Reconfigurable Intelligent Surfaces for Future Wireless Communications

Alessio Zappone
Univ. of Cassino and Southern Lazio
Cassino, Italy
alessio.zappone@unicas.it

Marco Di Renzo
CNRS, Univ. Paris-Saclay
Paris, France
marco.direnzo@centralesupelec.fr

Shi Jin
Southeast University
Nanjing, China
jinshi@seu.edu.cn

Merouane Debbah
Huawei France R&D
Paris, France
merouane.debbah@huawei.com

I. Abstract

As 5G networks take their final form, connectivity demands continue to increase exponentially and new services pose more constraints on the performance that end-users expect. A recent technological breakthrough that holds the potential to meet these demands is that of **reconfigurable intelligent surfaces**. We believe that a tutorial on the principles and latest approaches of reconfigurable intelligent surfaces for beyond 5G wireless communications will be of great value for both academics and industry practitioners.

II. Length of the tutorial

The tutorial is intended to be a full-day tutorial, but it can be easily adapted to be a half-day tutorial if necessary.

III. Experience of the tutorial speakers on the tutorial topic

A first element that shows the expertise of the tutorial speakers on RIS is that this tutorial proposal is endorsed by the Emerging Technology Initiative (ETI) on "RISs for Smart Radio Environments" of the IEEE Communications Society (link), in which:

- Alessio Zappone serves as the founding Vice-Chair;
- Marco Di Renzo serves as the founding ETC Liaison Officer on behalf of the Emerging Technical Committee;
- Shi Jin serves as the founding Officer for Testbeds, Devices and Proof-of-Concepts;
- Merouane Debbah serves as the founding Industry Liaison Officer.

Moreover, this tutorial is endorsed by the following special interest groups (SIG) of the IEEE Communications Society:

- Reconfigurable Intelligent Surfaces for Smart Radio Environments (RISE), chaired by M. Di Renzo and supported by the Wireless Communications Technical Committee.
- REconFigurabLE Intelligent Surfaces for Signal Processing and CommunicatIONS (REFLECTIONS), chaired by A. Zappone, and supported by the Signal Processing and Computing for Communications Technical Committee.

Moreover, all tutorial speakers have published seminal research and comprehensive surveys on the topic of RIS-based communications (see the articles listed in the rest of this tutorial, which form the basis of the tutorial content). Moreover, S. Jin developed one of the first demonstrators for RIS-based communications, while A. Zappone, M. Di Renzo, M. Debbah are guest editors of several special issues and chairs of workshops on RIS-based communications. Specifically:

- A. Zappone, M. Di Renzo, M. Debbah guest edited the JSAC special issue on "Wireless Networks Empowered by Reconfigurable Intelligent Surfaces", that has been recently finalized.
- A. Zappone, M. Di Renzo, M. Debbah are guest editing the FRONTIERS research topic "Wireless Communications with Reconfigurable Intelligent Surfaces: Fundamentals, Experimentation, and Applications", 2020.
- M. Di Renzo and M. Debbah are guest editing the TCCN special issue "Intelligent Surfaces for Smart Wireless Communications", to be finalized in 2021, second quarter.
- A. Zappone and M. Di Renzo are chairs of the workshop "Reconfigurable Intelligent Surfaces for Wireless Communication for Beyond 5G", (GLOBECOM 2020), and of the workshop "Reconfigurable Intelligent Surfaces for future wireless communications", at ICC 2021.

IV. Objectives, motivation, intended audience

Between 2020 and 2030, the number of IP connections will rise by 55% annually, reaching 607 exabytes in 2025 and 5,016 exabytes in 2030. In addition, future wireless networks will have to support many innovative vertical services, each with its own specific requirements, e.g.

- End-to-end latency of $1\,\text{ns}$ and reliability higher than 99.999% for URLLCs.
- Terminal densities of 1 million of terminals per square kilometer for massive IoT applications.
- Per-user data-rate of the order of Tera-bit/s for broadband applications.
- Terminal location accuracy of the order of $0.1\,\text{m}$ for V2X communications.

These requirements are beyond what 5G networks have been designed to handle, and indeed, according to Huawei, they set the requirements of future 6G networks, as shown in Fig. 1.

