

IEEE/CIC ICC 2021 Tutorial Proposal

1. Title of tutorial: 6G Wireless Channel Measurements and Models: Recent Advances and Future Challenges

2. Abstract of the tutorial

For the design, performance evaluation, and optimization of wireless communication systems, 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 course to communication professionals/academics, aiming to address recent advances and future challenges on channel measurements and models for sixth generation (6G) wireless systems. Network architecture and key technologies for 6G that will enable global coverage, all spectra, and full applications will be first discussed. Channel measurements and non-predictive channel models are then reviewed for challenging 6G scenarios and frequency bands, focusing on millimeter wave, terahertz, and optical wireless communication channels under all spectra, satellite, unmanned aerial vehicle, and maritime communication channels under global coverage scenarios, and high-speed train, vehicle-to-vehicle, ultra-massive multiple-input multiple-output (MIMO), industry Internet of things (IoT), and intelligent reflecting surface communication channels under full application scenarios. New machine learning based predictive channel models will also be investigated. A general non-predictive 6G benchmark channel model will then be proposed, which is expected to serve as a baseline for future standardized 6G channel models. Future research challenges and trends for 6G channel measurements and models will be discussed in the end of the tutorial.

3. Length of the tutorial: Half-day

4. Intended audience

The intended audience are students, academic researchers, industry affiliates, and individuals working for government and technology institutions who would like to learn about emerging 6G air interface and transmission technologies, network architecture, and in particular channel measurements, characteristics, and models in different 6G scenarios and frequency bands. The tutorial is intended to provide the audience with a complete overview of the channel measurements, characteristics, and models for various 6G related scenarios and frequency bands, as well as future challenges. In fact, all attendees working in 6G communication networks should be interested in attending the proposed tutorial.

5. Objective and motivation

Compared to fourth generation (4G), fifth generation (5G) systems can provide higher spectrum efficiency, network energy efficiency, area traffic capacity, connection density, peak data rate, user experienced data rate, mobility, and much less latency. For the future 6G communication system, we believe it will provide a global coverage by establishing space-air-ground-sea integrated networks, access all available spectra, support full applications with the aids of artificial intelligence (AI) technologies, and guarantee endogenous network security. No matter what the eventual systems will be, it is apparent that 5G cellular networks are coming to the commercial deployment stage, while the research of 6G is starting. The fundamental questions are: What channel models and evaluation methodologies shall be used for the analysis, design, and optimization of 6G technologies? How to compare different 6G proposals with a widely accepted standardized channel model? What channel measurements are available to support 6G channel models? What are the potential 6G technologies and channel models?

The fundamental and radical paradigm-shift in 6G network design and architecture requires cross-sectoral skills and background, which can very unlikely be realized by researchers that have not received sufficient training on innovative technologies and adequate methodological tools to their analysis. The **fundamental objective of this tutorial** is to offer academic and industrial researchers,

graduate students, and professors a crash course on these essential elements that are expected to significantly shape 6G wireless communication systems. More specifically, this tutorial will **aim to address recent advances and future challenges on 6G related channel measurements and models.**

6. Outlines

- 1) Fundamentals of Wireless Channel Characterization
- 2) Evolution of Wireless Channel Models From 2G to 5G
- 3) Standard 5G Channel Models
- 4) 6G Architecture and Key Technologies
- 5) 6G All-Spectra Channel Measurements and Models
 - a. MmWave Channel Measurements and Models
 - b. THz Channel Measurements and Models
 - c. Optical Wireless Channel Measurements and Models
- 6) 6G Global-Coverage Scenario Channel Measurements and Models
 - a. Satellite Communication Channel Measurements and Models
 - b. UAV Communication Channel Measurements and Models
 - c. Maritime Communication Channel Measurements and Models
- 7) 6G Full-Application Scenario Channel Measurements and Models
 - a. (Ultra) Massive MIMO Channel Measurements and Models
 - b. High-Speed Train Channel Measurements and Models
 - c. V2V Channel Measurements and Models
 - d. Industry IoT Channel Measurements and Models
 - e. IRS Channel Measurements and Models
- 8) Machine Learning based Channel Measurements and Models
- 9) A General 6G Wireless Channel Model: Towards Standardization
- 10) Conclusions and Future Challenges

