# Spatial Modulation Based on Reconfigurable Antennas -A New Air Interface for the IoT

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**HAL Id: hal-02324415**

**https://centralesupelec.hal.science/hal-02324415**

Submitted on 21 Oct 2019

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*Abstract*— **The emerging market of the Internet of Things (IoT) requires new energy-efficient and low-complexity Multiple-Input-Multiple-Output (MIMO-) aided radio access technologies. This trend will have a profound impact on both the theory and practice of future communication networks, which will not be purely optimized for approaching the attainable capacity anymore, but will explicitly include the energy efficiency for the design and optimization of the entire protocol stack. In this paper, we discuss a recently introduced modulation scheme for IoT applications, which leverages the concepts of Reconfigurable Antennas (RecAnts) and Spatial Modulation (SM). RecAnt-SM constitutes a promising new air interface in the context of MIMO-aided transmission, which can be beneficially invoked for the design of medium-throughput, low-complexity and energy-efficient communication systems by relying on a limited number of RF chains and the flexibility of simple RecAnt designs.**

## I. 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. A NATO Science and Technology Organisation (STO) task group was recently established to identify the potential military applications of the IoT (IST-147) and various potential areas have been identified and are currently under analysis [1]. This includes: 1) logistics – command and control of combined operations logistics support, 2) situational awareness – building on the tactical level of a battlefield (from global, to company, platoon and squad commanders down to single soldiers level) including monitoring, sensing, threat identification (e.g., sniper), target positioning, marking, vehicles and soldiers status monitoring, environmental monitoring (environment conditions), and 3) medical care – battlefield health monitoring, patients monitoring, etc.

In the context of IoT-based military and civilian applications, the so-called connected objects are expected to require more modest data rates, lower power consumption, and smaller form factors compared to those of typical mobile multi-media services. By contrast, they are expected to support higher data rates at a higher power consumption, and at a more bulky form factor compared to typical wireless sensor nodes. Hence, new air interface techniques have to be developed, which are capable of satisfying these new emerging requirements and of offering a better Spectral Efficiency (SE) vs. Energy Efficiency (EE) design flexibility. In this context, Multiple-Input-Multiple-Output (MIMO) techniques [2] are expected to provide the necessary design flexibility to meet these requirements. For emerging IoT applications, however, new MIMO paradigms are necessary. Why?

The capacity of MIMO systems is proportional to $\min\{N_t, N_r\}$, where $N_t$ and $N_r$ represent 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 [3]. 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 [4]. 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 and decreases with the number of active transmit antennas, if realistic power consumption models are considered [5]. These results highlight that, at the time of writing, 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 [3]. Usually, this family of MIMO designs is referred to as single-RF MIMO. Suffice to say, however, that there are also various compromise-schemes, which rely on diverse antenna selection schemes, where a specific 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 [3].

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 [3]. 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 constituted by either 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 [6]– [13]. Readers interested in further information on SM-MIMO systems are invited to consult recently published and comprehensive survey papers [14]– [17]. It is worth mentioning that the SM-MIMO concept was recently validated via experimental activities [18] and was successfully implemented in a testbed platform [19]. SM-MIMO is one of the proposed technologies for next-generation communication systems [20].

In this paper, we will first review the basic principle of SM-MIMO and will then describe a new air interface that synergistically combines SM and RecAnts for application to the IoT, aiming to the design of medium-throughput, low-complexity and energy-efficient communication systems that are specifically tailored to meet the requirements of the connected objects for military and civilian applications [21].

