东南大学

2023 年国际暑期学校

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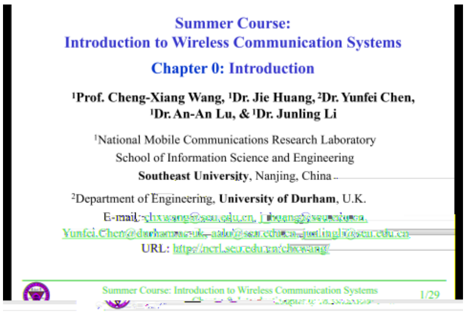

Summer Course:
Introduction to Wireless Communication Systems

Chapter 0: Introduction

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

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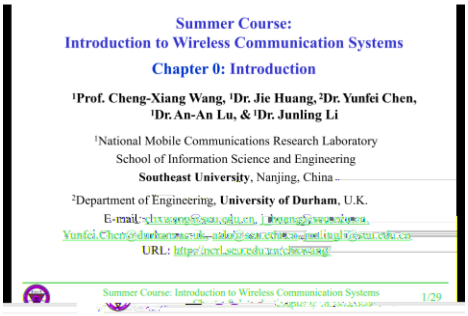

Summer Course:
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Chapter 0: Introduction

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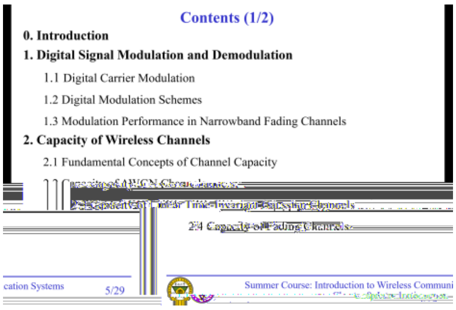
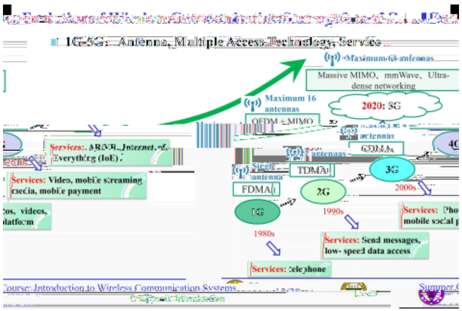


Contents (1/2)



[illegible]

- 1G-5G: Antenna, Multiple Access Technology, Service

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

Rui Zhang

香港中文大学（深圳）理工学院校长学勤讲座教授
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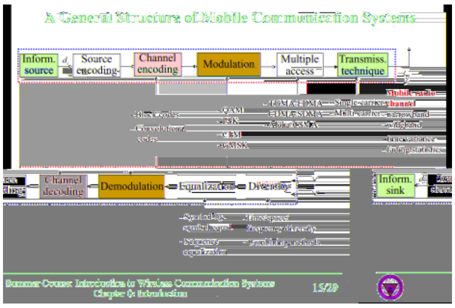
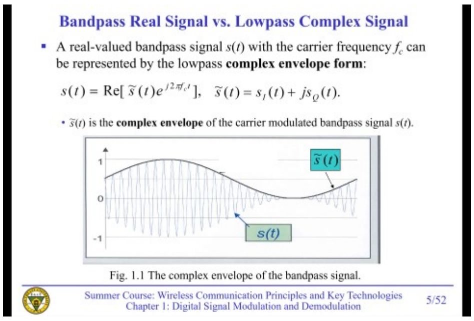
July 21, 2023



A General Structure of Mobile Communication Systems



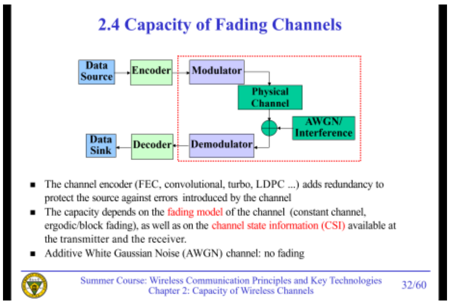
Bandpass Real Signal vs. Lowpass Complex Signal

- A real-valued bandpass signal $s(t)$ with the carrier frequency f_c can be represented by the lowpass **complex envelope form**:

$$s(t) = \mathrm{Re}[\tilde{s}(t)e^{j2\pi f_c t}], \quad \tilde{s}(t) = s_I(t) + js_Q(t).$$

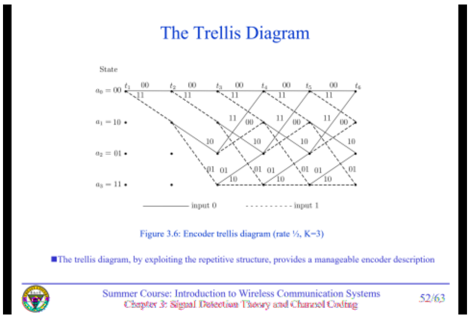
- $\tilde{s}(t)$ is the **complex envelope** of the carrier modulated bandpass signal $s(t)$.

