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# Energy Efficient Dynamic Directional Modulation with Electrically Small Antennas

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***Abstract*—This letter proposes a compact and energy efficient Directional Modulation (DM) scheme for small and power constrained devices (e.g. Internet of Things wireless sensors). The scheme uses a uniform circular array of monopole antennas, with a single radiofrequency (RF) chain and antenna active at a time. The antennas can be located in close proximity, offering significant size reduction. Furthermore, the scheme was demonstrated to operate successfully with an array of 0.6 λ diameter. The system does not generate additional artificial noise, limiting interference to other systems. Finally, the antenna switching sequence can be randomly generated and without fine-tuned synchronization with the transmitter.**

***Index Terms* — Electrically small antennas, Directional modulation, PHY-layer security, Internet of Things, IoT**

## I. INTRODUCTION

PHYSICAL LAYER SECURITY is an area of growing interest in modern wireless communications, as it offers increased secrecy and privacy of genuinely open radio transmissions. This solution is of special interest for small platforms, such as Internet of Thing (IoT) devices or Wireless Sensor Networks, where the compactness of the platform and power consumption constraints limit the use of sophisticated state-of-the-art cryptography executed in higher layers of the telecommunication stack. Usually, the physical layer security is intended to complement the existing algorithms, not replace them [1].

A prominent example of such a physical layer security technique is Directional Modulation (DM). The technique first introduced in 2009 [2] uses a beamsteering capability to direct the intelligible modulation toward the desired direction, while scrambling the modulated constellation elsewhere. In [3] a vector-based approach to directional modulation was proposed. The technique interprets the constellation scrambling as an artificial noise that has a null in the direction of the legitimate receiver. It proposes a control of the beamwidth of the intelligible communication by increasing the power of the artificial noise being generated. However, in a real life scenario this may increase the interference level to other users.

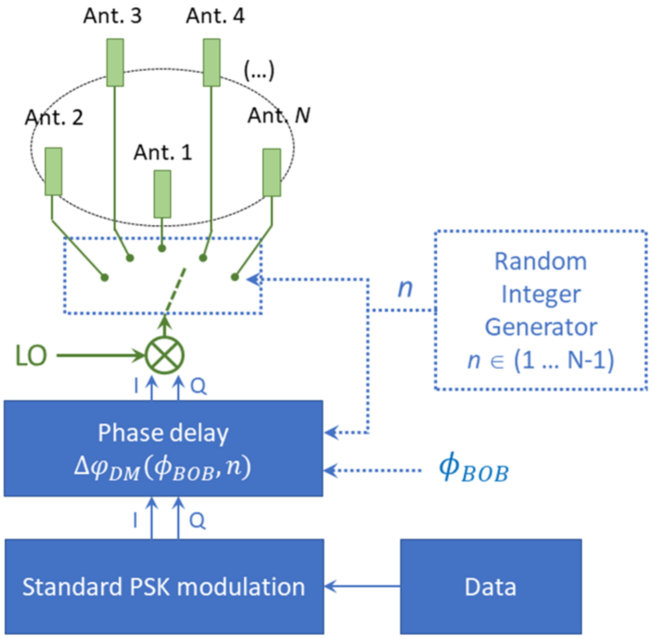

Fig. 1. Block diagram of the proposed DM scheme. Baseband digital components are in dark blue, RF components in light green.

Recently, multiple works proposed various functional improvements to directional modulation techniques [4 - 6]. Most of the works involved the use of antenna arrays with complex signal processing that is difficult to deploy with compact IoT devices. In [6] a zero-forcing technique was proposed to reduce the computational complexity of DM, however the solution still required a large antenna array. The use of DM with small antennas was studied in [7 – 8]. Even though both solutions succeeded in antenna miniaturization, they require individual amplitude and phase control over each port. This requires additional RF chains, which increases complexity and power consumption of the device. Recently [9] proposed the DM system with a single RF chain and time-modulated array, where a switching network generated vectors for antenna array excitations. However, the design of an appropriate switching sequence is a complicated process, requiring synchronization between switches [10] that may be challenging for simple IoT devices.

