several case studies in detail (to illustrate the applications of supervised, unsupervised, and deep learning techniques in wireless networks) and the current research trends and potential future research directions. The useful technical resources on this topic (including programming codes written using MATLAB machine learning tool box) will also be introduced.

Motivation: Many of the fundamental challenges in designing wireless networks (e.g. radio resource allocation, interference management, mobility prediction) are often formulated and solved using tools from optimization theory. These problems need to be solved for specific network scenarios taking into account the rapidly varying wireless channels and quality-of-service (QoS) requirements of the users. When the optimization problems are non-convex (which is often the case in a real-world scenario), the optimal solutions are obtained by applying exhaustive search methods, genetic algorithms, combinatorial, and branch and bound techniques which incur significantly high time and computational complexities. Therefore, these methods are not appealing for large-scale heterogeneous cellular networks with ultra-dense base station (BS) deployments, massive connections, and different resources (e.g. transmission time, frequency channels, antennas, transmit power) and diverse QoS requirements for different classes of users. Sub-optimal solutions obtained based on techniques such as Lagrangian relaxations, iterative distributed optimization, heuristic algorithms, and cooperative game theory are also often very computation intensive and/or may not be feasible for large cellular networks due to high signaling overhead. Also, these sub-optimal solutions can be far from optimal solutions and their convergence properties and the optimality gap could be unknown.

In the above context, machine learning (ML) tools can be used to obtain practical solutions for large and dense wireless networks by exploiting the historical data/behavior of the system, especially in today's 5G/B5G and "big data" era. Depending on the learning procedure, ML algorithms are classified into three categories: Supervised learning, unsupervised learning, and reinforcement learning. Due to software advancement and increase in computational capabilities another type of powerful ML algorithm known as Deep Learning (DL) is getting popular nowadays. It has already been applied to applications such as computer vision and pattern recognition, object detection, face detection, speech recognition. Some ML techniques have been applied to cellular networks for mobility prediction, traffic prediction, resource allocation, handover optimization, load balancing, fault detection, fault classification, cell outage management and caching. Application of ML techniques can also be found in cognitive radio networks for spectrum sensing, bandwidth allocation, interference and power management.

Compared to iterative distributed optimization and heuristic sub-optimal techniques, ML-based algorithms can be implemented online. With ML, the required information is learned directly from the data samples instead of complicated mathematical models. ML automatically extracts complex features from data samples which is difficult for humans. From the perspective of reducing capital and operation expenditures (CAPEX/OPEX) and increasing network performance in terms of network capacity, coverage and service quality, self-organized networking (SON) will be key requirement of future wireless networks. And ML is considered as a tool to achieve this self-organization and automation. Again, ML techniques can bring intelligence in network management as ML can learn from experience. For the above reasons, machine learning (deep learning in particular) is emerging as a potential technique to obtain practical solutions for many decision and management problems in wireless networks. This motivates the development of this tutorial for wireless researchers, which will enable them to have a handle on this topic and explore this exciting area of research.

Timeliness and intended audience:

The research on using ML and artificial intelligence (AI) techniques is gaining increasing popularity and it is highly likely that ML and AI techniques will be among the key ingredients for designing beyond 5G (B5G) networks. This tutorial will be of interest to the audience (researchers and engineers) from both the wireless communications and networking community who are interested in design and optimization of future-generation wireless networks (e.g. B5G networks), data analytics for wireless networks, as well as intelligent/smart/self-organizing wireless networks. Due to the timeliness of the topic as well as the track record of the speaker, the tutorial is expected to attract a good crowd of attendees. The primary audience will consist of the following groups:

i) Researchers and communication engineers interested in learning the basics of ML, deep neural networks, and deep learning,
ii) Researchers and communication engineers interested in the state-of-the-art research in using ML and AI in wireless networks,
iii) Graduate students researching on next-generation wireless systems.

Name, affiliation, and biography of the tutorial speaker:

- **Ekram Hossain**, Ph.D., P.Eng., IEEE Fellow
  Member, College of the Royal Society of Canada
  Professor, Department of Electrical and Computer Engineering, University of Manitoba
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- **Ekram Hossain** (F'15) is a Professor in the Department of Electrical and Computer Engineering at University of Manitoba, Canada. He is a Member (Class of 2016) of the College of the Royal Society of Canada. Dr. Hossain's current research interests include design, analysis, and optimization of wireless communication networks with emphasis on 5G and B5G cellular networks. He has authored/edited several books in these areas (http://home.cc.umanitoba.ca/∼hossaina). To date, his research works have received close to 23,000 citations (in Google Scholar, with h-index = 77). He has presented numerous invited talks/seminars as well as tutorials in IEEE conferences including IEEE Globecom, ICC, WCNC, and VTC. He was a Distinguished Lecturer of the IEEE Communications Society for two consecutive terms (2012-2015). Currently he is a Distinguished Lecturer of the IEEE Vehicular Technology Society. He was elevated to an IEEE Fellow "for contributions to spectrum management and resource allocation in cognitive and cellular radio networks". He received the 2017 IEEE ComSoc TCGCC (Technical Committee on Green Communications & Computing) Distinguished Technical Achievement Recognition Award "for outstanding technical leadership and achievement in green wireless communications and networking". *He was listed as a Clarivate Analytics Highly Cited Researcher in Computer Science in 2017 and 2018*. Dr. Hossain has won several research awards including the "2017 IEEE Communications Society Best Survey Paper Award", IEEE VTC 2016-Fall "Best Student Paper Award" as a co-author, IEEE Communications Society Transmission, Access, and Optical Systems (TAOS) Technical Committee's Best Paper Award in IEEE Globecom 2015, University of Manitoba Merit Award in 2010, 2013, 2014, and 2015 (for Research and Scholarly Activities), the 2011 IEEE Communications Society Fred Ellersick Prize Paper Award, and the IEEE Wireless Communications and Networking Conference 2012 (WCNC'12) Best Paper Award. Currently he serves as the Editor-in-Chief of IEEE Press (2018-). Also, he serves as an Editor for *IEEE Wireless Communications*. Previously, he served as the Editor-in-Chief for the *IEEE Communications Surveys and Tutorials* (2012-2016), Area Editor for the *IEEE Transactions on Wireless* in the area of "Resource Management and Multiple Access" (2009-2011), an Editor for the *IEEE Transactions on Mobile Computing* (2007-2012), and an Editor for the *IEEE Journal on Selected Areas in Communications - Cognitive Radio Series* (2011-2014).

Description of the technical issues that the tutorial will address and timeliness:

In this tutorial, the following technical issues will be addressed:

- Trends in the evolution of future generation wireless networks (e.g. ultra-densification, ultra-reliability and low-latency, distributed large antenna technologies along with non-orthogonal multiple access, traffic uncertainty, wide diversity in requirements, "no-cell" concept, virtualization, and "softwarization") and convergence of sensing, communications, and computing.
- Relevance of machine learning in design and control of future generation wireless networks
- Basics of different machine learning methods (supervised, unsupervised, reinforcement learning, as well as deep reinforcement learning) along with the mathematical preliminaries
- Current state-of-the-art on using machine learning in wireless networks
- Case studies on the applications of supervised deep learning, supervised learning, and reinforcement learning in large cellular networks, cognitive radio networks, and mobile edge computing.
- Open challenges and future research directions.

