Spatial Modulation for Multiple-Antenna Communication

Application to the Internet of Things (IoT): From Theory to Practice

Introduction

The Internet of Things (IoT) can be broadly defined as the current commercial effort for integrating a wide variety of technical and commercial information-generating components to provide new business opportunities based upon device and system intelligence. Several potential application areas have been identified for the IoT, which include smart homes, wearables, smart cities, the smart grid, the industrial Internet, connected cars, connected health, smart retail, smart supply chain, and smart farming.

In the context of IoT-based applications, the so-called connected objects are expected to require more modest data rates, lower power consumption, and smaller form factors compared with those of typical mobile multimedia services. By contrast, they are expected to support higher data rates at a higher power consumption, and at a more bulky form factor compared with typical wireless sensor nodes. Hence, new air interface techniques have to be developed, which are able to satisfy these new emerging requirements and to offer a better Spectral Efficiency (SE) vs. Energy Efficiency (EE) design flexibility. In this context, Multiple-Input-Multiple-Output (MIMO) techniques [1] are expected to provide the necessary design flexibility to meet these requirements.

Why for emerging IoT applications is a new MIMO paradigm necessary?

The capacity of MIMO systems is proportional to the minimum of the number of transmit and receive antennas. This implies that the throughput may be increased linearly with the number of antennas. As a consequence, MIMO techniques can provide high data rates without any bandwidth expansion and without increasing the transmit power [2]. However, in practice, conventional MIMO systems rely on a multiplicity of independent circuits for each available antenna element, such as power amplifiers, RF front-ends, mixers, synthesizers, filters, etc., which substantially increase the circuit power dissipation of all network elements. It is known, in particular, that the power amplifiers dissipate the majority of the power consumed in current cellular base stations [3].

Recent studies, in fact, have proved that the EE gain of MIMO transmission increases with the number of antennas, provided that only the transmit power is taken into account and that their circuit power dissipation is neglected. On the other hand, the EE gain of MIMO transmission remains modest...
Spatial Modulation for Multiple-Antenna Communication

and decreases with the number of active transmit antennas, if realistic power consumption models are considered [3]. These results highlight that the design of energy efficient and low-complexity MIMO transmission schemes is an open research issue, especially in the context of IoT applications.

In this context, the design of MIMO transmission schemes that exploit fewer RF chains compared to the number of available radiating elements is currently emerging as a promising research field [2]. Usually, this family of MIMO designs is referred to as single-RF MIMO. Suffice to say, however, that various compromise-schemes exist, where a subset of the antennas is activated, which determines the number of RF-chains that is needed. Hence, in parlance, we can refer to these schemes as single-RF, full-RF and few-RF arrangements.

Why having fewer RF chains than radiating elements is beneficial for designing spectral-and energy-efficient MIMO schemes?

The fundamental idea behind the few-RF MIMO concept is to attain spatial multiplexing and/or transmit-diversity gains with the aid of many antenna-elements, where only a subset of them – or possibly just a single antenna-element – is activated at the transmitter at any modulation instant. The rationale behind the full-RF to few-RF paradigm shift in MIMO design originates from the consideration that multiple transmit antennas (radiating elements) may be accommodated at both the transmitters and receivers, bearing in mind that the complexity and power consumption/dissipation of MIMO transmission is mainly determined by the number of simultaneously active transmit antennas, i.e., by the number of RF chains [2].

Fueled by these considerations, Spatial Modulation (SM) has recently established itself as a promising transmission concept, which belongs to the few-RF MIMO wireless system family, whilst exploiting the availability of multiple antennas in a novel fashion compared to state-of-the-art high-complexity and power-hungry classic MIMO systems [2]. In simple terms, SM can be regarded as a MIMO concept that possesses a larger set of radiating elements than the number of transmit-electronics chains. SM-MIMO takes advantage of the entire antenna-array at the transmitter, whilst using a limited number of RF chains. The main distinguishing feature of SM-MIMO is that it maps additional information bits onto a "SM constellation diagram", where each constellation element is formed either by a single antenna-element or a subset of antenna-elements. These unique characteristics result in high-rate MIMO implementations relying on a reduced signal processing and circuit complexity, as well as an improved EE. Recent analytical and simulation studies have shown that SM-MIMO has the inherent potential of outperforming many state-of-the-art MIMO schemes under the fair assumption that the number of RF chains is the same [4]-[6]. Readers interested in further information on SM-MIMO systems are invited to consult recently published and comprehensive survey papers [7]-[11]. It is worth mentioning that the SM-MIMO concept is one of the proposed technologies for next-generation communication systems [12].

Spatial Modulation

We introduce the SM-MIMO concept with the aid of a simple example. We denote by Nt and Nr the number of Transmit Antennas (TAs) and Receive Antennas (RAs), respectively. The cardinality of the signal-constellation diagram is denoted by M. In general, Nt, Nr and M can be chosen independently of each other. If a Maximum-Likelihood (ML) optimum demodulation is considered at the receiver, Nr can be chosen independently of Nt [7]. For ease of illustration, a single RF chain is assumed to be available at the transmitter (single-RF MIMO).

In figure 1, the SM-MIMO concept is illustrated for Nt = M = 2 and is compared to Spatial Multiplexing (SMX) and...
Orthogonal Space-Time Block Code (OSTBC) schemes. In the latter case, the Alamouti scheme is considered [7]. Compared with SMX and OSTBC, we observe that only one (S1) out of the two symbols is explicitly transmitted in SM-MIMO, while the other symbol (S2) is implicitly transmitted by determining the index of the active TA in each channel use. In SM-MIMO, in other words, the information symbols are modulated onto two information carrying units: 1) a modulated symbol and 2) a single active TA via an information-driven antenna-switching mechanism.

