东南大学

2023 年国际暑期学校

项目主题：无线通信原理与关键技术国际暑期学校

开课院系：信息科学与工程学院

开设课程：无线通信系统概论

移动衰落信道建模

微波、毫米波与太赫兹前沿技术

开课时间：2023 年 7 月 3 日-2023 年 8 月 8 日

1. 项目介绍

1.1. 项目主题：无线通信原理与关键技术国际暑期学校

International Summer School of Wireless Communication Principles and Key Technologies

1.2. 开课院系：信息科学与工程学院

School of Information Science and Engineering, Southeast University

1.3. 项目简介：

项目立足于东南大学信息学科综合优势，坚持学术导向，强化拓展培养，将通识教育、专业教育、学术交流和创新创业教育有机结合，全面提升学生综合素质。围绕无线通信系统的基本原理与前沿技术这一主题，开设《无线通信系统概论》、《移动衰落信道建模》、《微波、毫米波与太赫兹前沿技术》3 门全英文课程，由 5 名校内专任教师、9 名海外教师、4 名企业教师共同参与，每门课程均包含理论授课、实验实践、国际大师讲座、企业教师讲座及参观座谈 5 部分内容。通过本项目的建设，学生将体验国内外专家学者的授课，接轨国际高校授课方式，紧密结合理论和应用，激发创新思维和学习积极性，为从事相关领域的工作和研究建立坚实基础。每门课程 32 学时，可获得 2 学分，校外/国际选课学生可提供课程证书。

This international summer school is based on the overall strengths of information subject of Southeast University (SEU). It adheres to academic-orientation and strengthens development training by integrating general education, professional education, academic exchange, and innovation & enterprise education, thus enabling overall improvements of students' comprehensive quality. The theme of the summer school is the basic principles and technology frontiers of wireless communication systems. Three English courses are included, i.e., Introduction to Wireless Communication System, Mobile Fading Channel Modeling, and Frontiers of Microwave, Millimeter-wave and Terahertz Technologies. Five SEU teachers, nine oversea teachers, and four company teachers will participate in this project. Each course has five parts, including theoretical lectures, labs/tutorials, invited talks given by international masters, invited talks given by industrial experts, and visits to state key labs. From this international summer school, students will experience lectures given by experts at home and abroad, be geared to teaching styles of international universities, closely combine theory and applications, inspire innovative thinking and learning enthusiasm, thus laying a solid foundation for future work and research in related areas. Each course has 32 class hours and 2 credits. Course certificates are available for international students and non-SEU students in Chinese universities.

2. 课程介绍

2.1. Introduction to Wireless Communication System (无线通信系统概论)

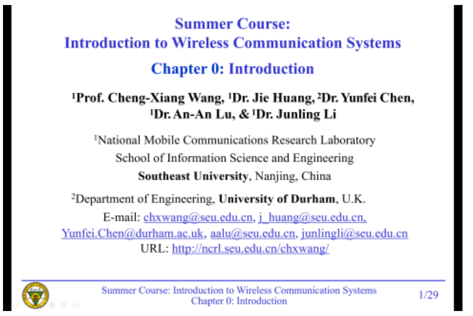
This course focuses on the fundamental theories and key technologies of wireless communication system, along with process of digital signal modulation, transmission, reception, and equalization techniques. Various modulation techniques will be discussed, as well as the performance analysis methods. We will also introduce some advanced topics in digital communications, such as channel equalization, channel coding and pulse shaping, multiple access, and OFDM. Four invited lectures on intelligent reflecting surface communications, green and intelligent communications, and 6G wireless communication technologies will also be given.

2.1.1. 教学日历

Time	Class	Content	Lecturer	Platform: FreeConferenceCall
27-Jun 14:00-15:35	**C1-C2**	Introduction to Wireless Communication System	Jie Huang	Access code: 635-508-3
5-Jul 16:00-16:45	**C3**	John Thompson's lecture: Overview of green and intelligent technologies for future wireless systems	John Thompson	Access code: 635-508-3
5-Jul 18:30-20:05	**C4-C5**	Digital Signal Modulation and Demodulation	Jie Huang	Access code: 635-508-3
11-Jul	**C6-**	Digital Signal	Jie Huang	Access code:

15:50-17:25	**C7**	Modulation and Demodulation		635-508-3
12-Jul 15:50-18:15	**C8-C10**	Capacity of Wireless Channels	Junling Li	Access code: 635-508-3
14-Jul 14:00-14:45	**C11**	Wei Zhang's lecture: Intelligent reflecting surface configurations for smart radio using deep reinforcement learning	Wei Zhang	Access code: 635-508-3
18-Jul 15:50-17:25	**C12-C13**	Experiments	Junling Li	Access code: 635-508-3
19-Jul 15:50-18:15	**C14-C16**	Signal Detection Theory and Channel Coding	An-An Lu	Access code: 635-508-3
21-Jul 14:00-14:45	**C17**	Rui Zhang's lecture: Movable antennas for wireless communications	Rui Zhang	Access code: 635-508-3
25-Jul 15:50-18:15	**C18-C20**	Multi-access	Junling Li, An-An Lu	Access code: 635-508-3
26-Jul 15:50-18:15	**C21-C23**	Experiments and visiting	An-An Lu	Access code: 635-508-3
28-Jul 18:30-19:15	**C24**	Jian Li's lecture: 6G: The next horizon	Jian Li	Access code: 635-508-3
2-Aug 09:50-11:25	**C25-C26**	MIMO	Yunfei Chen	Access code: 635-508-3
2-Aug 14:00-15:35	**C27-C28**	MIMO	Yunfei Chen	Access code: 635-508-3
3-Aug 09:50-11:25	**C29-C30**	MIMO and OFDM	Yunfei Chen	Access code: 635-508-3
3-Aug 14:00-15:25	**C31-C32**	OFDM	Yunfei Chen	Access code: 635-508-3

2.1.2. 课程情况



Summer Course:
Introduction to Wireless Communication Systems
Chapter 0: Introduction
¹Prof. Cheng-Xiang Wang, ¹Dr. Jie Huang, ²Dr. Yunfei Chen, ¹Dr. An-An Lu, & ¹Dr. Junling Li
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Summer Course: Introduction to Wireless Communication Systems
Chapter 0: Introduction
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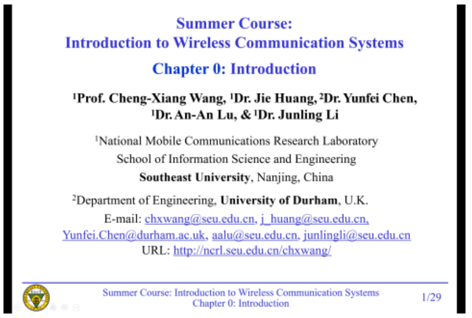

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Summer Course: Introduction to Wireless Communication Systems
Chapter 0: Introduction
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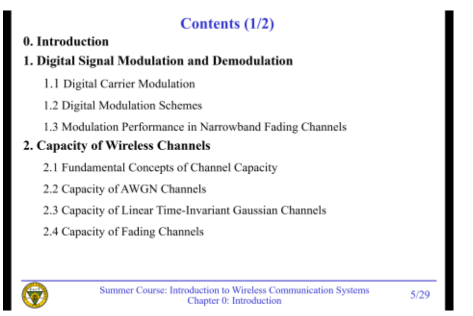

Contents (1/2)
0. Introduction
1. Digital Signal Modulation and Demodulation
1.1 Digital Carrier Modulation
1.2 Digital Modulation Schemes
1.3 Modulation Performance in Narrowband Fading Channels
2. Capacity of Wireless Channels
2.1 Fundamental Concepts of Channel Capacity
2.2 Capacity of AWGN Channels
2.3 Capacity of Linear Time-Invariant Gaussian Channels
2.4 Capacity of Fading Channels
Summer Course: Introduction to Wireless Communication Systems
Chapter 0: Introduction
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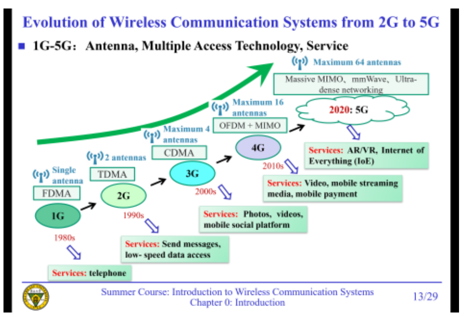