7. Names, addresses, and a short CV (no more than 300 words) of tutorial speakers and the specific parts they will cover in the tutorial

1) **Names:** Prof. Cheng-Xiang Wang^{1,2}, Prof. Haiming Wang^{3,2}, Dr. Jie Huang^{1,2}, and Prof. Harald Haas⁴

2) **Addresses:**

¹National Mobile Communications Research Laboratory, School of Information Science and Engineering, Southeast University, Nanjing 210096, China

²Purple Mountain Laboratories, Nanjing 211111, China

³State Key Laboratory of Millimeter Wave, School of Information Science and Engineering, Southeast University, Nanjing 210096, China

⁴LiFi Research and Development Centre, Department of Electrical & Electronic Engineering, University of Strathclyde, Glasgow G1 1XW, UK

3) **CVs:**

Prof. Cheng-Xiang Wang received the B.Sc. and M.Eng. degrees in Communication and Information Systems from Shandong University, China, in 1997 and 2000, respectively, and the Ph.D. degree in Wireless Communications from Aalborg University, Denmark, in 2004.

He has been with Heriot-Watt University, Edinburgh, United Kingdom, since 2005 and became a professor in 2011. In 2018, he joined Southeast University, China, and Purple Mountain Laboratories, China, as a professor. He is now the Executive Dean of the School of Information Science and Engineering, Southeast University.

He has authored four books, three book chapters, and more than 410 papers in refereed journals and conference proceedings, including 24 Highly Cited Papers. He has also delivered 22 Invited Keynote Speeches/Talks and 7 Tutorials in international conferences. His current research interests include wireless channel measurements and modeling & 6G wireless communication networks.

Prof. Wang is a member of the Academia Europaea, a fellow of the IEEE and IET, an IEEE Communications Society Distinguished Lecturer in 2019 and 2020, and a Highly-Cited Researcher recognized by Clarivate Analytics, in 2017-2020. He is currently an Executive Editorial Committee member for the IEEE TRANSACTIONS ON WIRELESS COMMUNICATIONS. 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 from 2011 to 2017, and the IEEE TRANSACTIONS ON COMMUNICATIONS from 2015 to 2017. He has served as a TPC Member, TPC Chair, and General Chair for over 80 international conferences. He received twelve Best Paper Awards from IEEE GLOBECOM 2010, IEEE ICCT 2011, ITST 2012, IEEE VTC 2013-Spring, IWCMC 2015, IWCMC 2016, IEEE/CIC ICC 2016, WPMC 2016, WOCC 2019, IWCMC 2020, and WCSP 2020. Also, he received the “2020 AI 2000 Most Influential Scholar Award Honorable Mention” in recognition of his outstanding and vibrant contributions in the field of Internet of Things between 2009 and 2019.

Prof. 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. He is also a part-time professor with the Purple Mountain Laboratories, Nanjing, China. In 2008, he was a Visiting Scholar with the Blekinge Institute of Technology (BTH), Sweden.

He has authored and co-authored over 50 journal papers in IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION and other peer-reviewed academic journals. Prof. Wang has authored and co-authored over more than 70 patents and 52 patents 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 AI-powered antenna and radiofrequency technologies, AI-powered channel measurement and modeling technologies, and millimeter-wave and THz wireless communications. He is currently serving 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.

Dr. Jie Huang received the B.E. degree in Information Engineering from Xidian University, China, in 2013, and the Ph.D. degree in Information and Communication Engineering from Shandong University, China, in 2018.