Outline of the tutorial content, including its tentative schedule:

i) *Emerging wireless networks and promises of machine learning* (**10 minutes**)

ii) *Basics of Machine Learning (ML) Methods* (**75 minutes**)
   a) Bayes' classifier
   b) K-Nearest Neighbor (K-NN)
   c) K-means clustering
   d) Decision Tree (DT) classifier
   e) Support Vector Machine (SVM)
   f) Recommender system
   g) Dimensionality reduction
   h) Artificial Neural Network (ANN)
   i) Deep Neural Network (DNN)
   j) Auto-Encoders
   k) Reinforcement learning
   l) Deep reinforcement learning

iii) *Applications of ML algorithms in wireless networks: Existing state-of-the-art* (**35 minutes**)
   a) Mobility prediction
   b) Handover (HO) optimization
   c) Resource allocation
   d) Interference management
   e) Fault detection & classification
   f) Coverage and capacity optimization
   g) Load balancing
   h) Neighbor Cell List (NCL) configuration
   i) Channel estimation

iv) *Detailed case studies:* (**75 minutes**)
   a) Unsupervised and supervised machine learning techniques for cooperative spectrum sensing
   b) Resource management in dense and large cellular networks using deep supervised learning
   c) Computation offloading using reinforcement learning

v) *Open Issues, Trends, and Future Research Directions* (**15 minutes**)

5. A description of the past/relevant experience of the speaker(s) on the topic of the tutorial:

The instructor has published on this topic (e.g., see Refs. [1]-[8] below) and also delivered invited seminars on this topic the most recent one being the following:

"Deep learning for resource allocation in wireless networks", keynote talk, the *14th International Conference on Advanced Data Mining and Applications (ADMA 2018)*, 16-18 Nov, 2018, Nanjing, China.

However, he has not given any tutorial on this topic.

A description of previous tutorial experience of the instructor:

The instructor has a track record of presenting tutorials in the IEEE conferences including *ICC'18*, *Globecom'17*, *ICC'16*, *VTC'16 -Fall*, *Globecom'16*, *ICC'14*, *Globecom'14*, *ICC'13*, *Globecom'13*, *ICC'12*, *Globecom'11*, *PIMRC'11*, *ICC'10*, *ICC'09*, *VTC'08-Fall*, *Globecom'07*, and *WCNC'07*.

Recent tutorials on this topic: To the best of my knowledge, *there have been only TWO* *tutorials on this topic in recent major IEEE conferences (e.g. in IEEE Globecom'18): one on "deep learning for communications" and the other one primarily on "artificial neural networks". Both of them seem to focus on neural networks and do not cover ML methods such as dimensionality reduction, recommender system, SVM, reinforcement learning, and deep reinforcement learning. This proposed tutorial will be, on the other hand, more general and cover all the basic machine learning techniques along with example "wireless" applications and detailed case studies.*

References

[1] K. N. R. Surya Vara Prasad, **E. Hossain**, and V. K. Bhargava, "Machine learning methods for user positioning with uplink RSS in distributed massive MIMO," *IEEE Transactions on Wireless Communications*, to appear.

[2] K. N. R. Surya Vara Prasad, **E. Hossain**, V. K. Bhargava, and S. Mallick, "Analytical approximation-based machine learning methods for user positioning in distributed massive MIMO," *IEEE Access*, to appear.

[3] K. N. R. Surya Vara Prasad, **E. Hossain**, and V. K Bhargava, "Low-dimensionality of noise-free RSS and its application in distributed massive MIMO," *IEEE Wireless Communications Letters*, vol. 7, no. 4, pp. 486-489, August 2018.

[4] K. M. Thilina, K. W. Choi, N. Saquib, and **E. Hossain**, "Machine learning techniques for cooperative spectrum sensing in cognitive radio networks," *IEEE Journal on Selected Areas in Communications - Cognitive Radio Series*, vol. 31, no. 11, November 2013, pp. 2209–2221.

[5] K. W. Choi and **E. Hossain**, "Opportunistic access to spectrum holes between packet bursts: A learning-based approach," *IEEE Transactions on Wireless Communications*, vol. 10, no. 8, August 2011, pp. 2497–2509.

[6] S. Ranadheera, S. Maghsudi, and **E. Hossain**, "Minority games with applications to distributed decision making and control in wireless networks," *IEEE Wireless Communications*, vol. 24, no. 5, Oct. 2017, pp. 184-192.

[7] S. Maghsudi and **E. Hossain**, "Multi-armed bandits with application to 5G small cells," *IEEE Wireless Communications*, vol. 23, no. 3, June 2016, pp. 64–73.

[8] K. I. Ahmed, H. Tabassum, and **E. Hossain**, "Deep learning for radio resource allocation in multi-cell networks," submitted.

Orthogonal Time Frequency Space (OTFS) Modulation

Tutorial Proposal for ICC 2019

A. Chockalingam, Yi Hong, and Emanuele Viterbo

Abstract

Emerging mass transportation systems – such as self-driving cars, high-speed trains, drones, flying cars, and supersonic flight – will challenge the design of future wireless networks due to high-mobility environments: a large number of high-mobility users require high data rates and low latencies. The physical layer modulation technique is a key design component to meet the system requirements of high mobility. Currently, orthogonal frequency division multiplexing (OFDM) is the modulation scheme deployed in 4G long term evolution (LTE) mobile systems, where the wireless channel typically exhibits time-varying multipath fading. OFDM can only achieve a near-capacity performance over a doubly dispersive channel with a low Doppler effect, but suffers heavy degradations under high Doppler conditions, typically found in high-mobility environments. Orthogonal time frequency space (OTFS) modulation has been very recently proposed by Hadani et al. at WCNC'17, San Francisco. It was shown to provide significant advantages over OFDM in doubly dispersive channels. OTFS multiplexes each information symbol over a 2D orthogonal basis functions, specifically designed to combat the dynamics of the time-varying multipath channels. As a result, all information symbols experience a constant flat fading equivalent channel. OTFS is only in its infancy, leaving many opportunities for significant developments on both practical and theoretical fronts.

I. Objectives and motivation

Attendees of this workshop will:

- recognize the challenges of high mobility channels affected by both multipath and multiple Doppler shifts in PHY layer waveform design and performance;
- understand the limitations of current multicarrier techniques such as OFDM in high mobility channels;
- recognize the mathematical and physical relations between the different domains for representing wireless channels as well as signals: time-frequency, time-delay, delay-Doppler;
- master analytically and by matlab hands-on examples the key blocks of an OTFS modulator and demodulator;
- understand the special features and advantages of OTFS with regard to channel estimation, MIMO and multiuser MIMO, precoding, and performance;
- realize the importance of OTFS for current and future applications to 5G and beyond.

II. Timeliness and intended audience

The following is a complete list of researchers that have already produced some new results in OTFS and are currently working on it. The organizers have received very positive feedback at their presentations on OTFS at the workshop ITA 2018, San Diego, February 2018. A tutorial was delivered at the IEEE Vehicular Technology Conference in August 2018, Chicago, highlighting the presence of a number of research groups interested in this area, both from industry and academia.

Ronny Hadani, Cohere Technologies <ronny.hadani@cohere-technologies.com>
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This tutorial will be of interest to all the participants of the ICC 2019 workshop *W08: Wireless Communications in High-Mobility*.