Evolution of Wireless Communication Systems from 2G to 5G
1G-5G: Antenna, Multiple Access Technology, Service
Maximum 64 antennas
Massive MIMO, mmWave, Ultra-dense networking
2020: 5G
Maximum 16 antennas
OFDM + MIMO
Maximum 4 antennas
CDMA
4G
Services: AR/VR, Internet of Everything (IoE)
2 antennas
TDMA
3G
Single antenna
FDMA
2G
Services: Video, mobile streaming media, mobile payment
1G
Services: Photos, videos, mobile social platform
Services: Send messages, low-speed data access
Services: telephone
1980s
1990s
2000s
2010s
Summer Course: Introduction to Wireless Communication Systems
Chapter 0: Introduction
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6G: The Next Horizon
From Connected People and Things to Connected Intelligence
Dr. Jian Li
Huawei Technologies
2021.8.4
HUAWEI

Movable Antenna (MA) Aided Wireless Communications: Opportunities and Challenges
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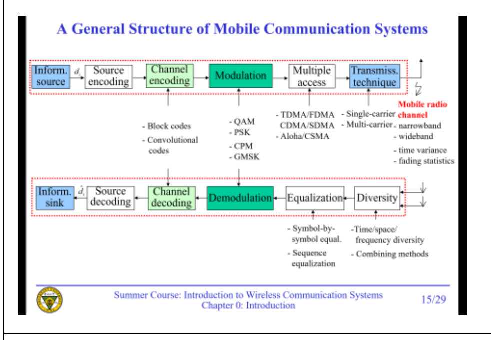
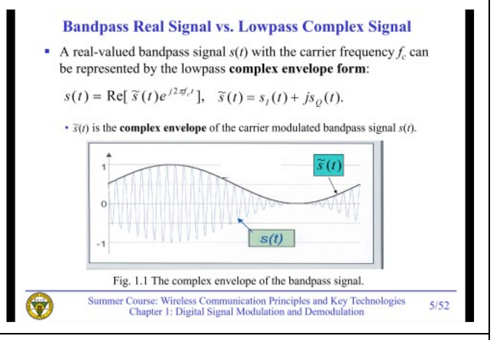


A General Structure of Mobile Communication Systems
Inform. source
Source encoding
Channel encoding
Modulation
Multiple access
Transmiss. technique
Mobile radio channel
- Block codes
- Convolutional codes
- QAM
- PSK
- CPM
- GMSK
- TDMA/FDMA
CDMA/SDMA
- Aloha/CSMA
- Single-carrier
- Multi-carrier
- narrowband
- wideband
- time variance
- fading statistics
Inform. sink
Source decoding
Channel decoding
Demodulation
Equalization
Diversity
- Symbol-by-symbol equal.
- Sequence equalization
-Time/space/frequency diversity
- Combining methods
Summer Course: Introduction to Wireless Communication Systems
Chapter 0: Introduction
15/29



Bandpass Real Signal vs. Lowpass Complex Signal
A real-valued bandpass signal s(t) with the carrier frequency f_c can be represented by the lowpass complex envelope form:
s(t) = Re[s̃(t)e^{j2πf_c t}], s̃(t) = s_I(t) + js_Q(t).
s̃(t) is the complex envelope of the carrier modulated bandpass signal s(t).
Fig. 1.1 The complex envelope of the bandpass signal.
Summer Course: Wireless Communication Principles and Key Technologies
Chapter 1: Digital Signal Modulation and Demodulation
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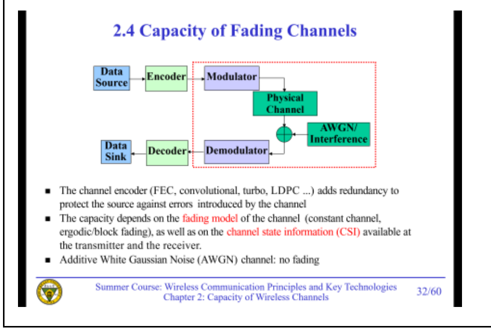

2.4 Capacity of Fading Channels
Data Source
Encoder
Modulator
Physical Channel
AWGN/Interference
Data Sink
Decoder
Demodulator
The channel encoder (FEC, convolutional, turbo, LDPC ...) adds redundancy to protect the source against errors introduced by the channel
The capacity depends on the fading model of the channel (constant channel, ergodic/block fading), as well as on the channel state information (CSI) available at the transmitter and the receiver.
Additive White Gaussian Noise (AWGN) channel: no fading
Summer Course: Wireless Communication Principles and Key Technologies
Chapter 2: Capacity of Wireless Channels
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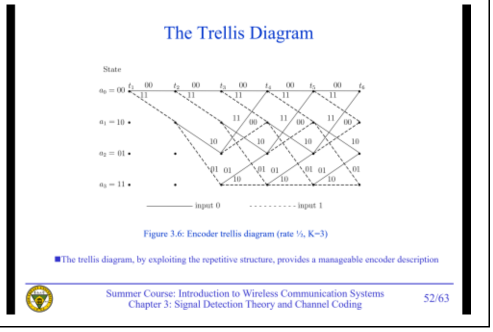

The Trellis Diagram
Figure 3.6: Encoder trellis diagram (rate ½, K=3)
The trellis diagram, by exploiting the repetitive structure, provides a manageable encoder description
Summer Course: Introduction to Wireless Communication Systems
Chapter 3: Signal Detection Theory and Channel Coding
52/63

2.1.3. 学生互动与反馈

1)Introduction

The origins of RIS can be traced back to the study of "metamaterials," a class of man-made materials with properties different from conventional materials. Studies have shown that the properties of light and electromagnetic waves can be changed through metamaterials, which cannot be done by natural materials, and this effect has important applications in communication.

Figure 1.1 Communication Process

As is known , the subject of communication is the source (transmitter), the channel (transmission channel), and the host (receiver).(Figure 1) In the traditional wireless channels, the signal has undergone a series of complex processes such as reflection, refraction, scattering, diffraction, penetration, interference, etc., and it is difficult to achieve perfect propagation. Studies have shown that the special properties of RIS to electromagnetic waves can be used to improve communication channels.

With the maturity of related theories and technologies, metamaterials have been widely used to manipulate electromagnetic waves in the past ten years. Early metamaterials have a single function, can only work according to the curing mode, can not control electromagnetic waves in real time, so we call it simulated metamaterials. Later, metamaterials can realize dynamic control of the state of artificial atoms inside through digital coding, so as to manipulate electromagnetic waves in real time, which is called "information metamaterials".

The basic structure of information metamaterials is shown in the figure below, each artificial atom (or superatom) can be composed of microcircuits containing bias diodes, and different states such as "ON" or "OFF" can be achieved at different voltages, and the response to electromagnetic waves is also different.

In actual implementation, artificial atoms can also use PIN tubes, transistors, MEMS, graphene, temperature-sensitive devices, photosensitive devices and other materials.

The two states of "ON" and "OFF" can correspond to 0 and 1 in the information world, and by configuring these units as 0 or 1, metamaterials have the ability to dynamically encode.

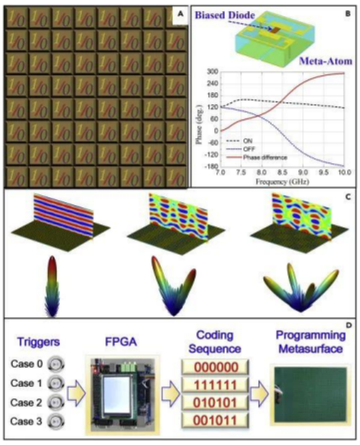

Figure 1.2 Structure of Information Metamaterials

Under different codes, information metamaterials can form electromagnetic beams of different shapes through reflection, so as to achieve the purpose of dynamic manipulation of electromagnetic waves.

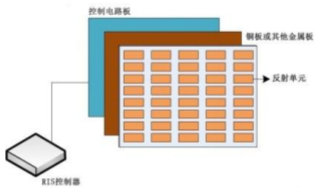

Figure 1.3 Structure of RIS

Movable Antenna for Wireless Communications

牛小顿 04021702

Abstract

Movable antenna (MA) is a new antenna architecture. Different from conventional fixed-position antennas (FPAs), the positions of MAs can be flexibly adjusted in a spatial region for improving the channel condition, which enhances the communication performance.