Fig. 1.1 The complex envelope of the bandpass signal.



2.4 Capacity of Fading Channels

- 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



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

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 channel, 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, and 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 [illegible] through digital coding ("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 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.

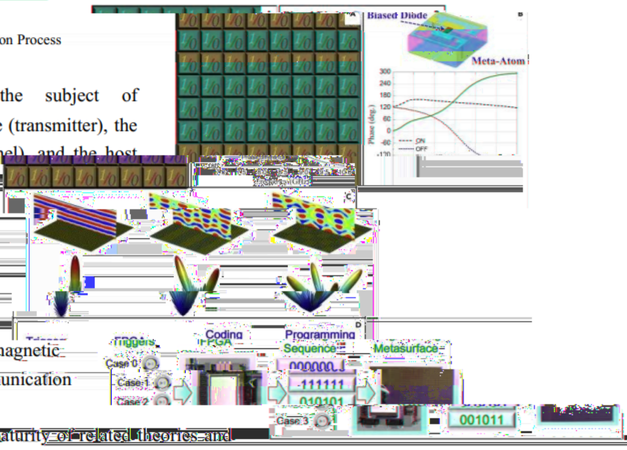


Figure 1.2 Structure of Information Metamaterials

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.

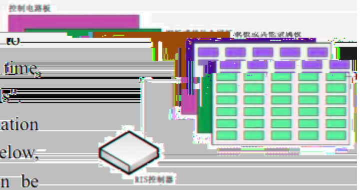


Figure 1.3 Structure of RIS

ications   Movable Antenna for Wireless Commun

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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.

Movable antenna architecture. Differen fixed-position antenna wireless channel varia capability of flexibl deployed at positions channel conditions to diversity gains. The s easily obtained by adj

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 MIMO systems. Besides, the transmi reliability can be significantly improv virtue of the spatial diversity provide multiple antennas at the transmitter receiver. With the current trend an expectation of wireless comm 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

is a new antenna t from conventional s that undergo random tion, the MAs with the movement can be with more favorable achieve higher spatial patial diversity can be justing the position of semble the widely explored tenna systems (DAS) where the enna units (RAUs) are graphically distributed in wireless works. The MA system implemented in a where the antenna is connected to the with radio-frequency (RF) chain via flexible ission cables. The position of the MA can be mechanically adjusted with the aid of drive components, such as stepper motors.

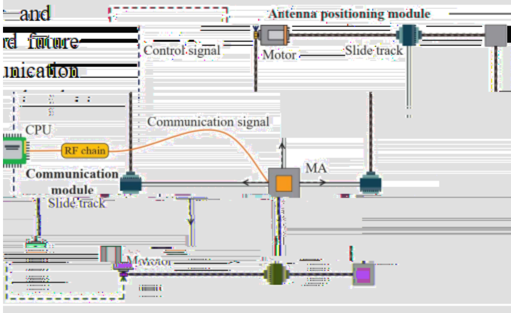

Figure 1. MA system structure

In a given receive region, if the MA can rapidly deployed at the position with the ghest channel gain, the receive signal-to-ise ratio (SNR) can be maximized, which n be regarded as a new way to acquire the atial diversity gain. Limited by the physical

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, 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 key 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 num

even a single antenna to achieve a higher spa

and allows the antenna Tx/Rx to move con

specified three-dimensional (3D) area

mechanical controllers and actuators to ma

spatial degrees of freedom (DoF) of this ar

-performant in mobile communication

ghly promising for future communication

on this, the second part of this paper will

it research status of the movable antenna

while the third part is a reflection on the

direction of MA and the technical challenges it faces,

e fourth part is a summary of the whole paper.

ntroduce the structure of the

mance advantages over FPA;

tion system; and finally, the section is an example

pplication.

e of The MA System

wn in Fig. 1, the MA system consists of a

tion module similar to a conventional FPA system

nna positioning module. In the positioning module,

connected to the radio frequency chain (RF) via a

ole and mounted on a motor-driven mechanical

receiving control signals from the CPU, the MA can

e within the localization module to change the

onditions of the transceiver. In addition, antenna

t by circular slide rotation has been proposed.

