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Published in IET Microwaves, Antennas & Propagation
Received on 5th November 2012
Revised on 1st March 2013
Accepted on 17th March 2013
doi: 10.1049/iet-map.2012.0644

ISSN 1751-8725

Enhancing the security of communication via directly modulated antenna arrays

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Abstract: A new approach to enhance the security of data transmission using direction dependent antenna modulation based on an array with wide element spacing combined with directional array elements is presented. For illustrative purposes, the system investigated, and reported here, consists of an array of only two elements but the approach is general and can be extended to multi-element array systems. It is shown that by increasing the element spacing of an array the directional error rate characteristics of the system, in a given direction, can be significantly improved. Furthermore, the directly modulated system shows superior error rate performance to that of an equivalent, conventionally modulated, system in the grating lobe directions. The error rate characteristics of the proposed system are analysed for two scenarios: firstly when the angular separation between an eavesdropper and the intended recipient is small and secondly for the case when a potential eavesdropper is located much closer to the transmit antenna than the intended recipient.

1 Introduction

Direct antenna modulation (DAM) has been proposed as a potential method for enhancing the security of wireless communication systems [1–10]. In DAM, baseband data modulation is applied to the carrier signal by directly modifying the radiation characteristics of the transmit antenna. Such a system can be configured to exhibit signal modulation characteristics which are a function of transmission angle and this introduces an additional degree of complexity which makes signal demodulation by an eavesdropper a difficult task. The concept of directional antenna modulation was first introduced in [1, 2], which describe a system in which the transmit antenna is an array consisting of a single driven element and several, closely coupled, parasitic elements. By controlling the level of coupling between the driven and the parasitic elements, data modulation can be introduced at the element level in a process termed by the authors as near field DAM (NFDAM). A similar implementation of a NFDAM system operating at 2.45 GHz has also been reported [3] and a system based on a four element linear phased array is described in [4, 5]. In this paper, we present results which are a significant extension of the preliminary work reported in [7–9] and show how a simple two element DAM system can be configured for enhanced transmission security. We focus on array systems which utilise 2-bit phase control to provide DAM because of the relative simplicity and low cost required implementing such systems in hardware. The required quadrature phase control can be achieved using simple diode phase shifters [9] or by using hybrids or mixers as described in [10].

When considering the use of DAM as a method for providing a secure means of wireless data transmission the most important attribute of the technique is the angular dependence of the directly imposed modulation scheme with transmission direction. In basic terms, a DAM system transmits a signal with a known form of modulation to an intended recipient in a desired direction. The transmitted signal can then be successfully demodulated by a receiver with knowledge of the modulation scheme. As the transmit angle moves away from the intended direction, the form of the modulation imposed on the transmitted signal changes. Thus although the signal may be detectable, accurate demodulation becomes increasingly difficult. Although DAM can be utilised to provide a means of secure data transmission, there are limitations on the effectiveness of the approach. Two particular scenarios in which DAM may be vulnerable to successful demodulation by an eavesdropper are: first, if an eavesdropper is located at angles close to the intended transmission direction; second, if the eavesdropper is located away from boresight, but close to the transmitter so that the received SNR is much higher than that at the location of the intended recipient.

Hence the novelty of this contribution is to address the limitations of DAM in the two aforementioned scenarios. In particular we present new results to compare the performance of DAM to that of conventional baseband modulation when applied to an array system with element spacing of greater than a half wavelength and with directive elements.

2 System description and analysis

For illustrative purposes, consider a system based on a two element array of isotropic radiators in which each element is controlled by a 2-bit phase shifter, as described in [7–9]. Next assume that the antenna is configured to transmit information using symmetrical 8-ary phase shift keying (8-PSK) to an intended recipient located broadside to the array. Two scenarios are considered: first, conventional baseband data modulation is assumed to be applied to the carrier signal prior to being fed to the array. Second, baseband data are imparted onto the carrier by directly controlling the phase shift components of each array element. The constellation representing the 8-PSK used in both examples is shown in Fig. 1. For the DAM array system, each constellation point is generated by a pre-defined combination of element phase shifts as described in Table 1.