From Oct. 2018 to Oct. 2020, he was a Postdoctoral Research Associate in the National Mobile Communications Research Laboratory, Southeast University, China, supported by the National Postdoctoral Program for Innovative Talents. From Jan. 2019 to Feb. 2020, he was a Postdoctoral Research Associate in Durham University, U.K. Since Mar. 2019, he is a part-time researcher in Purple Mountain Laboratories, China. Now he is a Lecturer in the National Mobile Communications Research Laboratory, School of Information Science and Engineering, Southeast University, China.

He has authored and co-authored more than 30 papers in refereed journals and conference proceedings. He received the Best Paper Awards from WPMC 2016 and WCSP 2020. His research interests include millimeter wave, massive MIMO, intelligent reflecting surface channel measurements and modeling, wireless big data, and 6G wireless communications.

Prof. Harald Haas received the Ph.D. degree in wireless communications from the University of Edinburgh, Edinburgh, U.K., in 2001.

He is the Director of the LiFi Research and Development Centre at the University of Strathclyde. He is also the Initiator, co-founder and Chief Scientific Officer of pureLiFi Ltd. He has authored 550 conference and journal papers, including papers in Science and Nature Communications. His main research interests are in optical wireless communications, hybrid optical wireless and RF communications, spatial modulation, and interference coordination in wireless networks. His team invented spatial modulation. He introduced LiFi to the public at an invited TED Global talk in 2011. This talk on Wireless Data from Every Light Bulb has been watched online over 2.72 million times. LiFi was listed among the 50 best inventions in TIME Magazine in 2011. He gave a second TED

Global lecture in 2015 on the use of solar cells as LiFi data detectors and energy harvesters. This has been viewed online over 2.75 million times. In 2016, he received the Outstanding Achievement Award from the International Solid State Lighting Alliance. In 2019 he was recipient of IEEE Vehicular Society James Evans Avant Garde Award. Haas was elected a Fellow of the Royal Society of Edinburgh (RSE) in 2017. In the same year he received a Royal Society Wolfson Research Merit Award and was elevated to IEEE Fellow. In 2018 he received a three-year EPSRC Established Career Fellowship extension and was elected Fellow of the IET. Haas was elected Fellow of the Royal Academy of Engineering (FREng) in 2019.

4) The specific parts:

Prof. Cheng-Xiang Wang will cover 1) Fundamentals of Wireless Channel Characterization, 2) Evolution of Wireless Channel Models From 2G to 5G, 3) Standard 5G Channel Models, 9) A General 6G Wireless Channel Model: Towards Standardization, and 10) Conclusions and Future Challenges.

Prof. Haiming Wang will cover 4) 6G Architecture and Key Technologies and 5) 6G All-Spectra Channel Measurements and Models (MmWave and THz).

Dr. Jie Huang will cover 6) 6G Global-Coverage Scenario Channel Measurements and Models, 7) 6G Full-Application Scenario Channel Measurements and Models, and 8) Machine Learning based Channel Measurements and Models.

Prof. Harald Haas will cover 5c) Optical Channel Measurements and Models.

8. A brief description (up to 1 page) of the technical issues that the tutorial will address, emphasizing its timeliness

The proposed tutorial will address many technical issues, such as follows.

- 1) What are the 5G and 6G requirements, cellular architecture, and key technologies?
- 2) What are the key features and requirements of 5G and 6G channel models?
- 3) What are the advantages and disadvantages of the existing standard 5G channel models?
- 4) What are future challenges of 6G channel measurements and models?
- 5) What are the essential criteria to evaluate channel measurements and models?
- 6) What are the key methodologies of channel measurements and models?
- 7) What are the specific characteristics of mmWave channels, THz channels, optical wireless channels, satellite channels, UAV channels, maritime channels, (ultra) HST channels, V2V channels, ultra-massive MIMO channels, industry IoT channels, and IRS channels?
- 8) How to model communication channels for 5G and 6G scenarios?
- 9) How to build channel models with machine learning technologies?
- 10) How to design more general 6G channel models towards standardization?

The proposed tutorial is offered at a time when 6G channel models are urgently needed but many researchers do not understand the key statistical properties of these challenging 6G scenarios and what corresponding channel measurements/models are available. This tutorial is also proposed at a time when some graduate students and research engineers have just started their research & development activities on B5G/6G and may benefit from the proposed comprehensive but focused crash course. In fact, B5G/6G 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 20 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.