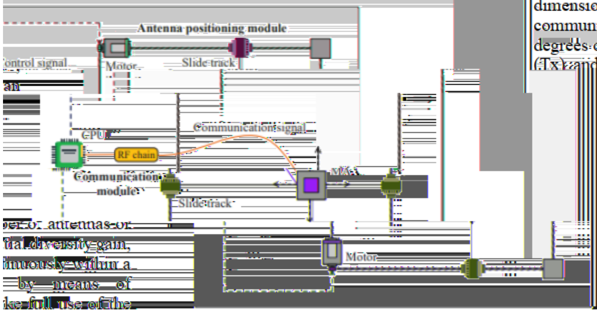

Fig. 1. An architecture for the MA system.

tal diversity gain,

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by means of

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ea to improve the

As mentioned above, movable antennas (MAs) are both

cost-effective and

systems, and are hig

applications. Based

introduce the curren

(MA) technology

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In this section, we will first i

MA system and analyze its perfor

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A. Structur

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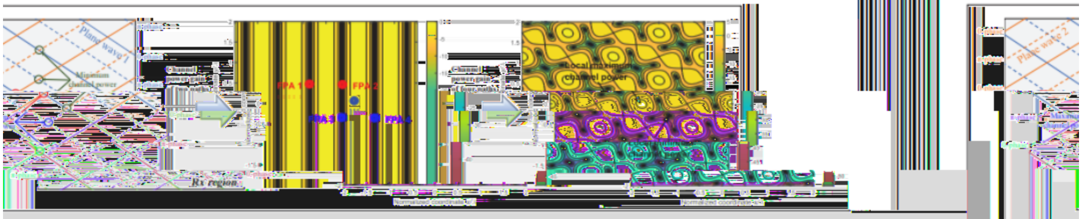
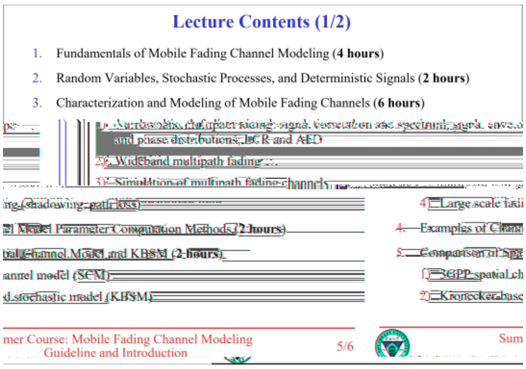


Fig. 2. Illustration of channel power gain (in dB) in the Rx region.



Lecture Contents (1/2)

1. Fundamentals of Mobile Fading Channel Modeling (**4 hours**)
2. Random Variables, Stochastic Processes, and Deterministic Signals (**2 hours**)
3. Characterization and Modeling of Mobile Fading Channels (**6 hours**)
    1) and phase distributions, LCR and AFD
    2) Wideband multipath fading
    3) Simulation of multipath fading channels
    4) Large scale fadi

ing (shadowing, path loss)

el Model Parameter Computation Methods (**2 hours**)

tial Channel Model and KBSM (**2 hours**)

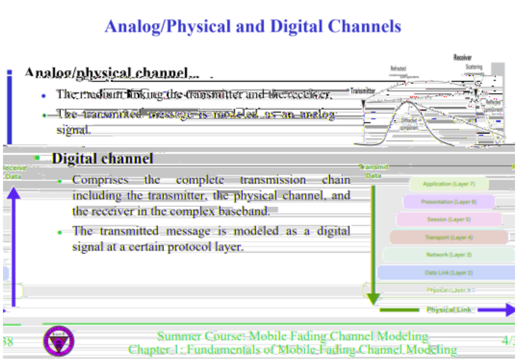
annel model (SCM)

d stochastic model (KBSM)

4. Examples of Chann
5. Comparison of Spa
    1) 3GPP spatial ch
    2) Kronecker-base

mer Course: Mobile Fading Channel Modeling
Guideline and Introduction 5/6

Sum



Analog/Physical and Digital Channels

- Analog/physical channel
    - The medium linking the transmitter and the receiver.
    - The transmitted message is modeled as an analog signal.
- **Digital channel**
    - Comprises the complete transmission chain including the transmitter, the physical channel, and the receiver in the complex baseband.
    - The transmitted message is modeled as a digital signal at a certain protocol layer.