I. Introduction

Multiple-input multiple-output (MIMO) communication has been a key enabling technology in pursuit of larger capacity and higher reliability. By leveraging the beamforming gain and multiplexing gain, the capacity can be drastically increased with MIMO systems. Besides, the transmission reliability can be significantly improved in virtue of the spatial diversity provided by multiple antennas at the transmitter and receiver. With the current trend and future expectation of wireless communication systems migrating to higher frequency bands, such as millimeter-wave and terahertz bands, the decreasing wavelength results in smaller antenna size, which renders the MIMO system to be of larger scale in order to compensate for the more severe propagation losses. Compared to conventional MIMO, massive MIMO is able to exploit the spatial correlation of large antenna arrays for attaining higher array gains and mitigating the multi-user interference more effectively. However, since the antennas are deployed at fixed positions in the space, MIMO and massive MIMO cannot fully explore the spatial variation of wireless channels in a given receive area or receive field.

Movable antenna is a new antenna architecture. Different from conventional fixed-position antennas that undergo random wireless channel variation, the MAs with the capability of flexible movement can be deployed at positions with more favorable channel conditions to achieve higher spatial diversity gains. The spatial diversity can be easily obtained by adjusting the position of the MA. For MIMO systems. The MA systems resemble the widely explored distributed antenna system (DAS), where the remote antenna units (RAUs) are geographically distributed in wireless networks. The MA system implemented in a way where the antenna is connected to the radio-frequency (RF) chain via flexible cables. The position of the MA can be mechanically adjusted with the aid of drive components, such as stepper motors.

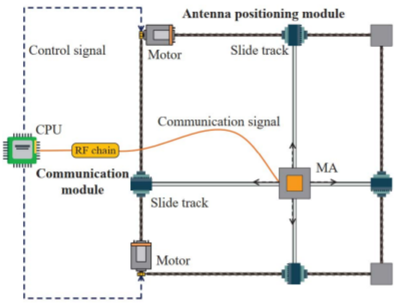

Figure 1. MA system structure

In a given receive region, if the MA can be rapidly deployed at the position with the highest channel gain, the receive signal-to-noise ratio (SNR) can be maximized, which can be regarded as a new way to acquire the spatial diversity gain. Limited by the physical characteristics, fluid antenna system (FAS)

东南大学 信息科学与工程学院
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The Overview of Movable Antennas

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***Abstract*—Movable antennas (MAs) make full use of the spatial variations of the wireless channel in a limited area by localized movement to obtain better channel conditions and improve the communication performance. In this paper, we first discuss the drawbacks associated with conventional Fixed Position Antennas (FPAs) and the resulting spawning of MA technology. Then, we introduce the current research status of MA technology, including the architecture of MA system, the performance advantages of MA technology in terms of signal power, interference mitigation and flexible beamforming, the simulation results of an MA-assisted communication system, and an application example of MA integrated with GNSS/INS. Finally, we analyze the broad application prospects of MA technology and the technical challenges and potential solutions.**

Keywords—Movable Antenna(MA), System Structure, Performance Analysis, challenges and directions.

I. INTRODUCTION

Antennas for wireless communication systems have evolved from single antenna, i.e., single-input-single-output (SISO), to multiple antennas, i.e., multiple-input-multiple-output (MIMO), over the past few decades. MIMO technology has greatly improved the performance of wireless communication systems through beamforming, spatial multiplexing, and so on. However, fixed antennas or antenna arrays (FPAs) exist only in one-dimensional (1D) or two-dimensional (2D) planes, which prevents wireless communication systems from fully utilizing the spatial degrees of freedom (DoF) in the region where the transmitter (Tx) and the receiver (Rx) are located; At the same time, although the traditional antenna selection (AS) technique can easily achieve spatial diversity and thus spatial diversity gain, it requires a large number of antennas to be configured within a specific region and the selection of antennas according to the channel state information (CSI), which inadvertently increases the operation cost. The moveable antenna (MA) technique is proposed as an effective solution to the above problem, which requires only a small number of antennas or even a single antenna to achieve a higher spatial diversity gain, and allows the antenna Tx/Rx to move continuously within a specified three-dimensional (3D) area by means of mechanical controllers and actuators to make full use of the spatial degrees of freedom (DoF) of this area to improve the wireless channel conditions.

As mentioned above, movable antennas (MAs) are both cost-effective and performant in mobile communication systems, and are highly promising for future communication applications. Based on this, the second part of this paper will introduce the current research status of the movable antenna (MA) technology, while the third part is a reflection on the future direction of MA and the technical challenges it faces, and the fourth part is a summary of the whole paper.

II. STATE-OF-THE-ARTS

In this section, we will first introduce the structure of the MA system and analyze its performance advantages over FPA; then we will give the simulation results of the MA-assisted communication system; and finally, the section is an example of an MA application.

A. Structure of The MA System

As shown in Fig. 1, the MA system consists of a communication module similar to a conventional FPA system and an antenna positioning module. In the positioning module, the MA is connected to the radio frequency chain (RF) via a flexible cable and mounted on a motor-driven mechanical slider. By receiving control signals from the CPU, the MA can then move within the localization module to change the channel conditions of the transceiver. In addition, antenna movement by circular slide rotation has been proposed.

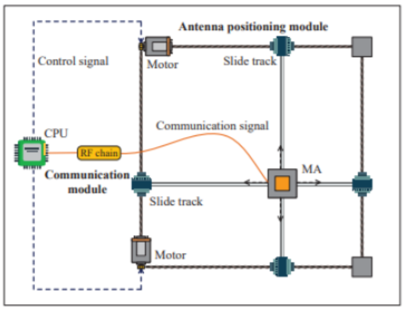


Fig. 1. An architecture for the MA system.

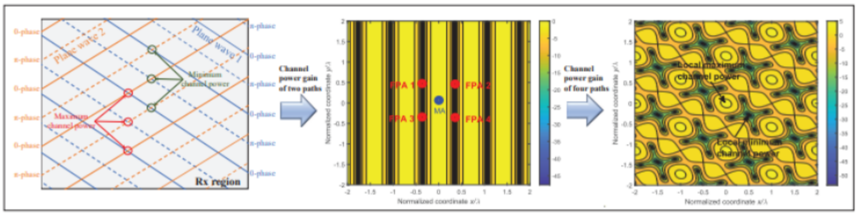


Fig. 2. Illustration of channel power gain (in dB) in the Rx region.

1

2.2. Mobile Fading Channel Modeling (移动衰落信道建模)

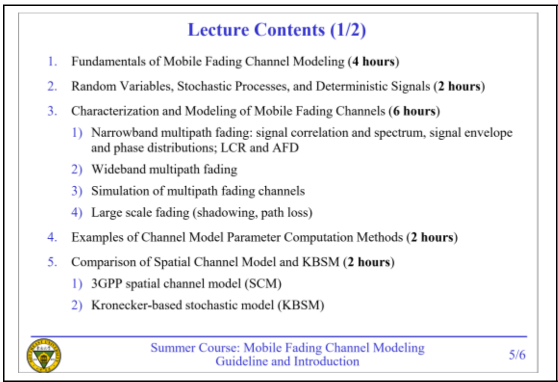
This course focuses on mobile fading channel modeling methods. A brief introduction of mobile fading channel will be given, followed by channel statistical properties, various channel model parameter computation methods, and different channel modeling methods will be discussed. An overview of standard 5G channel models is then provided. Meanwhile, 6G key technologies and challenges in channel modeling will be investigated. Three invited lectures on vehicle-to-vehicle (V2V) channel measurements and modeling, LiFi channel modeling, and channel model evolution from 5G to beyond 5G will also be given.