9. Prior history of the tutorial presentations

Prof. Cheng-Xiang Wang delivered 22 Invited Keynote Speeches/Talks and 7 Tutorials in international conferences/workshops. Also, he gave numerous invited talks in various institutions/companies.

Invited Keynote Speeches/Talks (22):

- 1) **C.-X. Wang**, “6G: Vision, Enabling Technologies, and Channel Models,” **invited keynote speech**, in *Proc. IEEE ICCT'20*, Nanning, China, Oct. 2020.
- 2) **C.-X. Wang**, “6G Wireless Channel Measurements and Models: Advances and Future Challenges,” **invited keynote speech**, in *Proc. WCSP'20*, Nanjing, China, Oct. 2020.
- 3) **C.-X. Wang**, “Channel measurement and modeling for 6G,” **invited talk**, *International Conference on Microwave and Millimeter Wave Technology and International Wireless Symposium (Joint ICMMT'20 & IWS'20)*, Shanghai, China, Sept. 2020.
- 4) **C.-X. Wang**, “6G wireless channel characteristics analysis and modeling developments” **invited talk**, *International Conference on Intelligent Networks and Communication Systems*, Shenzhen, China, 11-12 Jan. 2020.
- 5) **C.-X. Wang**, “Evolution of wireless channel models from 1G to 6G,” **invited keynote speech**, *IEEE Computing, Communications and IoT Applications Conference (ComComAp'19)*, Shenzhen, China, 26-28 Oct. 2019.
- 6) **C.-X. Wang**, “Can Current Standard 5G Channel Models Satisfy Requirements?” **invited talk**, *International Workshop on Advances in Information Coding and Wireless Communications (AICWC'2017)*, Chengdu, China, 7 Nov. 2017.
- 7) **C.-X. Wang**, “5G Channel Models: From Fundamentals to Standardization,” **invited keynote speech**, *IEEE 5G Tutorial*, Shanghai, China, 27 July 2017.
- 8) **C.-X. Wang**, “5G Key Technologies and Standardized Channel Models,” **invited keynote speech**, *The 14th International Symposium on Pervasive Systems, Algorithms, and Networks (I-SPAN 2017)*, Exeter, UK, 21-23 June 2017.
- 9) **C.-X. Wang**, “Recent Developments and Future Challenges of 5G Massive MIMO Channel Models,” **invited plenary talk**, *The 19th International Symposium on Wireless Personal Multimedia Communications (WPMC 2016)*, Shenzhen, China, 14-16 Nov. 2016.
- 10) **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.
- 11) **C.-X. Wang**, “Spectral-energy efficiency trade-off of cellular systems with MFemtocell deployment,” **invited talk**, *IEEE Online Green Communications*, 11 Nov. 2015.
- 12) **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.
- 13) **C.-X. Wang**, “A non-stationary IMT-A MIMO channel model for high-mobility systems,” **invited keynote speech**, *4th International Workshop on High Mobility Wireless Communications (HMWC 2015)*, Xi'an, China, 21-23 Oct. 2015.
- 14) **C.-X. Wang**, “Recent advances and future challenges for standardized 5G channel models,” **invited keynote speech**, *2015 International Forum on Advances in Information Coding and Wireless Communications (AICWC 2015)*, Chengdu, China, 18-20 Oct. 2015.
- 15) **C.-X. Wang**, “Non-stationary wideband MIMO channel models for high-speed train wireless communication systems,” **invited talk**, *3rd International Workshop on High Mobility Wireless Communications (HMWC 2014)*, Beijing, China, 1-3 Nov. 2014.
- 16) **C.-X. Wang**, “Non-stationary wideband channel models for massive MIMO systems,” **invited talk**, *2nd International Symposium on Wireless Sensor and Cellular Networks (WSCN 2013)*, Jeddah, Saudi Arabia, 13-16 Dec. 2013.
- 17) **C.-X. Wang**, “Characterization and modeling of rapid time-varying MIMO channels for high-mobility wireless communication systems,” **invited talk**, *2013 International Forum on Advances in Information Coding and Wireless Communications (AICWC 2013)*, Chengdu, China, 4-6 Nov. 2013.