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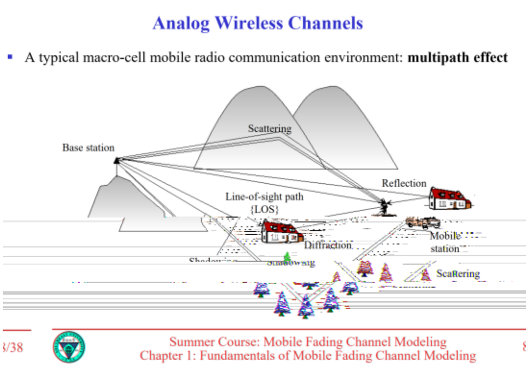
Chapter 1: Fundamentals of Mobile Fading Channel Modeling 4/



Analog Wireless Channels

- A typical macro-cell mobile radio communication environment: **multipath effect**

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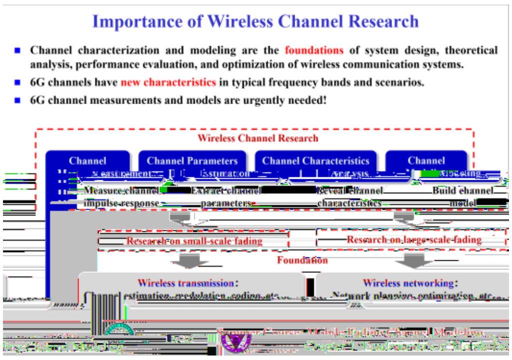
Chapter 1: Fundamentals of Mobile Fading Channel Modeling



Importance of Wireless Channel Research

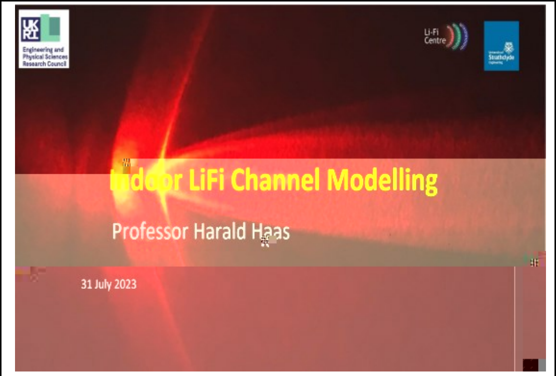
- **Channel characterization and modeling are the foundations of system design, theoretical analysis, performance evaluation, and optimization of wireless communication systems.**
- **6G channels have new characteristics in typical frequency bands and scenarios.**
- **6G channel measurements and models are urgently needed!**

Wireless Channel Model Evolution from 5G to Beyond 5G (5.5G)

Chao Li 李超
Wireless Network Research Department
Channel & Spectrum Research Center

HUAWEI

无线网络研究部
Research Dept. WN



Engineering and Physical Sciences Research Council

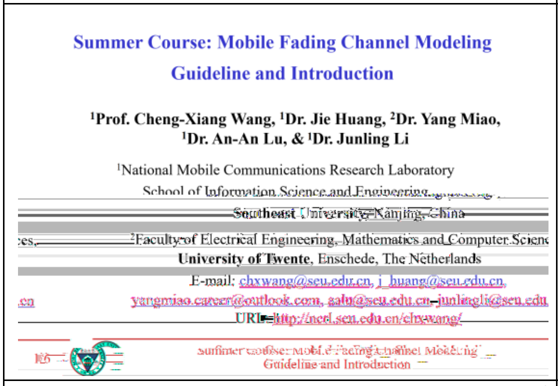
LiFi Centre

University of Strathclyde

Indoor LiFi Channel Modelling

Professor Harald Haas

31 July 2023



Summer Course: Mobile Fading Channel Modeling
Guideline and Introduction

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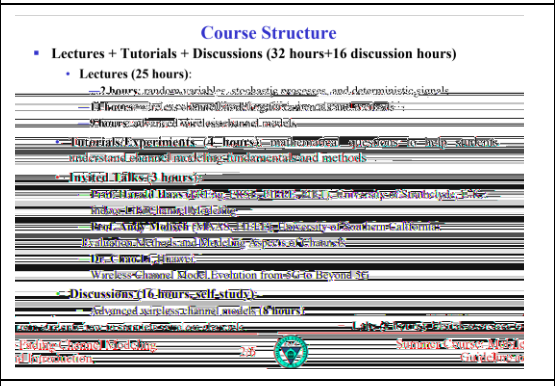
Summer Course: Mobile Fading Channel Modeling
Guideline and Introduction



Course Structure

- Lectures + Tutorials + Discussions (32 hours+16 discussion hours)
  - Lectures (25 hours):
    - 2 hours: random variables, stochastic processes, and deterministic signals
    - 14 hours: [illegible]
    - 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 Modelling
    - Prof. Andy Molisch (NAAS, 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)

Fading Channel Modeling
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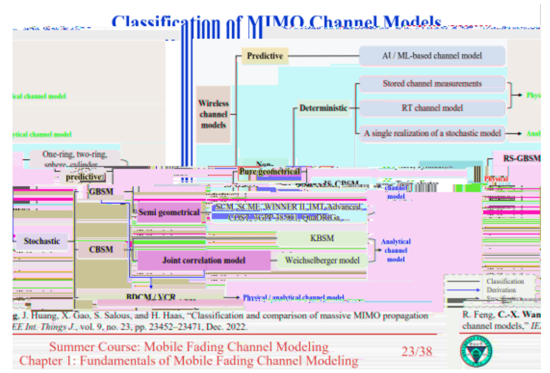
Summer Course: Mobile
Guideline a



Classification of MIMO Channel Models

J. Huang, X. Gao, S. Salous, and H. Haas, "Classification and comparison of massive MIMO propagation ... IEEE Int. Things J., vol. 9, no. 23, pp. 23452–23471, Dec. 2022.