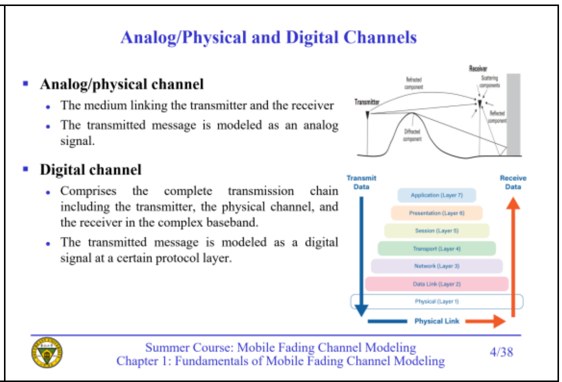
2.2.1. 教学日历

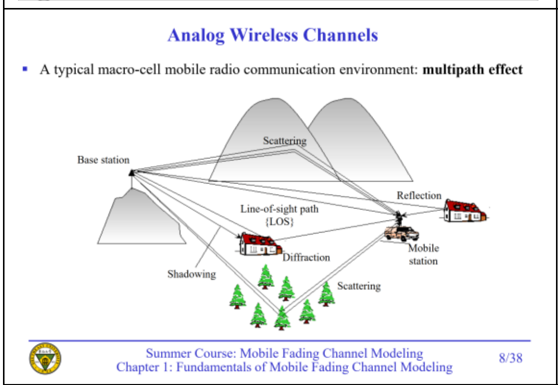
Time	Class	Content	Lecturer	Platform: FreeConferenceCall
28-Jun 09:50-11:25	**C1-C2**	Fundamentals of Mobile Fading Channel Modeling	Cheng-Xiang Wang	Access code: 635-508-3
29-Jun 14:00-15:35	**C3-C4**	Fundamentals of Mobile Fading Channel Modeling	Jie Huang	Access code: 635-508-3
3-Jul 14:00-15:35	**C5-C6**	Random Variables, Stochastic Processes, and Deterministic Signals	Yang Miao	Access code: 635-508-3
4-Jul 14:00-15:35	**C7-C8**	Characterization and Modeling of Mobile Fading Channels	Yang Miao	Access code: 635-508-3
5-Jul 14:00-15:35	**C9-C10**	Characterization and Modeling of Mobile Fading Channels	Yang Miao	Access code: 635-508-3
6-Jul 14:00-15:35	**C11-C12**	Characterization and Modeling of Mobile Fading Channels	Yang Miao	Access code: 635-508-3
10-Jul 14:00-15:35	**C13-C14**	Channel Model Parameter Computation Methods	Junling Li	Access code: 635-508-3
13-Jul 14:00-15:35	**C15-C16**	Experiments	Junling Li	Access code: 635-508-3
17-Jul 14:00-15:35	**C17-C18**	Experiments	Junling Li	Access code: 635-508-3
20-Jul 14:00-15:35	**C19-C20**	Comparison of Spatial Channel Model and KBSM	An-An Lu	Access code: 635-508-3
24-Jul 14:00-	**C21-C24**	Non-Stationary High-Speed Train Wireless	An-An Lu	Access code: 635-508-3

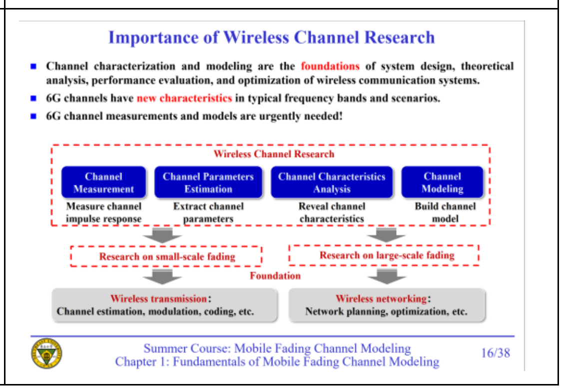
17:25		Channel Models		
24-Jul 18:30-19:15	**C25**	Chao Li's Lecture: Wireless channel model evolution from 5G to beyond 5G (5.5G)	Chao Li	Access code: 635-508-3
27-Jul 14:00-16:35	**C26-C28**	Wireless Channel Models for 5G and Beyond	Jie Huang	Access code: 635-508-3
28-Jul 10:00-10:45	**C29**	A. F. Molisch's Lecture: Evaluation methods and modeling aspects of channels	A. F. Molisch	Access code: 635-508-3
31-Jul 14:00-15:35	**C30-C31**	Wireless Channel Models for 5G and Beyond	Jie Huang	Access code: 635-508-3
31-Jul 21:00-21:45	**C32**	Harald Haas's lecture: Indoor LiFi channel modeling	Harald Haas	Access code: 635-508-3

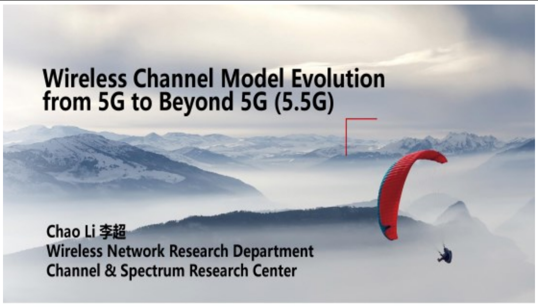
2.2.2. 课程情况











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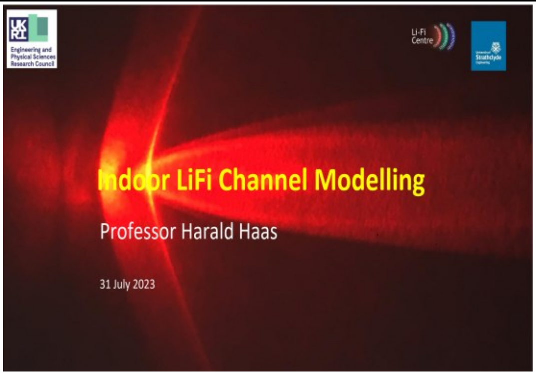

Summer Course: Mobile Fading Channel Modeling
Guideline and Introduction

[1]Prof. Cheng-Xiang Wang, [1]Dr. Jie Huang, [2]Dr. Yang Miao, [1]Dr. An-An Lu, & [1]Dr. Junling Li

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School of Information Science and Engineering
Southeast University, Nanjing, China

[2]Faculty of Electrical Engineering, Mathematics and Computer Sciences,
University of Twente, Enschede, The Netherlands

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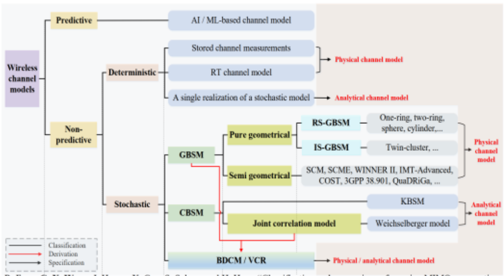
URL: http://ncrl.seu.edu.cn/chxwang/

Course Structure

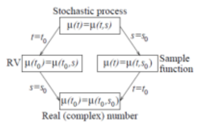
- **Lectures + Tutorials + Discussions (32 hours+16 discussion hours)**
  - **Lectures (25 hours)**:
    - —**2 hours**: random variables, stochastic processes, and deterministic signals
    - —**14 hours**: wireless channel modeling fundamentals and methods
    - —**9 hours**: advanced wireless channel models
  - **Tutorials/Experiments (4 hours)**: mathematical questions to help students understand channel modeling fundamentals and methods
  - **Invited Talks (3 hours)**:
    - —**Prof. Harald Haas** (FREng, FRSE, FIEEE, FIET), University of Strathclyde, U.K.: Indoor LiFi Channel Modeling
    - —**Prof. Andy Molisch** (MAAS, FIEEE), University of Southern California: Evaluation Methods and Modeling Aspects of Channels
    - —**Dr. Chao Li**, Huawei: Wireless Channel Model Evolution from 5G to Beyond 5G
  - **Discussions (16 hours, self-study)**:
    - Advanced wireless channel models (**8 hours**)
    - **Labs (8 hours)**: Matlab exercises to train students how to simulate wireless channels

Classification of MIMO Channel Models

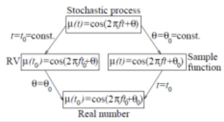


R. Feng, **C.-X. Wang**, J. Huang, X. Gao, S. Salous, and H. Haas, "Classification and comparison of massive MIMO propagation channel models," *IEEE Int. Things J.*, vol. 9, no. 23, pp. 23452–23471, Dec. 2022.