- 18) **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.
- 19) **C.-X. Wang**, “Recent developments on realistic MIMO channel models,” **invited keynote speech**, *International Workshop on Planning and Optimization of Wireless Networks (OPTNet 2012)*, Sheffield, UK, 21-23 Mar. 2012.
- 20) **C.-X. Wang**, “Key wireless technologies for B4G,” **invited keynote speech**, *Wireless World Research Forum (WWRf), Meeting 25*, London, UK, 16-18 Nov. 2010.
- 21) **C.-X. Wang**, “Cognitive radio networks: recent advances and future challenges,” **invited keynote speech**, *IEEE International Conference on Intelligent Computing and Integrated Systems (ICISS2010)*, Guilin, China, 22-24 Oct. 2010.
- 22) **C.-X. Wang**, “Sum-of-sinusoids mobile radio channel models: principles and applications,” **invited keynote speech**, *CIE-YC 2005*, Jinan, Shandong, P. R. China, 24-26 Sept. 2005.

Tutorials (7):

- 1) **C.-X. Wang, Z. Zhang, and H. Wang**, “Wireless channel measurements and models for 5G and beyond,” Tutorial, in *IEEE ICC’19*, Shanghai, China, 14 May. 2019 (**about 50 attendees**).
- 2) **C.-X. Wang**, “Wireless channel models and standards development for 5G and beyond,” Tutorial, in *IEEE/CIC ICC’18*, Beijing, China, 16 Aug. 2018. (**about 30 attendees**)
- 3) **C.-X. Wang**, “Channel characterization and modeling of 5G wireless communication systems,” Tutorial, in *IEEE ICC’16*, Chengdu, China, 27 July 2016 (**about 30 attendees**).
- 4) **C.-X. Wang**, “Modeling, analysis and optimization of 5G wireless communication networks: 5G channel models,” Tutorial, in *IEEE ICC’15*, Shenzhen, China, 2 Nov. 2015 (**about 50 attendees**).
- 5) 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**).
- 6) 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**).
- 7) 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. Haiming Wang gave a tutorial at IEEE ICC 2019 and the following 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.

Prof. Harald Haas delivered 55 Invited Keynote Speeches/Talks and was twice an invited TED Global Speaker. He gave 13 Invited Tutorials and Lectures, including IEEE ComSoc Training Courses.

Invited Keynote Speeches/Talks (55):

