1. Tutorial Title

MetaEverything: Intelligent Meta-Material Aided Sensing and Communications

2. Abstract

The future wireless networks are exhibiting a trend towards the intelligent communication and sensing system to support a variety of applications requiring high data rates, low hardware cost, and fine-resolution sensing. Fortunately, with the recent development of new materials, reconfigurable intelligent meta-material provides an efficient approach to reshape and control the electromagnetic characteristics of the environment, which can be utilized to enhance the performance of communication and sensing. In this tutorial, we will first provide a general introduction of the intelligent meta-material along with the state-of-the-art research in different areas. We then introduce the unique features of intelligent meta-material which enlighten its broad applications to communication and sensing, in a comprehensive way. Related design, analysis, optimization, and signal processing techniques will be presented. Typical meta-material based applications for both cellular communications and radio-frequency sensing as well as localization will be explored. The implementation issues along with our developed prototypes and experiments will also be discussed. Formalized analysis of several up-to-date challenges and technical details on system design will be provided for different applications.

3. Length of the Tutorial

Half-day

4. Intended Audience

The aim of this tutorial is to educate control, signal processing engineers, computer and information scientists, applied mathematicians and statisticians, as well as systems engineers to carve out the role that analytical and experimental engineering has to play in meta-material related research and development.

The primary audience for the proposed tutorial will consist of

- Researchers and communications engineers interested in the new applications and techniques of meta-materials.
- Newcomers interested in the state-of-the-art research on meta-materials for future wireless systems.
- Engineers, industry managers, and government research agency in the field of meta-material deployment
- Graduate and undergraduate students interested in obtaining comprehensive information on the design, evaluation, and applications of meta-materials.

5. Objectives and Motivation

Launching from fifth-generation communications, evolution towards the next generation has been kicked off, envisioning future wireless networks to be a distributed intelligent communication and sensing system. Though such demands have gained support from existing techniques such as massive MIMO, small cells, and a variety of wireless sensor devices enabled by MIMO and integrated circuits, their applicability is limited by the conflicts between 1) low hardware costs and high data rates, 2) high detection accuracy and light-weight deployment. Fortunately, meta-material, as a new type of ultra-thin two-dimensional meta-material inlaid with sub-wavelength scatters, provides a groundbreaking technology that has the potential of enhancing the performances of sensing and directional transmission without extra hardware costs.

Meta-material is capable to actively shape uncontrollable wireless environments into a desirable form via flexible phase shift reconfiguration without extra hardware or power costs. This has given rise to an emerging concept of “smart radio environments”. To exploit such a technique, the network is expected to coordinate the meta-material

and cellular access points (APs) to improve the data rates and cell coverage. As such, challenges have been posed to conduct extensive research to develop new protocols and communication diagrams including channel estimation and beamforming schemes.

Moreover, benefited from its inherently sensitive electromagnetic responses to the environment, meta-material provides a new approach to achieve sensing applications with high accuracy. One typical application is radio frequency (RF) sensing where the meta-material customizes the wireless channels intelligently and generates a massive number of independent paths interacting with the sensing objectives. The information contained in the complicated environment is excavated via a rich set of phase shift reconfigurations of the meta-material. Another application is high-resolution wireless sensors. Due to their inclusions (geometry, material), meta-materials exhibit an electromagnetic property sensitive to the environment, such as temperature and humidity, which motivates their applications as high-resolution sensors. Both applications require new meta-material structures, protocols for data acquisition and processing, and meta-material configuration optimization.

Meta-material represents a trend towards developing future intelligent radio techniques with the potential to lead the revolution of wireless network design and wireless sensor techniques. However, design, analysis, optimization, and implementation of meta-material systems require multidisciplinary knowledge of wireless communications, applied electromagnetics, compressive sensing, and optimization. Therefore, a tutorial containing the basic concepts/theories for addressing the research advances that enable meta-material aided communication and sensing will be very useful for researchers and engineers. This is the primary motivation of writing this tutorial proposal.

There are three main objectives of writing this tutorial. The first objective is to provide a general introduction of the intelligent meta-material along with the state-of-the-art research in different areas. The second objective is to introduce the unique features of intelligent meta-material which enlighten its broad applications to communication and sensing, in a comprehensive way. Related design, analysis, optimization, and signal processing techniques will be presented. The third objective is to explore typical meta-material applications and discuss implementation issues. Formalized analysis of several up-to-date challenges and technical details on system design will be provided for different applications.