## II. CONVENTIONAL SPATIAL MODULATION

### A. How It Works

In this section, we introduce the SM-MIMO concept with the aid of simple examples. We denote by $N_t$ and $N_r$ the number of Transmit Antennas (TAs) and Receive Antennas (RAs), respectively. The cardinality of the signal-constellation diagram is denoted by $M$. Either Phase Shift Keying (PSK) or Quadrature Amplitude Modulation (QAM) are considered. In general, $N_t$, $N_r$ and $M$ can be chosen independently
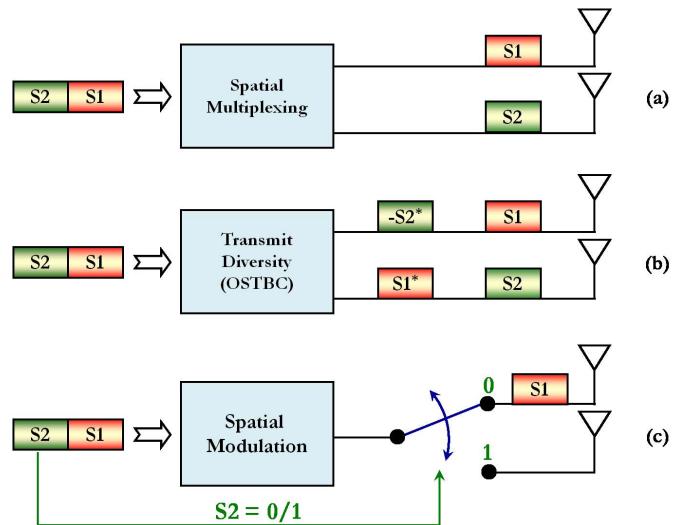


Fig. 1.    Illustration of three MIMO concepts: (a) spatial-multiplexing; (b) transmit-diversity; and (c) spatial modulation [14].

of each other. At the receiver, Maximum-Likelihood (ML-) optimum demodulation is considered. Thus, $N_r$ can be chosen independently of $N_t$ [17]. For ease of presentation, we assume $N_t = 2^{n_t}$ and $M = 2^m$ with $n_t$ and $m$ being two positive integers. For ease of illustration, a single RF chain is available at the transmitter (single-RF MIMO).

In Fig. 1, the SM-MIMO concept is illustrated for $N_t = M = 2$ and is compared to Spatial Multiplexing (SMX) and Orthogonal Space-Time Block Code (OSTBC) schemes. In the latter case, the Alamouti scheme is considered [14].

1) In SMX-MIMO, two PSK/QAM symbols ($S_1$ and $S_2$) are simultaneously transmitted from a pair of TAs in a single channel use. For arbitrary $N_t$ and $M$, the rate of SMX is $R_{\text{SMX}} = N_t \log_2(M)$ bpcu.

2) In OSTBC-MIMO, two PSK/QAM symbols ($S_1$ and $S_2$) are first encoded and then simultaneously transmitted from a pair of TAs in two channel uses. For arbitrary $N_t$ and $M$, the rate of OSTBC is $R_{\text{OSTBC}} = R_c \log_2(M)$ bpcu, where $R_c = N_{\text{M}}/N_{cu} \leq 1$ is the rate of the space-time block code and $N_{\text{M}}$ is the number of information symbols transmitted in $N_{cu}$ channel uses. If, as shown in Fig. 1, the Alamouti code is chosen, then $R_c = 1$.

3) In SM-MIMO, only one ($S_1$) out of the two symbols is *explicitly* transmitted, while the other symbol ($S_2$) is *implicitly* transmitted by determining the index of the active TA in each channel use. In other words, in SM-MIMO the information symbols are modulated onto two information carrying units: 1) a PSK/QAM symbol; and 2) a single active TA via an *information-driven* antenna-switching mechanism. For arbitrary $N_t$ and $M$, the rate of SM is $R_{\text{SM}} = \log_2(M) + \log_2(N_t)$ bpcu [3].

