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Introduction

1.1 Wireless History

Wireless technology revolution started in 1896 when Guglielmo Marconi demonstrated a transmission of a signal through free space without placing a physical medium between the transmitter and the receiver [1, 2]. Based on the success of that experiment, several wireless applications were developed. Yet, it was widely believed that reliable communication over a noisy channel can be only achieved through either reducing data rate or increasing the transmitted signal power. In 1948, Claude Shannon characterizes the limits of reliable communication and showed that this belief is incorrect [3]. Alternatively, he demonstrated that through an intelligent coding of the information, communication at a strictly positive rate with small error probability can be achieved. There is, however, a maximal rate, called the channel capacity, for which this can be done. If communication is attempted beyond that rate, it is infeasible to drive the error probability to zero [4].

Since then, wireless technologies have experienced a preternatural growth. There are many systems in which wireless communication is applicable. Radio and television broadcasting along with satellite communication are perhaps some of the earliest successful common applications. However, the recent interest in wireless communication is perhaps inspired mostly by the establishment of the first-generation (1G) cellular phones in the early 1980s [5–7]. 1G wireless systems consider analog transmission and support voice services only. Second-generation (2G) cellular networks, introduced in the early 1990s, upgrade to digital technologies and cover services such as facsimile and low data rate (up to 9.6 kbps) in addition to voice [8, 9]. The enhanced versions of the second–generation (2G) systems, sometimes referred to as 2.5G systems, support more advanced services like medium-rate (up to 100 kbps) circuit- and packet-switched data [10–12]. Third-generation (3G) mobile systems were standardized around year 2000 to support high bit rate (144–384) kbps for fast-moving users and up to 2.048 Mbps for slow-moving users [13–15]. Following the third–generation (3G) concept, several enhanced technologies...
generally called 3.5G, such as high speed downlink packet access (HSPDA), which increases the downlink data rate up to 3.6 Mbps were proposed [16, 17]. Regardless of the huge developments in data rate from 1G to 3G and beyond systems, the demand for more data rate did not seem to layover at any point in near future. As such, much more enhanced techniques were developed leading to fourth-generation (4G) wireless standard. 4G systems promise data rates in the range of 1 Gbps and witnessed significant development and research interest since launched in 2013 [18]. However, a recent CISCO forecast [19] reported that global mobile data traffic grew 74% in 2015, where it reached 3.7 EB per month at the end of 2015, up from 2.1 EB per month at the end of 2014. As well, it is reported that mobile data traffic has grown 4000-fold over the past 10 years and almost 400-million-fold over the past 15 years. It is also anticipated in the same forecast that mobile data traffic will reach 30.6 EB by 2020, and the number of mobile-connected devices per capita will reach 1.5 [19]. With such huge demand for more data rates and better quality services, fifth-generation (5G) wireless standard is anticipated to be launched in 2020 and has been under intensive investigations in the past few years [20]. 5G standard is supposed to provide a downlink peak date rate of 20 Gbps and peak spectral efficiency of 30 b (s/Hz)$^{-1}$ [20]. Such huge data rate necessitates the need of new spectrum and more energy-efficient physical layer techniques [21].

1.2 MIMO Promise

Physical layer techniques such as millimeter-wave (mmWave) communications, cognitive and cooperative communications, visible light and free-space optical communications, and multiple-input multiple-output (MIMO) and massive MIMO techniques are under extensive investigations at the moment for possible deployments in 5G networks [21]. Among the set of existing technologies, MIMO systems promise a boost in the spectral efficiency by simultaneously transmitting data from multiple transmit antennas to the receiver [22–28].

In 1987, Jack Winters inspired by the work of Salz [23], investigated the fundamental limits on systems that exploit multipath propagation to allow multiple simultaneous transmission in the same bandwidth [29]. Later in 1991, Wittneben proposed the first bandwidth-efficient transmit diversity scheme in [30], where it was revealed that the diversity advantage of the proposed scheme is equal to the number of transmit antennas which is optimal [31]. Alamouti discovered a new and simple transmit diversity technique [24] that is generalized later by Tarokh et al. and given the name of space–time coding (STC) [32]. STC techniques achieve diversity gains by transmitting multiple, redundant copies of a data stream to the receiver in order to allow
1.3 Introducing Space Modulation Techniques (SMTs)