In this paper, we propose a simple DM scheme aimed for

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IoT devices. The scheme requires a single RF chain and by using an array of closely spaced antennas, it is capable to efficiently operate DM from apertures smaller than 1λ (i.e. 1 wavelength). The use of a single RF chain allows cost saving and improves energy efficiency over traditional DM systems with multiple RF chains [9]. It does not introduce additional artificial noise in undesired directions. The proposed solution relies on switches, with only a single antenna being active at any one time and no specific sequence is required. The switching sequence can be guided by a fully random process, independent of the operating frequency or the direction of the legitimate receiver.

Throughout this letter, the direction of the intended receiver is denoted as $\phi_{\mathrm{BOB}}$, which is a reference to the traditional terms Alice and Bob used in cryptography to denote respectively the transmitter and receiver of the encrypted message.

## II. PROPOSED SYSTEM

The proposed system is outlined in Fig. 1. It is comprised of multiple antennas, where only a single antenna is transmitting at a time with other antennas switched to open to avoid signal leakage. Unlike in time-modulated antenna arrays [10], the active antenna is chosen fully randomly and independently from the transmitted signal. This is executed by a Random Integer Generator, which operates independently from the data being modulated.

The data to be transmitted is first mapped to the control I/Q signals for any standard Phase Shift Keying (PSK) modulator; without loss of generality, this work uses QPSK as an example. The control signal is then corrected with an additional phase shift $\Delta\varphi_{DM}$ that is dependent on both the direction of legitimate receiver $\phi_{BOB}$ and the random number $n$ of the antenna being used to transmit given information. The correction phase shift can be described as:

$$\Delta\varphi_{DM}(\phi_{BOB}, n) = -phase\big(\,P_n(\phi_{BOB})\big) \tag{1}$$

where $P_n(\phi)$ is the radiation pattern of the $n$-th antenna. In this study a circular array is used, which offers 360° field of view in the horizontal plane. If the antennas' phase-centers are spread uniformly on a circle of diameter $D$, the phase delay from (1) can be approximated as:

$$\Delta\varphi_{DM}(\phi_{BOB}, n) = \; -\pi k D \; \mathrm{Re}\left(exp\left(2\pi j\left(\frac{n}{N} + \phi_{BOB}\right)\right)\right) \tag{2}$$

where $k = 2\pi/\lambda$ stands for the wavenumber.

Based on the above, the directional modulation is executed as follows: Firstly, the system establishes communication through a designated reference antenna, e.g. $n$ = 1. Once the handshake is over, the directionally modulated signal can be transmitted through any randomly selected antenna, except for the reference antenna. For increased privacy, a new random integer should be generated as often as practicable, which is equivalent to dynamic directional modulation. However, contrary to prior works, no synchronization is required, and the switching can be controlled independently from the transmission, e.g., by an external random number generator.

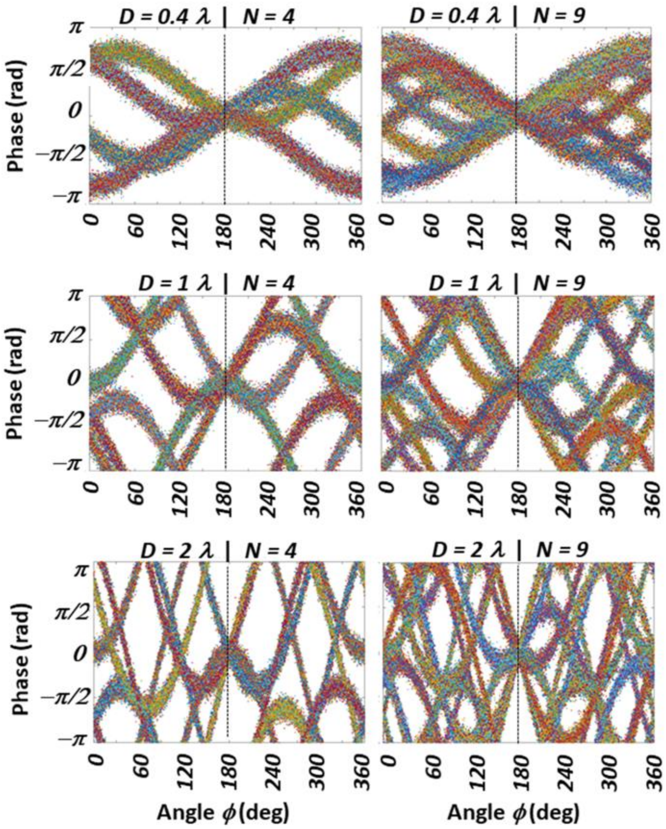

Fig. 2. Phase of the transmitted signal vs. direction $\phi$ for different diameters $D$ and number of antennas $N$. All plots show different instances of transmission of the same symbol '00' toward the direction $\phi_{BOB}$ = 180° (marked with a dashed vertical line).