In order to face these new challenges, it will not be enough to develop only a more performing transmission /reception technology, as it was the case for all previous wireless generations. Being simply able to transmit data at a faster rate

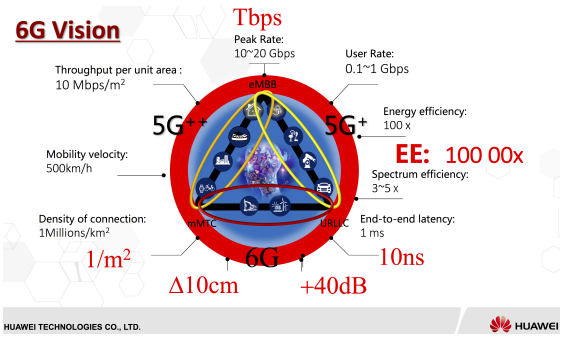

Fig. 1. 6G requirements.

does not ensure the flexibility required to accommodate diverse classes of users with extremely diverse service requirements.

A recent technological breakthrough that holds the potential to revolutionize the traditional approach to wireless network design and operation is that of **reconfigurable intelligent surfaces** (RISs). RIS-based communications put forth the idea of treating the communication environment not as an entity fixed by nature, but as a variable to be customized. It should be mentioned that, in principle, the possibility of creating more convenient electromagnetic paths between a transmitter and a receiver is already provided by the use of relay stations. However, the use of relays is based on traditional active antenna technology that requires the use of transmit amplifiers and complex hardware circuitry, which leads to large power consumptions, large size of the devices, and high costs. Instead, RISs are nearly-passive structures with very limited power consumption, size, and deployment costs. RISs are planar structures made of special materials, known as meta-materials, on which elementary electromagnetic reflectors are placed and spaced at sub-wavelength distances. This allows a RIS to reflect/refract the incoming electromagnetic signal in directions that are not bound by the conventional reflection and diffraction laws, but that instead can be fully customized. Moreover, a RIS provides the possibility of adapting its electromagnetic response in real-time in response to the sudden changes in the network and/or in the traffic demands. RISs can be deployed on the walls of buildings or can be used to coat the environmental objects between the communicating devices, which effectively makes the wireless channel a new variable to be optimized, besides the design of the transmitters and receivers. Moreover, thanks to their reduced size and cost, a RIS can be equipped with a number of electromagnetic reflectors that is significantly larger than the number of antennas of an active (massive) MIMO antenna array.

The intended audience of the tutorial is composed of students, academic researchers, industry affiliates and individuals working for government, military, science and technology institutions who are interested in learning the fundamental and the latest research directions of the emerging field of RIS-based wireless networks. The present tutorial is intended to provide the audience with a complete overview of the potential benefits, research challenges, implementation efforts and applications of technologies and protocols to manage and operate RIS-based wireless networks. This tutorial is unique of its kind, as it provides a cohesive vision of the emerging field of RIS-based communications. Therefore, the audience will receive a unique training experience.

V. Outline of the Tutorial

A. *Introduction*

The tutorial starts by discussing 5G standardization activities, the performance that 5G networks will be able to grant, and how this appears inadequate to keep the pace with the exponentially increasing number of connected devices and with the rise of many new heterogeneous services. The main challenges that stand in our way towards meeting the requirements of Fig. 1 will be identified, namely the extreme heterogeneity of the tasks to execute, which range from broadband communications, to very low-latency communications, extreme energy efficiency and high data rates, and localization. The use of RIS to enable this 6G vision will be discussed. Both an academic and industrial perspective will be provided. Moreover, the economical and societal opportunities that overcoming 5G holds will be analyzed. After this first part, the audience will have a proper understanding of the main principles that make the RIS technology possible, of the potential of RISs, and of the challenges and opportunities related to overcoming 5G networks. This part of the tutorial is based on the comprehensive survey on RISs:

M. Di Renzo, A. Zappone, M .Debbah, M.-S. Alouini, C. Yuen, J. de Rosny, S. Tretyakov, "Smart radio environments empowered by reconfigurable intelligent surfaces: How it works, state of research, and road ahead", *IEEE Journal on Selected Areas in Communications*, vol. 38, no. 11, pp. 2450 - 2525, November 2020.