Another group of MIMO techniques, called space modulation techniques (SMTs), consider an innovative approach to tackle previous challenges of MIMO systems. In SMTs, a new spatial constellation diagram is added and utilized to enhance the spectral efficiency while conserving energy resources and receiver computational complexity. The basic idea stems from [35] where a binary phase shift keying (BPSK) symbol is used to indicate an active antenna among the set of existing multiple antennas. The receiver estimates the transmitted BPSK symbol and the antenna that transmits this symbol. However, the first popular SMT was proposed by Mesleh et al. [36, 37] and called spatial modulation (SM), and all other SMTs are driven as spacial or generalized cases from SM. Opposite to traditional modulation schemes, SM conveys information by utilizing the multipath nature of the MIMO fading channel as an extra constellation diagram referred to as spatial constellation. The incoming data bits modulate the spatial constellation symbol, which represents the spatial position, or index, of one of the available transmit antennas that will be activated at this particular time to transmit a modulated carrier signal by a complex symbol drawn from an arbitrary constellation diagram. SM was the first scheme to define the concept of spatial constellation and proposes the use of modulating spatial symbols to convey information. It was shown that SM can achieve multiplexing gain while maintaining free ICI [37], reduced receiver computational complexity [38], enhances the bit error probability [39], and promises the use of single radio frequency (RF)-chain transmitter [40]. As reliable decoding. Shortly after, Foschini introduced multilayered space–time architecture, called Bell Labs layered space time (BLAST), that uses spatial multiplexing to increase the data rate and not necessarily provides transmit diversity [27]. Capacity analysis of MIMO systems was reported by Telatar and shown that MIMO capacity increases linearly with the minimum number among the transmit and receiver antennas [25] as compared to a system with single transmit and receive antennas. However, spatial multiplexing (SMX) MIMO systems, as BLAST, suffer from several limitations that hinder their practical implementations. Simultaneous transmission of independent data from multiple transmit antennas creates high inter-channel interference (ICI) at the receiver input, which requires high computational complexity to be resolved. In addition, the presence of high ICI degrades the performance of SMX MIMO systems, significant performance degradations are reported for any channel imperfections [33, 34]. On the other hand, STC techniques alleviate SMX challenges at the cost of achievable data rate. In STCs, the maximum achievable spectral efficiency is one symbol per channel use and can be achieved only with two transmit antennas.
such, the concept of SM attracted significant research interests, and different performance aspects were studied thoroughly in few years [41–88]. Hence, multiple variant schemes applying similar SM concept were proposed. In [89], space shift keying (SSK) system was proposed where only spatial symbols exist and no data symbol is transmitted. Generalized spatial modulation (GSM) where more than one transmit antenna is activated at each time instant to transmit identical data is proposed in [67]. Similarly, generalized space shift keying (GSSK) was proposed in [69]. In all these schemes, single-dimensional spatial constellation diagram was created and used to convey spatial bits. In [65, 70], an additional quadrature spatial constellation diagram is defined where the real part of the complex data symbol is transmitted from one spatial symbol and the imaginary part of the complex symbol is transmitted from another spatial symbol. As such, data rate enhancement of base two logarithm of the number of transmit antennas is achieved while maintaining all previous SM advantages. These schemes are called quadrature spatial modulation (QSM) and quadrature space shift keying (QSSK). In addition, their generalized parts can be defined as generalized quadrature spatial modulation (GQSM) and generalized quadrature space shift keying (GQSSK). These eight schemes are the basic SMTs and their working mechanism, performance and capacity analysis, limitations, and practical implementations will be the core of this book. Yet, there exist many other advanced techniques that were proposed utilizing the working mechanism of these techniques.

1.4 Advanced SMTs

1.4.1 Space–Time Shift Keying (STSK)

Space–time shift keying (STSK) is a generalization scheme that was developed based on the concept of SMTs [78–80, 90–93]. In space–time shift keying (STSK), and instead of activating a specific transmit antenna, dispersion matrices are designed to achieve certain performance metric, and incoming data bits activate one of the available dispersion matrices at each block time. It is shown that different MIMO configurations, including, STC, SMX, and SMTs, can be derived as special cases from STSK by properly designing the dispersion matrices. STSK and its system model will be discussed in Chapter 3.

1.4.2 Index Modulation (IM)

Index modulation (IM) is another interesting idea based on multicarrier communications, such as orthogonal frequency division multiplexing (OFDM), that has been proposed with inspiration from the concept of SMTs and can be applied to frequency domain without requiring multiple transmit antennas.
An illustration model for IM system is depicted in Figure 1.1. In IM, SMTs can be efficiently implemented for the OFDM subcarriers, where subcarriers are divided into groups, and certain subcarriers within each group are only activated. The index of such subcarriers is an extra information that can be utilized to convey additional data bits. In IM, the incoming bit stream is divided into two blocks, one of which modulates the index or indexes of active subcarriers and other block of bits modulates an ordinary constellation symbol to be transmitted on the activated subcarriers. In principle, this is very similar to the concept of SMTs but instead of having spatial symbols, index symbols are created now to modulate index bits [60, 94–96]. Very recently, a book was published entitled *Index Modulation for 5G Wireless Communications*, which covers the working principle and latest development of IM system. These techniques will not be covered in this book as they fall beyond the main scope of this book.