III. Tutorial speakers

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Ananthanarayanan Chockalingam (S'92–M'93–SM'98) was born in Rajapalayam, Tamil Nadu, India. He received the B.E. (Hons.) degree in electronics and communication engineering from the PSG College of Technology, Coimbatore, India, in 1984; the M.Tech. degree in electronics and electrical communication engineering (with specialization in satellite communications) from the Indian Institute of Technology, Kharagpur, India, in 1985; and the Ph.D. degree in electrical communication engineering (ECE) from the Indian Institute of Science (IISc), Bangalore, India, in 1993. From 1986 to 1993, he was with the Transmission R&D Division, Indian Telephone Industries Limited, Bangalore. From December 1993 to May 1996, he was a Postdoctoral Fellow and an Assistant Project Scientist with the Department of

Electrical and Computer Engineering, University of California, San Diego, CA, USA. From May 1996 to December 1998, he was with Qualcomm, Inc., San Diego, as a Staff Engineer/Manager in the Systems Engineering Group. In December 1998, he joined as an Assistant Professor in the Department of ECE, IISc, Bangalore, where he is currently a Professor working in the area of wireless communications and networking. Dr. Chockalingam served as an Associate Editor of the IEEE TRANSACTIONS ON VEHICULAR TECHNOLOGY, as an Editor of the IEEE TRANSACTIONS ON WIRELESS COMMUNICATIONS, and as a Guest Editor of the IEEE JOURNAL ON SELECTED AREAS IN COMMUNICATIONS (Special Issue on Multiuser Detection for Advanced Communication Systems and Networks), and of the IEEE JOURNAL OF SELECTED TOPICS IN SIGNAL PROCESSING (Special Issue on Soft Detection on Wireless Transmission). He received the Swarnajayanti Fellowship and the J. C. Bose National Fellowship from the Department of Science and Technology, Government of India. He is a Fellow of the Indian National Academy of Engineering; the National Academy of Sciences, India; the Indian National Science Academy; and the Indian Academy of Sciences.

Yi Hong (S'00–M'05–SM'10) is currently a Senior lecturer at the Department of Electrical and Computer Systems Eng., Monash University, Melbourne, Australia. She obtained her Ph.D. degree in Electrical Engineering and Telecommunications from the University of New South Wales (UNSW), Sydney, and received the NICTA-ACoRN Earlier Career Researcher Award at the Australian Communication Theory Workshop, Adelaide, Australia, 2007. Dr. Hong was an Associate Editor for IEEE Wireless Communication Letters and Transactions on Emerging Telecommunications Technologies (ETT). She was the General Co-Chair of IEEE Information Theory Workshop 2014, Hobart; the Technical Program Committee Chair of Australian Communications Theory Workshop 2011, Melbourne; and the Publicity Chair at the IEEE Information Theory Workshop 2009, Sicily. She was a Technical Program Committee member for many IEEE leading conferences. Her research interests include communication theory, coding and information theory with applications to telecommunication engineering.

Emanuele Viterbo (F'2011) received his degree (Laurea) in Electrical Engineering in 1989 and his Ph.D. in 1995 in Electrical Engineering, both from the Politecnico di Torino, Torino, Italy. From 1990 to 1992 he was with the European Patent Office, The Hague, The Netherlands, as a patent examiner in the field of dynamic recording and error-control coding. Between 1995 and 1997 he held a post-doctoral position in the Dipartimento di Elettronica of the Politecnico di Torino. In 1997-98 he was a post-doctoral research fellow in the Information Sciences Research Center of AT&T Research, Florham Park, NJ, USA. He became first Assistant Professor (1998) then Associate Professor (2005) in Dipartimento di Elettronica at Politecnico di Torino. In 2006 he became Full Professor in DEIS at University of Calabria, Italy. From September 2010 he is Professor in the ECSE Department and Associate Dean Graduate Research of the Faculty of Engineering at Monash University, Melbourne, Australia. Emanuele Viterbo is a 2011 Fellow of the IEEE, an ISI Highly Cited Researcher and Member of the Board of Governors of the IEEE Information Theory Society (2011-2013 and 2014-2016). He served as Associate Editor of IEEE Transactions on Information Theory, European Transactions on Telecommunications and Journal of Communications and Networks. His main research interests are in lattice codes for the Gaussian and fading channels, algebraic coding theory, algebraic space-time coding, digital terrestrial television broadcasting, and digital magnetic recording.

IV. Description of the technical issues

The physical layer modulation scheme is a key component in wireless communication systems deployed in rapidly varying channels. Currently, OFDM is the scheme deployed in 4G Long-Term Evolution (LTE) mobile systems, where the wireless channel typically exhibits some time-varying multipath fading. The time variations of the wireless channel are due to Doppler effects, caused by either i) transmitter or receiver mobility; or ii) rapidly moving scatterers (i.e., objects that reflect, scatter, or diffract the propagating signals), even if both link ends are static. Such a channel can be modelled as a linear doubly dispersive channel; that is, the transmitted signal experiences dispersion in both time and frequency as it passes through the channel. OFDM can achieve near-capacity performance over a doubly dispersive channel with low single Doppler shift, but suffers heavy degradations under multiple Doppler shifts, which is typical in high-mobility environments. Hence, there is a need for new modulation techniques that are robust to doubly dispersive channels for next-generation (5G) cellular networks. One such modulation scheme is the recently proposed (2017) OTFS [1], [2], [3], which has significant advantages over OFDM in doubly dispersive channels. OTFS multiplexes each information symbol over 2D orthogonal basis functions, which are specifically designed to address the dynamics of the time-varying multipath channels. In contrast to traditional OFDM, all information symbols experience a constant flat fading equivalent channel. The key features of OTFS are illustrated in Figs 1,2,3. The system diagram in Fig. 1 shows how OTFS modulation is produced by a cascade of a pair of 2D transforms at both the transmitter and the receiver. The modulator first maps the information symbols x[k,l] in the delay-Doppler domain (Figs 2b and 3b) (to symbols X[n,m] in the time–frequency domain (Figs 2a and 3a)) using the inverse symplectic finite Fourier transform (ISFFT). Next, the Heisenberg transform (modulator) is applied to time–frequency symbols X[n,m] to create the time domain signal s(t) transmitted over the wireless channel. At the receiver, the received time-domain signal r(t) is mapped to the time–frequency domain through the Wigner transform (the inverse of the Heisenberg transform, acting as matched filter), and then to the delay–Doppler domain for symbol demodulation. Note that OTFS can also be interpreted as a method of precoding an OFDM system (inner dotted box in Fig. 1). The bibliography comprises most of the papers recently appeared on OTFS ([1]–[10]) as well as some more classical papers about doubly dispersive channels and other related topics ([11]–[22]).

