

AN ANALYSIS OF SPATIAL MODULATION IN WIRELESS COMMUNICATION SYSTEMS

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ABSTRACT

Spatial modulation (SM) is a contemporary and promising digital modulation technique that offers an intriguing balance between spectral efficiency and energy efficiency, accompanied by a convenient graphical approach. SM brings numerous advantages and exhibits remarkable potential in meeting the demands of future wireless communications. The fundamental concept behind SM is to transmit more information by utilizing the ON/OFF states of transmit antennas, while simultaneously reducing implementation costs by minimizing the number of radio frequency chains. Consequently, the concept of SM has significant implications across various domains, including frequency, time, code, angle, and even multiple domains. This survey provides a comprehensive overview of the latest findings and advancements in SM research. It delves into the core principles, system design variations, and enhancements of SM in meticulous detail. Additionally, the survey extensively explores the integration of the SM family with other promising techniques, its applications in emerging communication systems, and its extensions to novel signal domains.

Keywords: Spatial modulation (SM), generalized (G)SM, differential (D) SM, massive MIMO, physical layer security, compressed-sensing, millimeter-wave communications, visible light communications etc

1. INTRODUCTION

Motivated by the exponential growth of mobile devices and the extensive applications of the Internet of Things (IoT), future wireless communication systems are faced with a pressing demand for ultra-high capacity, ultra-low latency, and extensive connectivity within the limited wireless resources [1]–[4]. Anticipated in the coming years is a significant surge in mobile data traffic, which has the potential to overwhelm the already scarce spectrum resources and significantly increase power consumption [2]–[4]. To address this unprecedented growth in mobile data traffic, researchers have been driven to develop new transmission technologies that maximize throughput while minimizing deployment costs. Among various technologies, spatial modulation (SM) has emerged as a promising digital modulation technique, offering high spectral efficiency and energy efficiency while maintaining a simple design concept. Although the initial works on SM were explored in the early 21st century [5], [6], they did not receive much attention at that time. However, after 2008, research on SM has experienced explosive growth, with the systematic introduction of the SM concept discussed in academic and review literature [7]–[10], attracting significant interest from researchers.

SM leverages the activation states of transmit antennas to transmit additional data bits, in addition to the information conveyed by conventional constellation symbols. By employing an antenna-switching mechanism, the active antenna index changes based on the spatial data bits. Notably, SM achieves spatial gain using a single radio frequency (RF) chain, offering several advantages [6], [7]:

- Improved energy efficiency [11], [12]
- Reduced detection complexity with fewer receive antennas and lower complexity of RF circuits
- Immunity to inter-channel interference
- No requirement for inter-antenna synchronization
- Compatibility with large-scale multiple-input multiple-output (MIMO) systems [13]

In SM, the index of an active transmit antenna is utilized to convey additional data bits, while the traditional constellation symbol conveys the remaining data bits. During constellation symbol transmission, only one RF chain is required at the SM transmitter to activate one out of multiple transmit antennas, resulting in significant power savings in downlink communications and a dramatic reduction in hardware costs at the user terminal in uplink communications. Furthermore, due to the absence of inter-channel interference, SM is a more suitable technology than Vertical Bell Laboratories Layered Space-Time (V-BLAST) for high-mobility wireless communication systems, where channel correlation is weakened and inter-channel interference is exacerbated [14]. Space shift keying (SSK) can be considered a simplified variant of SM [15]–[21], which solely embeds data into the index of an active antenna without involving any constellation symbol. Other variations of SM technology include generalized (G)SM [22]–[24], quadrature SM (QSM) [6], differential (D)SM [7]–[9], gain (R)SM [3], and generalized (G)SSK [4]. In general, SM refers to a new modulation family in communication systems that conveys additional data by utilizing the activation states of transmit antennas. By selecting different activation patterns at the transmitter, various SM configurations provide a flexible design approach

to meet specific requirements and trade-offs in terms of spectral efficiency, energy efficiency, deployment costs, and system performance. For successful data recovery, SM receivers must perform two main tasks [5]:

- Detecting the indices/states of active antennas
- Demodulating the constellation symbols embedded on the active antennas/states (if applicable).