R. Feng, C.-X. Wan... channel models," IE...

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Chapter 1: Fundamentals of Mobile Fading Channel Modeling
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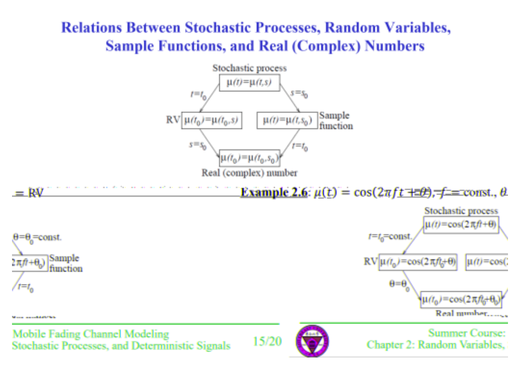

Relations Between Stochastic Processes, Random Variables, Sample Functions, and Real (Complex) Numbers

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

Mobile Fading Channel Modeling
Stochastic Processes, and Deterministic Signals
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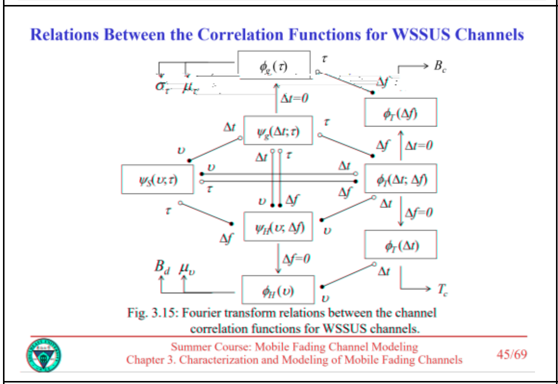
Summer Course:
Chapter 2: Random Variables,



Relations Between the Correlation Functions for WSSUS Channels

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

Summer Course: Mobile Fading Channel Modeling
Chapter 3. Characterization and Modeling of Mobile Fading Channels
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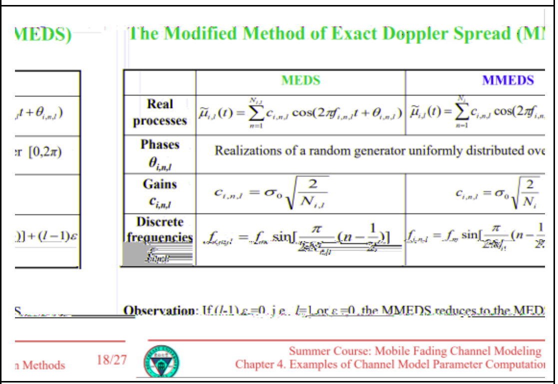

The Modified Method of Exact Doppler Spread (MMEDS)

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

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

Summer Course: Mobile Fading Channel Modeling
Chapter 4. Examples of Channel Model Parameter Computatio
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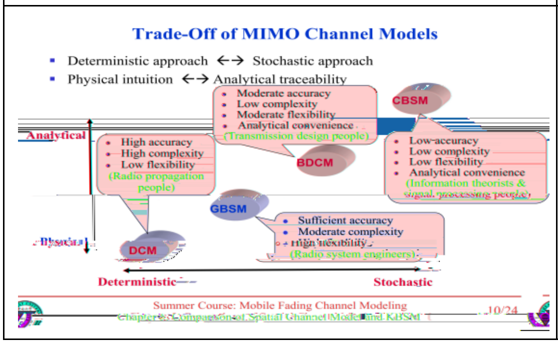

Trade-Off of MIMO Channel Models

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

- Moderate accuracy
- Low complexity
- Moderate flexibility
- Analytical convenience
(Transmission design people)

- High accuracy
- High complexity
- Low flexibility
(Radio propagation people)

- Low accuracy
- Low complexity
- Low flexibility
- Analytical convenience
(Information theorists & signal processing people)

- Sufficient accuracy
- Moderate complexity
- High flexibility
(Radio system engineers)