Next we model a simple communication system, in which the element spacing of the transmit DAM array is initially set at a half wavelength, and calculate the system error rate performance as a function of receive angle in the far-field of the array. For the simulations reported here, data corresponding to each of the 8-PSK states are transmitted with the addition of additive Gaussian white noise. The simulated received signals for both the conventional base-band modulation system and the DAM system are then demodulated according to a minimum distance decoding algorithm in which a received constellation point is compared with a known set of expected constellation points and a demodulation decision is made on the proximity of a received signal to a reference data set [4, 11]. In order to generate a representative system performance the symbol error rate (SER) data are calculated from approximately 10^6 individual simulations for each detection angle and at a given signal (symbol) to noise ratio (E_s/N_0). In order to make a valid comparison between conventional base-band modulation and the DAM system both schemes adhere to the 8-PSK modulation illustrated by the constellation diagram shown in Fig. 1.

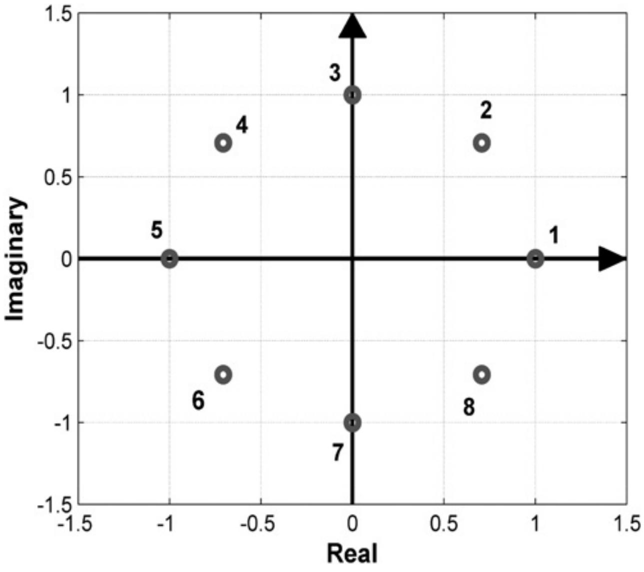

Fig. 1 *8-PSK signal constellation transmitted in the direction of the intended recipient for both a conventional and a DAM array*

Table 1 Element phase shift of the array

Constellation point	Phase shift of element 1	Phase shift of element 2
1	22.5°	−22.5°
2	22.5°	67.5°
3	112.5°	67.5°
4	112.5°	157.5°
5	−157.5°	157.5°
6	−157.5°	−112.5°
7	−67.5°	−112.5°
8	−67.5°	−22.5°

The SERs of conventional baseband modulation and the DAM systems are calculated as a function of transmission angle in the half-plane from −90 to +90° and are shown in Fig. 2. There are two points to be noted for the SER plotted in Fig. 2. Firstly, the given signal (symbol) to noise ratio E_s/N_0 is 15 dB because of the un-coded 8-PSK symbols shown in Fig. 1. Secondly, the *Y*-axis has a linear scale because this paper focuses on investigating the error rate performance at sidelobe angles rather than at broadside (the numerical value of the probability of symbol error for the 8-PSK modulation at broadside is approximately 6×10^{-3} at the given E_s/N_0 of 15 dB). Next we comment on the difference in the SER performance of the two systems: (i) at angles away from boresight, the SER of the directly modulated system is higher than that produced by conventional baseband modulation; and (ii) at some transmission angles the SER is higher than 7/8 (Note that a SER of 7/8 corresponds that of conventional 8-PSK when the received power tends, to zero, i.e. a random guess.). This is because the error rate performance of the two different modulation systems are because of different processes: for conventional modulation, and in the absence of multi-path, the error rate is purely a function of the relative amplitude of the array transmit pattern with respect to the noise level, as the signal constellation pattern is independent of angle (ignoring the trivial aspect of pattern rotation). For the DAM system, however, the situation is more complex as the angular error rate performance is a function of both the radiated signal power level and the angular dependence of the signal constellation pattern. We illustrate the difference in two processes with the aid of Figs. 3 and 4. The radiation patterns corresponding to the