Due to the different location of each antenna, the phase of the transmitted signal will have a different spatial distribution for each antenna. The phase shift calculated in (2) offers compensation for the phase variation when switching between antennas, however only in the direction $\phi_{\mathrm{BOB}}$. Any other direction will be impacted, observing random phase changes that are superimposed on the phase-modulated signal.

To illustrate the principle, Fig. 2 shows the phases of the transmitted signal in different directions, when communicating the same symbol '00', i.e., phase of 0°. It can be seen that for each case the phase always converges to the desired value at $\phi_{BOB}$ = 180°, while spreading into multiple possible values for any other direction. This ambiguity is designed to prevent the eavesdropper from correctly interpreting the received symbol. Similar to classical DM, for larger apertures (i.e., diameter $D$) we observe faster changes of the phase of the signal from the intelligible value, translating into a narrower and thus more secure beam. A larger number of antennas $N$ does not contribute to increased phase variation, as the aperture size remains constant. However, more antennas allow less repetitive phase changes.

## III. IDEAL ARRAY

The performance of the proposed scheme was calculated using QPSK modulation with Signal to Noise Ratio (SNR) of

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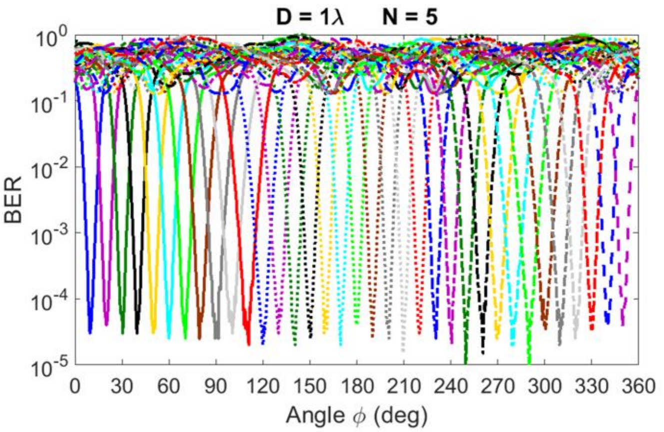


Fig. 3. BER calculations for different 'beams' of the proposed scheme, demonstrating that the directionally modulated transmission can be targeted to any direction of $\phi_{BOB}$ without leakage into undesired directions (example generated for ($N$ = 5, D = 1λ and $SNR$ = 12 dB).

12 dB (which is a typical SNR value for QPSK modulation). The eavesdropper demodulates the signal as follows: first the phase delay is adjusted, based on the open information intercepted from the handshake between the legitimate transmitter and receiver. Subsequently, it measures the closest distance between the received symbol and the adjusted reference constellation points.

Fig. 3 shows the Bit Error Rate (BER) for the proposed scheme using $N$ = 5 antennas and diameter $D$ = 1λ. A total of 35 different secure beams are generated, for the direction of $\phi_{BOB}$, varied from 10° to 350° in 10° steps. The proposed system is thus demonstrated to flexibly steer a secure beam in any direction, without sidelobes.

Fig. 4 shows the Bit Error Rates (BER) for $\phi_{BOB}$ = 90° and an array using $N = 5$ antennas. The diameter $D$ is varied between 0.2λ – 2λ. For the most compact case of $D$ = 0.2λ the beamwidth with BER < $10^{-1}$ is very wide, i.e., 114°. Despite this, it is the smallest antenna array reported to perform DM. Once the diameter increases, the larger aperture allows for greater directionality of the array factor. This can be observed as a more selective secure beamwidth, which narrows down dramatically to 40° with diameter $D$ = 0.6λ and 12° for $D$ = 2λ. The results were again obtained for SNR = 12 dB.