Summer Course: Mobile Fading Channel Modeling
Chapter 6: Comparison of Spatial Channel Models and KBSM
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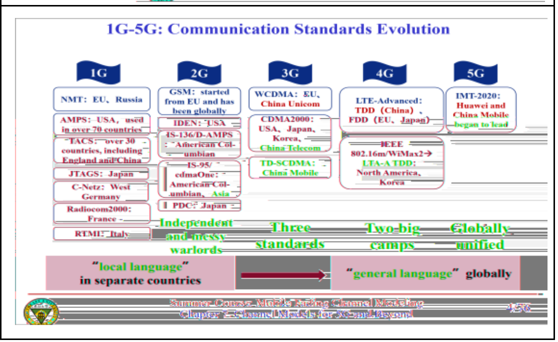

1G-5G: Communication Standards Evolution

1G	2G	3G	4G	5G
NMT：EU、Russia	GSM：started from EU and has been globally	WCDMA：EU、China Unicom	LTE-Advanced：TDD（China）、FDD（EU、Japan）	IMT-2020：Huawei and China Mobile began to lead
AMPS：USA，used in over 70 countries	IDEN：USA	CDMA2000：USA、Japan、Korea、China Telecom	IEEE 802.16m/WiMax2→LTA-A TDD：North America、Korea	
TACS：over 30 countries，including England and China	IS-136/D-AMPS：American Columbian	TD-SCDMA：China Mobile		
JTAGS：Japan	IS-95/cdmaOne：American Columbian、Asia			
C-Netz：West Germany	PDC：Japan			
Radiocom2000：France				
RTMI：Italy				
	Independent and messy warlords	Three standards	Two big camps	Globally unified

"local language" in separate countries → "general language" globally

Summer Course: Mobile Fading Channel Modeling
Chapter 7: Channel Models for 5G and Beyond
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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 [illegible] research directions. 5G [illegible] 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, [illegible] and enhanced spectral efficiency.

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 [illegible] 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.

1. Introduction

[illegible] wireless communication [illegible] unprecedented [illegible] 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 [illegible] 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 [illegible] accommodate the unique requ[illegible]

2. State-of-the-Arts

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

[illegible]

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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

Index Terms—LiFi, Channe

Fidelity (LiFi) network, bidirectional wireless commu... with light. It is used to connect fixed and mobile ...s at very high data rates by harnessing the visible light ...frared spectrum [1]. Combined, these spectral resources ...000 times larger than the entire radio frequency (RF) ...um [2]. The fundamental differences between RF and ... are shown as Table I.

TABLE I: Fundamental differences between RF and OWC

	Spectrum	Information	Signal
RF		Carried in	Complex
OWC		Carried in optical intensity	Unipolar and real

II. FEATURES OF LIFI N

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 ne... enabling data exchange. It affects network performan... can use wired (Ethernet) or wireless (Wi-Fi, cellular) c... tions.

B. Random Orientation and Blockage

LiFi requires direct line of sight between tra... receiver. Challenges arise when devices are ... obstacles block the signal. Adaptiv... manage such issues.

C. Interference

Interference in LiFi comes from natural/artificial light sources. Techniques like frequency modulation are used to 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.

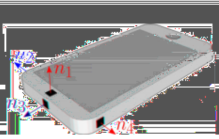


Fig. 2: The MDR structures for hand-held smartphone

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 MDR and SR:* ... that for the same received SNR, MDR has the better error performance than SR [3].

...le Fading Channel Modeling
...l Modelling

Course Report of Mobile Fading Channel Modeling

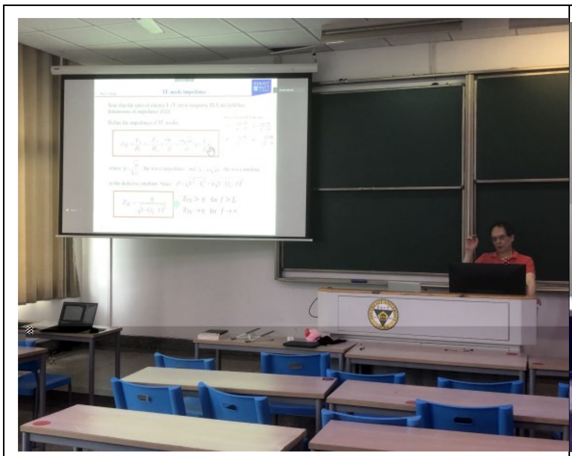
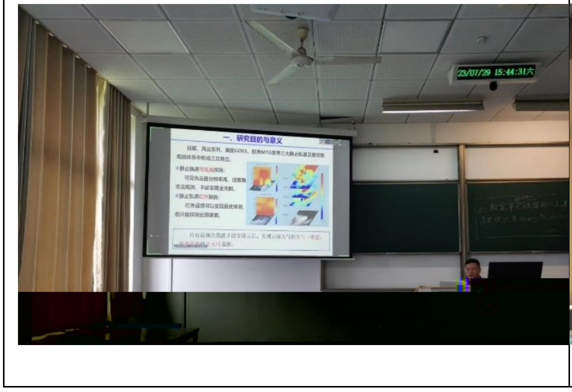
04020432 帅杰博

abstract

LiFi (Light Fidelity), also known as

[redacted]

bands that have not been traditionally used for wireless communication. As existing frequency bands become congested due to the increasing