In Figure 2 and Figure 3, the encoding principle of SM-MIMO is illustrated for $N_t = M = 4$ by considering two generic channel uses, and the concept of “SM or spatial-constellation diagram” is introduced.

The illustrations shown in Figure 2 and Figure 3 highlight some unique characteristics of SM-MIMO:

- The activated TA may change every channel use according to the input information bits. Thus, TA switching is an effective way of mapping the information bits to TA indices and of increasing the transmission rate.
Spatial Modulation for Multiple-Antenna Communication

The information bits are modulated onto a three-dimensional constellation diagram, which generalizes the known two-dimensional (complex-valued) signal-constellation diagram of conventional modulation schemes.

The third dimension is provided by the antenna array, where some of the bits are mapped to the TAs. In SM-MIMO research, this third dimension is often termed as the “spatial-constellation diagram” [2].

Spatial Modulation Based on Reconfigurable Antennas (RectAnt-SM)

Reconfigurability can be thought of as a software-defined functionality, where flexibility is controlled predominately through the specification of bit patterns. Reconfigurable systems can be as simple as a single switch, or as abstract and powerful as programmable matter. One of the most prevalent pursuits in reconfigurable RF research has been in the development of antennas, which have been studied extensively. For the most part, a Reconfigurable Antenna (RectAnt) is a set of passive structures infused with switches, which are opened and closed to elicit desired resonances for end-user applications. In the burgeoning IoT market, RectAnts are expected to provide the opportunity for better designing communication systems that fulfill important conflicting trade-offs, such as reducing the size, power consumption, and cost of the IoT devices, while simultaneously increasing their data rate through innovative MIMO technologies [13].

More precisely, the transmitted electromagnetic wave is radiated by the RectAnt according to one of the radiation patterns depicted in Figure 4, which then interacts with the scatterers that are spatially distributed in the environment. Depending on the radiation pattern being activated by the data stream to be transmitted, as a result, the received signal depends on the interaction between the spatial distribution of the scatterers and the directional characteristics of the antenna. In general, different radiation patterns interact with different scatterers, which results in a unique received signal (fingerprint) for every possible radiation pattern.

The potential advantages of this approach compared with conventional SM lie in the possibility of realizing very compact

![Spatial Modulation for Multiple-Antenna Communication](image-url)
and low-complexity antennas that are inherently used for modulating data. In addition, the use of RectAnts may avoid the need of using mechanical switches, which, on the other hand, are replaced by appropriate circuits that are integrated in the antenna design and that are capable of modifying the distribution of the current of the RectAnt. These peculiarities are suitable for IoT applications.

**RectAnt-SM: From Theory to Practice – The ANR Project “SpatialModulation”**

Even though the idea of using RectAnts in the context of SM research was proposed in [7] just recently, several theoretical and experimental activities are now available. The RectAnt-SM technology is currently being researched and experimented by the author under the auspices of the ANR-funded research project titled “SpatialModulation”, which is coordinated by Orange Labs [13]. Notably, the team of researchers and engineers of the project has realized and implemented the world’s first visual demonstration of a testbed that adopts RectAnts for implementing the SM principle [14]. New RectAnts have been designed and have been used as a means for encoding the information bits. Their different energy patterns can be visualized with the aid of an innovative radio wave display that is capable of measuring the received power. The display shows that distinct received energy patterns are obtained if different radiation patterns of the RectAnts are activated at the transmitter. This world’s first demonstration was showcased at the Int. ITG Workshop on Smart Antennas in Berlin, Germany, in March 2017 and at the IEEE Int. Conference on Communications in Paris, France, in May 2017. Further information is available in [15].

**Conclusion**

The emerging market of the IoT requires new energy-efficient and low-complexity MIMO-aided radio access technologies. We have introduced and discussed a new radio access technology, conceived to satisfy the IoT requirements, that synergistically combines the potential of SM and RectAnts. The basic technology and current theoretical and experimental research activities have been discussed. Notably, we have illustrated the recent innovations made in the context of the ANR-funded project “SpatialModulation” in terms of theoretical, algorithmic, and implementation of this emerging and promising multi-antenna technology.

**References**


---

**L’AUTEUR**

**Marco Di Renzo** was born in L’Aquila, Italy, in 1978. He received the Laurea (cum laude) and Ph.D. degrees in electrical engineering from the University of L’Aquila, Italy, in 2003 and 2007, respectively, and the Habilitation à Diriger des Recherches from University Paris-Sud, France, in 2013. Since 2010, he has been a Chargé de Recherche CNRS in the Laboratory of Signals and Systems (L2S) of Paris-Saclay University. He serves as the associate editor-in-chief of IEEE Communications Letters, and as an editor of IEEE Transactions on Communications, and IEEE Transactions on Wireless Communications. He is a distinguished lecturer of the IEEE Vehicular Technology Society and IEEE Communications Society, and a Senior Member of the IEEE. He is a recipient of several awards, including the 2013 IEEE COMSOC Best Young Researcher award (EMEA), the 2013 NoE-NEWCOM# Best Paper award, the 2015 IEEE Jack Neubauer Memorial award, and six Best Paper awards at IEEE conferences.