In Fig. 2 and Fig. 3, the encoding principle of SM-MIMO is illustrated for $N_t = M = 4$ by considering two generic channel uses, where the concept of "SM or spatial-constellation diagram" is also introduced. The rate of this
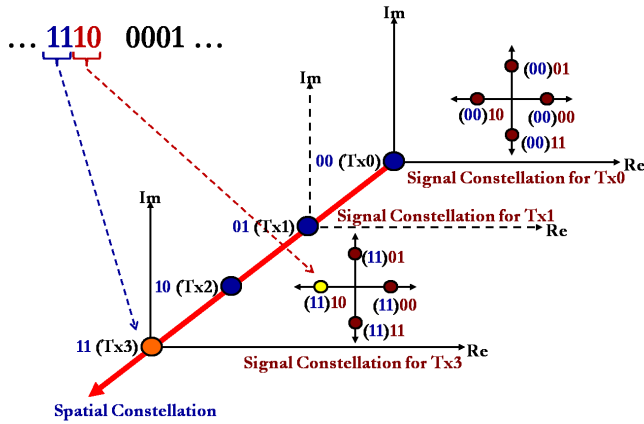
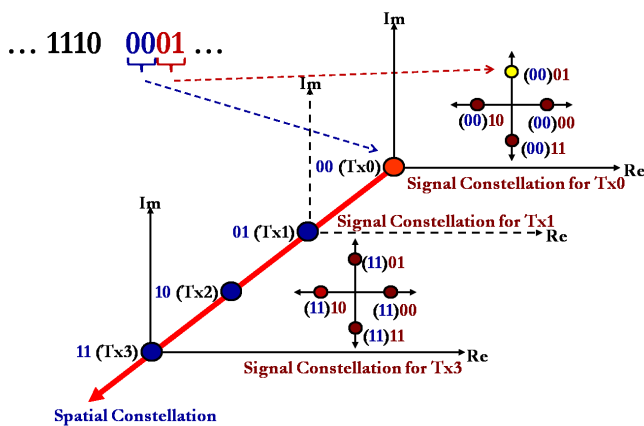Fig. 2.   Three-dimensional encoding of SM (first channel use) [14].



Fig. 3.   Three-dimensional encoding of SM (second channel use) [14].

MIMO setup is $R_{\text{SM}} = \log_2(M) + \log_2(N_t) = 4$ bpcu, hence the encoder processes the information bits in blocks of 4 bits each. In the first channel use shown in Fig. 2, the block of bits to be encoded is "1100". The first $\log_2(N_t) = 2$ bits, "11," determine the single active TA (TX$_3$), while the second $\log_2(M) = 2$ bits, "00," determine the transmitted PSK/QAM symbol. Likewise, in the second channel use shown in Fig. 3, the block of bits to be encoded is "0001". The first $\log_2(N_t) = 2$ bits, "00," determine the single active TA (TX$_0$), while the second $\log_2(M) = 2$ bits, "01," determine the transmitted PSK/QAM symbol.

The illustrations shown in Fig. 2 and Fig. 3 highlight a pair of unique characteristics of SM-MIMO:

1) 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.
2) The information bits are modulated onto a three-dimensional constellation diagram, which generalizes the known two-dimensional (complex-valued) signal-constellation diagram of PSK/QAM modulation. The third dimension is provided by the antenna-array, where some of the bits are mapped to the TAs. Again, in SM-

MIMO research, this third dimension is often termed as the "spatial-constellation diagram" [3].

### B. Why It Works

From Section II-A, we have learned that the fundamental operational principle of SM-MIMO relies on transmitting part of the information bits via an implicit information-driven antenna-switching mechanism. In this section, we provide some insights on how the receiver becomes capable of retrieving the information bits encoded into the TA-indices. This, in fact, showcases the underlying "essence" that equips SM-MIMO with its innate properties.