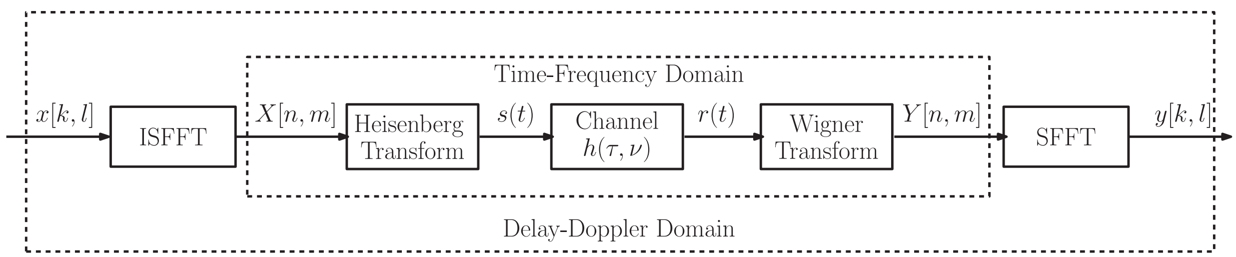

Figure 1. OTFS mod/demod

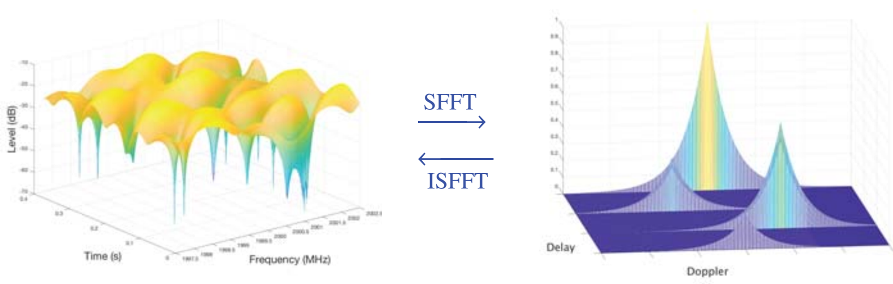

Figure 2. Channel in time–frequency $H(t, f)$ and delay–Doppler $h(\tau, \nu)$

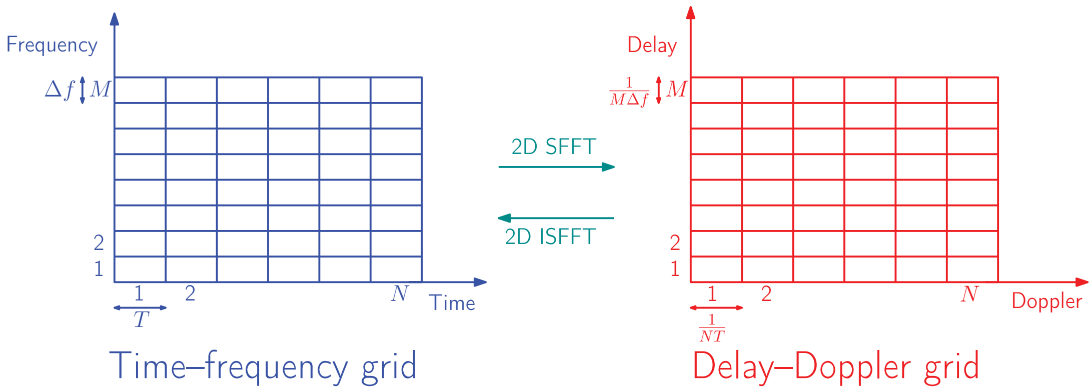

Figure 3. Time–frequency and delay–Doppler grids

V. Outline of the Tutorial Content

This 180 minutes tutorial will be delivered under the following structure.

1) Introduction (20 minutes)
   1.1. Evolution of wireless
   1.1. High-Doppler wireless channels
   1.2. Conventional modulation schemes (e.g., OFDM)
   1.3. Effect of high Dopplers in conventional modulation
2) Wireless channel representation (30 minutes)
   2.1. Time-frequency representation
   2.2. Time-delay representation
   2.3. Delay-Doppler representation
3) OFTS modulation (40 minutes)
   3.1. Signaling in the delay-Doppler domain
   3.2. Roots in representation theory
   3.3. OTFS signaling architecture
   3.4. Compatibility with OFDM architecture
4) OTFS signal detection (30 minutes)
   4.1. Vectorized formulation of the input-output relation
   4.2. Message passing based detection
   4.3. MCMC based detection
   4.4. Performance and complexity
5) OTFS channel estimation (30 minutes)
   5.1. Channel estimation in delay-Doppler domain
   5.2. Time-frequency shift problem
   5.3. PN-pilot based estimation
   5.4. Performance and complexity
6) MIMO/multiuser MIMO and precoding with OTFS (15 minutes)
   6.1. Delay-doppler precoding
   6.2. Performance and complexity
7) Applications in 5G and beyond (10 minutes)
   7.1. Key use cases
   7.2. V2X, High-speed train, mmWave, IoT communications
8) Conclusions (5 minutes)

VI. Experience of Speakers

A. Chockalingam has been a Tutorial Speaker at the IEEE VTC2011-Spring, Budapest, May 2011 where he presented a half-day tutorial on “Low-Complexity Algorithms for Large-MIMO Detection”

(http://www.ieeevtc.org/vtc2011spring/tutorials.php)
Yi Hong has been a lecturer for over ten years designing and teaching undergraduate and master level courses on Communications Theory, Wireless Communications and Error Control Coding.
Emanuele Viterbo has been a Tutorial Lecturer at the 2016 European School of Information Theory, April 4-8, 2016 (http://www.itsoc.org/conferences/schools/past-schools/european-school-2016) where he presented a half day course on "Lattice Index Codes: How to Utilize Side Information at the PHY Layer".
The authors have delivered a first edition of this tutorial at the VTC Fall 2018, Chicago. Since then a number of new results have been published and will be integrated in the ICC 2019 revised version.

VII. Similar tutorial

This is the first time a tutorial on OTFS is presented at Globecom or ICC.

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[1] R. Hadani, S. Rakib, M. Tsatsanis, A. Monk, A. J. Goldsmith, A. F. Molisch, and R. Calderbank, "Orthogonal time frequency space modulation," in *Proc. IEEE WCNC*, San Francisco, CA, USA, March 2017.

[2] Ronny Hadani and Anton Monk, "OTFS: A new generation of modulation addressing the challenges of 5G," *OTFS Physics White Paper*, Cohere Technologies, 7 Feb. 2018. Available online: https://arxiv.org/pdf/1802.02623.pdf

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Orbital Angular Momentum for Wireless Communications: Theory, Challenges, and Future Trends

1. Abstract

It is now very difficult to use the traditional plane-electromagnetic (PE) wave based wireless communications to satisfy the ever-lasting capacity demand growing. Fortunately, the electromagnetic (EM) wave possesses not only linear momentum, but also angular momentum, which includes the orbital angular momentum (OAM). The orbital angular momentum (OAM), which is a kind of wave front with helical phase and has not been well studied yet, is another important property of EM wave. The OAM-based vortex wave has different topological charges, which are independent and orthogonal to each other, bridging a new way to significantly increase the capacity of wireless communications. This proposal will be discussing the fundamental theory of using orbital angular momentum (OAM) for wireless communications. This proposal would start with the background introduction on what is OAM based wireless communication and how OAM is important in current and future wireless communications. Then, the fundamental theory of OAM will be elaborated on in details, including OAM versus MIMO, OAM signal generation/reception, and OAM beam converging. Moreover, we would also like to share our latest research progress regarding how to apply OAM into wireless communications, including mode modulations, OAM mode convergence, mode hopping, OAM based MIMO, orthogonal mode division multiplexing, concentric UCAs based low-order OAM transmission, degree of freedom in mode domain as well as orthogonality of OAM mode. Finally, the applications of OAM based wireless communication are also discussed.

2. Objectives and motivation

In the future wireless communications, the amount of traffic becomes larger and larger than ever. Thus, the existing crowded spectrum will face higher pressure than ever. Although OAM has the potential to increase the spectrum efficiency, we observe that OAM has not been received sufficient efforts when we study the new vortex wireless communication techniques. Towards this end, this tutorial will highlight the importance, modeling, and solutions of our latest research progress for OAM based radio vortex wireless communication.

