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Directional Modulation for Compact Devices

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Directional Modulation for Compact Devices

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Abstract— **A new directional modulation system which uses radiation pattern data for modulation encoding is proposed. The approach allows compact multiport antennas (e.g. MIMO capable antennas) to be used for directional modulation, replacing extensive arrays. The modulation weighting coefficients are calculated with a fixed, antenna specific equation, thus reducing computational complexity. The solution is intended to enhance privacy in small, battery-operated wireless devices, required for "Internet of Things" applications.**

Index Terms—smart antenna, directional modulation, physical layer security, Internet of Things

I. INTRODUCTION

T HE forthcoming implementation of "Smart Cities" and "Internet of Things" (IoT) will see proliferation of wireless connections to sensors and daily-use devices. Consequently, highly sensitive personal data will be present in the open wireless medium. Even partial interception of such data may lead to devastating consequences for individuals or even societies, opening-up multiple abuse possibilities. Thus the need for secure communication is greater than before. However many IoT implementations face physical constraints due to the need for small, cost efficient modules, limited by battery performance and low computational power. Due to necessity, some manufacturers attempt to use unsecure bespoke or customized protocols, while others strip standard protocols from certain safety features [1] – both methods resulting in vulnerable communications.

To provide strong security, good cryptography protocols are required. However the proposed use of radio hardware can provide an additional layer of privacy, capable of impeding data interception. One technique investigated for this purpose is Directional Modulation (DM) [2-6], which in its most common implementation requires a large and bulky antenna array with a complex weighting system. Some simplification was proposed by Tao Hong et al. in [6], where a two-antenna system is used with antenna ports connected directly to the I and Q outputs of the standard QAM transceiver. Although the solution is cost- and power-efficient, it still requires an antenna array with a certain spacing to transmit the signal.

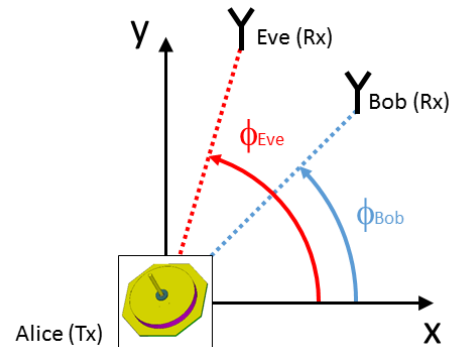In [7] a compact antenna was proposed for 360° beamsteering. To allow this functionality, the antenna

Fig. 1. Coordinate system used throughout the paper. Alice (transmitter) uses antenna proposed in [7], while Bob and Eve may use any antenna.

introduces a spatial variation of its radiation pattern phase, i.e. a signal sent in the ϕ direction has a phase shift roughly proportional to 2ϕ. This not only allows a beam steering capability, but combined with a linear array offers more flexibility to shape the desired pattern [8].

This paper demonstrates the first implementation of DM with a compact antenna. Unlike other approaches, it relies on a newly proposed antenna with a phase variation across its main beam (in this example an omnidirectional pattern) and uses the complex radiation pattern data for the DM coding. Distinct from previous works, the weights for directional modulation are calculated based on complex radiation patterns of the antenna. This allows a substantial size reduction and consequently operation from a spatially limited platform. Although the technique can be also implemented for larger arrays, it is intended as a compact and simple low-cost solution for enhanced privacy in future "Internet of Things" wireless communication that is power efficient, requiring little computational complexity and small antenna size. The proposed solution is the first that allows DM without the need for a large antenna array.

It should be noted that the proposed work demonstrates a different concept to [5], which uses only a simple phase shifter to control the direction of DM, without considering the antenna radiation patterns. Incorporation of the radiation patterns into the modulation technique provides a more generic solution, more robust to manufacturing inaccuracies, offers more precise control of the direction ϕ_{Bob} and allows the use of amplitude variations, in addition to phase, to scramble the modulation

plane.