B. *Meta-material fundamentals and experimental results*

This part of the tutorial will introduce the fundamentals of meta-material technology and, in order to substantiate the gains that RIS can bring to wireless communications, will present experimental results obtained by using the world's first meta-surface assisted wireless prototype testbed for RIS-based communications, which has been developed at Southeast university by the group of Prof. Shi Jin (Fig. 2). The tutorial will explain how packing reflecting elements at sub-wavelength distances enables to obtain a non-homogeneous surface for which the conventional Snell's laws do not hold. Experimental results will show that, despite not having any transmit amplifier, by properly designing the elementary reflecting elements, it is possible to achieve high data-rates. Moreover, by embedding stimuli-responsive materials in the meta-surface, e.g. liquid crystals or magnetic ferrite, which can rapidly vary their physical properties in response to external stimuli, it is possible to dynamically program the behavior of the meta-surface in real-time. The tutorial will show how RISs can be used to improve the communication reliability (e.g. by ensuring that the different signal paths add coherently

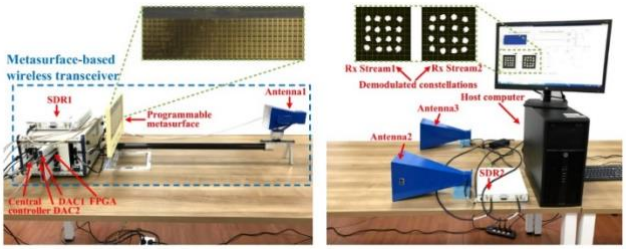

Fig. 2. RIS demonstrator developed at Southeast university

at the receiver), energy efficiency (since RISs can increase the data-rate with an extremely limited energy consumption), and security (since RIS can be used to focus the reflected/refracted energy only towards desired directions).

This part of the tutorial is based on the publications:

W. Tang, X. Li, J. Y. Dai, S. Jin, Y. Zeng, Q. Cheng, and T. J. Cui, "Wireless communications with programmable metasurface: Transceiver design and experimental results", *China Communications*, vol. 16, no. 5, pp. 46 - 61, May 2019.

W. Tang, J. Y. Dai, M. Chen, X. Li, Q. Cheng, S. Jin, K.-K. Wong, and T. J. Cui, "Programmable metasurface-based RF chain-free 8PSK wireless transmitter", IEEE Electronic Letters, vol. 55, no. 7, pp. 417 - 420, 2019.

C. *Modeling and Design of RIS-based wireless networks*

1) Modeling of RIS-based wireless networks: The tutorial will introduce equivalent electromagnetic-based and physics-inspired mathematical models of RIS, showing how they can be employed to model RIS-based wireless networks, in order to come to new expressions of the SNR in a RIS-based communication channel. Next, it will be shown how the unique properties of RISs are expected to yield different scaling laws from those currently encountered in wireless networks, e.g., a different received power expression as a function of the distance between transmitters and receivers, or a received SNR as a function of the number of reflecting elements equipped at the RIS. As a result of this discussion, the advantages and limitations of RISs will be discussed, in comparison with other more traditional transmission technologies, such as massive MIMO and relaying. In this context, it will be also observed how RISs can be used to perform specific tasks in a much simpler and more energy-efficient way than with available transmission technologies, such as implementing spatial modulation techniques, improving the security and reliability of wireless networks. Also, the tutorial will elaborate on how RISs can be used for improving the performance of wireless networks, e.g., for communication at high frequency bands, such as the mmWave frequency range. This part of the tutorial is based on the publications:

M. Di Renzo, J. Song "Reflection probability in wireless networks with metasurface-coated environmental objects: an approach based on random spatial processes", EURASIP Journal on Wireless Communications and Networking, 2019.

M. Di Renzo et al, "Reconfigurable Intelligent Surfaces vs. Relaying: Differences, Similarities, and Performance Comparison", *IEEE Open Journal of the Communication Society*, vol. 1, pp. 798 - 807, June 2020.

2) Design of RIS-based wireless networks: The new optimization challenges posed by the use of RISs will be identified, and a thorough literature survey about resource allocation for RIS-based wireless networks design will be given. Namely, the fact that the RIS is a (nearly) passive device without neither a dedicated transmit and receive hardware, nor a digital signal processor, results in: 1) more challenging resource allocation problems to solve; 2) more sophisticated channel estimation and feedback protocols, which poses additional constraints on the resource allocation algorithms, and leads to the need of performing overhead-aware resource allocation as well as joint channel estimation and resource allocation, unlike what typically happens for the design of present wireless communication systems. The overhead associated to channel estimation and to the computation and configuration of the optimal RIS phase matrix will be explicitly accounted for in the resource allocation problem. Both point-to-point and multi-user MIMO wireless networks will be considered and different performance metrics will be optimized, including the system spectral efficiency, energy efficiency, and their trade-off, with respect to the RIS phase shifts, the number of RIS reflecting elements, the transmit powers, transmit beamforming, and receive filters.