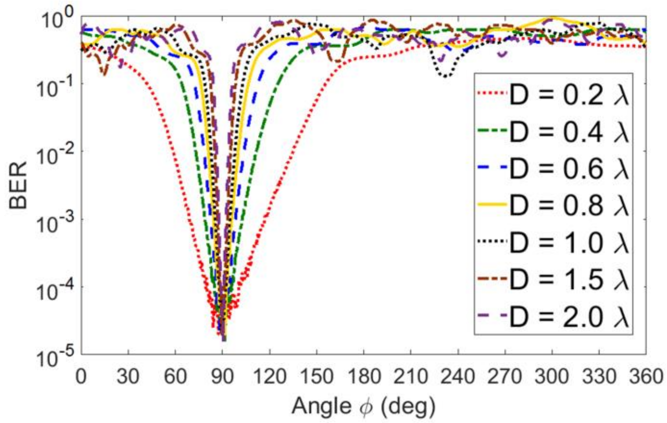


Fig. 4. BER calculations for the proposed scheme for different array diameter (D) for $N$ = 5, $SNR$ = 12 dB and $\phi_{BOB}$ = 90°.

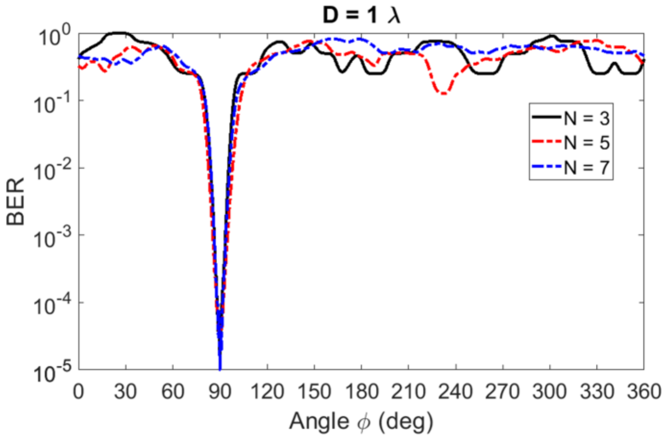
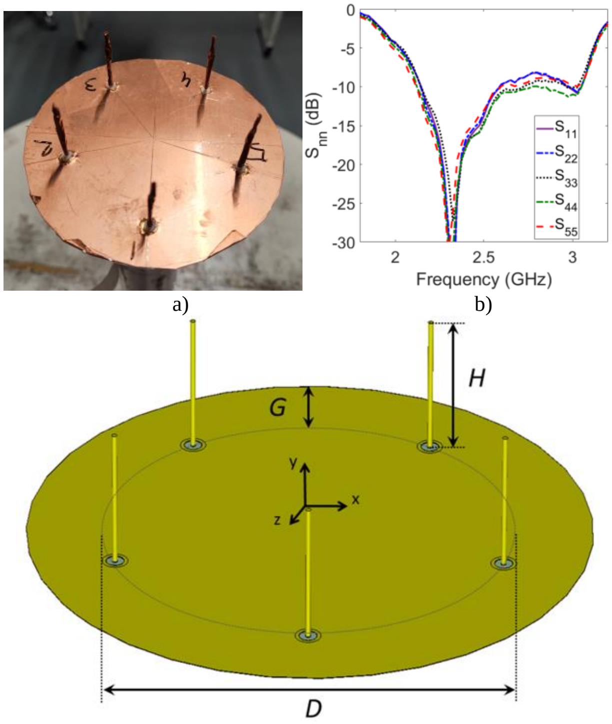


Fig. 5. BER calculations for the proposed scheme for different number of antennas ($N$) with $D$ = $1\lambda$, $SNR$ = 12 dB and $\phi_{BOB}$ = 90°.

Fig. 5 shows BER performance for the fixed diameter $D$ = 1λ and the number of antennas varied between 3, 5 and 7 (SNR = 12 dB and $\phi_{BOB}$ = 90°). Overall, the BER < $10^{-1}$ beamwidth does not change significantly with the number of antennas, once the aperture size is constant. This is in agreement with the theory of antenna arrays. There are no significant sidelobes visible, however for $N$ = 7 the overall BER is higher, with less variation than using smaller number of antennas.