Throughout the paper we will use terminology and the coordinate system as shown in Fig. 1. In the center of the coordinate system there is a transmitter which uses the proposed DM scheme with a switchless reconfigurable antenna [7]. This transmitter will be denoted as Alice. The intended recipient of the message will be denoted as Bob and is located at an angle ϕ_{Bob} with respect to Alice. The eavesdropper will be denoted as Eve and is located at ϕ_{Eve} with respect to Alice. There are no limitations imposed on the antennas used by either Bob or Eve.
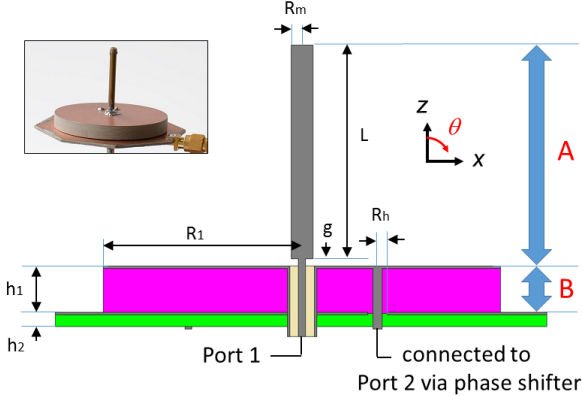

Fig. 2. Antenna used for the proposed directional modulation.

II. Antenna

The antenna used for the proposed technique is depicted in Fig 2. It comprises of two radiators, denoted as A and B. The top-most (A) is a standard quarter-wavelength monopole, connected via a semi-rigid coaxial line to port 1. Below (B) is located a dielectric-loaded patch, operating with two orthogonal TM_{21} modes excited with 90° phase shift. This generates a rotating electric field, producing phase variation of the radiation pattern (seen in Fig. 3b). The antenna is discussed in more detail in [7].

The antenna was manufactured and measured. The S_{11} in the 2.5 GHz band is -12 dB for port 1 and -17 dB for port 3, with isolation better than 18 dB [7]. The phase and amplitude radiation patterns in the xz-plane (dominant horizontal polarization) are shown in Fig 3. It can be seen, that while the monopole A generates a signal with constant phase-shift around 0°, part B produces a signal with a phase linearly dependent on the angle ϕ. This property is a key feature which allows large arrays to be replaced by a small antenna structure in DM applications. In general, the proposed technique is expected to be effective with any two antenna types, which exhibit sufficient phase variation between their radiation patterns.

The antenna dimensions are: L = 28 mm; R_m = 1.5 mm; R_1 = 26 mm; g = 2 mm; h_1 = 6 mm; h_2 = 1.5 mm; R_h = 2 mm.

III. Directional modulation

Unlike previous work, the proposed technique combines the antenna properties with a modulation scheme to execute simple DM without the need for computationally complex optimization. If the intended recipient (Bob) is located in the direction ϕ_{Bob}, the DM might be realized by exciting the antenna
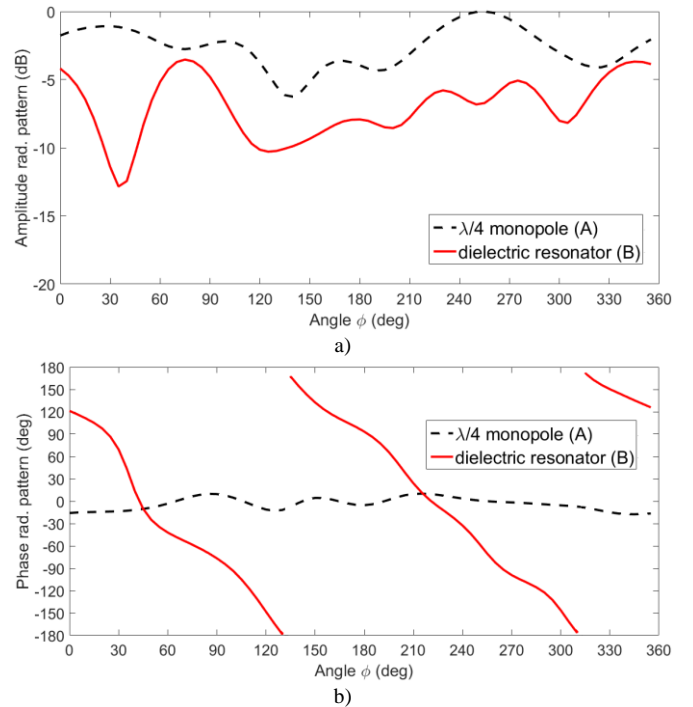

Fig. 3. Measured radiation patterns of the proposed antenna in xz-plane (θ = 90°) at 2.5 GHz, vertical polarization: a) amplitude; b) phase.

ports 1 and 2 respectively with signals Tx_1 and Tx_2 defined as follows:

$$Tx_1 = \frac{\text{Re}(\vec{m})}{G_A(\phi_{Bob})} \tag{1a}$$

$$Tx_2 = \frac{j\,\text{Im}(\vec{m})}{G_B(\phi_{Bob})} \tag{1b}$$

where $\vec{m}$ is a complex modulation vector and $G_A(\phi)$, $G_B(\phi)$ are complex (i.e. including phase delay) radiation patterns generated by the A and B elements respectively, as shown in Fig. 3. Please note, that in order to perform the proposed scheme the antenna has to be well characterized in an anechoic chamber – at least with respect to the plane, where the DM should occur.