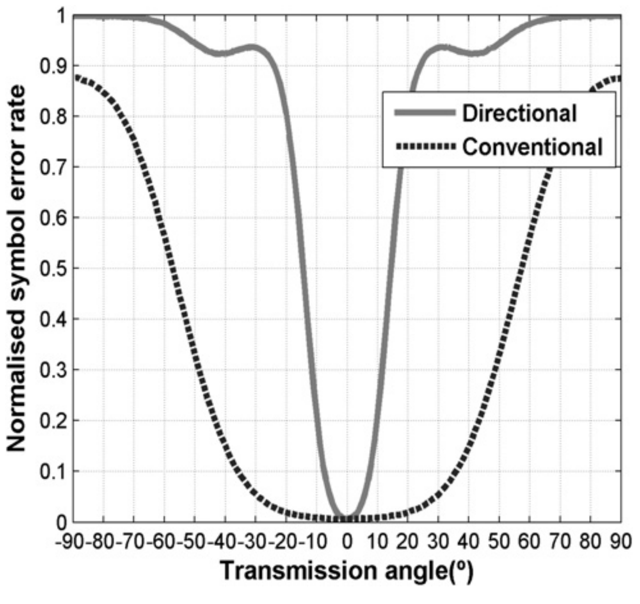

Fig. 2 *Simulated error rates obtained for DAM (solid line) and conventional modulation (dashed line) schemes for a two element array with 0.5λ spacing and isotropic radiators*

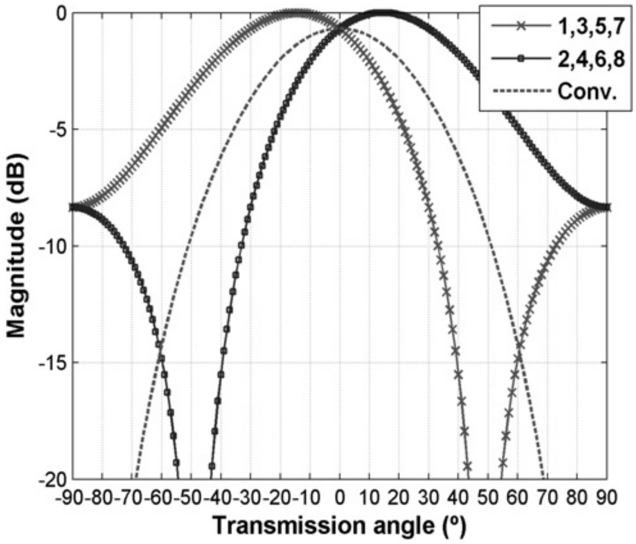

Fig. 3 *Radiation patterns of DAM transmitter when sending constellation points '1, 3, 5, 7' (crossed) and '2, 4, 6, 8' (squared) and relative magnitude of the radiation pattern sent by a conventional transmitter (dashed) to achieve the same power level at broadside*

