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Directional Modulation Enhanced Retrodirective Array

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Unlike the mathematical techniques adopted in the classical cryptographic technology at the higher protocol layers it is shown that characteristics intrinsic to the physical layer can be exploited to secure useful information. In this paper we show that a retrodirective array, RDA, can be made to operate more securely by borrowing directional modulation, DM, concepts. The new approach provided in this paper allows DM to operate in a multipath environment. Previously DM systems could only operate in free-space.

Introduction: The lack of a physical boundary surrounding wireless transmission makes confidential information that is transmitted wirelessly vulnerable to interception [1]. Key-based cryptographic technologies inserted at the higher protocol layers are currently used to secure data transmission. However these algorithms may eventually be compromised through massive computational breakthrough. In order to gain fundamental level security, i.e., information theoretical security, [2], encryption has to be performed at the physical-layer at the point where the interchange between bits of information and modulated signals takes place.

A retrodirective antenna array (RDA) has the property of retransmitting a signal back along the path along which a co-frequency pilot tone signal was incident irrespective of spatial and/or temporal variations in the propagation path [3]. It is shown in Section II that by combining directional modulation (DM) spatial scrambling techniques, defined in [4] and [5], with RDA methods that an additional dynamic factor is introduced which enable secure communications in static multipath environments while preserving static as well as free space wireless channel secure performance. This is beyond what can be achieved by conventional RDA systems, dynamic multipath only, and DM systems, free space only. This DM enabled RDA configuration is validated by two simplified static multipath wireless channel models in Section III. Conclusions are drawn in Section IV.

Directional Modulation (DM) Enhanced Retrodirective Array (RDA): With regard to the secrecy performance, it has been previously shown that the RDA works best in dynamic multipath-rich environments [3], [6]. In order to extend RDA application to a static multipath wireless channel scenario, we show how the DM concept, [4], [5], can be borrowed to enable and enhance physical layer secrecy performance.

In order to apply the DM technique onto the RDA method we proceed as follows:

The normalised channel vector between a RDA and the intended receiver is denoted as $\boldsymbol{H}$, of which each entry is the conjugated pilot tone signal detected by each antenna in the RDA, subject to an identical scaling factor for power normalisation. The pilot tone is transmitted from a place where the intended legitimate receiver is located. Similar to the orthogonal vector concept proposed in [5] for DM, orthogonal vectors, $\boldsymbol{W}_{ov}$, can be generated in the null space of the conjugated channel vector, $\boldsymbol{H}^*$, '[ ]*' refers to the vector conjugation operator.

After the orthogonal vectors are generated, they can be combined with the phase conjugation output of a conventional RDA, i.e., $\boldsymbol{H}$.

$$D_m\boldsymbol{H}^\dagger(\boldsymbol{H}+\boldsymbol{W}_{ov}) = D_m(\boldsymbol{H}^\dagger\boldsymbol{H}+\boldsymbol{H}^\dagger\boldsymbol{W}_{ov}) = D_m||\boldsymbol{H}||^2 \qquad (1)$$

In (1) it is noted that the transmitted information data, D_m for the m^{th} symbol, can be recovered by a receiver positioned at the pilot tone location, since detected signals at this location are unaffected by the artificially injected vector $\boldsymbol{W}_{ov}$, i.e., $\boldsymbol{H}^\dagger\boldsymbol{W}_{ov} = 0$, operator '[ ]†' denotes complex conjugate transpose (Hermitian). However, for receivers at other positions, the channel vector $\boldsymbol{H}$ becomes $\boldsymbol{G}$, and $\boldsymbol{W}_{ov}$ and $\boldsymbol{G}^*$ are not orthogonal, $\boldsymbol{G}^\dagger\boldsymbol{W}_{ov} \neq 0$. Thus the detected signals S_m are additionally corrupted by this artificially injected interference $\boldsymbol{W}_{ov}$ at locations away from the pilot tone location, see (2).

$$S_m = D_m\boldsymbol{G}^\dagger(\boldsymbol{H}+\boldsymbol{W}_{ov}) = D_m(\boldsymbol{G}^\dagger\boldsymbol{H}+\boldsymbol{G}^\dagger\boldsymbol{W}_{ov}) \qquad (2)$$

DM Enhanced RDA Example Simulations: In this section the operation of DM enabled RDAs in static multipath environment is illustrated via two examples. The first one uses a simplified two-ray model shown in Fig. 1. An interrogating receiver is positioned along the boresight (θ_1 = 90°) of an N-by-1 uniformly half wavelength, $\lambda/2$, spaced RDA, at a distance of 100λ, and N is set to 7. An ideal electromagnetic reflector of infinite size is placed perpendicular to the RDA. Its purpose is to reflect a portion of the co-frequency pilot tone radiated from the intended receiver location towards the RDA which in the example here is at an incident angle of θ_2 = 150°. The phase centre of the RDA is chosen as its geometric centre, i.e., the 4th array element, without loss of generality the radiation pattern of each antenna in the array is assumed to be identical and isotropic.