The physical meaning of (1) is that the in-phase component of the original modulation vector is transmitted solely by the $\lambda/4$ monopole (A), while the quadrature component of the original vector is transmitted solely by the dielectric-loaded patch (B). Due to the components $G_A(\phi_{Bob})$ and $G_B(\phi_{Bob})$ in (1), the modulation constellation will be seen unobstructed at ϕ_{Bob} while scrambled elsewhere. This also necessitates that every change in ϕ_{Bob} will yield change in the modulation scheme used.

Fig 4 illustrates the modulation vector trajectories on the complex modulation plane as a function of ϕ_{Eve} for 8-PSK. Four exemplary values of ϕ_{Bob} were used. It can be seen, that although the general performance is similar, there are indeed some variations with different ϕ_{Bob} values.

The 8-PSK modulation is chosen, because two points (i.e. on I axis) are transmitted solely by the $\lambda/4$ monopole, two points (i.e. on Q axis) are transmitted solely be the dielectric-loaded patch and the four remaining are transmitted with a
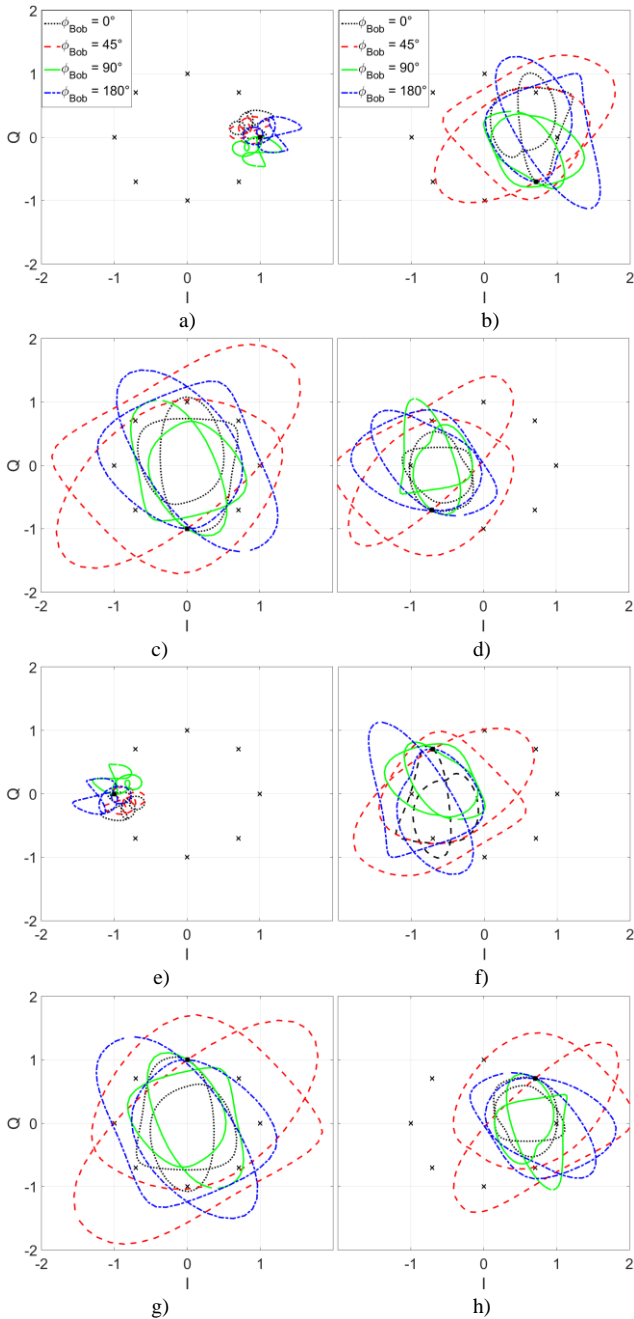
Fig. 4. Trajectories of modulation points in 8-PSK as a function of angle φ: a) phase 0°; b) phase -45°; c) phase -90°; d) phase -135°; e) phase 180°; f) phase 135°; g) phase 90°; h) phase 45°.

superposition of both antennas. It can be seen, that as expected from Fig. 2, the points with phase 0° and 180° are almost constant, while -90° and +90° scribe a full circle due to the phase variation of the radiation pattern.