Relations Between Stochastic Processes, Random Variables, Sample Functions, and Real (Complex) Numbers



Example 2.6: $\mu(t) = \cos(2\pi f t + \theta)$, f = const., θ = RV



Relations Between the Correlation Functions for WSSUS Channels

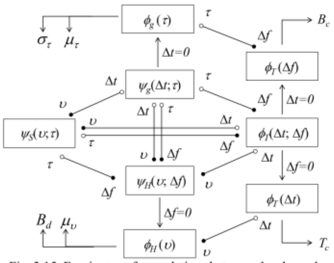


Fig. 3.15: Fourier transform relations between the channel correlation functions for WSSUS channels.

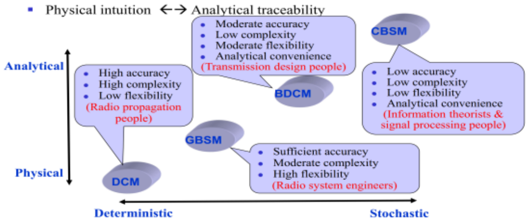
The Modified Method of Exact Doppler Spread (MMEDS)

	MEDS	MMEDS
Real processes	$\tilde{\mu}_{i,l}(t) = \sum_{n=1}^{N_{i,l}} c_{i,n,l}\cos(2\pi f_{i,n,l}t + \theta_{i,n,l})$	$\tilde{\mu}_{i,l}(t) = \sum_{n=1}^{N_i} c_{i,n,l}\cos(2\pi f_{i,n,l}t + \theta_{i,n,l})$
Phases $\theta_{i,n,l}$	Realizations of a random generator uniformly distributed over $[0,2\pi)$	
Gains $c_{i,n,l}$	$c_{i,n,l} = \sigma_0\sqrt{\frac{2}{N_{i,l}}}$	$c_{i,n,l} = \sigma_0\sqrt{\frac{2}{N_i}}$
Discrete frequencies $f_{i,n,l}$	$f_{i,n,l} = f_m \sin[\frac{\pi}{2N_{i,l}}(n-\frac{1}{2})]$	$f_{i,n,l} = f_m \sin[\frac{\pi}{2N_i}(n-\frac{1}{2})] + (l-1)\varepsilon]$

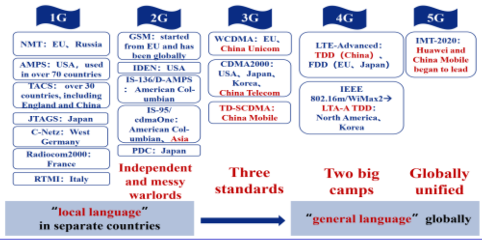
Observation: If $(l-1)\varepsilon=0$, i.e., l=1 or $\varepsilon=0$, the MMEDS reduces to the MEDS.

Trade-Off of MIMO Channel Models

- Deterministic approach ←→ Stochastic approach
- Physical intuition ←→ Analytical traceability



1G-5G: Communication Standards Evolution



2.2.3. 学生互动与反馈

Summer Course: Mobile Fading Channel Modeling

Student Name: 牛泽原（Zeyuan Niu）
Student Number: 04020131

Title: A Study on Wireless Channel Model Evolution from 5G to Beyond 5G (5.5G)

0.Abstract

The evolution of wireless communication from 5G to Beyond 5G (5.5G) has led to a transformative shift in wireless channel models. This comprehensive report navigates through this evolution, spotlighting the developments, challenges, and forthcoming research directions.[1] As 5G introduced groundbreaking concepts, Beyond 5G ventures even further, demanding novel channel models to cater to unique requirements such as ultra-reliable and low-latency communications, IoT proliferation, and enhanced spectral efficiency.

1. Introduction

Wireless communication has witnessed unprecedented growth and innovation over the past decades, fundamentally altering the way societies interact, businesses operate, and technologies evolve.[1] The advent of 5G, with its promise of enhanced data rates, lower latency, and massive device connectivity, marked a significant milestone in the realm of wireless technology. However, the surge in data-intensive applications, the proliferation of Internet of Things (IoT) devices, and the emergence of novel use cases, such as autonomous vehicles and smart cities, have prompted the wireless industry to explore even more advanced communication paradigms.[2]

Beyond 5G, often referred to as 5.5G, represents the next frontier in wireless communication systems. As the foundational principles of 5G are refined and extended, Beyond 5G seeks to address the limitations and harness the opportunities that have emerged in its wake. This transition is not merely about incremental enhancements; it signifies a fundamental shift in the design and operation of wireless networks.[1] The central tenets of Beyond 5G encompass ultra-reliable and low-latency communications (URLLC), massive machine-type communications (mMTC), enhanced spectrum efficiency, and seamless integration of terrestrial and non-terrestrial networks.

The journey from 5G to Beyond 5G has ignited a paradigm shift in wireless channel modeling. Channel models are the bedrock upon which wireless communication systems are built, providing insights into signal propagation, fading characteristics, interference patterns, and spatial distribution of users.[3] The accuracy and adaptability of these models directly influence the performance and efficiency of communication systems. As the wireless landscape becomes more intricate, the conventional channel models tailored for 5G must evolve to accommodate the unique requirements of Beyond 5G applications.

This report embarks on an exploratory journey through the evolution of wireless channel models from 5G to Beyond 5G. By delving into the advancements and challenges associated with this evolution, we aim to offer a comprehensive understanding of the transformative landscape of wireless communication. As wireless systems extend their reach into the realms of healthcare, manufacturing, entertainment, and beyond, the evolution of channel models stands as a linchpin for enabling seamless and ubiquitous connectivity. In the subsequent sections, we delve into the state-of-the-art channel modeling techniques, emerging research directions, and the intricate challenges that define the trajectory towards realizing the full potential of Beyond 5G communication systems.

2. State-of-the-Arts

The current landscape of wireless communication is characterized by a myriad of innovative technologies and paradigms that have evolved from the foundations laid by 5G. In the quest to meet the escalating demands of data-hungry applications and ever-expanding

Report on Indoor LiFi Channel Modelling

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***Abstract*—This paper introduces Light fidelity (LiFi), feature of LiFi network and LiFi network system. To give a better perspective of LiFi, this paper introduces the indoor LiFi channel modelling result. Finally, future research directions and challenges are introduced. This paper is a report on the invited talk 'indoor LiFi channel modelling' from professor Harald Haas in SEU summer course 'Mobile Fading Channel Modeling'.**

***Index Terms*—LiFi; Channel Modelling;**

I. Introduction

Light fidelity is networked, bidirectional wireless communication with light. It is used to connect fixed and mobile devices at very high data rates by harnessing the visible light and infrared spectrum [1]. Combined, these spectral resources are 2600 times larger than the entire radio frequency (RF) spectrum [2]. The fundamental differences between RF and OWC are shown as Table I.

TABLE I: Fundamental differences between RF and OWC

Spectrum	Information	Signal
RF	Carried in electric field	Bipolar and complex valued
OWC	Carried in optical intensity	Unipolar nonnegative and real valued

II. Features of LiFi Networking

The features of LiFi Networking is shown in Fig.1.

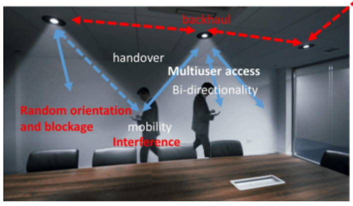


Fig. 1: Features of LiFi Networking

A. Backhaul

Backhaul in LiFi connects access points to the core network, enabling data exchange. It affects network performance and can use wired (Ethernet) or wireless (Wi-Fi, cellular) connections.

B. Random Orientation and Blockage

LiFi requires direct line of sight between transmitter and receiver. Challenges arise when devices are misaligned or obstacles block the signal. Adaptive algorithms and processing manage such issues.

C. Interference

Interference in LiFi comes from natural/artificial light sources. Techniques like frequency modulation and coding counter interference, ensuring reliable data transfer even in the presence of other light sources.

III. LiFi Networking System

A. Multi-directional receiver

1) Multiple directional receiver (MDR): A multi-directional receiver in LiFi technology captures data-carrying light signals from different angles simultaneously. It enhances communication by receiving signals from all directions, improving connectivity in environments with obstacles or complex layouts. This feature is particularly valuable in settings like factories, hospitals, and smart homes where traditional wireless technologies might struggle due to line-of-sight limitations. The sketch map of it is shown as Fig.2.