## IV. EXPERIMENTAL VALIDATION

The performance of the system was experimentally validated using a circular antenna array operating at 2.4 GHz,

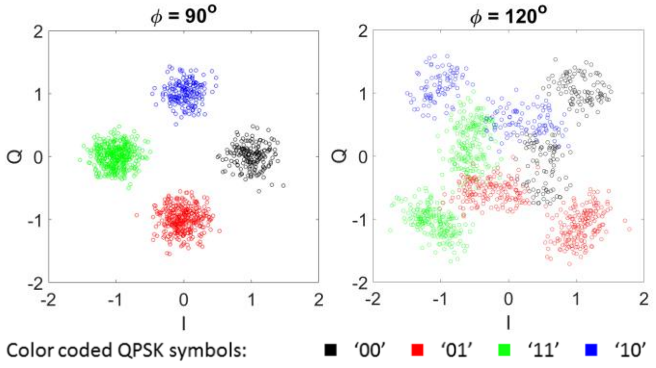


a) b)

c)

Fig. 6. Array used for experimental validation: a) photo of the manufactured antenna; b) measured reflection coefficients; c) drawing of the antenna with key dimensions.

shown in Fig. 6. The array has $N = 5$ antennas with diameter between antennas $D = 0.6\lambda = 76$ mm. This is considered to provide a good trade-off between the array's size and secure beamwidth. The antenna used is a standard λ/4 monopole with length $L = 28$ mm. All the antennas exhibit similar reflection coefficients of -15 dB at 2.4 GHz. Only a single antenna is active at a time, with the remaining ports being switched to open. This prevents any leakage between ports, even for antennas located very close to each other. The use of open is preferred over a matched load, as the latter introduces losses and could degrade radiation efficiency. To preserve uniform radiation pattern the array is surrounded by an additional ring of the copper groundplane, extending by $G = 15$ mm beyond the diameter $D$. The total antenna diameter including groundplane is thus 106 mm. All dimensions as shown in Fig. 6 are: $D = 76$ mm; $H = 28$ mm; $G = 15$ mm.



a) b)

Fig. 7. Visualization of the measured QPSK modulation for $\phi_{BOB} = 90°$ configuration: a) direction of the legitimate receiver $\phi = 90°$; b) $\phi = 120°$.

Fig. 7 visualizes two exemplary QPSK constellations generated with the above array, where different transmitted symbols are marked with different colors. Fig. 7a shows the direction of the legitimate receiver, i.e. $\phi = \phi_{BOB} = 90°$. For this direction a clear QPSK constellation is visible, with four clusters each consisting of the same transmitted symbol. On the contrary, for $\phi = 120°$ the four clusters are less distinct, with each cluster containing the mixture of all possible symbols. This makes it challenging for the eavesdropping receiver to correctly interpret transmitted symbol, thus deteriorating its BER.

Fig. 8 shows the performance of the proposed system including the effects of the antenna for 3 randomly picked values of $\phi_{\mathrm{BOB}}$. It can be seen that the direction of the beam is well aligned between experimental results and the theoretical prediction. For secure beamwidths with BER < $10^{-1}$, the theoretical predictions vary between 27° - 51°, whereas the measured results yield a narrower beamwidth of 24° - 25°. This improvement is most likely due to the small variations in the amplitude of the radiation pattern: the conductive structure of adjacent antennas reflects a fraction of the signal, causing ripples in the radiation pattern. Those ripples further disturb the modulation constellation and are smallest in directions where an antenna is located, hence for $\phi_{BOB} = 222°$ the agreement between theory and measurement is better than for $\phi_{BOB} = 90°$ or 300°.