6. Outlines

1. Introduction (Presenter: Prof. Lingyang Song)
   - 1.1. 6G Background and Requirements
     - i. Cellular Communications
     - ii. Challenges of the State-of-the-Art
   - 1.2. Meta-Material Basics
     - i. Historical Development
     - ii. Working Principle
     - iii. Channel Modelling
     - iv. Prototypes
   - 1.3. Meta-Material Applications
     - i. Propagation Environment Control for Communications
     - ii. Radio Frequency Sensing for Mobile Internet of Things
     - iii. Wireless Sensors with High Resolution
2. Basic Theoretical Backgrounds (Presenter: Prof. Zhu Han)

2.1 Optimization Theory
2.2 Machine Learning Techniques

3. Intelligent Meta-Material aided Cellular Communications: Theoretical Analysis (Presenter: Dr. Boya Di)
   3.1 Goals and Challenges
   3.2 System Design and Analysis
      i. Limited Phase Shift Effect of the Meta-Material
      ii. Size Effect of the Meta-Material
      iii. Deployment Optimization

4. Intelligent Meta-Material aided Multi-User Communications: Optimization and Application (Presenter: Dr. Boya Di)
   4.1 Protocol Design
   4.2 Reflective-Type Meta-Material aided Communications
      i. Digital Beamforming
      ii. Meta-Material based Analog Beamforming
   4.3 Intelligent Omni-directional Meta-Material aided Communications
      i. Hybrid Beamforming
      ii. Deployment Optimization
      iii. Prototypes and Experimental Results

5. Intelligent Meta-Material aided Smart Sensing (Presenter: Dr. Hongliang Zhang)
   5.1. Meta-Material aided Posture Recognition
      i. System Overview
      ii. Meta-Material aided RF Sensing for Posture Recognition
      iii. Joint RIS Phase Shift and Detection Function Optimization
      iv. Implementation and Prototypes
   5.2. Meta-Material aided 3-Dimentional Sensing
      i. System Construction
      ii. Mapping from RF Signals and 3D Shapes
      iii. Simulation and Evaluation
   5.3 Meta-Material aided Localization
      i. Protocol Design
      ii. Analysis of Fingerprint-based Localization
      iii. Implementation

6. Meta-Material Enabled IoT Sensors (Presenter: Dr. Hongliang Zhang)
   6.1 Meta-Material based Indoor Climate Monitoring
      i. Meta-Material based Multi-function Sensor Design
      ii. Protocol Design for Data Acquisition and Processing
      iii. Experiment Results

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

Boya Di, *Post-doctoral Research Associate, IEEE Member*

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Boya Di (S'17-M'19) received the B.S. degree from Peking University in 2014, and the Ph.D. degree from Peking University in 2019. Currently she is post-doctoral research associate in Imperial College London, London, UK. Her main research interests include reconfigurable intelligent materials, multi-agent systems, wireless resource allocation and management, edge computing, and optimization theory. She has published over 10 journal papers on the topic of reconfigurable intelligent material aided communications and sensing, including 2 first-author ones. One of her journal papers is currently listed as highly cited papers in Web of Science. She is currently an Editor for IEEE Transactions on Vehicular Technology. She has also served as a reviewer for multiple IEEE journals including IEEE JSAC, TWC, TCOM, etc., and a TPC member for IEEE GLOBECOM and ICC several times.

Hongliang Zhang, *Post-doctoral Associate, IEEE Member*
Department of Electrical Engineering, Princeton University, Princeton, NJ 08544, USA
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Hongliang Zhang (S'15-M'19) received the B.S. and Ph.D. degrees at the School of Electrical Engineering and Computer Science at Peking University, in 2014 and 2019, respectively. He was a Postdoctoral Fellow in the Electrical and Computer Engineering Department at the University of Houston, Texas from Jul. 2019 to Jul. 2020. Currently, he is a Postdoctoral Associate in the Department of Electrical Engineering at Princeton University, New Jersey. His current research interest includes cooperative communications, Internet-of-Things networks, hypergraph theory, and optimization theory. He received the best doctoral thesis award from Chinese Institute of Electronics in 2019. He has served as a TPC Member for many IEEE conferences, such as Globecom, ICC, and WCNC. He is currently an Editor for IET Communications. He also serves as a Guest Editor for IEEE IoT-J special issue on Internet of UAVs over Cellular Networks.

Lingyang Song, *Boya Distinguished Professor, IEEE Fellow, IEEE ComSoc Distinguished Lecturer*
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Lingyang Song (S'03-M'06-SM'12-F'19) received his PhD from the University of York, UK, in 2007, where he received the K. M. Stott Prize for excellent research. He worked as a research fellow at the University of Oslo, Norway until rejoining Philips Research UK in March 2008. In May 2009, he joined the School of Electronics Engineering and Computer Science, Peking University, and is now a Boya Distinguished Professor. His main research interests include wireless communications, mobile computing, and machine learning. Dr. Song is the co-author of many awards, including IEEE Leonard G. Abraham Prize in 2016, IEEE ICC 2014, IEEE ICC 2015, IEEE Globecom 2014, and the best demo award in the ACM Mobihoc 2015. He received National Science Fund for Distinguished Young Scholars in 2017, First Prize in Nature Science Award of Ministry of Education of China in 2017. Dr. Song has served as a IEEE ComSoc Distinguished Lecturer (2015-2018), an Area Editor of IEEE Transactions on Vehicular Technology (2019-), Co-chair of IEEE Communications Society Asia Pacific Board Technical Affairs Committee (2020-). He is a Clarivate Analytics Highly Cited Researcher.