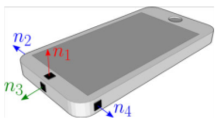


Fig. 2: The MDR structures for hand-held smartphone

2) Single direction receiver (SR): A single-direction receiver in LiFi technology captures data-carrying light signals from one specific direction. This targeted reception is useful for establishing focused and reliable communication links, especially in scenarios where maintaining a consistent line of sight is feasible and desired. The sketch map of it is shown as Fig.3.

3) Performance comparison of SR and MDR: Fig.4 shows that for the same received SNR, MDR has the better error performance than SR [3].

Course Report of Mobile Fading Channel Modeling

04020432 帅杰博

abstract

LiFi (Light Fidelity), also known as visible light communication (VLC), is an emerging wireless communication technology that utilizes visible light or infrared signals for data transmission. Unlike traditional radio frequency (RF)-based communication, LiFi leverages light-emitting diodes (LEDs) or laser diodes to modulate data onto light waves, enabling high-speed and secure wireless connectivity.

LiFi offers several advantages over RF communication. It provides significantly higher data rates, reaching several gigabits per second in laboratory conditions, due to the broad bandwidth available in the visible light spectrum. LiFi also offers enhanced security as light signals do not penetrate obstacles, reducing the risk of external interception. Additionally, LiFi can be deployed in environments where RF signals face challenges, such as areas with high electromagnetic interference or where radio signals are restricted.

One of the key applications of LiFi is indoor wireless communication. By utilizing existing lighting infrastructure, LiFi can provide both illumination and data connectivity simultaneously, making it suitable for office spaces, hospitals, schools, and retail environments. LiFi can also be deployed in secure environments like government facilities and financial institutions to ensure data privacy.

Introduction

The utilization of new spectrum refers to the exploration and allocation of frequency bands that have not been traditionally used for wireless communication. As existing frequency bands become congested due to the increasing demand for wireless services, new spectrum bands offer an opportunity to address the growing capacity requirements and enable new wireless applications

LiFi is a wireless communication technology that utilizes visible light or infrared signals to transmit data. And it is an emerging technology with promising potential. While indoor LiFi (Light Fidelity) channel modeling involves characterizing the wireless communication channel for LiFi systems operating in indoor environments.

Figure 1: The "Lifi" coming on the way

State-of-the-arts

The IEEE has developed the IEEE 802.15.7 standard specifically for Visible Light Communication (VLC), which encompasses LiFi. This standard provides guidelines for the physical layer and media access control (MAC) layer for LiFi systems.

Several companies and organizations have conducted LiFi pilot projects and commercial deployments in various sectors. These include office spaces, hospitals, museums, retail environments, and industrial settings. However, LiFi adoption was still relatively limited compared to traditional wireless technologies

2.3. Frontiers of Microwave, Millimeter-wave and Terahertz Technologies (微波、毫米波与太赫兹前沿技术)

This course introduces the fundamental knowledge and application of microwave, millimeter-wave and terahertz techniques, as well as their recent developments. Specially, the following contents are introduced in detail: the basic knowledge of electromagnetic equations and electromagnetic waves; microwave network and its applications; electromagnetic guided-wave theory and its applications, as well as its applications in the advanced filter design; microwave and millimeter-wave techniques in the next-generation satellite and 5G/6G communication systems; function-integrated passive devices and antennas; new manufacturing techniques for millimeter-wave and terahertz components, as well as microwave and millimeter-wave filters based on additive manufacturing; high-power microwave technologies for satellite applications; basic knowledge of radar system: advanced phased array radar technology and its recent development. This course helps students master the basic knowledge of microwave, millimeter-wave and terahertz technology, understand their applications, and establish the "field" concept of microwave technology.

2.3.1. 教学日历

Time	Class	Content	Lecturer	Location
03-Jul 09:50-11:25	**C1-C2**	Fundamental Equations of Electromagnetic Waves and Their Applications (Unit 1A)	Jia-Sheng Hong	Jiulonghu campus J2-101; Tecent Meeting: 757-996-544
04-Jul 09:50-11:25	**C3-C4**	Fundamental Equations of Electromagnetic Waves and Their Applications (Unit 1B)	Jia-Sheng Hong	Jiulonghu campus J2-101; Tecent Meeting: 165-343-195
05-Jul 09:50-11:25	**C5-C6**	Microwave Network and Applications (Unit 2A)	Jia-Sheng Hong	Jiulonghu campus J2-101; Tecent Meeting: 395-510-980
06-Jul 09:50-11:25	**C7-C8**	Microwave Network and Applications (Unit 2B)	Jia-Sheng Hong	Jiulonghu campus J2-101; Tecent Meeting: 182-766-976
07-Jul	**C9-**	Guide-Wave Techniques	Jia-Sheng	Jiulonghu

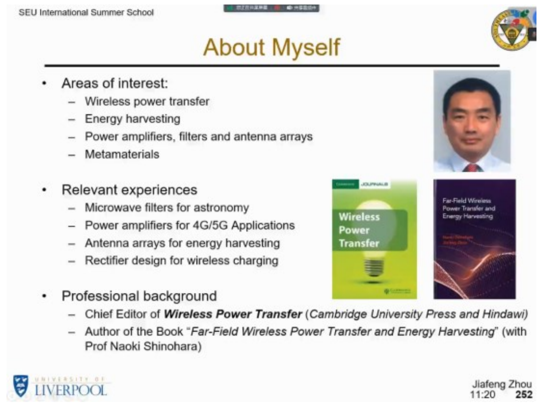
09:50-11:25	**C10**	and Fundamental Theories of Filters (Unit 3A)	Hong	campus J2-101; Tecent Meeting: 906-248-822
08-Jul 09:50-11:25	**C11-C12**	Guide-Wave Techniques and Fundamental Theories of Filters (Unit 3B)	Jia-Sheng Hong	Jiulonghu campus J2-101; Tecent Meeting: 762-654-005
09-Jul 09:50-11:25	**C13-C14**	Microwave and Millimeter-wave Techniques in the Next Generation Satellite and 5G/6G Communication Systems (Unit 4A)	Jia-Sheng Hong	Jiulonghu campus J2-101; Tecent Meeting: 708-102-179
10-Jul 09:50-11:25	**C15-C16**	Microwave and Millimeter-wave Techniques in the Next Generation Satellite and 5G/6G Communication Systems (Unit 4B)	Jia-Sheng Hong	Jiulonghu campus J2-101; Tecent Meeting: 948-478-941
29-Jul 14:00-17:25	**C17-C20**	Development of Meteorological Satellites and Microwave Detection Technology	Zhen-Hua Zhu	Jiulonghu campus J2-101; Tecent Meeting: 105-785-531
30-Jul 14:00-17:25	**C21-C24**	Introduction of Radar Techniques and Relative Theory	Hong-Chao Wu	Jiulonghu campus J2-101; Tecent Meeting: 502-641-862
31-Jul 09:50-11:25	**C25-C26**	Introduction of Wireless Energy Harvesting Techniques (Unit 1A)	Jiafeng Zhou	Jiulonghu campus J2-101; Tecent Meeting: 288-895-074
01-Aug 09:50-11:25	**C27-C28**	Introduction of Wireless Energy Harvesting Techniques (Unit 1B)	Jiafeng Zhou	Jiulonghu campus J2-101;

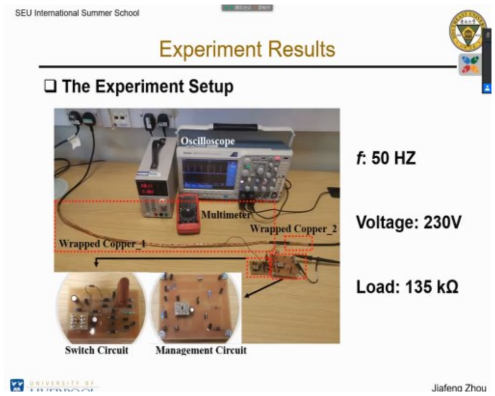
				Tecent Meeting: 725-616-588
07-Aug 09:50-11:25	**C29-C30**	Introduction of Wireless Power Transfer Techniques (Unit 2A)	Jiafeng Zhou	Jiulonghu campus J2-101; Tecent Meeting: 231-848-474
08-Aug 09:50-11:25	**C31-C32**	Introduction of Wireless Power Transfer Techniques (Unit 2B)	Jiafeng Zhou	Jiulonghu campus J2-101; Tecent Meeting: 950-921-951

