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Acronyms

2D	Two-Dimensional
3D	Three-Dimensional
3GPP	3rd Generation Partnership Project
4G	Fourth Generation
5G	Fifth Generation
AA	Antenna Array
ABS	Almost Blank Subframe
AEs	Antenna Elements
AoA	Azimuth of Arrival
AR	Augmented Reality
AWGN	Additive White Gaussian Noise
BE	Bandwidth Efficiency
BER	Bit Error Ratio
BF	Beamformer
BI-GDFE	Block-Iterative Generalized Decision Feedback Equalizer
BS	Base Station
CBSM	Correlation-Based Stochastic Model
CEP	Constant Envelope Precoding
CIRs	Channel Impulse Responses
CPS	Cyber-Physical System
CR	Correlation Rotation
CRE	Cell Range Extension
CRS	Cell Specific Reference Signals
CSI	Channel State Information
CSIT	CSI at the Transmitter
DASs	Distributed Antenna Systems
DL	Downlink
DoF	Degrees of Freedom
DPC	Dirty Paper Coding
EE	Energy Efficiency
eMBB	Enhanced Mobile Broadband

eNB	evolved Node B
EoAs	Elevation angle of Arrivals
FD	Frequency Domain
FDD	Frequency Division Duplex
FFR	Fractional Frequency Reuse
FFT	Fast Fourier Transform
FIR	Finite Impulse Response
HetNet	Heterogeneous Network
HetSNets	Heterogeneous and Small Cell Networks
HIET	Hybrid information and Energy Transfer
HomoNet	Homogeneous Network
ICI	Inter-cell Interference
ICIC	Inter-cell Interference Coordination
i.i.d.	Independent and Identically Distributed
IoT	Internet of Things
ISD	Inter-Site Distance
ISI	Inter-Symbol Interference
IUI	Inter-User Interference
LoS	Line of Sight
LS-MIMO	Large-Scale MIMO
LTE	Long Term Evolution
MAC	Media Access Control
MAP	Maximum Posterior Probability
MAX-MIN	Maximizing the Minimum
MeNB	Macro-cell eNB
MF	Matched Filter
MIMO	Multiple-Input and Multiple-Output
MIN-MAX	Minimizing the Maximum
ML	Maximum-Likelihood
mm-wave	millimeter-wave
MMSE	Minimum Mean Square Error
MMSE-SIC	MMSE based Soft Interference Cancellation
mMTC	Massive Machine Type Communications
MRC	Maximum Ratio Combining
MRT	Maximum Ratio Transmission
MSE	Mean Square Error
MU-MIMO	Multi-User MIMO
MUEs	Macro-cell UEs
NLoS	Non Line of Sight
NOMA	Non-Orthogonal Multiple Access
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
PAPR	Peak to Average Power Ratio
PAs	Power Amplifiers
PBCH	Physical Broadcasting Channel

PDF	Probability Density Function
PDSCH	Physical Downlink Shared Channel
PSS/SSS	Primary/Secondary Synchronization Signals
QoE	Quality of Experience
QoS	Quality of Service
RF	Radio-Frequency
RMS	Root Mean Squared
RRC	Radio Resource Control
RRUs	Remote Radio Units
RSRP	Reference Signal Received Power
RTDD	Reversed TDD
RZF	Regularized ZF
SDMA	Spatial Division Multiple Access
SE	Spectrum Efficiency
SeNBs	Small-cell eNBs
SER	Symbol Error Ratio
SFR	Soft Frequency Reuse
SINR	Signal-to-Interference-plus-Noise Ratio
SNR	Signal-to-Noise Ratio
SUEs	Small-cell UEs
TD	Time-Domain
TDD	Time-Division Duplex
TPC	Transmit Precoding
TS	Tabu Search
Tx-Rx	Transmitter-Receiver
UEs	User Equipments
UL	Uplink
URLLC	Ultra-Reliable and Low Latency Communications
VP	Vector Perturbation
VR	Virtual Reality
WiGig	Wireless Gigabit Alliance
WPAN	Wireless Personal Area Networks
ZF	Zero-Forcing