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

The tutorial proposal with title “MetaEverything: Intelligent Meta-Material Aided Sensing and Communications” will provide the state-of-the-art of research on meta-material assisted sensing and communications from the perspectives of physical, MAC, network, and application layers. It focuses on three types of meta-material based applications, i.e., cellular communications, RF sensing, and high-resolution IoT sensors. The tutorial will discuss the meta-material hardware design as well as data processing techniques for different sensing applications. Technical issues related to communications will also be addressed including beamforming scheme design, channel estimation, phase shift optimization, and signal detection. The contents will be organized in the following way:

- Background
  1. An introduction to wireless communications (including channel models) and wireless sensor technologies with a potential to satisfy the requirements of 6G urging an intelligent world will be reviewed.
  2. The working principle, structure, historical development, and state-of-the-art applications of intelligent meta-materials will be introduced in detail. Both the reflective-type and reflective-transmissive types of meta-materials will be illustrated, along with our prototypes. Models of channel propagation, transmission, and sensing will be presented as well.

- Meta-material aided Cellular Communications
  3. Meta-material aided cellular communications will be discussed where the meta-material reflects signals from the cellular AP towards a user via its inherent analog beamforming. Theoretical analysis on achievable rates influenced by meta-material size and phase shift discretization will be delivered. Coverage extension enabled by the meta-material will also be investigated, providing a guideline for system design.
  4. Meta-material aided multi-user communications will be investigated. To support diverse requirements, e.g., high energy efficiency and high throughput, it is desirable to design hybrid beamforming schemes and to develop discrete phase shift optimization of the meta-material. The multi-user systems aided by the reflective-type (RIS) and the intelligent omni-directional meta-surfaces (IOS) are discussed in detail, respectively.
- Meta-material aided Smart Sensing
  5. In smart sensing, the influence of the sensing objectives on the wireless signal propagation can be potentially recognized by the receivers, which is then utilized to identify the objectives. It is desirable to design image recovery algorithms, optimize meta-material configurations, and study tracking methods. Two RIS-aided applications, i.e., posture recognition and 3-dimensional sensing, are illustrated, respectively.
  6. For enhanced localization, meta-material is deployed between the AP and users such that the AP can analyze the reflected signals from users via different configurations to obtain the accurate locations of users. To deal with the mutual influence between multiple users and the meta-material, a new localization protocol for device coordination and a meta-material configuration optimization algorithm is required.
- Meta-material Enabled IoT

  The application of indoor climate monitoring is deployed based on the meta-material high-resolution sensors. Unlike traditional sensors, one small piece of meta-material can enable an integration of multiple types of sensors which collects data simultaneously and provides the integrated temperature and humidity information with an ultra-high resolution. The goal is to develop a new meta-material based data collection, sensing, and processing approach that strikes a balance between the low cost and

high resolution.