2. RELATED WORK

Efficiently recognizing both spatial and constellation information while maintaining low complexity for SM users under different channel conditions presents a non-trivial challenge [25], [6]. Link-adaptive SM, on the other hand, has been extensively investigated to enhance overall system performance and channel utilization by incorporating receiver feedback to adjust transmission parameters such as modulation order, transmit power, and antenna selection [7]. It is important to note that the detection performance of basic SM heavily relies on the distinguishability of channel signatures associated with different transmit antennas, making it suitable for rich scattering propagation and stationary environments [1]. However, the lack of channel distinguishability can be effectively addressed in SM systems through the use of gain preprocessing techniques like orthogonal pulse shaping [2] and trellis coded modulation (TCM) [3], [4]. Furthermore, in plain SM, which utilizes spatial location to transmit index information through a single active antenna, transmit diversity gain is not provided, resulting in vulnerability to channel fading effects. To overcome this limitation, transmit diversity enhanced SM, employing space-time block coding (STBC), has shown promise in improving error performance [5]–[9]. Given its numerous advantages, SM serves as an energy-efficient modulation technique that can operate in conjunction with other emerging communication systems. The sparsity inherent in SM signals makes compressed sensing (CS) a suitable approach for low-complexity signal reconstruction, even when the number of available measurements is significantly smaller than the signal dimension, particularly in large-scale MIMO scenarios [3]. Furthermore, mmWave structures, with their significantly reduced wavelength, enable the deployment of a large number of antennas in a compact manner, facilitating the implementation of large-scale MIMO systems [4]. As a result, the SM family has emerged as a promising cost-effective and high-efficiency candidate for large-scale MIMO, requiring a smaller number of RF chains for antenna activation. Recently, the combination of non-orthogonal multiple access (NOMA) with SM has gained attention as an attractive and novel approach for multi-user communications, offering high spectral efficiency, energy efficiency, and low-complexity transceiver design [5]–[7]. This NOMA-aided SM technique strikes a favorable balance between spectral efficiency, energy efficiency, deployment cost, and interference mitigation [8]. Simultaneous wireless information and power transfer (SWIPT) is another emerging technology that aims to deliver both wireless data and power simultaneously. SM finds a natural fit in SWIPT-enabled wireless systems as it can utilize inactive antennas for energy harvesting without compromising spectral efficiency. Additionally, due to the broadcast nature of wireless communications, ensuring the security of SM transmissions is a crucial concern [9]. Notably, both physical layer security (PLS) and SM rely on the randomness and distinguishing properties of the wireless interface, which can be exploited to achieve secure communication between legitimate nodes while impeding potential eavesdroppers. SM employs a rapid antenna-switching mechanism that confuses eavesdroppers by introducing rapid variations based on spatial data bits and channel state information (CSI), providing a high potential for secure transmission. Furthermore, SM is not limited to the spatial domain and can be generalized and applied to various signal domains such as frequency, time, code, angle, and even across multiple domains. Consequently, significant attention and interest have been devoted to enhancing different forms of the SM concept in various wireless communication applications [3], [6]. The ON/OFF keying mechanism for embedding index information has been widely applied to single domains, including spatial location (e.g., antennas, RF mirrors, and LEDs), frequency domain (e.g., subcarriers), time domain (e.g., time slots), code domain (e.g., spreading code and modulation type), and angle domain (e.g., angle of arrival (AoA) and polarization state). To further enhance system performance and enable more flexible designs, multidimensional entities have also been developed, incorporating multiple dimensions for implementing the ON/OFF keying mechanism.

3. SPATIAL MODULATION

In this section, we will begin by presenting the fundamental principle of SM and subsequently explore various variations of SM, such as (G)SM and (D)SM. We will then delve into the implementations of SM within a MIMO system, considering NT transmit antennas and NR receive antennas.