3. Timeliness and intended audiences

As the wireless communications networks move from 5G to 5G-beyond or even 6G, it is very urgent to develop some fundamental technologies for next negation wireless networks. OAM based wireless communications, although facing critical challenges, can offer spectrum efficiency enhancement for LOS transmission, ultra-reliability with different modes, and anti-jamming with new dimensions. The ICC audiences, who concerns the wireless transmissions and wireless networks, can learn how to use OAM based wireless communication for future wireless communications.

4. Brief CVs for each tutorial speaker

This tutorial will be presented by

Dr. Wenchi Cheng with State Key Laboratory of Integrated Services Networks,
Department of Telecommunications Engineering, Xidian University
Email：wccheng@xidian.edu.cn

The speaker's brief CV is as follows:

Wenchi Cheng (M’14-SM’18) received the B.S. and Ph.D. degrees in telecommunication engineering from Xidian University, Xian, China, in 2008 and 2014, respectively, where he is an Associate Professor. He joined the Department of Telecommunication Engineering, Xidian University, in 2013, as an Assistant Professor. He was a Visiting Scholar with Networking and Information Systems Laboratory, Department of Electrical and Computer Engineering, Texas A&M University, College Station, TX, USA, from 2010 to 2011. His current research interests include 5G wireless networks and orbital-angular-momentum based wireless communications. He has published more than 70 international journal and conference papers in IEEE Journal on Selected Areas in Communications, IEEE Magazines, IEEE INFOCOM, GLOBECOM, and ICC, etc. He received the Young Elite Scientist Award of CAST, the Best Dissertation (Rank 1) of China Institute of Communications, the Best Paper Award for IEEE/CIC ICCC 2018, the Best Paper Nomination for IEEE GLOBECOM 2014, and the Outstanding Contribution Award for Xidian University. He has served or serving as the Associate Editor for IEEE Access, the IoT Session Chair for IEEE 5G Roadmap, the Publicity Chair for IEEE ICC 2019, the Next Generation Networks Symposium Chair for IEEE ICCC 2019, the Workshop Chair for IEEE ICC 2019 Workshop on Intelligent Wireless Emergency Communications Networks, the Workshop Chair for IEEE ICCC 2017 Workshop on Internet of Things.

5. Key technical issues

Some important technical problems for OAM based wireless communications and the corresponding methods will be discussed in this tutorial such as:

(1) Sequence scrambling for non-hollow-OAM based wireless communications

(2) Achieving practical OAM based wireless communications with non-aligned transceiver

(3) Mobility issues regarding radio vortex wireless communication

(4) OAM based long distance wireless communications

(5) Multiple modes for anti-jamming

(6) OAM for multiple access in wireless networks

6. Outline

Part I: Background of OAM

1. What is OAM based wireless communication: back ground and motivation
2. Mode domain versus frequency/time domain

Part II: Fundamental Theory of Using OAM for Wireless Communications

1. High Spectrum efficiency radio vortex wireless communication: multiple-mode OAM signal generation/adaptation/reception;
2. Non-hollow-OAM based wireless transmissions;
3. Long distance radio vortex wireless communications: OAM beam converging;
4. Mobility issues regarding radio vortex wireless communication;
5. OAM versus MIMO: degree of freedom, orthogonality, and capacity;
6. Anti-Jamming: Mode hopping;
7. Orthogonal mode division multiplexing;
8. Concentric UCAs based low-order OAM.

Part III: Application of Using OAM for Wireless Communications

1. Practical OAM Based Wireless Communications With Non-Aligned Transceiver;
2. Mode-Division-Multiple-Access Based MAC Protocol for Radio-Vortex Wireless Networks;
3. OAM for ultra-dense wireless networks.

7. Related experience

The speaker has published multiple papers in the aspect of OAM based wireless communications in recent two years. Some novel schemes for resolving critical problems in OAM based wireless communications have been developed. Related papers are listed as follows:

[1] **Wenchi Cheng**, Wei Zhang, Haiyue Jing, Shanghua Gao, and Hailin Zhang, "Orbital Angular Momentum for Wireless Communications," to appear in IEEE Wireless Communications Magazine, 2018.

[2] Liping Liang, **Wenchi Cheng**, Wei Zhang, and Hailin Zhang, "Mode Hopping for Radio Vortex Wireless Communications," IEEE Transactions on Vehicular Technology, vol. 67, no.8, pp.7018-7032, Aug. 2018.

[3] Yuewen Yang, **Wenchi Cheng**, Wei Zhang, and Hailin Zhang, "Mode-Modulation for Wireless Communications With a Twist", IEEE Transactions on Vehicular Technology, vol. 67, no.11, pp.10704-10714, Nov. 2018.

[4] **Wenchi Cheng**, Hailin Zhang, Liping Liang, Haiyue Jing, and Zan Li, "Orbital-Angular-Momentum em[ant]bedded Massive MIMO: Achieving Multiplicative Spectrum-Efficiency for mmWave Communications," IEEE Access, vol. 6, pp 2732-2745, 2018.

[5] Haiyue Jing, **Wenchi Cheng**, and Xiang-Gen Xia, "Concentric UCAs Based Low-Order OAM for High Capacity in Radio Vortex Wireless Communications," submitted to IEEE Transactions on Wireless Communications, under revision.

[6] Haiyue Jing, **Wenchi Cheng**, and Xiang-Gen Xia, "A Simple Channel Independent Beamforming Scheme with Parallel Circular Array," submitted to IEEE Wireless Communications Letter, 2018.

[7] Fan Qin, **Wenchi Cheng**, and Hailin Zhang, "A High-Gain Ku-Band Transmit array with Both Pencil Beams and OAM Beams," submitted to IEEE Transactions on Antennas and Propagation, 2018.

[8] Liping Liang, **Wenchi Cheng**, Wei Zhang, and Hailin Zhang, "Orthogonal Frequency and Mode Division Multiplexing for Wireless Communications," IEEE GLOBECOM, Abu Dhabi, 2018.

[9] Yuwen Yang, Wenchi Cheng, Wei Zhang, and Hailin Zhang, "Mode Modulation for Orbital-Angular-Momentum Based Wireless Vorticose Communications," IEEE GLOBECOM, Singapore, Dec. 2017

[10] Liping Liang, **Wenchi Cheng**, Wei Zhang, and Hailin Zhang, "Mode Division Multiplexing for Radio Vortex Wireless Communication," IEEE PIMRC, Bologna, Italy, 2018.

[11] Haiyue Jing, **Wenchi Cheng**, and Xiang-Gen Xia, "Orbital-Angular-Momentum Versus MIMO: Orthogonality, Degree of Freedom, and Capacity," IEEE PIMRC, Bologna, Italy, 2018.

[12] **Wenchi Cheng**, Zan Li, Feifei Gao, Liping Liang, and Hailin Zhang, "Mode Hopping for Anti-Jamming in Cognitive Radio Networks," IEEE ICCC 2018**. (Best paper Award)**

[13] Fan Qin, S. Gao, **Wenchi Cheng**, Yi Liu, Hailin Zhang, and Wei Gao, "A High-Gain Transmitarray for Generating Dual-Mode OAM Beams," IEEE Access, 2018.

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Multi-Orbital-Angular-Momentum-Mode-Multiplexing Vortex Radio MIMO," China Communications, 2018.