IV. RESULTS

To demonstrate the proposed concept, a BER for four modulation configurations was calculated for various ϕ_{Bob} directions. The calculation was performed in Matlab and is based on real data, as measured in the spherical near-field anechoic chamber. The calculation assumes the strict condition, that Eve has full knowledge of the system, including the antenna orientation and radiation patterns. On the contrary, it is

assumed that Bob has no knowledge of the DM system or antenna involved and expects to receive standard 4-PSK or 8-PSK modulation.

A. 4-PSK Modulation

The proposed system was firstly tested with a 4-PSK modulation and a 12 dB Signal to Noise Ratio (SNR), where all four points are transmitted as a superposition of both radiators. This corresponds to the ϕ-dependent trajectories seen in Figs. 3b), 3d), 3f) and 3h).

Since Bob has no information on the patterns G_A and G_B which are used to modulate the signal in (1), his BER is calculated with respect to the idealized 4-PSK constellation. On the contrary, for Eve we assume the worst possible scenario that she obtained the complex radiation patterns G_A and G_B, thus
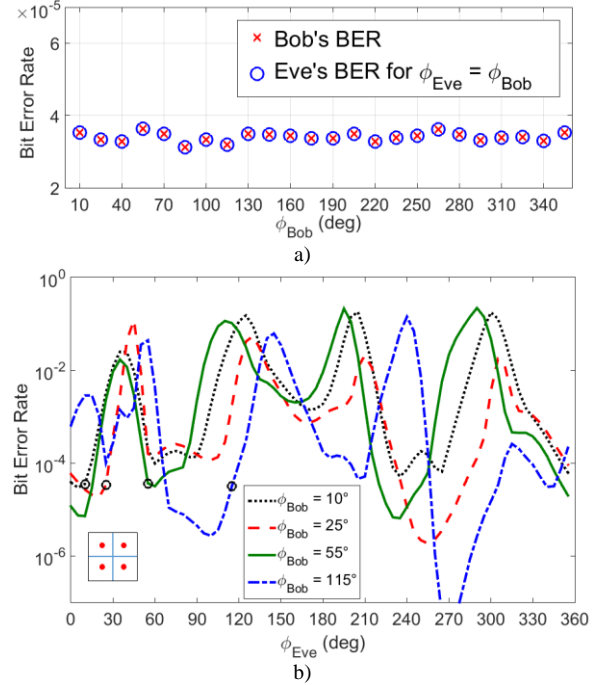

Fig. 5. Bit error rate for the simple 4-PSK modulation: a) BER for Bob vs. Eve when $\phi_{Eve} = \phi_{Bob}$; b) Eve's BER as a function of direction ϕ_{Eve} in four exemplary ϕ_{Bob} cases.

possesses full system knowledge and can partially compensate for the scrambling of the modulation points. Consequently, when $\phi_{Bob} = \phi_{Eve}$ the BER seen by Bob can be only as good or worse than that seen by Eve. This is a generally known limitation of all currently available DM implementations, although there are some mitigation research efforts [3].

Fig. 5a shows the BER for 24 different configurations, each generated for different directions ϕ_{Bob} in 15° steps. The figure compares Bob and Eve's BER for the worst possible case when $\phi_{Bob} = \phi_{Eve}$ (i.e. Bob and Eve are located in the same direction). The BER for Eve is quite low, as the DM − in its core concept − does not distinguish between function of devices, but only their angular orientation with respect to transmitter. However BER for Bob can be seen equally low, despite Bob missing data required to calculate (1). This allows good communication, as for all configuration BER is consistently better than 10^{-4}.