In SM-MIMO, the signal emitted by the active TA traverses through a generic wireless channel, which is characterized by a unique channel impulse response. Owing to the different spatial locations occupied by the TAs in the antenna-array, the signal transmitted by the active TA experiences different propagation conditions due to the different dispersive and reflecting environmental objects along any transmitter-to-receiver wireless links. As such, the same PSK/QAM symbol emitted by each TA-element travels through a communication channel, which introduces a specific "channel signature or fingerprint," *i.e.*, the channel impulse response, that makes it unique compared to the same symbol emitted by any other TAs. This constitutes the fundamental essence of SM-MIMO: the more different the channel signatures/fingerprints are from each other, the simpler it becomes to distinguish the signals at the receiver. Hence, the communication channel plays the role of a "modulation unit," where the channel impulse responses are the actual messages being transmitted.

At the receiver, the demodulation unit exploits the unique fingerprint introduced by the wireless channel for retrieving the information bits. The receiver is assumed to be aware of the $N_t$ channel impulse responses, however the actual channel impulse response that is received in each channel use depends on the index of the active TA. The demodulator performs an exhaustive search among all the possible combinations of channel impulse responses and modulation symbols, and makes a decision in favor of the hypothesis associated with the lowest Euclidean distance. In a nutshell, due to the information-driven antenna-switching mechanism of SM-MIMO transmission, the $N_t$ channel impulse responses become part of the search space of the hypothesis-testing problem solved by the receiver. Based on the estimated channel impulse response, the demodulator is capable of retrieving the information bits associated with it. In summary, the essence of SM-MIMO transmission is all about exploiting the TA-specific property of the wireless channel, *i.e.*, the uniqueness of each transmit-to-receive wireless link, for data communication.

### III. SM Based on Reconfigurable Antennas

In this section, we motivate and introduce the concept of RecAnt-SM and highlight its potential benefits for the IoT.

### A. The IoT Motivation

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 [22]. One of the most prevalent pursuits in reconfigurable RF research has been in the development of antennas, which have been studied extensively [23]. For the most part, a reconfigurable antenna is a set of passive structures infused with switches, which are opened and closed to elicit desired resonances for end-user applications. Reconfigurability has become an important and desired feature of modern, agile, RF systems for wireless communications and sensing. The use of reconfigurable antennas can significantly reduce the number of components, and, thus, hardware complexity, size, and cost compared to today's radio technology, which are based on communication systems with inflexible (non-reconfigurable) hardware. In the burgeoning IoT market, the size of the mobile devices ("the connected objects") will continue to shrink compared to the past while their data rate and energy efficiency capabilities will continue to raise in light of the envisioned use cases. The IoT will likely create an enormous demand for small wireless systems with sizes comparable to those of tiny sensors but with higher data rate requirements and similar or higher energy efficiency requirements. In this context, RecAnts are expected to better design communication systems satisfying the conflicting trade-offs of reducing the size, power consumption, and cost of the IoT, while simultaneously increasing their data rate through innovative MIMO technologies [21].

The idea of using reconfigurable antennas for implementing and generalizing the SM principle was introduced in [14] with the twofold attempt of increasing the achievable data rate and reducing the implementation complexity, e.g., by avoiding the need of using mechanical or RF switches. In this section, the idea of using RecAnts for application to SM systems is summarized and ongoing research activities are discussed.

### B. Reconfigurable Antennas – Preliminaries

Before going into the details of applying RecAnts to SM, we briefly summarize the fundamental working principle of RecAnts and illustrate an example of RecAnt-SM system.