[15] Qinfan, Jianjia Yi, **Wenchi Cheng**, Yi Liu, Hailin Zhang, and Steven Gao, "A High-Gain Shared-Aperture Dual-Band OAM Antena with Parabolic Reflector," EuCap, London, Apr. 2018.

[16] Haiyue Jing, **Wenchi Cheng**, Zan Li, and Hailin Zhang, "Concentric UCAs Based Low-Order Radio Vortex Wireless Communications with Co-Mode Interference," IEEE ICCC, Qingdao, Oct. 2017. (Invited Paper)

[17] Liping Liang, **Wenchi Cheng**, Hailin Zhang, Zan Li, and Yongzhao Li, "Orbital-Angular-Momentum Based Mode-Hopping: A Novel Anti-Jamming Technique," IEEE ICCC, Qingdao, Oct. 2017.

[18] Shanghua Gao, **Wenchi Cheng**, Hailin Zhang, and Zan Li, "High-Efficient Beam-Converging for UCA Based Radio Vortex Wireless Communications," IEEE ICCC, Qingdao, Oct. 2017.

[19] Fan Qin, Lulan Wan, Lilong Li, Jia Xie, Yi Liu, **Wenchi Cheng**, and Hailin Zhang, "A Wideband High-gain Transmitarray Based on Quasi-Yagi Antenna Element", APMC 2018.

8. Tutorial experience

The speaker’s tutorial experience is listed as follows:

- Wenchi Cheng, "Orbital Angular Momentum for Wireless Communications: Theory Challenge，and Future Trends", IEEE/CIC International Conference on Communications in China (ICCC) 2018, Beijing;

- Wenchi Cheng and Qinghe Du, "Statistical Queuing and Delay Analysis and Its Applications in Wireless Networking ", IEEE/CIC International Conference on Communications in China (ICCC) 2017, Qingdao;

- Qinghe Du and Wenchi Cheng, "Statistical Queuing and Delay Analysis and Its Applications in Wireless Networking", International Conference on Communications and Networking in China (ChinaCom) 2017, Xi'an.

Wireless Channel Measurements and Models for 5G and Beyond

1. Abstract, objectives and motivation of the ICC 2019 proposal:

1) **Abstract**:

To meet the challenging requirements of supporting greatly enhanced spectrum efficiency, energy efficiency, data rate, connection density, and mobility, fifth generation (5G) wireless communication networks need to employ dramatically new network architecture and key technologies. These include massive multiple-input multiple-output (MIMO), millimeter wave (mmWave) communications, high-speed train (HST) communications, and vehicle-to-vehicle (V2V) communications. The 5G wireless communication networks are being standardized worldwide and will be deployed from 2020. However, forthcoming releases of 5G will not fully be able to meet all diverse, but often contradictory requirements, of the future. Beyond 5G (B5G) networks, expected to be developed over the next decade, will have to provide a ubiquitous always-on global network coverage and enhanced spectral/energy/cost efficiency, higher data rate, lower latency, larger connection density, etc.

For the design, performance evaluation, and optimization of 5G and B5G wireless communication systems, experimental channel measurements and realistic channel models with good accuracy-complexity-generality trade-off are indispensable. The proposed tutorial is intended to offer a comprehensive and in-depth crash course to communication professionals and academics, aiming to address recent advances and future challenges for (B)5G channel measurements and models. The tutorial will start with illustrating the fundamentals of wireless channel characterization and evolution of wireless channel models from 2G to 5G. Channel measurements and models are then reviewed for some challenging 5G scenarios, including massive MIMO, millimetre wave, V2V, and HST communication channels. We will also review existing standard 5G channel models in terms of their capabilities and drawbacks. Two more general three-dimensional (3D) non-stationary 5G channel models are proposed, filling the gaps of standard 5G channel models. It is shown that the proposed 5G channel models have statistical properties agreeing well with corresponding channel measurements and are expected to serve as good basis for future standard (B)5G channel models. B5G requirements and potential technologies will be further discussed, including the newly proposed optical mobile communication (OMC) which incorporates traditional optical wireless communication (OWC) into the mobile communication architecture. Future research challenges and trends for (B)5G channel measurements and models will be discussed in the end of the tutorial.

2) Objectives and motivation:

Compared to today standards, 5G systems need to be capable of providing higher spectrum efficiency, network energy efficiency, area traffic capacity, connection density, peak data rate, user experienced data rate, and mobility, and much less latency. These expected targets require the definition and optimization of radically-changing architectures and technologies, thus leading to a wholesale re-thinking of cellular operational principles & architectures, transmission technologies and methods to their analysis, design and optimization. There is also the possibility that 5G networks will enable digital sensing, communication and processing capabilities to be ubiquitously embedded into everyday objects, turning them into the Internet of Things (IoT). In this new paradigm, smart devices will collect data, will relay information or will contend for wireless access, and will perform most processing collaboratively over the 5G cellular network.

No matter what the eventual systems will be, it is apparent that 5G cellular networks are coming. The fundamental questions are: What channel models and evaluation methodologies shall be used for the analysis, design, and optimization of 5G technologies? How to compare different 5G proposals with a widely accepted standardized channel model? What channel measurements are available to support 5G channel models? What are the potential B5G technologies and channel models?

The fundamental and radical paradigm-shift in B5G network design and architecture requires cross-sectoral skills and background, which can very unlikely be realized by researchers that have not received personalized training on innovative technologies and adequate methodological tools to their analysis. The **fundamental objective of this tutorial** is to offer to academic and industrial researchers, graduate students and professors a crash course on these essential elements that are expected to significantly shape 5G mobile cellular systems. More specifically, this tutorial will **aim to address recent advances and future challenges for 5G and B5G related channel measurements and models**. The tutorial will first focus on illustrating the channel characteristics and models for four most challenging channel scenarios in 5G, i.e., massive MIMO, mmWave, V2V, and HST communication channels. Also, more general 3D non-stationary 5G channel models are proposed, extending from the 4G standardized channel model with additional features supporting 3D extension, mmWave bands, space-time-frequency non-stationarity, massive MIMO, HST, and V2V scenarios. The general 5G channel models are expected to serve as a good basis for future standardized (B)5G channel models.

At the end of the present tutorial, the audience will receive a thorough understanding of state-of-the-art, current research activities, theoretical & practical issues, and opportunities for research & development of essential elements for (B)5G communications, with particular focus on new channel characteristics, measurements, and models.

2. Timeliness and intended audience:

Students, academic researchers, industry affiliates, and individuals working for government and technology institutions who would like to learn about emerging (B)5G cellular architecture, transmission technologies, and in particular channel characteristics, measurements, and models in different 5G and B5G scenarios. The tutorial is intended to provide the audience with a complete overview of the channel characteristics, measurements, and models for various (B)5G related scenarios, as well as future challenges. In fact, all attendees working in (B)5G communication networks may be interested in attending the proposed tutorial.

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

Prof. Cheng-Xiang Wang, Prof. Zaichen Zhang, and Prof. Haiming Wang,
School of Information Science and Engineering
Southeast University, Nanjing 210096, China

1) Biography of Prof. Cheng-Xiang Wang:

Cheng-Xiang Wang received the BSc and MEng degrees in Communication and Information Systems from Shandong University, China, in 1997 and 2000, respectively, and the PhD degree in Wireless Communications from Aalborg University, Denmark, in 2004.