Chapter 1
Introduction

Massive Multiple-Input and Multiple-Output (MIMO) technology is an important and timely topic, which is largely motivated by the requirements of the Fifth Generation (5G) or future wireless communications. By offering a large number of Degrees of Freedom (DoF), 5G is capable of simultaneously serving multiple users with high gains and thus improving the system Spectrum Efficiency (SE), Energy Efficiency (EE) and reliability. Different from existing studies in the literature, this book focuses specifically on the state-of-the-art of massive MIMO and its typical applications, such as millimeter-wave (mm-wave) communications and wireless energy transfer. In this chapter, we first present the motivations of massive MIMO following a short overview on the requirements and techniques of 5G communications. Then, basic concepts alongside the pros and cons of both MIMO and massive MIMO systems are given. The aim of the monograph is provided at the end of this chapter.

1.1 5G Brief

1.1.1 5G Requirements

Mobile Internet and the Internet of Things (IoT) are two key market drivers for 5G communications. The applications of 5G communications include cloud computing, eHealth services, automotive driving, tactile Internet, Augmented Reality (AR)/Virtual Reality (VR), Cyber-Physical System (CPS) and so on. These applications could be classified into three use scenarios, i.e., Enhanced Mobile Broadband (eMBB), Massive Machine Type Communications (mMTC), and Ultra-Reliable and Low Latency Communications (URLLC) [1, 2].

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In order to support the requirements of the three use scenarios, some performance targets of 5G communications are defined, i.e., increasing throughput by 1000-fold, improving EE by 10-fold, shortening the end-to-end delay to 1/5–1/10, increasing the number of connected equipment by 10–100 folds, and prolonging the battery lifespan of low-power equipment by 10-fold. Some research projects for 5G communications have been launched at home and abroad in order to achieve the performance targets of 5G before 2020 year [1].

1.1.2 5G Technology

There are three key techniques for 5G communications from the perspective of system capacity. That is, the massive MIMO technique is first adopted to improve system SE; mm-wave spectral resources are employed to expand system bandwidth; and multi-layer and ultra-dense networks are deployed to increase geographic spectral reuse. The systems employing massive antenna arrays to serve multiple users are dubbed massive MIMO communication systems. Massive MIMO systems are capable of combatting the severe fading of mm-wave signals, providing the wireless backhaul, and suppressing interference in multi-layer and denser networks. Therefore, this monograph focuses on massive MIMO technology and their typical application scenarios in an attempt to provide the basic theory and paradigms for practical system designs.

1.2 MIMO Technology

Bandwidth Efficiency (BE) or SE is usually one of the most important metrics to select candidate technologies for next-generation wireless communications systems. Meanwhile, with excessive power consumption in wireless communications networks, both carbon emissions and operator expenditure increase year by year [3, 4]. As a result, EE has become another significant metric for evaluating the performances of wireless communications systems with some given BE constraints [5–7].

1.2.1 Traditional MIMO

MIMO technology has attracted much attention in wireless communications, because it offers significant increases in data throughput and link range without an additional increase in bandwidth or transmit power. In 1993 and 1994, a MIMO approach was proposed and the corresponding patent was issued [8], where multiple transmit antennas are co-located at one transmitter with the objective of improving the attainable link throughput. Then, the first laboratory prototype of spatial multiplexing was implemented to demonstrate the practical feasibility of MIMO technology [9]. Nowadays, MIMO has been accepted as one of key technologies in Fourth Generation (4G) wireless communication systems. When an evolved Node B (eNB) equipped with multiple antennas communicates with several User Equipments (UEs) at the same time-frequency resources, it is referred to as Multi-User MIMO (MU-MIMO). MU-MIMO is capable of improving either the BE or the reliability by improving either the multiplexing gains or diversity gains [10].

1.2.2 Massive MIMO

In order to scale up these gains of traditional MIMO, the massive MIMO concept, which is also known as Large-Scale MIMO (LS-MIMO) scheme often also associated with the terminologies of large-scale antenna systems, very large MIMO, very large MU-MIMO, full-dimensional MIMO, hyper MIMO, etc., was proposed by Marzetta in [11]. More explicitly, massive MIMO refers to the system that uses hundreds of antennas to simultaneously serve dozens of UEs. Both theoretical and measurement results indicate that massive MIMO is capable of significantly improving the BE, which simultaneously reducing the transmit power [12, 13]. As a result, massive MIMO is regarded as a candidate technique for next-generation wireless communications systems conceived for the sake of improving both their BE and EE.