This part of the tutorial will be based on the following journal publications.

C. Huang, A. Zappone, G. C. Alexandropoulos, M. Debbah, C. Yuen, "Reconfigurable intelligent surfaces for energy efficiency in wireless communication", *IEEE Trans. on Wireless Commun.*, vol. 18, no. 8, pp. 4157-4170, 2019.

A. Zappone, M. Di Renzo, et al. "Overhead-aware design of reconfigurable intelligent surfaces in smart radio environments", *IEEE Trans. on Wireless Commun.*, vol. 20, no. 1, pp. 126 - 141, January 2021.

A. Zappone, M. Di Renzo, et al. "On The Optimal Number of Reflecting Elements for Reconfigurable Intelligent Surfaces", *IEEE Wireless Communications Letters*, in press, 2021.

D. *Conclusions.*

The tutorial will end by summarizing the take-home points of the tutorial, and highlighting the most relevant research directions and open problems to be investigated towards the development of beyond 5G RIS-based wireless networks.

VI. Detailed Outline

Assuming a 6-hour tutorial (duration can be adapted to the specific conference schedule), the detailed outline is:

1) **Introduction** (60 min. - M. Debbah)
   - Limitations of 5G.

- Overcoming 5G by RISs - A 6G vision.

2) **Fundamentals / experimental results** (90 min. - S. Jin)
   - Meta-materials technology for RISs.
   - The SouthEast univ. RIS-based demonstrator.
   - Proof-of-concept results.
3) **Modeling RIS-based networks** (90 min. - M. Di Renzo)
   - Models for dense RIS-based networks.
   - Scaling laws for large RIS-based networks.
   - Comparison with other transmission technologies
4) **Design of RIS-based networks** (90 min. - A. Zappone)
   - Spectral and energy efficiency maximization of RIS-based networks.
   - Overhead-aware design of RIS-based networks.
   - Joint channel estimation and resource allocation in RIS-based networks.
5) **Conclusions** (30 min. - M. Debbah)
   - Take-home messages
   - Open challenges and future research directions

VII. Tutorial Speakers

- **Dr. Alessio Zappone** - University of Cassino and Southern Lazio, Italy; alessio.zappone@unicas.it, (G-Scholar)
- **Dr. Marco Di Renzo** - CNRS - CentraleSupelec - Univ. Paris-Sud, Paris, France; marco.direnzo@centralesupelec.fr, (G-Scholar)
- **Dr. Shi Jin** - Southeast University, Nanjing, China, jinshi@seu.edu.cn, (G-Scholar)
- **Dr. Merouane Debbah** - Huawei France R&D, Paris, France, merouane.debbah@huawei.com, (G-Scholar)

VIII. Short CVs of the tutorial speakers

Dr. Alessio Zappone obtained his Ph.D. degree in electrical engineering in 2011 from the University of Cassino and Southern Lazio, Cassino, Italy. His Ph.D. studies were focused on distributed algorithms for energy-efficient resource allocation in wireless networks. After obtaining his Ph.D. Alessio has been with the Technische Universität Dresden, Germany, managing the project CEMRIN on energy-efficient resource allocation in wireless networks, funded by the German Research Foundation. From 2017 to 2019 he has been the recipient of the H2020 Individual Marie Curie fellowship for experienced researchers BESMART, carried out in the LANEAS group of CentraleSupelec, Paris, France. He is now a tenured professor at the university of Cassino and Southern Lazio, Italy. He was appointed exemplary reviewer for the IEEE Transactions on Communications and IEEE Transactions on Wireless Communications in 2017. Alessio is an IEEE Senior Member, serves as senior area editor for the IEEE Signal Processing Letters and as guest editor for the IEEE Journal on Selected Areas on Communications (Special Issues on Energy-Efficient Techniques for 5G Wireless Communication Systems and on Wireless Networks Empowered by RIS).