different constellation points of the DAM transmission are shown in Fig. 3, along with a comparable power pattern of a conventional transmitter. From Table 1, the phase sets that map to the points '1,3,5,7' are different from those that map to the points '2,4,6,8'. This process results in two different radiation patterns (the squares and crosses as shown in Fig. 3). An important point to note here is that the DAM system does not radiate maximum power to the broadside recipient. Hence to make a valid comparison with the SER performance of a conventionally modulated system (i.e. the constellation patterns sent to broadside are exactly the same), power of conventional transmitter (dashed line) is reduced to ensure it matches the power radiated by DAM system in the boresight direction. It is clear that the SER performance of the conventionally modulated system (Fig. 2) is basically a direct response to its transmit power pattern (Fig. 3), but that the SER of DAM system shows no obvious response to its transmit power pattern. To further explain this, Fig. 4 illustrates the received noiseless constellation patterns at an angle of 75° compared with the ideal 8-PSK pattern. The transmission angle of 75° is chosen for illustration because according to Fig. 2, the SER of DAM system approaches 100% while that of conventional modulated system is still below the theoretical upper bound of 7/8. Referring to Fig. 4*a*, the noiseless constellation pattern received from the traditional baseband modulated system maintains the shape of 8-PSK, but with a significantly reduced power level (also shown in Fig. 3) and the theoretical SER has an upper bound of 7/8 when the signal power is approaches zero. However, in the DAM system (Fig. 4*b*), the power level of constellation at 75° is more than 10 dB greater than that of the corresponding traditional 8-PSK constellation, but the new mapping of DAM constellation is significantly distorted from that of the original 8-PSK. Hence, for an undesired recipient at 75°, who has no knowledge of the new mapping relationship, but uses the traditional 8-PSK constellation as a reference for demodulation, the SER will be significantly increased and could exceed the 7/8 bound.

2.1 Potential eavesdropper located at an angle close to the intended transmission direction

We now consider the performance of the DAM system for two specific scenarios. This first example is presented to illustrate how the angular dependence of the DAM system constellation can be exploited to minimise interception by an eavesdropper located close to the intended recipient. From Fig. 2, it is clear that the DAM system exhibits a much smaller modulation error rate beamwidth than that of the conventionally modulated system. Here we arbitrarily define modulation error rate beamwidth as the angular width within which the demodulated SER is less than 50%. The dramatic difference in the modulation error beamwidth of the two systems is a direct consequence of the angular dependence of the signal constellation generated by the DAM approach as discussed in the previous section. To further reduce the modulation error rate beamwidth of the

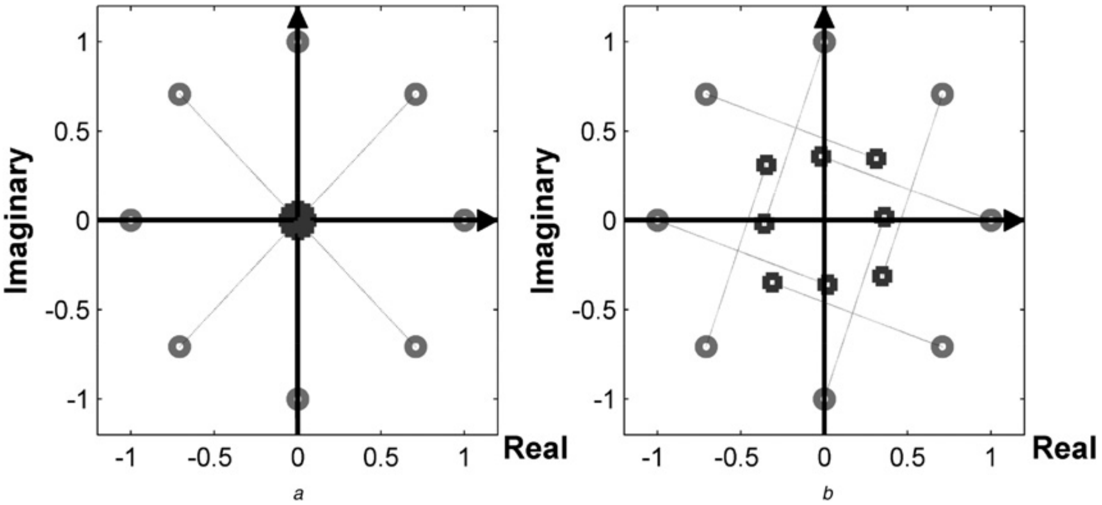

Fig. 4 *Constellation diagrams showing a comparison between ideal 8-PSK (circles) and received noiseless constellation pattern (squares) at 75° in*