	TESLA Research Topics
23/07/29 15:44:31六 一、研究目的与意义	23/07/29 14:13:57六 我国气象卫星现状

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
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

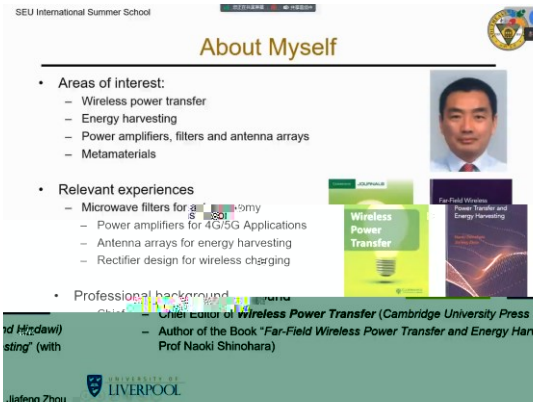
从无源到有源、从模拟到数字、从自适应到智能化，相控阵天线的技术的研究范畴正日趋扩大，已经成为衡量信息化水平的重要标志之一

SEU International Summer School

How to Design a Filter?

- Real life experience

Jiafeng Zhou
10:50 202



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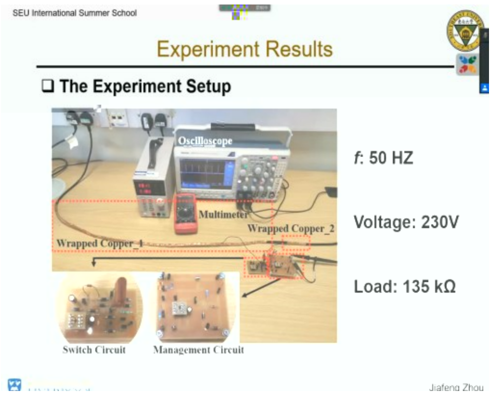
About Myself

- Areas of interest:
  - Wireless power transfer
  - Energy harvesting
  - Power amplifiers, filters and antenna arrays
  - Metamaterials
- Relevant experiences
  - Microwave filters for a
    - 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)

Jiafeng Zhou



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Experiment Results

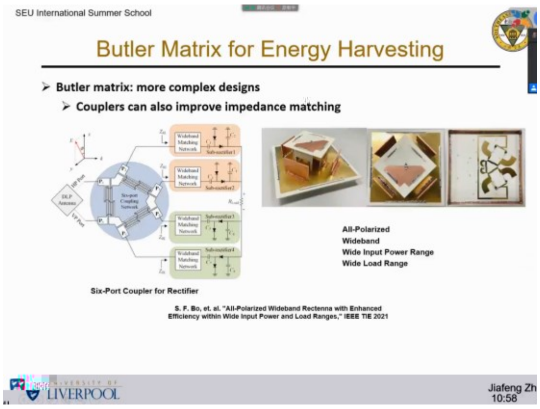
❑ **The Experiment Setup**

f: 50 HZ

Voltage: 230V

Load: 135 kΩ

Jiafeng Zhou



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Butler Matrix for Energy Harvesting

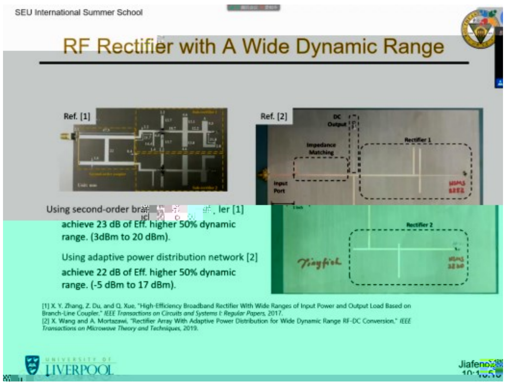
- ➢ **Butler matrix: more complex designs**
  - ➢ **Couplers can also improve impedance matching**