9. Prior history of the tutorial presentations

- Boya Di, Hongliang Zhang, Zhu Han, and Lingyang Song, “MetaEverything: Intelligent Meta-Material Aided Sensing and Communications”, IEEE Wireless Communications and Networking Conference (WCNC), March. 2021.
- Boya Di, Hongliang Zhang, Zhu Han, and Lingyang Song, “Reconfigurable Intelligent Surface for 6G: Communication, Sensing, and Localization”, IEEE International Conference on Communications in China (ICCC), Aug. 2020. (Over 50 attendees)
- Lingyang Song, Zhu Han, Boya Di, and Hongliang Zhang, “Aerial Access Networks for 6G: Integration of UAV, HAP, and Satellite Communication Networks”, IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC), Sep. 2020. (Over 50 attendees)
- Lingyang Song, Zhu Han, and Boya Di, “Aerial Access Networks for 6G: From UAV, HAP, to Satellite Communication Networks”, IEEE International Conference on Communications (ICC), June 2020. (Over 70 attendees)
- Lingyang Song, Zhu Han, and Hongliang Zhang, “UAV Communications in 5G and Beyond: Integration of Sensing, Control, and Learning”, IEEE Wireless Communications and Networking Conference (WCNC), Apr. 2020. (Over 30 attendees)
- Kaigui Bian, Lingyang Song and Zhu Han, “Cellular Internet of UAVs for 5G and Beyond,” IEEE International Conference on Communications in China (ICCC), Aug. 2019. (Over 80 attendees)
- Lingyang Song and Zhu Han, “UAV Applications over Cellular Networks: Sensing, Communication, and Computation,” IEEE International Conference on Communications (ICC), June 2019. (Over 100 attendees)
- Lingyang Song and Zhu Han, “Signal Processing for Big Data Analytics: Fundamental and Applications," IEEE Global Communications Conference (Globecom), 2018. (Over 90 attendees)
- Lingyang Song and Zhu Han, “Big Data Signal Processing for Communication Networks," IEEE Global Communications Conference (Globecom), 2017. (Over 100 attendees)
- Lingyang Song and Zhu Han, “5G Wireless Communications: Enabling Technologies and Resource Management," IEEE Global Communications Conference (Globecom), 2016.
- Lingyang Song and Zhu Han, “Full-Duplex Communications and Networks," IEEE International Conference on Communications in China (ICCC), 2016.
- Lingyang Song and Zhu Han, “Distributed Resource Allocation for 5G Communications and Networks," IEEE International Conference on Communications (ICC), 2016.
- Lingyang Song and Zhu Han, “Full-Duplex Communications and Networks: Fundamentals, Technologies, and Applications," IEEE Global Communications Conference (Globecom) 2015.
- Lingyang Song and Zhu Han, “Resource Allocation for Full-Duplex Communication and Networks," IEEE International Conference on Communication (ICC) 2015.
- Lingyang Song and Zhu Han, “Full-Duplex Wireless Communication and Networks: Key Technologies and Applications", IEEE International Conference on Communication in China (ICCC) 2014.
- Lingyang Song and Zhu Han, “Game-theoretic Methods for Device-to-Device Communications", IEEE International Conference on Communication (ICC) 2014.
- Lingyang Song and Zhu Han, “Resource Allocation for Physical-Layer Security,” 2013 IEEE Wireless Communications and Networking Conference (WCNC), Shanghai China, Apr. 2013.

- Zhu Han and Lingyang Song, “Smart Grid Communications and Networking, IEEE International Conference on Communications (ICC), Budapest, Hungary, June 2013.

10. Lecture experience of the tutorial speaker(s)

- Boya Di, Hongliang Zhang, Zhu Han, and Lingyang Song, “MetaEverything: Intelligent Meta-Surface Aided Sensing and Communications”, IEEE Wireless Communications and Networking Conference (WCNC), March. 2021.
- Lingyang Song, Zhu Han, Boya Di, and Hongliang Zhang, “Aerial Access Networks for 6G: Integration of UAV, HAP, and Satellite Communication Networks”, IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC), Sep. 2020. (Over 50 attendees)
- Boya Di, Hongliang Zhang, Zhu Han, and Lingyang Song, “Reconfigurable Intelligent Surface for 6G: Communication, Sensing, and Localization”, IEEE International Conference on Communications in China (ICCC), Aug. 2020. (Over 50 attendees)
- Lingyang Song, Zhu Han, and Boya Di, “Aerial Access Networks for 6G: From UAV, HAP, to Satellite Communication Networks”, IEEE International Conference on Communications (ICC), June 2020. (Over 70 attendees)
- Lingyang Song, Zhu Han, and Hongliang Zhang, “UAV Communications in 5G and Beyond: Integration of Sensing, Control, and Learning”, IEEE Wireless Communications and Networking Conference (WCNC), Apr. 2020. (Over 30 attendees)
- Kaigui Bian, Lingyang Song and Zhu Han, “Cellular Internet of UAVs for 5G and Beyond,” IEEE International Conference on Communications in China (ICCC), Aug. 2019. (Over 80 attendees)
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- Lingyang Song and Zhu Han, “Signal Processing for Big Data Analytics: Fundamental and Applications," IEEE Global Communications Conference (Globecom), 2018. (Over 90 attendees)
- Lingyang Song and Zhu Han, “Big Data Signal Processing for Communication Networks," IEEE Global Communications Conference (Globecom), 2017. (Over 100 attendees)

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

- Boya Di, Hongliang Zhang, Zhu Han, and Lingyang Song, “MetaEverything: Intelligent Meta-Surface Aided Sensing and Communications”, IEEE Wireless Communications and Networking Conference (WCNC), March. 2021.
- Boya Di, Hongliang Zhang, Zhu Han, and Lingyang Song, “Reconfigurable Intelligent Surface for 6G: Communication, Sensing, and Localization”, IEEE International Conference on Communications in China (ICCC), Aug. 2020. (Over 50 attendees)