In general terms, reconfiguring an antenna is achieved through deliberately changing its radiation characteristics, e.g., its far field radiation pattern. In practice, this change is obtained in a controlled manner, by adequately redistributing the antenna currents and, thus, altering the electromagnetic fields of the antenna's effective aperture. In other words, thus, the far field antenna radiation pattern can be modified by appropriately controlling the distribution of the current of the antennas. Based on [23], e.g., there are several techniques for obtaining RecAnts, which include i) electrically-reconfigurable, ii) optically-reconfigurable, iii) physically-reconfigurable, and iv) material-reconfigurable antennas. Among the many potential benefits of RecAnts, important peculiarities for application to the IoT include the minimization of cost, volume requirements, and a simplified integration. It worth mentioning, in addition, that RecAnts are different from smart antennas, since the reconfiguration process lies inside the antenna rather than in
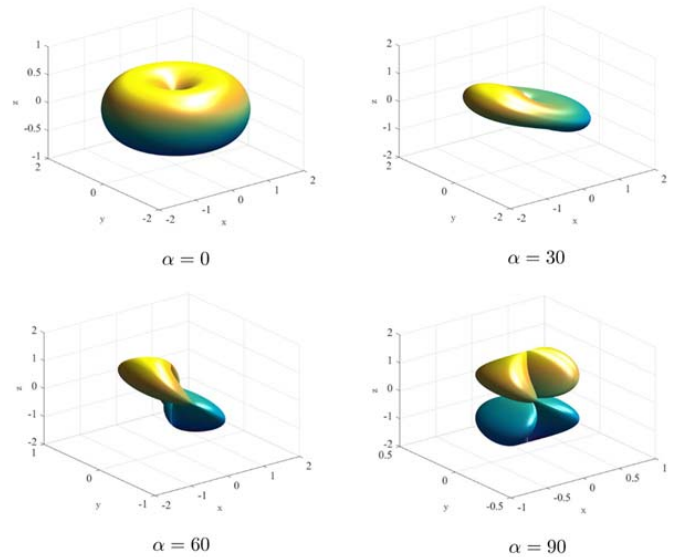


Fig. 4.  Example of different radiation patterns of a RecAnt (dipole).

the external network as in beamforming network.

In Fig. 4, we illustrate a simple example of reconfigurable dipole antenna, where the radiation pattern (vertical polarization) depends on the inclination angle ($\alpha$) of the dipole antenna itself (the so-called polarization parameter) [24].

### C. How It Works

The idea of using RecAnts for providing a low-complexity implementation solution for realizing SM systems was proposed in [14]. In this section, we briefly discuss the idea with the aid of Fig. 4 and by considering the simplest case study.

Let us assume that the transmitter is equipped with a RecAnt that is capable of producing the far field radiation patterns depicted in Fig. 4. For ease of illustration, let us assume that the data stream to be transmitted is encoded exclusively into one of the four radiation patterns of Fig. 4. For example:

- If "00" needs to be transmitted, the polarization parameter $\alpha$ is set equal to 0 degrees and the corresponding antenna radiation pattern is generated and used for transmission.
- If "01" needs to be transmitted, the polarization parameter $\alpha$ is set equal to 30 degrees and the corresponding antenna radiation pattern is generated and used for transmission.
- If "10" needs to be transmitted, the polarization parameter $\alpha$ is set equal to 60 degrees and the corresponding antenna radiation pattern is generated and used for transmission.
- If "11" needs to be transmitted, the polarization parameter $\alpha$ is set equal to 90 degrees and the corresponding antenna radiation pattern is generated and used for transmission.

It is known that the characteristics of multipath radio channels are determined by the distribution of the scatterers in the RF propagation environment and by the interplay between multipath components and antenna radiation patterns. More

precisely, the transmitted electromagnetic wave is radiated by the RecAnt according to the radiation pattern in Fig. 4 and it 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. This is another way of exploiting the SM principle [14] and of encoding the information not only in the impulse response of the channel, but in the interplay between antenna radiation pattern and nearby scatterers. Similar to the conventional SM principle [14], the receiver is capable of retrieving the information by solving a hypothesis testing problem based on the four radiation patterns depicted in Fig. 4, as discussed in Section II for conventional SM systems.

The potential advantages of this approach compared to conventional SM is the possibility of realizing very compact and low-complexity antennas that are inherently used for modulating data. In addition, the use of RecAnts 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 changing the distribution of the current of the RecAnt. These peculiarities are suitable for IoT applications and the research project "SpatialModulation", led by Orange Labs in France, is focused on designing and optimizing RecAnts for realizing this vision and for applying SM to IoT, 5G and WLAN systems [21].