a Conventionally modulated system
b Directional modulated system

antenna array system we may take the intuitive approach of increasing the spacing between the array elements, as this reduces the conventional power beamwidth of the main lobe of radiation. Unfortunately, this approach results not only in traditional, power-pattern, grating lobes but also in ‘modulation’ grating lobes – angles at which the signal constellation repeats its boresight distribution. As an example, Fig. 5 shows the corresponding system error rates for a two-element array with two wavelength element spacing. In this example, the boresight error rate beamwidth has been reduced from 102° and 29° to 22° and 7.5° for the conventional and the DAM systems, respectively, but with the penalty of generating grating lobe error rate regions at which the error rate approaches that at the intended boresight direction.

To reduce, or even eliminate the error rate grating lobe regions shown in Fig. 5 the assumed isotropic radiators may be replaced with more directional array elements. If elements are used which have a directive main beam response and low sidelobes (or even nulls) in the angular directions corresponding to the grating lobe directions, then by using the principle of pattern multiplication, the directional error rate of the system can be enhanced without introducing error lobe regions. To illustrate this scenario, re-consider the above example of a two element array with two wavelengths spacing but with the isotropic elements replaced by waveguide horns with 2λ wide apertures [12]. The results for these examples are shown in Fig. 6 where it is observed that the grating lobe error rate angles associated with both the conventional and the DAM modulation schemes have been suppressed. Also, the error rate performance of the DAM scheme compared with the conventional baseband modulation scheme shows improved error rate characteristics at angles away from boresight and exhibits a significantly narrower detection bandwidth at boresight (7° compared with 20°). Obviously the error rate beamwidth can be further reduced by increasing the element spacing and using correspondingly larger aperture antennas as the array elements. As an example, Fig. 7 shows the error rate performance of an array with 6λ element spacing and 6λ wide aperture elements for both conventional and DAM transmission systems. From Fig. 7, it is observed that the error rate beamwidths have been reduced to 7° and 2.6° for the conventional and DAM schemes, respectively. The main conclusion to draw from the results shown in Figs. 2 and 5–7, is that the DAM array system has a narrower angular detection region than that of the conventionally modulated system, so the possibility of successful demodulation from potential eavesdroppers located at angles very close to the intended transmission direction is significantly reduced. Another conclusion which can be draw from Fig. 2, Figs. 6 and 7 is that DAM array system has a higher error rate performance than conventional system at almost all transmission angles away from broadside.

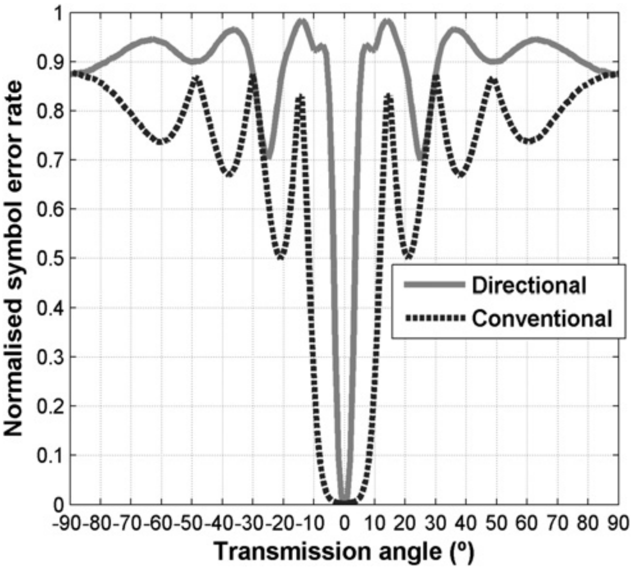

Fig. 6 *Simulated error rates obtained for DAM (solid line) and conventional modulation (dashed line) schemes for a two element array with 2λ spacing and directive elements*