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

Jiafeng Zh
10:58



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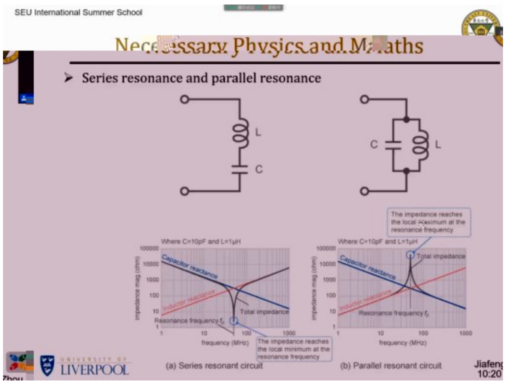
RF Rectifier with A Wide Dynamic Range

Using second-order bra ler [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).

[1] X. Y. Zhang, Z. Du, and Q. Xue, "High-Efficiency Broadband Rectifier With Wide Ranges of Input Power and Output Load Based on Branch-Line Coupler," *IEEE Transactions on Circuits and Systems I: Regular Papers*, 2017.
[2] X. Wang and A. Mortazawi, "Rectifier Array With Adaptive Power Distribution for Wide Dynamic Range RF-DC Conversion," *IEEE Transactions on Microwave Theory and Techniques*, 2019.

Jiafeng



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Necessary Physics and Maths

- ➢ Series resonance and parallel resonance

(a) Series resonant circuit

(b) Parallel resonant circuit

Jiafeng
10:20

SEU International Summer School

Wireless Power Transfer (WPT)

- Method 2: Magnetic-electric coupling

《微波、毫米波与太赫兹前沿技术》课程报告

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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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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

04020212 Wang Yaqi

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

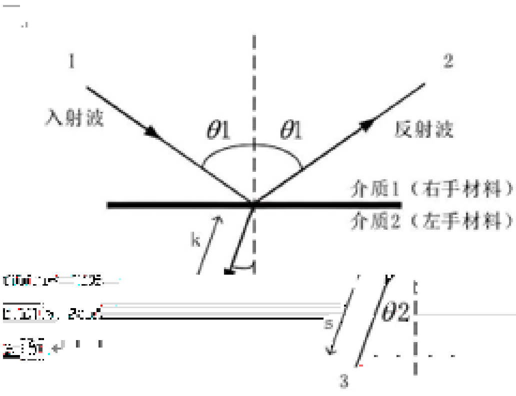
Electromagnetic phenomenon is a general term for the electrical and magnetic properties of matter. Electromagnetism studies the interaction between electric field, magnetic field and matter and its practical application. Regardless of the form in which electromagnetic waves propagate,the electromagnetic characteristics of the propagation medium play an important role. As is well known, when electromagnetic waves [illegible] electric field, magnetic field and propagation [illegible] mutually perpendicular [illegible]

[illegible] negative properties [illegible] the dielectric [illegible] ity μ. To describe [illegible] materials, [illegible] in 1968. Because [illegible] properties, the [illegible] waves in them will [illegible] ies, so the proposed [illegible] the application of [illegible]

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 [illegible] [1][2].

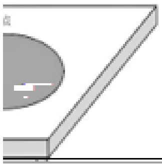
[illegible] civilian, has put forward higher requirements for the speed and quality of information transmission. Antennas, as devices used to radiate and receive electromagnetic waves in communication systems, are used as devices for conversion of guided-wave energy and electromagnetic wave energy. Their performance directly affects the quality and performance of communication systems. Modern [illegible]

[illegible] of natural materials [illegible] Corresponding to [illegible] Metamaterial was proposed [illegible] Metamaterial has strange [illegible] propagation of electromagnetic [illegible] show unusual physical propert[illegible] of Metamaterial enriches [illegible] 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 [illegible]



(b)

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



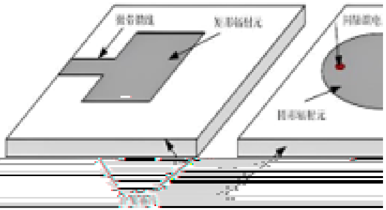


Fig2.3 The schematic diagram of common Microst

As shown in Fig 2.2, when an electromagnetic wave is incident between the interface 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.

III. Design of MIMO antenna based on electromagnetic Metamaterial

In the design of MIMO antenna, AeonAD255C substrate with a thickness of 1.9m is used, with relative dielectric constant and l 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 radiat

Microstrip antennas are widely used in various design because of its small size, light weight, easy integration and low cost. The schematic diagram of common Microstrip antennas 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, etc.

[illegible] has been etched on the ground of [illegible] rectangular patch of the antenna [illegible] effectively reduce the size of the [illegible] The plane size of the antenna ranges [illegible] reduction of [illegible] [illegible]