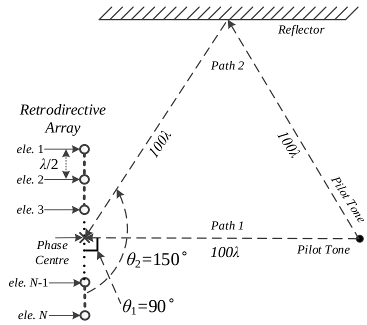


Fig. 1 *Two-ray model of an N-by-1 RDA.*

Following design principles described in the last section, a DM enabled RDA, based on the two-ray model in Fig. 1, is constructed for Gray-coded QPSK transmission. The far-field radiation patterns at a distance of 100λ to the RDA for each QPSK symbol are presented in Fig. 2. In this example the DM power efficiency (PE_{DM}), which describes what percentage of total radiated energy is utilized for useful information transmission, defined as (25) in [6], is held at 50%. It can be seen in Fig. 2 that only at the pilot tone location the magnitudes of the four QPSK symbols overlap each other, and their phases are 90° spaced, indicating that a standard QPSK constellation is formed. The constellation patterns detected in all other locations are distorted, an

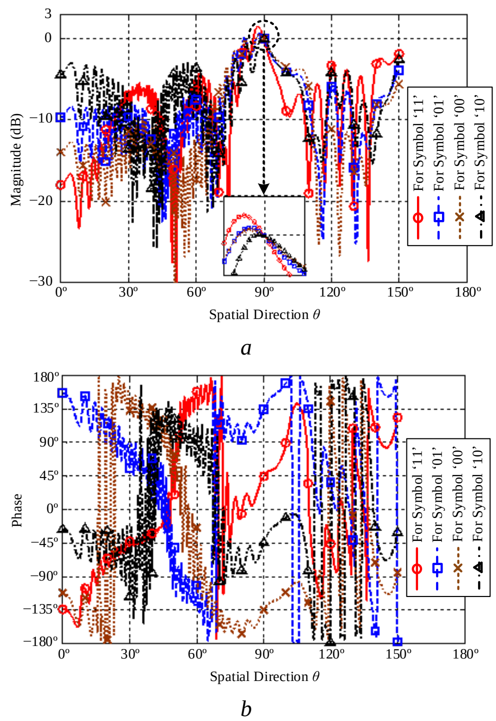


Fig. 2 *Normalized electric field at a distance of 100λ to the RDA along spatial directions from 0° to 150° for each unique QPSK symbol transmitted.*

a Normalised magnitude patterns

b Phase patterns

aspect that cannot be achieved by a conventional RDA in a purely static multipath wireless channel.

In order to further investigate the performance advantage a multipath-rich environment illustrated in Fig. 3 is considered. In this example a one dimensional 7-element RDA with $\lambda/2$ spacing, operating at 2.4 GHz, is placed in a 2.5×2.5×2.5 m^3 metal cube, and a 1.5×1.5 m^2 square metal wall is inserted between the RDA and the intended receiver to prevent line-of-sight transmission, Fig. 3. We use the wave propagation software WinProp version 11.06 [7] to generate the transmission coefficients between each transmit antenna element and each point in the two dimensional (2-D) 1×2.5 m^2 simulation area consisting of 160×64 pixels. We assume that pixel (80, 32) represents the intended receiver location. The 7 metallic plates, i.e., 6 sides of the cube and one metallic wall in the cube, have a thickness of 5 *mm*, and their reflection loss is 0.05 dB, and diffraction loss is between 8 to 15 dB. In the simulation up to 100 rays with largest energy between each transmit antenna and each pixel in the simulation area are calculated, and then summed to get the transmission coefficients.

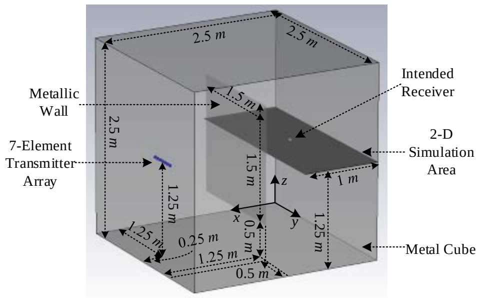
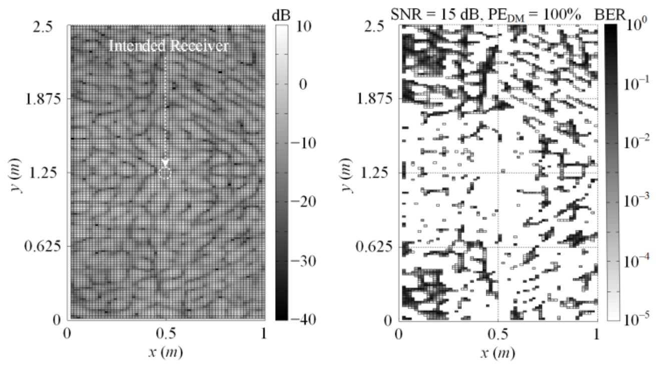