3.1 Single-RF SM

Single-RF Spatial Modulation (SR-SM) is a variant of spatial modulation (SM) that aims to reduce the hardware complexity and power consumption by employing a single radio frequency (RF) chain. In traditional SM, each active transmit antenna requires a dedicated RF chain, which can limit its practical implementation in multi-antenna systems. In SR-SM, only one RF chain is used to activate a single transmit antenna at a time, while the remaining antennas remain inactive. The selection of the active antenna is determined by the index or state information that needs to be transmitted.

This allows for efficient utilization of the available antennas, reducing the complexity and power consumption associated with multiple RF chains. By using a single RF chain, SR-SM provides a trade-off between spectral efficiency and hardware complexity. It achieves higher spectral efficiency compared to traditional single-antenna transmission schemes while reducing the implementation cost and power consumption associated with multiple RF chains. SR-SM has garnered significant attention in both research and practical applications owing to its capacity to find a balance between performance and complexity. It presents a promising solution for enhancing capacity and energy efficiency in wireless communication systems equipped with multiple antennas. Since the early 2000s, SM has emerged as an innovative MIMO technique that operates with a single RF chain and exploits the active antenna index to transmit additional data through an antenna-switching mechanism [6], [7]. Consequently, SM does not solely convey information explicitly through phase-shift keying (PSK) or quadrature amplitude modulation (QAM) symbols but also implicitly by selecting the index of an active antenna for each channel usage. By considering the number of transmit antennas (N_T) and the modulation order of the signal constellation (M), the spectral efficiency of SM can be determined.

$$SSM = \log_2 N_T + \log_2 M \text{ [bpcu]} \quad (1)$$

where [bpcu] stands for bits per channel use. Specifically, the first phase of $\log_2 N_T$ bits determines the index of the lively antenna j and the 2d section of $\log_2 M$ bits is used to modulate the constellation images.

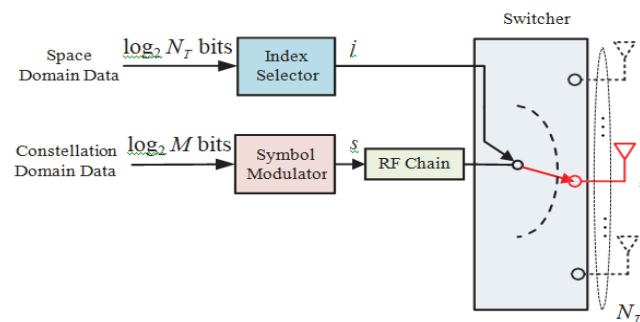


Figure 1: Transmitter diagram for the SM system.

3.2 Generalized (G)SM

While single-RF SM offers high power efficiency by utilizing a single active antenna, it encounters a drawback wherein the spectral efficiency exhibits slow logarithmic growth as the number of transmit antennas increases. To overcome this limitation, (G)SM relaxes the constraint of a single active antenna and enables multiple antennas to be simultaneously activated to transmit the same PSK/QAM symbol [22], [23]. In this (G)SM scheme, since identical PSK/QAM symbols are transmitted from all active antennas, only one RF chain is required, and the system remains immune to inter-channel interference without the need for inter-antenna synchronization. During each channel utilization, K out of N_T ($K \leq N_T$) transmit antennas are selected to transmit the same constellation symbol, while the remaining $N_T - K$ antennas remain inactive.

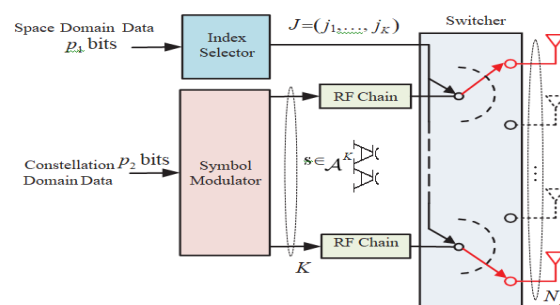


Figure 2: Transmitter diagram for the (G)SM system.