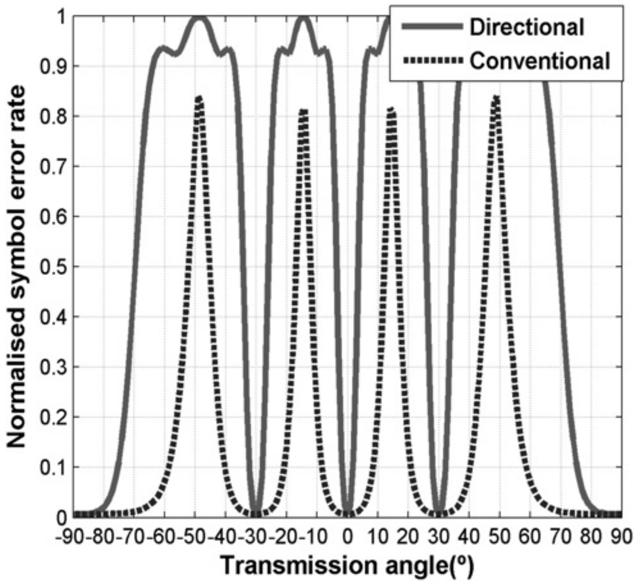

Fig. 5 *Simulated error rates obtained for DAM (solid line) and conventional modulation (dashed line) schemes for a two element array with 2λ spacing and isotropic radiators*

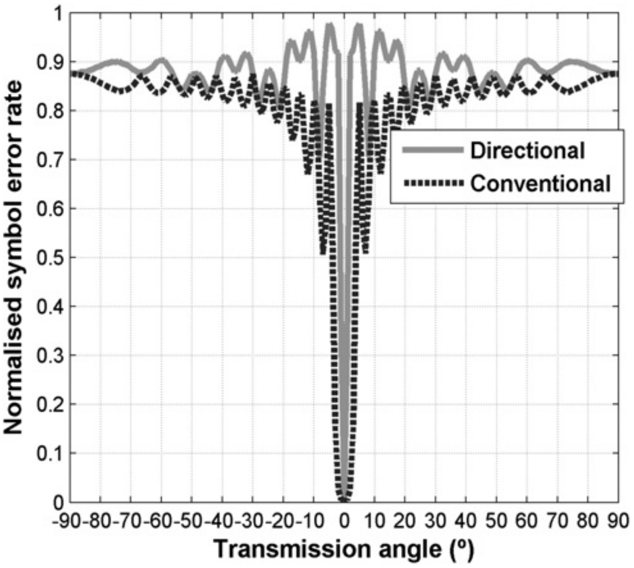

Fig. 7 *Simulated error rates obtained for DAM (solid line) and conventional modulation (dashed line) schemes for a two element array with 6λ spacing and directive elements*

2.2 Potential eavesdropper located close to the transmitter

This second example is presented to illustrate how the DAM system constellation can minimise the possibility of interception by an eavesdropper located closer to the transmitter than the intended recipient. In this situation the signal power received by eavesdropper may be several dB higher than that received by desired recipient. To investigate this scenario, we first examine and compare the effect of the system E_s/N_0 on the error rate performance of the two modulation schemes. To illustrate this difference we return to our previous example of a two element array with 2λ spacing. Consider first the case of transmitting 8-PSK using conventional modulation for boresight E_s/N_0 levels of 15 and 20 dB, respectively. The simulated error rate against transmission angle for this example is shown in Fig. 8. The main points to note from Fig. 8 are that the error rate performance around the grating lobe angles is dramatically reduced – for example, at about ± 20°, the error rate drops from approximately 50 to 25%. This indicates that a potential eavesdropper located away from boresight, but at a grating lobe direction and closer to the transmitter than the intended recipient (so that the received power level is higher) could potentially demodulate the transmission. Next consider a similar example but with the system configured to transmit DAM. The results of this simulation are given in Fig. 9. It is observed that not only does the DAM scheme result in a much narrower error rate modulation beamwidth at boresight, but it also provides much higher error rates at the grating lobe directions compared with conventional modulation scheme. It is also noted that the fluctuations of error rate in DAM system is much smaller than that observed in the conventional modulation system. This property provides enhanced security against eavesdroppers located close to the transmit antenna.