Fig. 3 *Metal shielded cube model for multipath-rich wireless transmission.*

With the obtained transmission coefficients the simulated electric fields radiated by the conventional RDA in the 2-D simulation area are depicted in Fig. 4a. The field at the intended receiver location is normalized to 0 dB. From Fig. 4a it is observed that a large portion of the space in the plane of the receiver has field power larger than 0 dB, and in this static multipath environment information recovery is unimpaired. This is validated by bit error rate (BER) simulations when 10^6 random Gray-coded QPSK symbols are transmitted through this conventional RDA system, see Fig. 4b, the details of the BER calculation method can be found in [4]. Here the signal to noise ratio (SNR) at the intended receiver location is set to 15 dB, and the AWGN contribution is identical over the entire simulated area.

However when the DM functionality is enabled by randomly updating the $\boldsymbol{W}_{ov}$ vector on a per symbol transmitted basis the error free areas are significantly reduced, while the signals detected at the intended receiver location are unaffected, i.e., BER = 0, see Figs. 5a and 5b for different system PE_{DM}s. The remaining error free zones, other

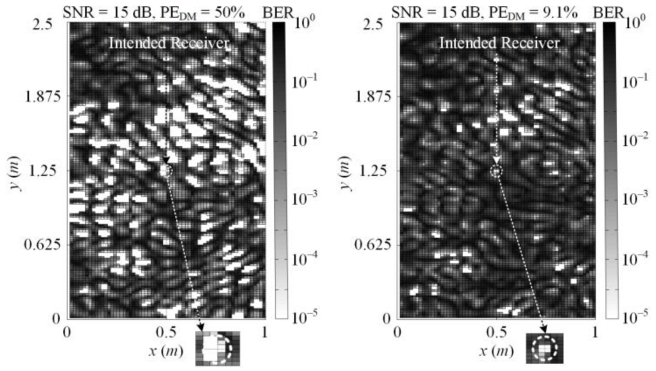


a *b*

Fig. 4 *Normalised Electric field and corresponding BER simulation results when SNR is set to 15 dB in conventional RDA system.*

a Normalized electric fields in the 2-D simulation area

b The corresponding BER simulation results when SNR is set to 15 dB at the intended receiver location



a *b*

Fig. 5 *BER simulation results in the 2-D simulation area in dynamic DM enabled RDA systems for various PE_{DM}s. SNR is set to 15 dB at the intended receiver location.*

a PE_{DM} = 50%

b PE_{DM} = 9.1%

than the intended receiver location, in Fig. 5 is because of high information power detected in these areas, concurrent with high correlation between ***H*** and ***G***, which makes artificial interference ineffectively injected. However it can still be concluded that the higher the injected interference power, namely the lower the PE_{DM}, the better the secure performance that the hybrid system can achieve.

Conclusion: In this paper two techniques, RDA (which adds physical layer security only in dynamic multipath environments) and DM (which adds physical layer security only in multipath free environments) were combined to result in a DM enhanced RDA system which operates under static as well as dynamic multipath wireless channel conditions. Example DM enabled RDA systems carrying QPSK were synthesized and their BER performance obtained. It is concluded that the hybrid system enables the decodable spatial areas to be reduced in such a fashion as to significantly lower the possibility of interception by eavesdroppers.

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References

1 Li, X., Hwu, J., Ratazzi, E.P.: 'Using antenna array redundancy and channel diversity for secure wireless transmissions', J. Commun., 2007, **2**, (3), pp. 24–32, doi: 10.4304/JCM.2.3.24-32

2 Bloch, M., Barros, J.: 'Physical-layer security from information theory to security engineering' (Cambridge, U.K.: Cambridge Univ. Press, Cambridge, UK, 2011)

3 Fusco, V., Buchanan, N.: 'Retrodirective antenna spatial data protection," IEEE Antennas Wireless Propag. Lett., 2009, **8**, pp. 490–493, doi: 10.1109/LAWP.2009.2021078

4 Ding, Y., Fusco, V.: 'Establishing metrics for assessing the performance of directional modulation systems," IEEE Trans. Antennas Propag., 2014, **62**, (5), pp. 2745–2755, doi: 10.1109/TAP.2014.2307318

5 Ding, Y., Fusco, V.: 'A vector approach for the analysis and synthesis of directional modulation transmitters', IEEE Trans. Antennas Propagat., 2014, **62**, (1), pp. 361–370, doi: 10.1109/TAP.2013.2287001

6 Buchanan, N., Fusco, V.: 'Bit error rate performance enhancement of a retrodirective array over a conventional fixed beam array in a dynamic multipath environment," IEEE Trans. Microw. Theory Tech., 2010, **58**, (4), pp. 757–763, doi: 10.1109/TMTT.2010.2041518

7 AWE Communications: 'WinProp release V 11.06', http://www.awe-communications.com, accessed August 2014