- 1) **H. Haas**, “LiFi – The Catalyst for New Applications,” **invited keynote speech**, in *Global LiFi Innovation and Industry Seminar*, Jan.2021
- 2) **H. Haas**, “Optical Communications and their role in future communications systems,” **invited talk**, in *DSTL Wireless Communications, Networking & Information Theory for Defence Symposium*, Jan. 2021
- 3) **H. Haas**, “Towards Multi-Gigabit/s LiFi for Network Convergence in 5G and Beyond,” **invited talk**, in *Photonic Wireless Communication Workshop*, Dec. 2020
- 4) **H. Haas**, “Recent Advancements in Optical Wireless Communications,” **invited talk**, in *IET UK Antennas and Propagation Conference*, Nov. 2020
- 5) **H. Haas**, “How LiFi Future-Proofs Wireless Communications,” **invited talk**, in *Global Foundries*, Oct. 2020
- 6) **H. Haas**, **invited talk**, in *2019 Workshop on Novel Photonics Technologies, European Conference of Optical Communications (ECOC)*, Dublin, Ireland, Sep. 2020
- 7) **H. Haas**, “Recent Advancements in Optical Wireless Communications,” **invited talk**, in *University College London Institute of Communications and Connected Systems Seminar*, Jun. 2020
- 8) **H. Haas**, “Secure Networking with Light,” **invited talk**, in *Airbus Cybersecurity Visit*, Edinburgh, Scotland, Dec. 2019
- 9) **H. Haas**, “Opportunities and Challenges of Future LiFi,” **invited talk**, in *IEEE Photonics Conference (IPC)*, San Antonio, USA, Oct. 2019
- 10) **H. Haas**, “Recent Advancements in LiFi,” **invited keynote speech**, in *Smart Cities Symposium on Future Smart Living & Lighting*, Weiz, Austria, Oct. 2019
- 11) **H. Haas**, “What is the Status of LiFi and What Comes Next?” **invited keynote speech**, in *Indian Institute of Technology Madras (IITM)*, Oct. 2019
- 12) **H. Haas**, “What is the Status of LiFi and What Comes Next?” **invited keynote speech**, in *Optics and Photonics*, Kista, Sweden, Oct. 2019
- 13) **H. Haas**, “Using Light to Build the Future Wireless Nervous System”, **invited keynote speech**, in *IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC)*, Istanbul, Turkey, Sep. 2019
- 14) **H. Haas**, “Recent Advancements in Optical Wireless Communication,” **invited talk**, in *Huawei UK Technology Workshop*, London, UK, Sep. 2019
- 15) **H. Haas**, “Recent Advancements in Optical Wireless Communication”, **invited talk**, in *Huawei Annual STW Summit*, London, UK, Sep. 2019
- 16) **H. Haas**, “A Vision of the Future of LiFi,” **invited keynote speech**, in *C-DOT Foundation Day*, Aug. 2019
- 17) **H. Haas**, “What is the Status of LiFi and What Comes Next?” **invited talk**, in *IEEE Conference on UK-China Emerging Technologies (UCET)*, Glasgow, Scotland, Aug. 2019
- 18) **H. Haas**, “Imagine a World Where Every Light Connects us with Unprecedented Data and Bandwidth,” **invited talk**, in *ConnectGov Leaders Summit (CIO)*, Edinburgh, UK, Jul. 2019
- 19) **H. Haas**, “A Future of the Vision of LiFi,” **invited keynote speech**, in *Global LiFi Congress*, Paris, France, Jun. 2019
- 20) **H. Haas**, **invited talk**, in *Institute of Physics (IOP)*, London, UK