3 Initial experimental work

At present, we are unable to present measured results to verify the simulated error rates of the DAM array system. Instead, we present some initial experiment results to verify the critical aspect of the DAM system, which is the angular dependence of the far-field constellations [9]. The prototype DAM system works at 8.3 GHz and consists of a two-element dipole array, each element of which is controlled by a 4-bit, digital phase shifter. A photograph of the experimental system is shown in Fig. 10. Measurements of the complex (phase and amplitude) radiated fields produced by the array for specific combinations of element phase shift at a frequency of 8.3 GHz were made inside a anechoic chamber using an automated measurement system [13] employing a E5071C network analyser [14]. These data were used to derive constellations at far-field angles of 0°, 7° and 21°, respectively and are shown in Fig. 11. Assuming that the pattern received at 0° is selected as the reference constellation, then in Fig. 11*a*, the constellation received at 7° shows a significant transformation from the reference pattern with some points converging to the same locations and reducing the number of distinct signal points from 16 (circles) to eight (dots). A second example is shown in Fig. 11*b* where the constellation at an angle of 21° is compared with reference. In this example, both

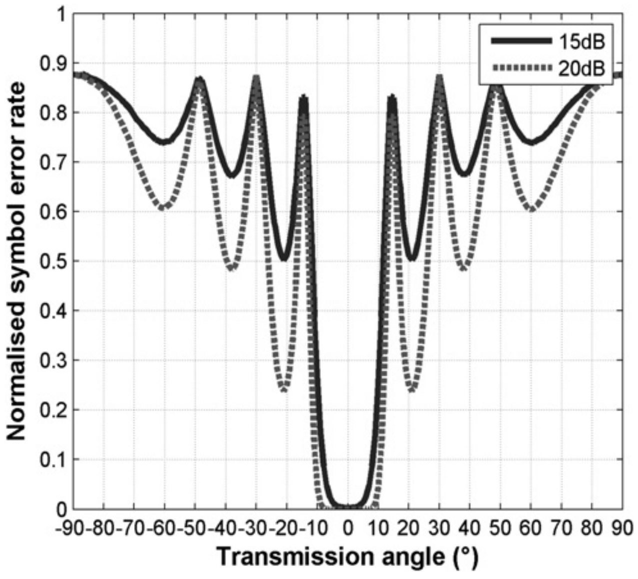

Fig. 8 *Simulated error rates obtained for conventional modulation using a two-element array with an element spacing of 2λ for E_s/N_0 = 15 dB (solid line) and E_s/N_0 = 20 dB (dashed line)*

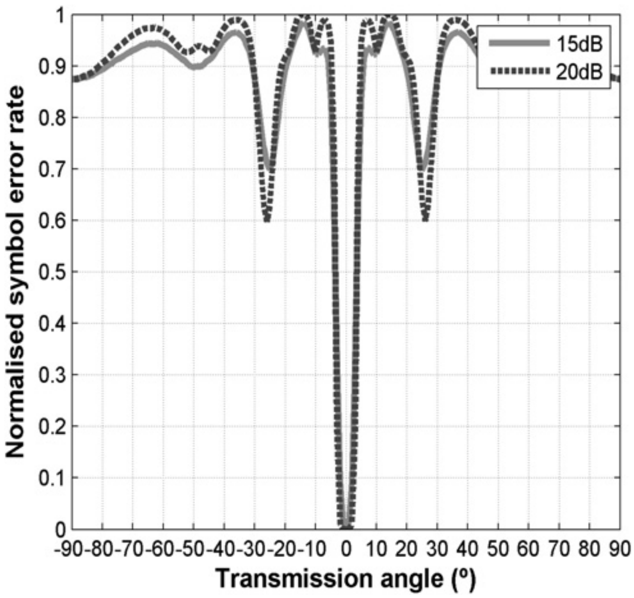

Fig. 9 *Simulated error rates obtained for DAM using a two-element array with an element spacing of 2λ for E_s/N_0 = 15 dB (solid line) and E_s/N_0 = 20 dB (dashed line)*