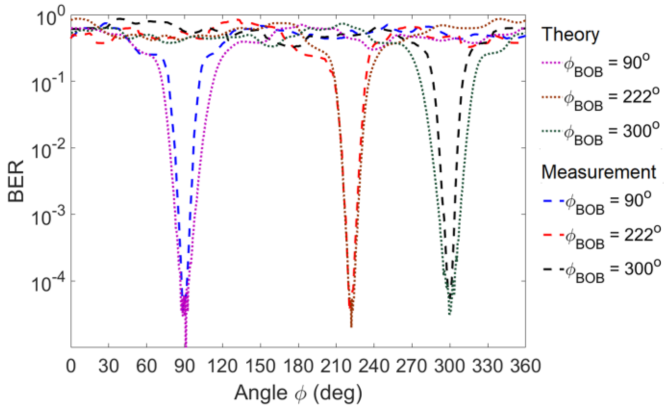


Fig. 8. BER calculations for theoretical (dotted lines) and measured results (dashed lines).

## V. CONCLUSION

This letter proposes a directional modulation scheme, that for the first time allows operation from a small platform with an aperture of 0.6λ or smaller. The scheme is intended to increase wireless communication privacy from simple devices that cannot avail of the benefits of computationally complex classical cryptography. This is achieved through the following innovative characteristics:

- Operation from a size constrained platform, making DM suitable for compact IoT devices.
- Simple architecture requiring a single RF chain, which results in reduced power consumption, complexity and cost.
- The system does not generate additional artificial noise, which may interfere with legitimate users of other systems.
- The switching sequence can be generated fully randomly and without fine-tuned synchronization with the transmitter, which simplifies the electronics used and makes the design more robust.

Overall, the above characteristics can make the proposed system a key enabling technology for future Internet of Things systems, introducing privacy in the communication between simple and compact nodes.

## REFERENCES

[1] Y. Liu, H. Chen and L. Wang, "Physical Layer Security for Next Generation Wireless Networks: Theories, Technologies, and Challenges," *IEEE Comm. Surveys & Tutorials*, vol. 19, no. 1, pp. 347-376, Q1 2017.

[2] M. P. Daly and J. T. Bernhard, "Directional Modulation Technique for Phased Arrays", *IEEE Trans. Antennas Propag.*, vol. 57, no. 9, pp. 2633-40, 2009.

[3] Y. Ding and V. F. Fusco, "A Vector Approach for the Analysis and Synthesis of Directional Modulation Transmitters", *IEEE Trans. Antennas Propag.*, vol. 62, no. 1, pp. 361-70, Jan. 2014.

[4] Y. Ding, V. Fusco, J. Zhang and W.-Q. Wang, "Time-Modulated OFDM Directional Modulation Transmitters", *IEEE Trans. Vehicular Tech.*, vol. 68, no. 8, pp. 8249-8253, Aug. 2019.

[5] E. A. Cabrera-Hernández, J. P. Granados and A. Tennant, "Multichannel Dynamic Directional Modulation with Software Defined Radio," In Proc.: *14th European Conference on Antennas and Propagation (EuCAP)*, Copenhagen, Denmark, 15-20 March 2020.

[6] T. Xie, J. Zhu and Y. Li, "Artificial-Noise-Aided Zero-Forcing Synthesis Approach for Secure Multi-Beam Directional Modulation," *IEEE Comm. Lett.*, vol. 22, no. 2, pp. 276-279, Feb. 2018.

[7] A. Narbudowicz, M. J. Ammann and D. Heberling, "Directional Modulation for Compact Devices," *IEEE Antennas Wirel. Propag. Lett.*, vol. 16, pp. 2094-2097, 2017

[8] J. Parron, E. A. Cabrera-Hernandez, A. Tennant and P. de Paco, "Multiport Compact Stacked Patch Antenna With 360° Beam Steering for Generating Dynamic Directional Modulation," *IEEE Trans. Antennas Propag.*, vol. 69, no. 2, pp. 1162-1167, Feb. 2021

[9] G. Huang, Y. Ding and S. Ouyang, "Multicarrier Directional Modulation Symbol Synthesis Using Time-Modulated Phased Arrays," *IEEE Antennas Wirel. Propag. Lett.*, vol. 20, no. 4, pp. 567-571, April 2021

[10] G. Bogdan, K. Godziszewski, Y. Yashchyshyn, C. H. Kim and S. -B. Hyun, "Time-Modulated Antenna Array for Real-Time Adaptation in Wideband Wireless Systems—Part I: Design and Characterization," *IEEE Trans. Antennas Propag.*, vol. 68, no. 10, pp. 6964-6972, Oct. 2020.