- 21) **H. Haas, invited keynote speech**, in *European Photonics Industry Consortium (EPIC)*, Glasgow, Scotland, Apr. 2019
- 22) **H. Haas, invited talk**, in *Health of Photonics Launch Event*, London, UK, 2019
- 23) **H. Haas, invited talk**, in *Huawei Vision Seminar*, 2018
- 24) **H. Haas, invited talk**, in *3rd IEEE British and Irish Conference on Optics and Photonics*, 2018
- 25) **H. Haas, invited talk**, in *International Workshop on Advances in Coding and Wireless Communications*, Chengdu, China, 2018
- 26) **H. Haas, “LiFi: High Speed Wireless Networking with Light,” invited keynote speech**, in *International School on Light Sciences and Technologies*, Santander, Spain, 2018
- 27) **H. Haas, invited keynote speech**, in *Signal Processing Advances in Wireless Communications (SPAWC)*, Sapporo, Japan, Jul. 2017
- 28) **H. Haas, invited keynote speech**, in *European Cybersecurity Forum (CYBERSEC)*, Krakow, Poland, 2017
- 29) **H. Haas, invited keynote speech**, in *Photonics West*, 2017
- 30) **H. Haas, invited talk**, in *International Symposium on Advanced Lighting Science and Technology (ALST)*, Shaoxing, China, 2017
- 31) **H. Haas, invited talk**, in *European Conference on Networks and Communications (EUCNC)*, Oulu, Finland, 2017
- 32) **H. Haas, invited keynote speech**, in *Scotland Policy Conferences: Implementing “Digital Scotland”*, Oct. 2016
- 33) **H. Haas, invited keynote speech**, in *IEEE Photonics Conference*, Hawaii, USA, Oct. 2016
- 34) **H. Haas, invited keynote speech**, in *IEEE Wireless for Space and Extreme Environments (WiSEE)*, Aachen, Germany, Sep. 2016
- 35) **H. Haas, invited keynote speech**, in *Wireless Broadband Alliance*, Liverpool, UK, Jun. 2016
- 36) **H. Haas, invited keynote speech**, in *IEEE Blacksea Conference*, Varna, Bulgaria, Jun. 2016
- 37) **H. Haas, invited talk**, in *Cheltenham Science Festival*, Jun. 2016
- 38) **H. Haas, invited keynote speech**, in *Future of Wireless Technology Workshop (Huawei)*, Stockholm, Sweden, Jun. 2016
- 39) **H. Haas, invited talk**, in *TEDxWHU 2016*, Koblenz, Germany, Mar. 2016
- 40) **H. Haas, invited talk**, in *Tate Modern*, London, UK, Nov. 2015
- 41) **H. Haas, “LiFi Technologies and Applications,” invited talk** in *IEEE Metropolitan Workshop*, Glasgow, UK, Oct. 2015
- 42) **H. Haas, invited talk**, in *NI Week*, Austin, USA, Aug. 2015
- 43) **H. Haas, “Light as a Service Enabled by LiFi”, invited keynote speech**, in *China SSL 2014*, Guangzhou, China, Nov. 2014
- 44) **H. Haas, invited keynote speech**, in *Terrorism and Counter Terrorism Innovation at the World Summit on Counter-Terrorism, International Institute for Counter-Terrorism*, Herzliya, Israel, Sep. 2014
- 45) **H. Haas, “How Light Can Change the World,” invited keynote speech**, in *Edinburgh University North America Office Opening*, New York, USA, Oct. 2014
- 46) **H. Haas, “Intelligent Lighting and Intelligent Building,” invited keynote speech**, in *ForumLED 2014*, Paris, France, Oct. 2014
- 47) **H. Haas, “LiFi-Enhancing Light Services,” invited talk**, in *OSRAM’s Science and Coffee Series*, Munich, Germany, Oct. 2014
- 48) **H. Haas, “Improving Spectral Efficiency in 5G With Visible Light Communications,” invited keynote speech**, in *NI Days*, Austin, USA, Aug. 2014
- 49) **H. Haas, invited talk**, in *BoldTalks 2014*, Dubai, UAE, Mar. 2014
- 50) **H. Haas, invited talk**, in *Global Leader Forum*, South Korea, Nov. 2013

- 51) **H. Haas**, “LiFi: Data Through Illumination,” **invited talk**, in *Edinburgh Science Festival*, Apr. 2013
- 52) **H. Haas**, “How to use Light to Transmit Data: Story of LiFi,” **invited talk**, in *Login 2013*, Vilnius, Lithuania, Apr. 2013
- 53) **H. Haas**, “LiFi: Broadband through Light,” invited keynote speech, in *Plasa Focus 2013*, Apr. 2013
- 54) **H. Haas**, **invited keynote speech**, in *Global Phosphor Summit on LiFi Technology*, New Orleans, USA, Mar. 2013
- 55) **H. Haas**, “Shedding Light on Future Wireless Communication”, **invited talk**, at the *Museum of Communication*, Mar. 2021

Tutorials (13):