As the down tilt of an Antenna Array (AA) is fixed, traditional MIMO technology can only adjust signal transmission in the horizontal dimension. In order to exploit the vertical dimension of signal propagation, AAs, such as rectangular, spherical and cylindrical AAs, were studied by the 3rd Generation Partnership Project (3GPP) [14–16]. MIMO with these arrays can adjust both azimuth and elevation angles, and propagate signals in Three-Dimensional (3D) space, thus termed 3D MIMO. To further increase capacity, 3D MIMO deploys more antennas to achieve larger multiplexing gains. Meanwhile, massive MIMO adopts rectangular, spherical or cylindrical AAs in practical systems considering the space of AAs. Therefore, 3D MIMO with massive antennas can be seen as a practical deployment means of massive MIMO.

Massive MIMO can improve BE since it can achieve large multiplexing gains when serving tens of UEs simultaneously [11, 17]. The significant increase in EE is due to the fact that the use of more antennas helps focus energy with an extremely narrow beam on small regions where the UEs are located [18]. Apart from these advantages, massive MIMO can enhance transmission reliability owing to the excessive DoF [19]. Inter-User Interference (IUI) can also be alleviated because of the extreme narrow beam [12]. In a massive MIMO system, individual element failure of the AA is not detrimental to the performance of the entire system [12]. Simple low-complexity signal processing algorithms are capable of approximating

Table 1.1 Current research directions of massive MIMO

Topics	Description [12, 13, 22]
AA configuration	Rational antennas deployment
Channel model	Channel measurement and modeling
Channel estimation	Efficient estimation algorithms for pilot reuse
Precoding and detection	Low-complexity and efficient precoder and detector
Performance and limitation	BE, EE and reliability performance and limitation factors
Practical applications	Network deployment and optimization
Resource management	Management of frequency, time and spatial resources
Interference controlling	Pilot contamination alleviation and interference suppression
Massive distributed antennas	Design and analysis of distributed antennas in indoor or outdoor

the performance achieved by optimal methods, such as Maximum-Likelihood (ML) multiuser detection and Dirty Paper Coding (DPC) [13]. The latency of the air interface can be reduced and the protocols at the Media Access Control (MAC) layer can be simplified because of the channel harden phenomenon and sufficient capacity [20].

Certainly, the complexity of signal processing, including Transmit Precoding (TPC), channel estimation and detection, increases with the increasing number of antennas. On the other hand, the maximum number of orthogonal pilot sequences is limited by the coherence interval and coherence bandwidth. Therefore, the performance of massive MIMO systems is constrained by pilot contamination due to pilot reuse in multi-cell scenarios [11]. Moreover, compared to the Physical Downlink Shared Channel (PDSCH) employing either precoding or beamforming, the Signal-to-Interference-plus-Noise Ratio (SINR) of the Physical Broadcasting Channel (PBCH) is lower due to the omni-directional signal transmission [21].

According to the current literature related to massive MIMO, the major research directions about massive MIMO are listed in Table 1.1, some of which have been investigated in [12, 13] and [22] while others are not.

1.3 Aim of Monograph

Currently, fundamental theoretical problems and several physical-layer techniques of massive MIMO have already been widely investigated. For example, the capacity and realistic performance of precoding and detection for massive MIMO have been analyzed from the viewpoint of information theory [13, 22]. Additionally, the advantages and disadvantages, and the limitations of massive MIMO are spelt out in [12]. However, the performance of massive MIMO and its potential applications are much more influenced by practical factors, which have not been well investigated so far.

Therefore, in addition to a comprehensive investigation on the theoretical performance of massive MIMO, this monograph first pays more attention to discussing issues from the system or network point of view, such as practical application scenarios of massive MIMO, networking techniques and so on. Then, based on basic theory, two typical applications of massive MIMO, i.e., mm-wave communication networks and wireless energy transfer networks, are discussed in detail. In massive MIMO-aided mm-wave communication networks for 5G communications, both the physical-layer and networking-layer techniques are discussed and designed. However, in massive MIMO-aided wireless energy transfer networks for future true wireless communications, cooperative resource allocation is emphasized in an effort to improve energy transfer efficiency.

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