Dr. Marco Di Renzo received the Ph.D. degree in Electrical and Information Engineering from the University of L'Aquila, Italy, in 2007. Since 2010, he is Associate Professor with Paris-Saclay University - CNRS, CentraleSupelec, Univ. Paris Sud, France. He is a Distinguished Visiting Fellow of the Royal Academy of Engineering (UK), and co-founder of the university spin-off company WEST Aquila s.r.l., Italy. Dr. Di Renzo received the THALES Communications fellowship (2003-2006), University of L'Aquila, Italy; the *Dérogation pour l'Encadrement de These* (2010), University of Paris-Sud, France; the 2012 IEEE CAMAD, 2014 IEEE CAMAD, 2014 IEEE ATC, 2015 IEEE ComManTel Best Paper Awards; the 2012 and 2014 IEEE WIRELESS COMMUNICATIONS LETTERS Exemplary Reviewer Certificate; the 2013 IEEE-COMSOC Best Young Researcher Award for Europe, Middle East and Africa; the 2015-2018 CNRS Award for Excellence in Research and in Advising Doctoral Students; the 2017 IEEE-SEE Alain Glavieux Award. He serves as Editor in Chief of the IEEE COMMUNICATIONS LETTERS and Editor of the IEEE TRANSACTIONS ON COMMUNICATIONS. He is an IEEE Fellow and a Distinguished Lecturer of the IEEE Communications and IEEE Vehicular Technology Societies.

Dr. Shi Jin received the M.S. degree from Nanjing University of Posts and Telecommunications, Nanjing, China, in 2003, and the Ph.D. degree in information and communications engineering from the Southeast University, Nanjing, in 2007. From June 2007 to October 2009, he was a Research Fellow with the Adastral Park Research Campus, University College London, London, U.K. He is currently with the faculty of the National Mobile Communications Research Laboratory, Southeast University. His research interests include space time wireless communications, random matrix theory, information theory. He serves as an Associate Editor for the IEEE Transactions on Wireless Communications, IEEE Communications Letters, IET Communications. Dr. Jin and his coauthors have been awarded the 2011 IEEE Communications Society Stephen O. Rice Prize Paper Award in communication theory and a 2010 Young Author Best Paper Award by the IEEE Signal Processing Society.

Dr. Merouane Debbah obtained his Ph.D. from the Ecole Normale Suprieure Paris-Saclay (France). He worked for Motorola (France) from 1999-2002 and Vienna Research Center for Telecommunications (Austria) until 2003. From 2003 to 2007, he joined the Mobile Communications department of Eurecom (France). Since 2007, he is Full Professor at CentraleSupelec (France). Since 2014, he is Vice-President of the Huawei France R&D center and director of the Mathematical and Algorithmic Sciences Lab. He is Associate Editor in Chief of the journal Random Matrix: Theory and Applications and was associate and senior area editor for IEEE Transactions on Signal Processing. He obtained the ERC grant MORE and is IEEE Fellow. He received 19 best paper awards, among which the 2007 IEEE GLOBECOM best paper award, 2014 WCNC best paper award, 2015 ICC best paper award, 2015 IEEE Communications Society Leonard G. Abraham Prize, 2015 IEEE Communications Society Fred W. Ellersick Prize, 2016 IEEE Communications Society Best Tutorial paper award, 2018 IEEE Marconi Prize Paper Award. He received the Mario

Boella award in 2005, the IEEE Glavieux Prize Award in 2011 and the Qualcomm Innovation Prize Award in 2012.

IX. Previous tutorial experience of the speakers

Dr. Alessio Zappone has given the tutorials: *Communication Network Design: Model-Based, Data-Driven, or Both?*, (IEEE ICC 2019, IEEE WNCN 2019, IEEE CCNC 2019, IEEE PIMRC 2019, EUSIPCO 2019), *Vertical-Oriented End-to-End Orchestration in 5G Networks: Modeling, Optimization, Implementation, and Verification*, (EUSPICO 2018, EuCNC 2018), *Energy-Neutral System-Level Analysis and Optimization of 5G Wireless Networks*, (IEEE PIMRC 2016, EUSIPCO 2016, IEEE GLOBECOM 2016, IEEE ISWCS 2016, EuWireless 2016); *Energy Efficiency in 5G Heterogeneous and Small-Cell Wireless Networks* (IEEE ISWCS 2014), *Energy-Efficient Resource Allocation for 5G Wireless Networks* (IEEE ICASSP 2016), *Energy-efficient design of (5G and beyond 5G) wireless networks*, (2016 Tyrrhenian Workshop on Digital Communications), as well as the keynote *Fractional programming for Energy Efficiency in 5G Wireless Networks*, at the workshop "Physical and Mathematical Foundations of next-generation Wireless Networks", (ISWCS 2015).