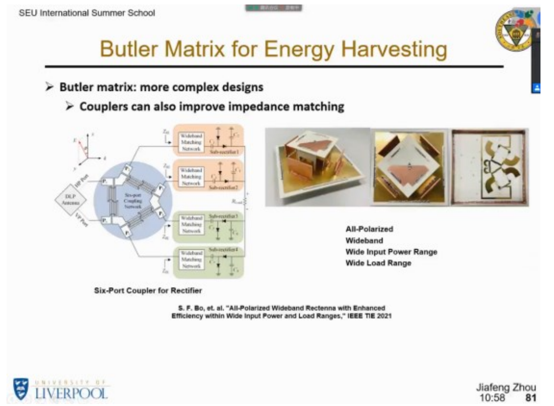
2.3.2. 课程情况


CETC 中国电子科技集团公司第十四研究所
技术突破引领相控阵天线变革
无源相控阵天线
有源相控阵天线
数字相控阵天线
下一代相控阵天线
上世纪60年代起
上世纪80年代起
本世纪初始
未来
天线发展史上重大飞跃，通过电扫完成波束扫描，具备波束捷变能力，可灵活搜索和跟踪目标
目前相控阵天线主流，突破了集中式发射机的限制，作用距离和整体可靠性大幅提升
数字波束形成技术带来相控阵自由度增加，抗干扰性能提升以及目标容量进一步增强
具备自适应、智能化等特征，从综合射频到数据处理逐步实现去中心化的演进，全面提升泛在智能探测感知能力
从无源到有源、从模拟到数字、从自适应到智能化，相控阵天线的研究范畴正日趋扩大，已经成为衡量信息化水平的重要标志之一


SEU International Summer School
How to Design a Filter?
• Real life experience
512Hz
440Hz
UNIVERSITY OF LIVERPOOL
Jiafeng Zhou
10:50 202


SEU International Summer School
About Myself
• Areas of interest:
– Wireless power transfer
– Energy harvesting
– Power amplifiers, filters and antenna arrays
– Metamaterials
• Relevant experiences
– Microwave filters for astronomy
– Power amplifiers for 4G/5G Applications
– Antenna arrays for energy harvesting
– Rectifier design for wireless charging
• Professional background
– Chief Editor of Wireless Power Transfer (Cambridge University Press and Hindawi)
– Author of the Book "Far-Field Wireless Power Transfer and Energy Harvesting" (with Prof Naoki Shinohara)
Wireless Power Transfer
UNIVERSITY OF LIVERPOOL
Jiafeng Zhou
11:20 252


SEU International Summer School
Experiment Results
❑ The Experiment Setup
Oscilloscope
Multimeter
Wrapped Copper_1
Wrapped Copper_2
Switch Circuit
Management Circuit
f: 50 HZ
Voltage: 230V
Load: 135 kΩ
Jiafeng Zhou


SEU International Summer School
Butler Matrix for Energy Harvesting
➢ Butler matrix: more complex designs
➢ Couplers can also improve impedance matching
All-Polarized
Wideband
Wide Input Power Range
Wide Load Range
Six-Port Coupler for Rectifier
S. F. Bo, et. al. "All-Polarized Wideband Rectenna with Enhanced Efficiency within Wide Input Power and Load Ranges," IEEE TIE 2021
UNIVERSITY OF LIVERPOOL
Jiafeng Zhou
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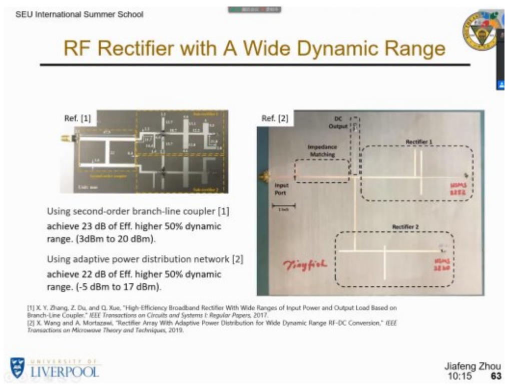
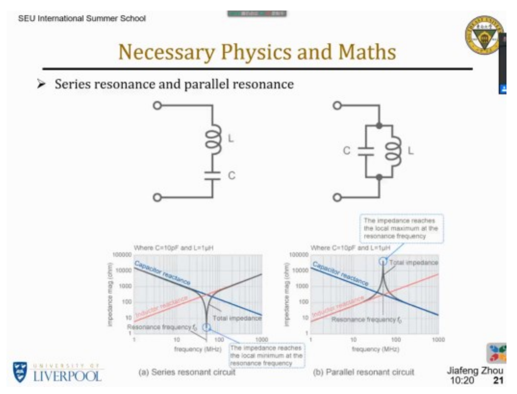
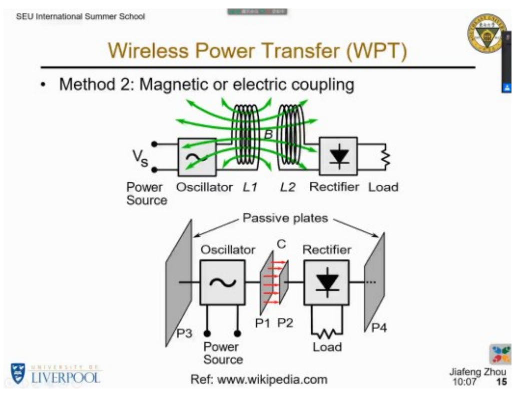

SEU International Summer School
RF Rectifier with A Wide Dynamic Range
Ref. [1]
Ref. [2]
Using second-order branch-line coupler [1]
achieve 23 dB of Eff. higher 50% dynamic range. (3dBm to 20 dBm).
Using adaptive power distribution network [2]
achieve 22 dB of Eff. higher 50% dynamic range. (-5 dBm to 17 dBm).
Rectifier 1
Rectifier 2
Impedance Matching
UNIVERSITY OF LIVERPOOL
Jiafeng Zhou
10:15 63


SEU International Summer School
Necessary Physics and Maths
➢ Series resonance and parallel resonance
L
C
(a) Series resonant circuit
(b) Parallel resonant circuit
UNIVERSITY OF LIVERPOOL
Jiafeng Zhou
10:20 21


SEU International Summer School
Wireless Power Transfer (WPT)
• Method 2: Magnetic or electric coupling
Power Source
Oscillator
L1
L2
Rectifier
Load
Passive plates
C
P1 P2
P3
P4
Ref: www.wikipedia.com
UNIVERSITY OF LIVERPOOL
Jiafeng Zhou
10:07 15

2.3.3. 学生互动与反馈

- 《微波、毫米波与太赫兹前沿技术》课程报告

姜钰学(04020104)
（东南大学信息科学与工程学院，南京，210000）

摘　要：微波、毫米波和太赫兹技术经过近几十年的迅速发展，为通信、微波器件、雷达、卫星等领域带来了革命性的改变，是如今促进人类科技发展的前沿推手之一。本文立足于 2023 年国际暑期学校的《微波、毫米波与太赫兹前沿技术》课程，首先对课程内容进行总体回顾。随后针对课程的各个主题，总结自己的学习收获。最后总结自己参与本次课程的心得体会。
关键词：微波；毫米波；太赫兹

Report on Frontiers of Microwave, Millimeter-wave and Terahertz Technologies

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(*School of Information Science and engineering, Southeast University, Nanjing* 210000, *China*)

Abstract: Microwave, millimeter wave, and terahertz technologies have undergone rapid development in recent decades, bringing revolutionary changes to fields such as communication, microwave devices, radar, and satellites. They are now one of the cutting-edge drivers promoting human technological development. This article is based on the "Microwave, Millimeter Wave, and Terahertz Frontier Technology" course of the International Summer School in 2023. Firstly, an overall review of the course content is provided. Subsequently, my learning gains based on the various themes of the course is summarized. Finally, the report summarizes my own experiences and experiences from participating in this course.
Key words:microwave；millimeter wave；terahertz