- 1) **H. Haas**, “The High Bandwidth Alternative,” *IEEE Communications Society (ComSoc) Training Course*, Nov. 2020
- 2) **H. Haas**, “The High Bandwidth Alternative,” *IEEE Communications Society (ComSoc) Training Course*, Nov. 2019
- 3) **H. Haas**, “The High Bandwidth Alternative,” *IEEE Communications Society (ComSoc) Training Course*, Apr. 2019
- 4) **H. Haas**, “Optical Wireless for Mobile Communications,” at *Optical Fiber Communications (OFC) Conference*, 2019
- 5) **H. Haas**, “The High Bandwidth Alternative,” *IEEE Communications Society (ComSoc) Training Course*, Oct. 2018
- 6) **H. Haas**, “The High Bandwidth Alternative,” *IEEE Communications Society (ComSoc) Training Course*, Apr. 2018
- 7) **H. Haas**, “The High Bandwidth Alternative to WiFi,” at *Optical Fiber Communications (OFC) Conference*, San Diego, USA, Mar. 2018
- 8) **H. Haas**, “The High Bandwidth Alternative,” *IEEE Communications Society (ComSoc) Training Course*, Oct. 2017
- 9) **H. Haas**, “The High Bandwidth Alternative to WiFi,” at *Optical Fiber Communications (OFC) Conference*, 2017
- 10) **H. Haas**, “Short Course on VLC,” at *Optical Fiber Communication Conference (OFC)*, San Diego, USA, 2017
- 11) **H. Haas**, Invited Tutorial, at *Optical Fiber and Communications Conference and Exhibition (OFC)*, Los Angeles, USA, 2015
- 12) **H. Haas**, “Visible Light Communication,” Invited Tutorial at *European Conference of Optical Communications (ECOC)*, Valencia, Spain, Sept. 2015
- 13) **H. Haas**, “LiFi: Pathway to 5G,” Invited Lecture, at *Alcatel Lucent, Bell Labs Ireland*, Nov. 2014

10. Lecture experience of the tutorial speaker(s).

Prof. Cheng-Xiang Wang delivered 22 Invited Keynote Speeches/Talks and 7 Tutorials in international conferences/workshops. Also, he gave numerous invited talks in various institutions/companies.

Prof. Haiming Wang frequently gave invited talks in international conferences and institutions/companies and had a lot of experience on mmWave channel measurements and standardization.

Prof. Harald Haas delivered 55 Invited Keynote Speeches/Talks and was twice an invited TED Global Speaker. He gave 13 Invited tutorials and lectures, including IEEE ComSoc Training Courses.

11. If appropriate, a description of past versions of the tutorials, including number of attendees, etc

Part of the tutorial (5G channel models) was presented 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 ICC'15. A half-day tutorial, focusing on 5G channel models, was presented at IEEE/CIC ICC'16 and ICC'18. A half-day tutorial, focusing on wireless channel measurements and modeling for 5G, was presented at IEEE ICC'19.

Motivated by the success of past tutorials given by Prof. Cheng-Xiang Wang and, in particular, by the interest of the audience on the **6G channel measurements and modeling**, we decided to put together a more detailed tutorial **adding more channel measurements/models and 6G materials**. This tutorial proposal aims to deliver more on 6G wireless channel measurements and models, e.g., THz, optical wireless, satellite, UAV, maritime, industry IoT, and IRS communication channels, and AI-based channel measurements and models, which have not been presented in any of the previous tutorials.

Tutorials (7):

- 1) **C.-X. Wang**, Z. Zhang, and **H. Wang**, “Wireless channel measurements and models for 5G and beyond,” Tutorial, in *IEEE ICC'19*, Shanghai, China, 14 May. 2019 (**about 50 attendees**).
- 2) **C.-X. Wang**, “Wireless channel models and standards development for 5G and beyond,” Tutorial, in *IEEE/CIC ICC'18*, Beijing, China, 16 Aug. 2018. (**about 30 attendees**)
- 3) **C.-X. Wang**, “Channel characterization and modeling of 5G wireless communication systems,” Tutorial, in *IEEE ICC'16*, Chengdu, China, 27 July 2016 (**about 30 attendees**).
- 4) **C.-X. Wang**, “Modeling, analysis and optimization of 5G wireless communication networks: 5G channel models,” Tutorial, in *IEEE ICC'15*, Shenzhen, China, 2 Nov. 2015 (**about 50 attendees**).
- 5) 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**).
- 6) 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**).
- 7) 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**).

12. Other information

The audience will 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 consolidating their knowledge on 6G communications, in particular on 6G wireless channel measurements and models.