3.3 Differential (D)SM

As the spatial information is implicitly embedded in the active antenna in SM transmission, the SM receiver must discern different channel fading states associated with various transmit antennas to detect such spatial information, requiring coherent detection based on channel state information (CSI). However, the need for CSI at the receiver increases the deployment cost due to pilot overhead and channel estimation complexity. Alternatively, differential encoding of SM symbols offers an appealing solution with lower deployment cost as it eliminates the requirement for CSI at the transceiver while retaining the advantages of SM. A differential encoding technique called differentially encoded space-time shift keying (STSK) modulation is introduced in [109] as the fundamental concept of (D)SM, utilizing the Cayley unitary transform to convey data through the activation state..

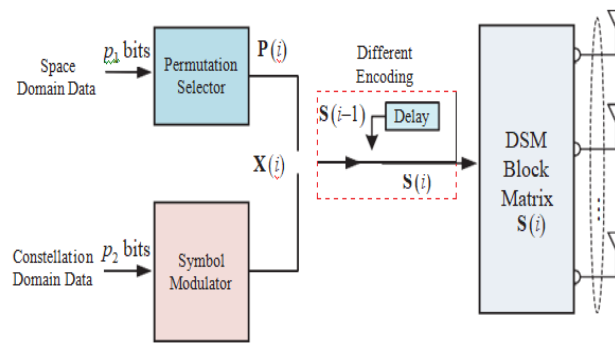


Figure 3: Transmitter diagram for the (D)SM system.

Table 1: Classification of Representative Forms of SM.

Type	Entity		Representative Schemes	Main Achievements
Single-Dimension Entity	Space Domain	Antenna	SM [6], SSK [1], (G)SM [2], (G)SSK [4], QSM [6]	Increased energy efficiency and reduced deployment cost
		LED	OSM [1]	Enhanced control over illumination and communications
		RF Mirror	RA-SSK [2], CM [3]	Improved system performance and reduced antenna cost
	Frequency Domain	Subcarriers	SIM-OFDM [24], OFDM-IM [9], OFDM-I/Q-IM [5], GFDM-IM [6]	Higher spectral efficiency and energy efficiency
		Subcarriers	CI-OFDM-IM [7], MIMO-OFDM-IM [8]–[11]	Enhanced reliability and energy efficiency
	Time Domain	Time slot	SC-IM [12]	Improved transmission efficiency for broadband systems
	Code Domain	Spreading Code	CIM-SS [09], GCIM-SS [14], IM-OFDM-SS [15]	Higher spectral efficiency and lower energy consumption
		Modulation Type	ESM [16], DM-OFDM [17], MM-OFDM-IM [18]	Increased spectral efficiency
	Angle Domain	Polarization State	PolarSK [19], 3-D PMod [20]	Higher spectral efficiency and lower hardware cost
		AoA	BACM [21]	Higher spectral efficiency
Multi-Dimension Entity	Space-Time		STSK [10]	Flexible tradeoff between diversity & multiplexing gain
	Space-Frequency		GSFIM [22]	Superior system performance
	Space-Time-Frequency		STFSK [23], GSTFIM [24]	Higher spectral efficiency

4. CONCLUSION

SM emerges as a promising digital modulation technology that meets the requirements of emerging wireless systems, offering high energy efficiency, low deployment cost, freedom from interchannel interference, relaxed inter-antenna synchronization requirements, and compatibility with large-scale MIMO systems. This survey has highlighted the potential of SM to achieve an appealing trade-off between spectral efficiency and energy efficiency with its simple design philosophy, as supported by extensive research. We have discussed the fundamental principles, variations, and advancements of SM, showcasing the diverse possibilities of this concept in various implementations. These include integration with other promising techniques, applications in emerging communication systems, and extensions to new domains. We trust that this survey, along with the research findings presented in this special issue, will provide readers with a deeper understanding and clearer insight into the advantages and potential applications of the SM technology and its wide-ranging possibilities

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