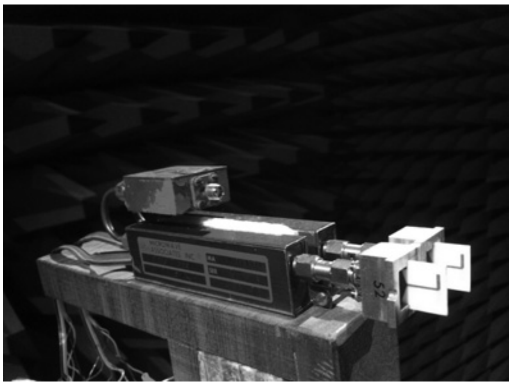

Fig. 10 *Photograph of the experimental system*

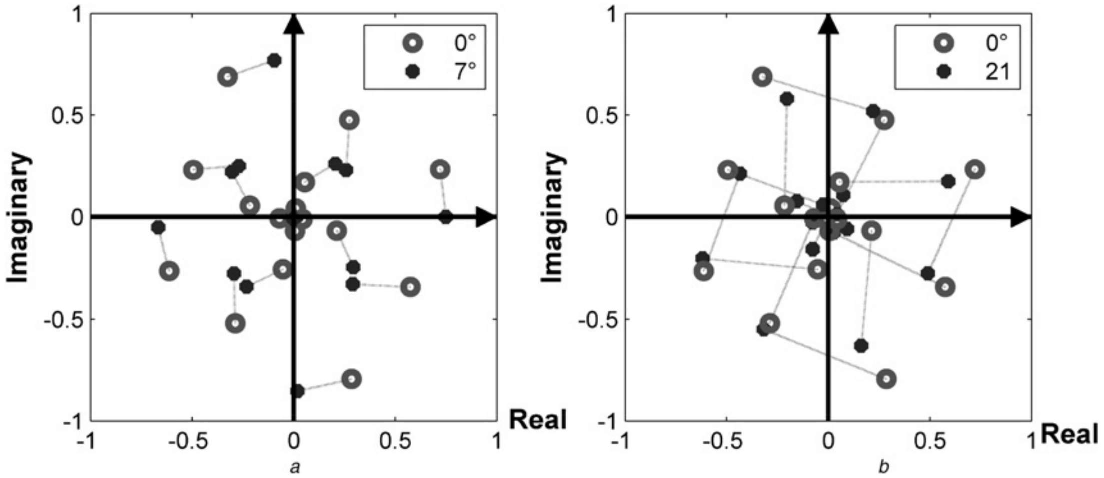

Fig. 11 *Comparisons between measured constellation patterns received at angles of*

a 0° and 7°
b 0° and 21°

constellations have 16 discrete points but the mappings are completely different.

4 Conclusion

The simulated error rate performances of a simple communication system based on a two element array antenna configured to transmit 8-PSK using both conventional modulation and DAM have been presented. For the case of an array with $\lambda/2$ element spacing and non-directional elements the DAM system is more secure than conventional baseband modulation, but both modulation schemes are vulnerable to detection by eavesdroppers. We have shown that for conventional modulation the error rate is purely a function of the relative amplitude of the array transmit pattern with respect to the noise level, but for the DAM system the angular error rate performance is a function of both the radiated signal power level and the angular dependence of the signal constellation pattern. By increasing the array element spacing and using directive elements the security of both modulation schemes can be improved but the security of the DAM system significantly outperforms that achieved using conventional modulation. The advantages of DAM are particularly significant at high SNR levels and at transmission angles away from boresight. Experimental results have been presented to illustrate the angular dependence of the constellation patterns radiated by a simple two-element DAM array. Future work will investigate multi-element array systems configured for DAM and higher level, QAM, modulation schemes.

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