He was a Research Assistant with the Hamburg University of Technology, Hamburg, Germany, from 2000 to 2001, a Research Fellow with the University of Agder, Grimstad, Norway, from 2001 to 2005, and a Visiting Researcher with Siemens AG-Mobile Phones, Munich, Germany, in 2004. He has been with Heriot-Watt University, Edinburgh, U.K., since 2005, where he became a Professor in wireless communications in 2011. In 2018, he joined Southeast University, Nanjing, China, as a Professor. His current research interests include wireless channel measurements/modeling and (B)5G wireless communication networks. He has published 2 books, 1 book chapter, 166 journal papers, and 177 conference papers. He gave 16 invited keynote/plenary speeches and 5 tutorials at international conferences/workshops, and numerous invited talks.

He was a recipient of Nine Best Paper Awards from IEEE GLOBECOM 2010, IEEE ICCT 2011, ITST 2012, IEEE VTC 2013- Spring, IWCMC 2015, IWCMC 2016, IEEE/CIC ICCC 2016, and WPMC 2016. He has served as a technical program committee (TPC) member, the TPC chair, and a general chair for over 80 international conferences. He has served as an Editor for nine international journals, including the IEEE TRANSACTIONS ON WIRELESS COMMUNICATIONS from 2007 to 2009, the IEEE TRANSACTIONS ON VEHICULAR TECHNOLOGY (2011-2017), and the IEEE TRANSACTIONS ON COMMUNICATIONS (2015-2017). He was the Lead Guest Editor of the IEEE JOURNAL ON SELECTED AREAS IN COMMUNICATIONS, Special Issue on Vehicular Communications and Networks. He was also a Guest Editor of the IEEE JOURNAL ON SELECTED AREAS IN COMMUNICATIONS, Special Issue on Spectrum and Energy Efficient Design of Wireless Communication Networks and Special Issue on Airborne Communication Networks, and a Guest Editor of the IEEE TRANSACTIONS ON BIG DATA, Special Issue on Wireless Big Data. He is a Fellow of the IEEE, IET, and HEA. He is recognized as a Web of Science 2017 Highly Cited Researcher.

2) Biography of Prof. Zaichen Zhang:

Professor Zaichen Zhang received B.S. and M.S. degrees in Electrical and Information Engineering from Southeast University, Nanjing in 1996 and 1999, respectively, and Ph.D. degree in Electrical and Electronic Engineering from the University of Hong Kong in 2002. From 2002 to 2004, he was a Postdoctoral Fellow at the National Mobile Communications Research Laboratory, Southeast University. He is currently the executive Dean of School of Information Science and Engineering, Southeast University. He has co-authored over 200 papers and issued over 30 patents. He is Senior Member of the IEEE. He served as IEEE ICC 2015 Keynote Chair, IEEE ICNC 2015 and PIMRC Symposium Chairs, and IEEE ICC 2019 Operation Chair. He was the Distinguished Visiting Fellow of Royal Academy of Engineering, UK, 2017 and the invited speaker of IEEE ICCC 2017. His current research interests include 5G/6G mobile information systems, optical wireless communications, quantum information technologies, and channel modeling.

3) Biography of Prof. Haiming Wang:

Haiming Wang received the B.Eng., M.S., and Ph.D. degrees in Electrical Engineering from Southeast University, Nanjing, China, in 1999, 2002, and 2009, respectively. Since 2002, he has been with the State Key Laboratory of Millimeter Waves, School of Information Science and Engineering, Southeast University, China, and he is currently a professor. In 2008, he was a Visiting Scholar with the Blekinge Institute of Technology (BTH), Sweden.

He has co-authored over 50 journal papers and over 50 patents, 21 of which have been granted. He received the first-class Science and Technology Progress Award of Jiangsu Province of China in 2009 and was awarded for contributing to the development of IEEE 802.11aj by the IEEE-SA in 2018. His current research interests include millimeter-wave wireless mobile communications, millimeter-wave radar and imaging, radio propagation measurement and channel modelling, multi-band and wideband antenna and array.

He is currently serves as the vice chair of IEEE 802.11aj Task Group. He served as the TPC member or the session chair of many international conferences such as IEEE ICCT 2011, IEEE IWS 2013, and IEEE VTC 2016.

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

The proposed tutorial will address many technical issues. Here, we only list some of them as follows.

1) What are the 5G requirements, cellular architecture and key transmission technologies?
2) What are the 5G channel model requirements?
3) What are the criteria to evaluate channel measurements and models?

4) What are the methodologies of channel measurements and models?
5) What are the key characteristics of massive MIMO channels, mmWave channels, V2V channels, HST channels, and UAV channels?
6) How to model massive MIMO channels, mmWave channels, V2V channels, and HST channels?
7) What are the advantages and disadvantages of the existing standard 5G channel models?
8) How to design more general (B)5G channel models towards standardization?
9) What are potential B5G technologies and new channel characteristics?
10) What is Optical Mobile Communications Towards B5G?
11) What are future challenges of B5G channel measurements and models?

The present tutorial is proposed at a time when the transmission technologies that constitute the core tenet of the tutorial are widely acknowledged as essential to meet 5G requirements. However, at the same time, these technologies are still at their research and development stage, often partially understood by many and in some cases even misunderstood by few. The proposed tutorial is offered at a time when 5G channel models are urgently needed but many researchers do not understand the key statistical properties of these challenging 5G scenarios and what corresponding channel measurmeents/models are available. This tutorial is also proposed at a time when some graduate students and research engineers have just started their research & developing activities on B5G and may benefit from the proposed comprehensive but focused crash course. In fact, (B)5G is receiving the interest from a broad research community across all continents. Thus, the proposed tutorial is expected to draw huge interests from the wireless communications community worldwide.

The potential impact and importance of the tutorial also lies in its in-depth nature, benefiting from the tutorial speakers' over 18 years' experience of working with channel characterization, measurements, and modeling. The audience will also receive a soft copy of the tutorial material, as well as a comprehensive list of state-of-the-art references that will be instrumental for beginning or for consolidating their knowledge on 5G communications and beyond.

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

1) Fundamentals of Wireless Channel Characterization and Evolution of Channel Models
2) 5G Requirements, Cellular Architecture, and Key Technologies
3) 5G Channel Model Requirements and New Channel Characteristics
4) Massive MIMO Channel Measurements and Models
5) High-Speed Train Channel Measurements and Models
6) MmWave Channel Measurements and Models
7) Standard 5G Channel Models
8) More General 3D Non-Stationary 5G Channel Models
9) B5G Communications and Optical Mobile Communications
10) B5G Channel Models

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

Prof. Cheng-Xiang Wang delivered 10 invited keynote/plenary speeches, 6 invited talks, and 6 tutorials in international conferences/workshops. Also, he gave numerous invited talks in various institutions/companies.

Invited Keynote/Plenary Speeches (10):
1) **C.-X. Wang**, "5G Channel Models: From Fundamentals to Standardization," **invited keynote speech**, *IEEE 5G Tutorial*, Shanghai, China, 27 July 2017.

