Compact Beamforming Antennas for Directional Modulation in IoT

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***Abstract*—The paper discuss a PHY-layer security technique known as Directional Modulation (DM) and its implementations with compact beamforming antennas. The motivation is to allow DM to operate from small and low-complexity IoT devices. While classical DM required large antenna arrays and complex hardware, recent work proposed an alternative algorithm that requires single RF chain. The technique was demonstrated with circular arrays of diameter of 0.6 wavelength, with only one antenna transmitting at each given time. This work revisits the concept and demonstrate its feasibility with multimodal compact beamforming antennas. Unlike circular arrays, for multimodal antennas the directional performance is directly dependent on the number of modes involved and not antenna size – albeit inclusion of higher order modes within limited volume will inevitably lead to the decrease in operational bandwidth and efficiency.**

Keywords—compact antennas, beamforming, directional modulation, Internet of Things, IoT

I. INTRODUCTION

Electrically small antennas have been focus of numerous research activities, owing to – among others - their miniaturization capabilities and potential integration into small Internet of Things (IoT) devices. Historically, initial designs focused mainly on omnidirectional antennas with fixed radiation patterns, while trying to increase their bandwidth [1] – a key limiting factor in miniaturization, known as Harrington limit [2]. While the limit attempts to place an upper bound on antenna's gain based on its electrical size, it provides little insight into the beamforming capabilities and multiport antennas. Recently the newly proposed Capek limit revisited the concept, based on recent advances of the theory of characteristic modes [3]. Importantly, the new limit offers beamforming analysis, as it allows for a direction-specific limit. This is a significant analysis tool for future development of compact beamforming antennas.

One of applications of compact beamforming antennas is the Directional Modulation (DM). This is a PHY-layer security technique, which ensures the communication can be demodulated only in the direction of the legitimate receiver. The technique is fully receiver based, eliminating issues with cryptographic key distribution. However, the classical implementation of directional modulation requires the use of bulky antenna arrays, with the capability to individually control both amplitude and phase at each antenna [4]. The solution cannot be applied to wireless IoT applications due to antenna size and hardware complexity.

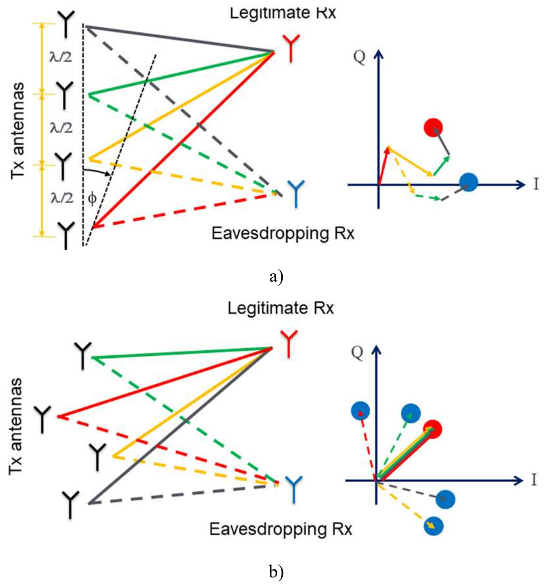

Fig. 1. Schematic explanation of two different directional modulation systems, with exemplary received symbols in IQ plane: a) classical implementation with antenna arrays; the modulated vector is divided into components which for the legitimate receiver superimpose to the desired point; b) low-complexity implementation with single RF-chain; where symbols are transmitted with different spatially located antenna with phase correction specific to each antenna and direction of legitimate receiver. The legitimate receiver receives the same symbol regardless of antenna used for transmission, while the eavesdropper observes scattered symbols.

However, recent developments in both antenna miniaturization and directional modulation offer new opportunities to increase security of wireless IoT applications. This paper aims to review those solutions. The work firstly compares and discussed classical and new directional modulation schemes in Section II, which is followed by theoretical analysis that demonstrates the use of the new DM technique with multimodal compact beamforming antennas in Section III.