Dr. Marco Di Renzo is a frequent tutorial/keynote speaker at IEEE international conferences. In the last five years, he has presented 20+ tutorials on *Spatial Modulation for MIMO Systems* (WCNC 2013, EW 2013, ICC 2013, VTC-Spring 2013 VTC-Fall 2013, CAMAD 2013, WCCN 2014, EW 2014, EUSIPCO 2014, PIMRC 2014, VTC-Fall 2014, ATC 2014), 7 tutorials on *Energy-Efficient Wireless Networks* (MASCOTS 2014, VTC-Fall 2014, CCNC 2014, CCNC 2015, GLOBECOM 2015, WCNC 2016, IEEE ICC 2016), and 20+ tutorials on *Stochastic Geometry Modeling and Analysis of Wireless Networks* (VTC- Spring 2015, EW 2015, ICC 2015, ICCC 2015, ICUWB 2015, ComManTel 2015, CCNC 2016, VTC-Spring 2016). He was frequent Invited Lecturer on *Stochastic Geometry Modeling* at IEEE ICNC 2016; Invited Plenary Speaker on *Stochastic Geometry Modeling* at the 2015 GTTI Meeting; Invited Distinguished Lecturer on *Stochastic Geometry Modeling* and *Spatial Modulation* at the 2015 IEEE Italy Section Summer Ph.D. School; Invited Distinguished Lecturer on *Stochastic Geometry Modeling* and *Spatial Modulation* at the 2015 Graduate School of the University of Malaga;

Dr. Shi Jin is a is a frequent tutorial/keynote speaker at international conferences, where he gave more than 20 lecture talks. For example, he gave the tutorial *Low-Cost Massive MIMO: From Theory to Practice* at several renowned IEEE conferences, such as VTC Spring 2016, IEEE GLOBECOM 2016, ICCC 2016, ICASSP 2017, and he gave the keynote *Model-Driven Deep Learning for Physical Layer Communications* at the 2018 International Conference on 5G for Ubiquitous Connectivity. He has also given several invited tutorial talks at several universities in China. He has more than ten years of experience as a university professor with the Southeast University, Nanjing, China, teaching courses at both the Master Degree and Ph.D. level.

Dr. Merouane Debbah is a frequent tutorial/keynote speaker at international conferences, with more than 50 talks. Recent examples include: Catalonia Distinguished Lectureship Program, 2009; Plenary at the Femtocell workshop at Globecom 2010; Newcom++ Spring School on Cognitive Wireless Communication Networks, 2010; Indoor and Outdoor Femto Cells workshop at PIMRC 2010; VTC 2011 BeFEMTO keynote WORKSHOP speaker; Keynote speaker at ICASSP 2011; Tutorial *Random Matrix Theory for Advanced Communication Systems* at IEEE WCNC 2012; Tutorial *Random Matrix Advances in Signal Processing* at SPAWC 2013; Plenary speaker at ISWCS 2014; Plenary speaker at Valuetools 2014; Plenary speaker at the International School on Small Cells and 5G, 2015; Tutorial Speaker *Massive MIMO for 5G* at ISWCS 2015; Plenary speaker at EUSIPCO 2015.

X. Relation to previous tutorials

RIS-based communications is an emerging topic in the wireless communication area. As a result, this tutorial has not been given to previous IEEE conferences.

XI. Suitability of virtual presentation

The tutorial format lends itself to a virtual presentation, if needed. The tutorial content can be easily presented via popular video conferencing systems, e.g. Zoom, or via any dedicated video conferencing system selected by the conference organizers, either live or by pre-recorded videos available on-demand. All registered tutorial attendees will receive the complete set of slides to be presented, before the tutorial date, thus facilitating their remote attendance. The tutorial speakers are also willing to have the tutorial lecture recorded and distributed to registered tutorial participants.