2) **C.-X. Wang**, "5G Key Technologies and Standardized Channel Models," **invited keynote speech**, *I-SPAN 2017*, Exeter, UK, 21-23 June 2017.
3) **C.-X. Wang**, "Recent Developments and Future Challenges of 5G Massive MIMO Channel Models," **invited plenary talk**, *WPMC 2016*, Shenzhen, China, 14-16 Nov. 2016.
4) **C.-X. Wang**, "Recent Developments and Future Challenges on 5G Channel Models," **invited keynote speech**, *The Global 5G Technology Summit 2016*, Shanghai, China, 20-22 July 2016.
5) **C.-X. Wang**, "A non-stationary IMT-A MIMO channel model for high-mobility systems," **invited keynote speech**, *HMWC 2015*, Xi'an, China, 21-23 Oct. 2015.
6) **C.-X. Wang**, "Recent advances and future challenges for standardized 5G channel models," **invited keynote speech**, *AICWC 2015*, Chengdu, China, 18-20 Oct. 2015.
7) **C.-X. Wang**, "MIMO vehicle-to-vehicle channel models: recent advances and future challenges," **invited keynote speech**, *International Workshop Series of Sensor Networks and Cellular Systems Research Centre*, University of Tabuk, Saudi Arabia, 7 April 2012.
8) **C.-X. Wang**, "Recent developments on realistic MIMO channel models," **invited keynote speech**, *OPTNet 2012*, Sheffiled, UK, 21-23 Mar. 2012.
9) **C.-X. Wang**, "Key wireless technologies for B4G," **invited keynote speech**, *Wireless World Research Forum (WWRF), Meeting 25*, London, UK, 16-18 Nov. 2010.
10) **C.-X. Wang**, "Cognitive radio networks: recent advances and future challenges," **invited keynote speech**, *IEEE ICISS 2010*, Guilin, China, 22-24 Oct. 2010.

Invited Talks (6):

1) **C.-X. Wang**, "Can Current Standard 5G Channel Models Satisfy Requirements?" **invited talk,** *AICWC'2017*, Chengdu, China, 7 Nov. 2017.
2) **C.-X. Wang**, "Spectral-energy efficiency trade-off of cellular systems with MFemtocell deployment," **invited talk**, *IEEE Online Green Communications*, 11 Nov. 2015.
3) **C.-X. Wang**, "Spectral, energy, and economic efficiency of 5G multi-cell massive MIMO systems with generalized spatial modulation," **invited talk**, *973 Project Workshop*, Shenzhen, China, 4 Nov. 2015.
4) **C.-X. Wang**, "Non-stationary wideband MIMO channel models for high-speed train wireless communication systems," **invited talk**, *HMWC 2014*, Beijing, China, 1-3 Nov. 2014.
5) **C.-X. Wang**, "Non-stationary wideband channel models for massive MIMO systems," **invited talk**, *WSCN 2013*, Jeddah, Saudi Arabia, 13-16 Dec. 2013.
6) **C.-X. Wang**, "Characterization and modeling of rapid time-varying MIMO channels for high-mobility wireless communication systems," **invited talk**, *AICWC 2013*, Chengdu, China, 4-6 Nov. 2013.

Tutorials (6):

1) **C.-X. Wang**, "Wireless channel models and standards development for 5G and beyond," **Tutorial**, in *IEEE/CIC ICCC'18*, Beijing, China, 16 Aug. 2018. **(about 30 attendees)**
2) **C.-X. Wang**, "Channel characterization and modeling of 5G wireless communication systems," **Tutorial**, in *IEEE ICCC'16*, Chengdu, China, 27 July 2016 **(about 30 attendees)**.
3) **C.-X. Wang**, "Modeling, analysis and optimization of 5G wireless communication networks: 5G channel models," **Tutorial**, in *IEEE ICCC'15*, Shenzhen, China, 2 Nov. 2015 **(about 50 attendees)**.
4) M. D. Renzo, C. Verikoukis, E. Björnson, E. Jorswieck, and **C.-X. Wang**, "The path towards 5G—essential technologies, protocols and tools for enabling 5G mobile communications," **Tutorial**, in *IEEE ICC'15*, London, U.K., 12 June 2015 **(about 40 attendees)**.
5) M. D. Renzo, C. Verikoukis, E. G. Larsson, E. Jorswieck, and **C.-X. Wang**, "The path towards 5G—essential technologies, protocols and tools for enabling 5G mobile communications," **Tutorial**, in *European Wireless'15*, Budapest, Hungary, 20 May 2015 **(about 60 attendees)**.

6) M. D. Renzo, C. Verikoukis, E. Björnson, E. Jorswieck, and **C.-X. Wang**, "The path towards 5G—essential technologies, protocols and tools for enabling 5G mobile communications," **Tutorial**, in *IEEE VTC'15-Spring*, Glasgow, U.K., 11 May 2015 **(about 40 attendees)**.

Prof. Zaichen Zhang gave an invited talk at IEEE/CIC ICCC 2017:

[1] Z. Zhang, "Optical mobile communications," **invited talk,** in *IEEE ICCC'17*, Qingdao, China, Oct. 2017.

Prof. **Haiming Wang** gave the following 10 invited talks in international conferences/workshops:

[1] Haiming Wang, "Key Technologies and Standardization Activities for Millimeter-Wave WLAN," **Invited Talk**, *Huawei Network Workshop*, Suzhou, China, Sept. 3, 2018.
[2] Haiming Wang, "Key Technologies and Standardization for Millimeter-Wave Wireless Systems," **Invited Talk**, *MWP Symposium*, Matsue, Japan, Aug. 6, 2018.
[3] Haiming Wang, "Design Intelligentization for Millimeter-Wave Antennas and Arrays," **Invited Talk**, *Huawei Wireless Workshop*, Chengdu, China, May 11, 2018.
[4] Haiming Wang, "Radio Propagation Measurement and Channel Modelling for New-Generation Millimeter-Wave Mobile Communications," **Invited Talk**, ICUWB 2016, Nanjing, China, Oct. 16-19, 2016.
[5] Haiming Wang, "Ultra-High Throughput Wireless LAN: IEEE 802.11aj (45 GHz)," **Invited Talk**, *IWS 2016*, Shanghai, China, Mar. 14-16, 2016.
[6] Haiming Wang, "IEEE 802.11aj (45 GHz): An Ultra High Throughput Wireless LAN," **Invited Talk**, *IWS 2013*, Beijing, China, Apr. 14-18, 2013.
[7] Haiming Wang, "IEEE 802.11aj (45 GHz): An Ultra High Throughput Wireless LAN," **Invited Talk**, *ICUWB 2012*, Syracuse, New York USA, Sept. 17-20, 2012.

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

Prof. Cheng-Xiang Wang presented part of the tutorial (5G channel models) in previous conferences/workshops. A much shorter version (40-minute presentation), with less emphasis on channel modeling, was presented at IEEE VTC'15-Spring, European Wireless'15, and IEEE ICC'15. Another shorter version (1.5-hour presentation) was presented at IEEE/CIC ICCC'15. A half-day tutorial, focusing on 5G channel models, was presented at IEEE/CIC ICCC'16 and ICCC'18. As noted above, all the previous tutorials were well attended.

Prof. Zaichen Zhang and Prof. Haiming Wang do not have tutorial experience but they frequently gave invited talks in international conferences and institutions/companies. Prof. Haiming Wang had a lot of experience on mmWave channel measurements and standardization, while Prof. Zaichen Zhang is an expert on Optical Mobile Communications towards B5G and wireless channel modeling.

Motivated by the success of past tutorials given by Prof. Cheng-Xiang Wang and, in particular, by the interest of the audience on the **(B)5G channel measurements and modeling**, we decided to put together a more detailed tutorial **adding more channel measurements/models and B5G materials**.

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

It was not offered in ICC & Globecom in the last two years.