### 1.4.3 Differential SMTs

As will be discussed in this book for all SMTs, channel knowledge is mandatory at the receiver side to properly estimate the transmitted data. Such channel knowledge requires channel estimation algorithms through pilot symbols, which entails considerable overhead and not feasible in all applications. As such, significant interest in differential encoding and decoding of different SMTs led to the development of differential space modulation techniques (DSMTs) [63, 80, 97, 98]. In DSMTs, the receiver relies on the received signal at time $t$ and the signal received at time $t-1$ to decode the message. Different differential schemes were proposed including differential spatial modulation (DSM) [63], differential space shift keying (DSSK), differential quadrature spatial modulation (DQSM) [97], differential quadrature space shift keying
(DQSSK), and differential space–time shift keying (DSTSK) [80]. These techniques will be discussed in detail in Chapter 3.

1.4.4 Optical Wireless SMTs

Another research area that benefited from SMTs is optical wireless communications (OWC) for both indoor and outdoor applications. Wireless transmission via optical carriers is motivated by the availability of a huge and unregulated spectrum at the optical frequencies. Traditional optical wireless communication was based on pulsed modulation since quadrature transmission of optical signals is not possible. However, OFDM was proposed for OWC by converting the time signal to real-unipolar signals through simple mathematical operations [99–105]. The use of OFDM for OWC facilitates the integration of SMTs, and optical spatial modulation (OSM) was proposed in [66]. Following similar concept of OSM, other SMTs can be considered as well for OWC.

SMTs found their way also in the application of outdoor optical wireless communication, generally called free-space optics (FSO). A direct application to FSO is foreseen through SSK scheme, where single transmitting laser among a set of available lasers is activated at each time instant to transmit unmodulated signal [106]. Other applications consider SM in conjunction with pulse amplitude modulation (PAM), pulse position modulation (PPM), or any other pulsed modulation scheme. Several recent books were published highlighting OWC techniques and include SMTs as promising techniques for OWC [107–110]. SMTs for OWC will not be addressed in this book.

1.5 Book Organization

The remaining of the book is organized as follows:

Chapter 2: MIMO System and Channel Models

MIMO system model is presented in this chapter along with different well-known channel models including Rayleigh, Nakagami-$m$, Rice, and generalized fading channel models such as $\eta-\mu$, $\kappa-\mu$, and $\alpha-\mu$. In addition, models for spatial correlation, mutual coupling, and channel estimation errors are discussed in this chapter.

Chapter 3: Space Modulation Transmission and Reception Techniques

This is the core chapter of the book presenting system models for the different SMTs, generalized space modulation techniques (GSMTs), and advanced SMTs. The working mechanism of each system, the maximum-likelihood (ML) receiver, the computational complexity, and a simplified low complexity sphere
decoder (SD) algorithm that are applicable for all SMTs, quadrature space modulation techniques (QSMTs), and GSMTs are presented as well. In addition, practical models for energy efficiency and power consumption and hardware implementation costs are presented and discussed.

Chapter 4: Average Bit Error Probability Analysis for SMTs
The derivation of the analytical error probability for the different SMTs, GSMTs, QSMTs, and DSMTs are presented in this chapter over different conventional and generalized fading channels. Results of comparative studies are presented and thoroughly discussed.

Chapter 5: Information Theoretic Treatments for SMTs
Capacity analysis and mutual information derivation for SMTs are presented in this chapter. Different examples and results are presented and discussed.

Chapter 6: Cooperative SMTs
SMTs for cooperative communication are discussed in this chapter. System models for different SMTs with different cooperative scenarios are presented and analyzed. Average bit error ratio (ABER) derivations for different system models and scenarios are presented and different numerical examples are illustrated.

Chapter 7: SMTs for Millimeter Wave Communications
mmWave communications is an emerging technology and one of the promising candidates for 5G wireless standard. Applying SMTs for mmWave systems is presented in this chapter along with detailed performance analysis, channel models, and numerical results.

Chapter 8: Summary and Future Directions
This chapter summarizes the entire book contents and provides directions for future research in the field of SMTs.

Appendix A: Matlab Codes
Matlab simulation codes for the different SMTs, GSMTs, and QSMTs are provided in the appendix. Also, Matlab codes for evaluating the derived analytical formulas are provided.