II. DIRECTIONAL MODULATION FOR IOT

Fig. 1a shows a typical scheme of classical directional modulation, as proposed in [4]. The transmitter uses *N*-element antenna array and it intends to securely transmit a certain symbol to the legitimate receiver located at direction ϕ_{Bob}. The IQ vector representing the symbol is divided into *N*-random components and each component is transmitted via different antenna, so that for the direction of legitimate receiver the superposition results in the intended transmitted

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symbol. Due to the physical principles of antenna array, any direction different from the legitimate receiver will observe different phase shift for each component and thus their superposition will results in a different location within the IQ plane. There is practically an infinite number of combinations to divide the modulation vector in accordance with the above principles, hence the transmitter can update the symbols as often as practicable without impacting communication with the legitimate receiver. As observed in [5], the technique might be interpreted as a superposition of two radiation patterns: one with the maximum of radiation pattern directed towards the legitimate user that transmits modulated signal and one with a null of the radiation pattern directed towards the legitimate users that is dynamically changed to transmit noise. Nevertheless, both transmitter's complexity and size of the required array practically eliminate those classical approaches for the use in IoT devices.

In contrast to the classical implementation, Fig. 1b shows the recently proposed directional modulation intended for low complexity IoT devices [6]. The technique uses an array of spatially distributed antennas, where only a single antenna is active at each time. The spatial distribution of antennas provides a phase variation, which is then corrected for the direction of legitimate receiver; therefore the legitimate receiver will always observe intended modulation point, regardless from which antenna it is transmitted. By contrast, an eavesdropper located at a different direction will observe different phase shift for different antennas, which makes proper interpretation of the demodulated symbol impossible.

Since only one antenna is active at a time, there are no coupling issues, and the antennas can be spaced within area of arbitrary size – although understandably larger separation provides a more directionally selective behavior. Fig. 2 provides theoretical analysis assuming 5 source points with ideal omnidirectional radiation patterns. The sources are scattered uniformly over a circle of different diameters: 1 λ, 0.5 λ and 0.2 λ. The modulation used is QPSK with Signal-to-Noise Ratio SNR = 12 dB, while the legitimate receiver is assumed to be at $\phi = 90°$. Each simulation calculated 10^5 symbols. Demodulation was performed by calculating distance to the nearest symbol within phase-corrected constellation.

III. Compact Beamforming Antennas

The investigated compact beamforming antennas are multimodal and multiport antennas, which do not require spacing between their radiating elements to provide reconfigurable beamforming. The beamforming is executed by superposition of different modes within antenna. A convenient solution is to use antennas generating different omnidirectional patterns with phase variation across the horizontal plane, as it allows easy and predictable beamforming by controlling phase shift at each port [7]. Antennas of this type have been proposed for spherical-mode inspired directional modulation [8], with a miniaturized wearable version to be used in a smart watch [9]. However, all those work report results of the classical directional modulation, i.e. by simultaneously exciting multiple ports.

Fig. 2 shows the theoretical prediction of Bite Error Rate (BER) for the 5-modal antenna comparable to [8] when implementing the single RF directional modulation as

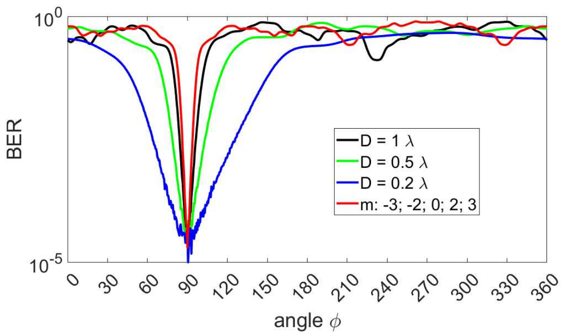

Fig. 2. Theoretical BER performance of the single RF chain with different antennas discussed in the paper.

proposed in [6]. The results were obtained by using idealized radiation pattern for mode *m* calculated as:

$$P_m = exp(\,-j\ m\ \phi\,) \qquad (1)$$

where $m \in \{-3; -2; 0; 2; 3\}$. The approximate size of the design to excite the above modes is ~ 0.5 λ. Please note that the spherical mode $m = \pm 1$ does not produce omnidirectional radiation pattern and as such is not included in the analysis.

It can be seen that spherical modes offer a very good spatial resolution. The resolution is not directly dependent on antenna size, but on the number of modes that can be effectively excited. Excitation of larger number of modes from a relatively small volume will result in significantly reduced bandwidth and losses [10] – thus providing indirect link between size and resolution. Those issues may be partially resolved by using non-Foster matching techniques.

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