1　引　言

微波技术是近一个世纪以来最重要的科学技术之一，从雷达到广播电视、无线电通信再到微波炉，微波技术对社会的发展和人们生活的进步产生着深远影响。在近几十年中，各种毫米波器件、芯片不断发展，逐渐为毫米波的广泛应用打下基础，毫米波频段凭借其频谱资源丰富、便于系统小型化等优势，日益成为研究者关注的热门。太赫兹频段则位于毫米波和红外光之间，频谱更宽，且在分辨力、透视性等方面具有突出优势，有着良好的应用前景[1]。

我计划在研究生阶段选择电磁场与微波技术专业，因此对微波的相关知识很感兴趣。在大三升大四的暑假，为了更进一步地了解微波、毫米波相关的知识和前沿技术，我参加了本次暑期学校课程，希望能丰富自己在这方面的知识储备。

Research of Electromagnetic Metamaterial on Antenna

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***Abstract*-**Electromagnetic Metamaterial is one of the research focuses in the field of electromagnetic microwave and new materials science. The emergence of metamaterial provides a new technical approach for antenna design and optimization. Based on the above background, on the basis of in-depth analysis and research of Metamaterial theory, this paper introduces a new type of Metamaterial structure, and then studies the Microstrip antenna and MIMO (Multiple Input Multiple Output) antenna using electromagnetic Metamaterial structure, focusing on the improvement and improvement of antenna performance by Metamaterial single element.

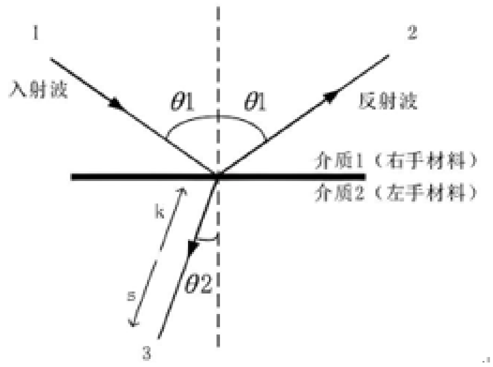
***Index Terms*-**Electromagnetic wave,Metamaterial,MIMO antenna,microstrip antenna.

I. Introduction

Electromagnetic phenomenon is a general term for the electrical and magnetic properties of matter. Electromagnetism studies the interaction between electric field, magnetic field and matter and its practical application. Regardless of the form in which electromagnetic waves propagate,the electromagnetic characteristics of the propagation medium play an important role. As is well known, when electromagnetic waves propagate in traditional media, the direction of the electric field, magnetic field, and propagation are in a mutually perpendicular spatial relationship, and meet the right-hand spiral rule. Traditional natural materials are an important part of classical Electromagnetism. The electromagnetic properties of natural materials usually use dielectric constant ε ,magnetic permeability μ To describe.

Corresponding to natural materials, Metamaterial was proposed in 1968. Because Metamaterial have strange properties, the propagation of electromagnetic waves in them will show unusual physical properties, so the proposal of Metamaterial enriches the application of electromagnetic functions. Metamaterial mainly refer to composite or hybrid materials that are made by rigorous artificial design according to application requirements and arranged by periodic or aperiodic artificial sub wavelength structural units. According to the equivalent medium theory, the electromagnetic properties of Metamaterial can be determined by the equivalent dielectric constant ε_r and equivalent permeability μ_r . By artificially designing Metamaterial elements, the equivalent permittivity ε_r and equivalent permeability μ_r at resonance frequency can be calculated to design Artificial Metamaterial with single negative or double negative dielectric constant ε and magnetic permeability μ [1,2].

The rapid development of modern wireless communication systems, whether military or civilian, has put forward higher requirements for the speed and quality of information transmission. Antennas, as devices used to radiate and receive electromagnetic waves in communication systems, are used to achieve the conversion of guided wave energy and electromagnetic wave energy. Their performance directly affects the quality and performance of communication systems. Modern communication methods often require antennas to



(b)

Fig2.2 Schematic diagram of (a) right-hand and (b) left-hand materials.

As shown in Fig 2.2, when an electromagnetic wave is incident between the dielectric surfaces of a right-handed material, both the reflected and refracted waves are on the same side of the normal. However, when an electromagnetic wave is incident on the surface of a left-handed material, the specificity of the left-handed material causes its phase to change abruptly, causing the reflected and refracted waves to be distributed on different sides of the normal. If the normal is taken as the zero degree reference line, At this time, the refracted wave has a "lag" with respect to the refracted wave in the right-handed material, and has a negative refraction angle, which is the Negative refraction index effect.

B. Theory of Microstrip antenna

Microstrip antenna is widely used in antenna design because of its small size, light weight, high integration and low cost. The schematic diagram of common Microstrip antenna is shown in Figure 2-3. The Microstrip antenna is mainly composed of metal radiation patch, dielectric substrate and feed structure. The feeding structures include microstrip feeding, coaxial feeding, coupled feeding, etc. Microstrip feeding is more conducive to system integration. There are various shapes of metal radiation patches, including rectangles, circles, and other polygons. The characteristic functions of electromagnetic waves on different patch shapes will vary, resulting in different transmission methods and radiation characteristics. The design and analysis of rectangular patches are relatively simple, making it easier to use the transmission line model method for impedance matching. The usual design method is to first determine the reference size of the patch based on a formula, and then optimize it using simulation software [6].

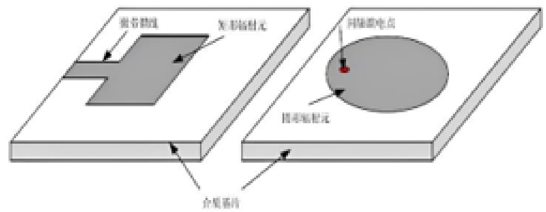


Fig2.3 The schematic diagram of common Microstrip antenna.

III. Design of MIMO antenna based on electromagnetic Metamaterial

In the design of MIMO antennas, ArlonAD255C substrate with a thickness of 1.6mm is used, with relative dielectric constant and loss tangent of 2.55 and 0.0014, respectively. Fig3.1 shows the entire design process of the designed MIMO antenna. The initial structure is shown in Fig3.1 (a), using a two unit MIMO antenna array arranged parallel and side by side. The radiation patch is selected as a regular rectangular patch, and the overall size of the rectangular microstrip can be calculated. We choose 50 Ω Microstrip as the feeding mode, which is coupled to the radiation patch via a quarter wavelength converter. Fig3.1 (b) shows that a gap has been etched on the ground at the back of the rectangular patch of two antenna units, which can effectively reduce the size of the antenna unit. The plane size of the antenna ranges from 70 × The reduction of 65mm2 to 55x50mm2 resulted in a relative area reduction of 39.6% [7].

3. 课程总结及反馈

这几门课程是全英文的研讨课，学生刚开始听全英文的课程还是有些难度，只能听懂60%-70%。此外暑期学校的课程节奏比较紧凑，学生跟进的有些吃力。在以后的授课中，为了改进授课效果，可以适当放慢速度，还会结合暑期学校的特点进一步改进。

此次暑期学校课程为学生介绍了无线通信的基本原理，包括数字信号调制与解调、信道容量、信号检测与信道编码、多址接入、MIMO、OFDM 等内容，无线信道相关的基础理论，包括移动衰落信道基础知识、信道特性分析、参数计算方法、信道建模方法、非平稳高铁信道模型、6G 信道模型，微波、毫米波与太赫兹前沿技术等内容。本次开展的国际暑期学校以坚持学术导向，强化拓展培养，将通识教育、专业教育、学术交流和创新创业教育有机综合，全面提升学生综合素质。国际知名学者、企业行业专家与青年教师共同授课，从不同角度、不同领域、不同层次为学生讲授学术前沿与个人发展成长经验，得到了学生的一致好评。线上授课方式，更利于授课老师和学生合理安排时间，从而可以邀请到更多国际顶尖专家学者为学生授课。当前课程安排形势对于学生的实践能力训练方面偏少，与专家面对面的沟通仍然缺乏，课程之间的匹配性和系统系还需要进一步加强，后面信息学院将进一步改进提高，力争打造理论实践融合、授课形势丰富的国际暑期学校项目。