### D. State-Of-The-Art: Theoretical and Experimental Activities

Even though the idea of using RecAnts in the context of SM research was proposed just recently, quite a few theoretical and experimental activities are currently available. They are briefly summarized in this section.

In [25], the author proposes a distributed antenna system, where a single-RF reconfigurable antenna is employed at the transmitter. More specifically, the use of a single-RF reconfigurable antenna, capable of switching/forming multiple antenna patterns, is used to create virtual multiple-antenna channels without relying on the cooperation with other nodes. The author shows that the proposed technique is capable of outperforming classical virtual multiple-antenna systems. The proposed scheme, in addition, is generalized to its non-coherent detection-based counterpart, which uses differential encoding of unitary pattern-time codewords. The proposed non-coherent scheme is capable of dispensing channel state information estimation at the receiver.

In [26], the author develops a Differential Spatial Modulation (DSM) scheme for amplitude phase shift keying modulation with better throughput or performance compared with conventional PSK modulation. The impact of time-varying fading is studied and it is shown that the performance degrades if the fading is too fast due to differential detection. The impact of a long outer error control code is also considered. It is shown that its performance is limited by the slowly varying channel required for differential detection. The author suggests using RecAnts to periodically changing the channel conditions and improving the coded performance of DSM systems.

In [27], the authors consider the application of RecAnts for data modulation. More precisely, the effect of RecAnts on the channel consists of changing the Rician K-factor of the channel itself. Based on this observation, the authors propose a system that encodes the information into the variation of the Rician K-factor. A mathematical framework for computing the bit error probability is proposed, and it is shown that the proposed scheme is capable of enhancing the system performance. In [28], the same authors extend their proposed modulation scheme for application to spectrum sharing systems and prove that the performance of the secondary users is improved while satisfying the constraints on the primary users.

In addition to these theoretical studies, some experimental activities that are aimed to design new RecAnts specifically tailored for SM applications have been proposed. In addition, preliminary testbed implementations have been realized.

In [29], the authors design a compact reconfigurable antenna suitable for communication systems based on the SM principle. The reconfigurable antenna is based on a meander line radiating element surrounded by two L-shaped wire resonators connected to a metallic ground plane with two PIN diodes. By switching the PIN diodes, the proposed printed antenna is capable of generating four different radiation patterns. The cross-correlation between the different patterns is shown to lie in the range 11% - 80%, which is shown to be acceptable for SM applications. Other antenna geometries are proposed in order to increase the number of radiation patterns that can be generated while still preserving good correlation properties for practical communication applications.

In [30], the authors report the world's first "visual" demonstration of a testbed implementation that adopts RecAnts for implementing the SM principle. Different new RecAnts are used for encoding the information bits and their different "energy patterns" are 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 RecAnts 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.

### IV. Conclusions and Research Outlook

The emerging market of the IoT requires new energy-efficient and low-complexity MIMO-aided radio access technologies. In this paper, we have discussed a new air interface, conceived for satisfying the IoT requirements, that synergistically combines the potential of SM and RecAnt concepts. The basic technology and current theoretical and experimental research activities have been discussed and summarized.

In spite of the pioneering contributions towards the application of RecAnts to SM, major theoretical, algorithmic, and

implementation issues need to be addressed. This includes, a deeper understanding of the achievable performance of SM systems based on RecAnts, the development of low-complexity demodulation schemes, e.g., without requiring channel state information at the receiver, and the implementation and test of RecAnts having multiple radiation patterns with controllable characteristics. For example, at the time of writing, there is no general understanding on the impact of the radiation pattern on the achievable performance if realistic (three-dimensional) multi-path fading channels are considered. In addition, all the activities conducted so far are based on the sub-6 GHz band, while no studies are available for higher transmission frequencies. The results reported in [31]- [33] on the application of SM to the millimeter-wave band highlights that this technology may be used for high frequencies as well, where RecAnts may be even more beneficial.

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