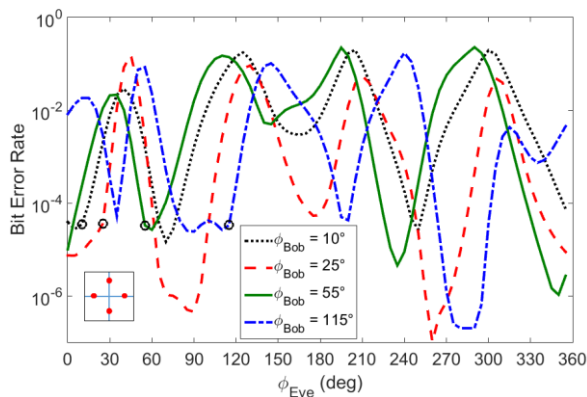Fig 5b demonstrates the BER patterns for Eve, when ϕ_{Bob} is

Fig. 6. Eve's BER for the 45°constellation rotated 4-PSK modulation: as a function of direction ϕ_{Eve} in four exemplary ϕ_{Bob} cases.

constant (shown for four exemplary values) and ϕ_{Eve} varies. Although only 4 exemplary configurations of ϕ_{Bob} are shown, they are representative for all 24 configurations generated (results not shown for clarity). Due to the assumption that Eve has full system information, the BER values correspond to the worst possible scenario. On each curve, the ϕ_{Bob} is marked by a black circle. It can be seen, that once the ϕ_{Eve} departs from ϕ_{Bob} the BER for Eve increases rapidly. An undesired minimum in BER-pattern can be seen when ϕ_{Eve} is approximately a multiplication of 90° from ϕ_{Bob}. This is due to the symmetry in this particular antenna design [7] and consequently in the radiation pattern (see Fig. 3).Due to manufacturing inaccuracies however some minima might be deeper than others. Please note however, that a similar problem will occur with classical DM using an antenna array with omnidirectional antennas. For the latter case, the undesired minima will be mirrored with respect to the array plane.

Fig. 6 demonstrates the proposed scheme when the 4-PSK modulation is rotated by 45° in the modulation plane, i.e. original modulation vectors are located on the I/Q axes. Although having the same information content as standard 4-PSK, the scheme might offer some benefits for the design of RF-frontends, as each symbol is transmitted solely by a single radiator. For all cases Bob's BER is kept below 10^{-4} and the overall performance is comparable with the results shown in Fig. 5. The proposed scheme offers comparable performance as other reported works, which however use large antenna arrays: [2] reports BER below 10^{-4} with 12 dB SNR and 4 element array
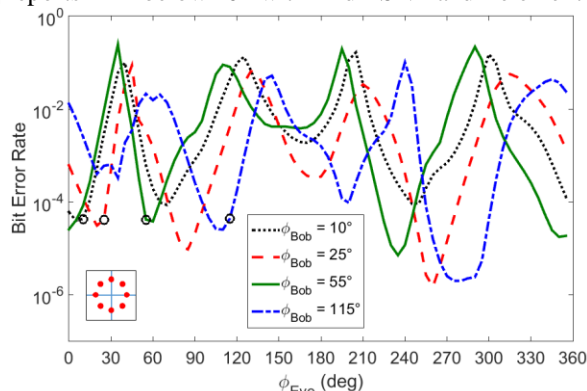
of total size 2λ; [3] reports BER below 10^{-5} with 17 dB SNR and 7 element array of total size 3.5λ; [6] reports BER below 10^{-3} with 8 dB SNR and the antenna's size is at least 1.5λ.

B. 8-PSK Modulation

Fig. 7 shows results for 8-PSK modulation. For this scenario, the SNR level had to be increased to 17 dB in order to achieve a comparable BER around 10^{-4}. With minor variations the same BER pattern as the previous cases can be seen, i.e. similar to 4-PSK modulation with 12 dB SNR. This demonstrates, that for channels with better SNR values, one can still maintain comparable privacy levels by using a more information-dense modulation scheme. This additionally increases the communication speed and can be especially useful for future implementations of adaptive OFDM schemes.

V. CONCLUSION

The paper proposes a directional modulation scheme, which for the first time uses a compact antenna rather than an extensive array. This is achieved by calculating the weighting scheme using a-priori known complex radiation patterns and an antenna with a sufficiently variable pattern, i.e. with a phase variation across the antenna beam. This enables DM schemes from spatially-constrained platforms, e.g. wireless sensor nodes or future antennas integrated into Internet of Things. It is demonstrated, that information-dense modulation schemes can be used without compromising privacy.

The proposed system is compact and simple, and is expected to only marginally increase the transceiver cost. The solution is considered as a promising candidate to increase privacy for radios operating from small platforms, as required in many "Internet of Things" applications.

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Fig. 7. Eve's BER for the 8-PSK modulation as a function of direction ϕ_{Eve} in four exemplary ϕ_{Bob} cases.