Progress In Electromagnetics Research, Vol. 116, 363–379, 2011

RF DIRECTIONAL MODULATION TECHNIQUE USING A SWITCHED ANTENNA ARRAY FOR PHYSICAL LAYER SECURE COMMUNICATION APPLICATIONS

T. Hong, M.-Z. Song, and Y. Liu

College of Electronic and Information Engineering
Nanjing University of Aeronautics and Astronautics
Nanjing 210016, China

Abstract—In this paper, we present a RF directional modulation technique using a switched antenna array for physical layer secure communication. The main idea is that a switching scheme of the switched antenna array is designed according to a spreading sequence for the purpose of spreading spectrum of the transmit signal. The transmit signal is associated with the spreading sequence and the direction of the desired receiver because of information data modulated both in the baseband and the antenna level. In this way, the desired receiver with a single antenna can demodulate the receive signal as traditional spread-spectrum signal, while eavesdroppers can not extract any useful information from the receive signal even if eavesdroppers know the spreading sequence of the RF directional modulation signal. Simulation results show that the proposed technique offers a more secure transmission method for wireless communication comparison with traditional spread-spectrum signal.

1. INTRODUCTION

In traditional wireless communication transmitter, the information data is modulated at the baseband and then up-converted to radio frequency (RF). The modulated RF signal goes through a power amplifier to drive the transmit antenna or antenna array. It is noteworthy that in this traditional transmitter, a receiver at the sidelobe of the transmit antenna receives the same information as the receiver located at the transmit antenna's main beam. The only

Received 16 March 2011, Accepted 29 April 2011, Scheduled 9 May 2011
Corresponding author: Tao Hong (hongtao3223@163.com).

different between the receive data at different directions is the signal power. Therefore, given a high-sensitivity receiver it would be possible for a receiver at an undesired direction to eavesdrop information data. Paper [1, 2] propose a direction modulation (DM) technique using a phased array, which synthesizes the digital modulation in RF portion of the transmitter. The constellation points of the transmit signal maintain their positions at the desired direction but scramble at the undesired directions. Paper [3] presents a similar DM signal transmitted by an array with pattern reconfigurable elements. Paper [4] introduces a near-field direct antenna modulation technique similar to the DM technique, which forms a DM signal by two transmit beams or multiple transmit beams. These DM techniques synthesize a digital modulation fully or partially in the RF portion of the transmitter, which cause the transmit signal to be direction-dependent. This characteristic is benefit for physical layer secure communication without relying on upper layer data encryption.

Due to the broadcast nature of wireless channel, the issues of privacy and security have taken on an increasingly important role in wireless communication, especially in military and homeland security applications [5]. Physical layer security is an emerging research area that explores the possibility of achieving perfect-secrecy data transmission among desired receiver. The paper to be found in this area can be clustered into two categories [6]: one is dealing with information theoretic aspects and the other is focusing on practical applications. The first category of paper provides information theoretic results for wireless physical layer security, such as secrecy capacity of the MIMO system [7–10], broadcast channel [11], and cooperation communication system [12–14]. The second category of literature focuses on more practical aspects of wireless physical layer security, such as security OFDM system [15, 16], deliberately randomized transmit array system [17], DM system [1–4], and artificial noise system [18]. The most important objective of physical layer security design is to guarantee wireless transmission signal with the characteristics of low-probability-of-interception (LPI) and low-probability-of-detection (LPD) for wireless communication system and radar system [19]. In particular, we are interested in LPI and LPD techniques at physical layer which do not directly rely on upper-layer data encryption or secret keys. Traditionally, spread spectrum is the most widely used technique for LPI and LPD at physical layer. However, traditional spread-spectrum signal transmit the same data in the beam space only different at the power levels. Therefore, LPI and LPD of spread-spectrum signal depends on that eavesdroppers have no information about the spreading sequence of the transmit signal. Unfortunately, this strong assumption can hardly hold in practical scenarios. The security communication signals proposed in the paper [1–4, 17] have the characteristic of LPI which means that eavesdroppers can not extract any useful information from the receive signal. However, eavesdroppers can detect these security communication signals easily, unlike the traditional spread-spectrum signal submerged in the noise. Determining how to combine the advantages of the DM signal with the traditional spread-spectrum signal in practical communication system is a crucial problem. Therefore, a goal of this paper is to design a RF directional modulation signal transmitted by a switched antenna array with the characteristics of LPI and LPD for physical layer secure communication applications.

Radiation pattern synthesis is widely used to obtain shaped Radiation pattern for wireless communication system and radar system [20–23]. Switched antenna array is also called time modulated linear array (TMLA) in the field of radiation pattern synthesis. In the late 1950s, "Time" as a design parameter is first proposed to suppress the sidelobes of the linear array in [24]. Researches on TMLA have followed this work for the purpose of achieving lower sidelobe level [25–28]. TMLA is widely applied to airborne pulsed Doppler radar system [29], direction of arrivals (DOAs) system [30] and digital beamforming (DBF) system [31]. However, an inherent drawback of TMLA is that there are many sideband signals spaced at multiples of the modulation frequency, called sideband radiation. In [32], a closed form expression associated to the sideband power losses is obtained. SR signals may not be desirable and should be suppressed to improve the efficiency of the TMLA. Paper [33] proposes a differential evolution algorithm to suppress the sideband radiation patterns in TMLA. Paper [34] presents a technique for the control of the sideband radiations in time-modulated planar arrays based on the particle swarm optimization. These researches consider that SR signals are major disadvantage of TMLA and should be suppressed or filtered. The major disadvantage of TMLA mentioned above may also be used as an advantage in applications. Fundamental frequency component and first harmonic of a two-element TMLA are used in direction finding by steering the deep null on broadside direction in [35], also with the aid of variable-switching instants first harmonic of a TMLA can also be used in beam-steering applications [36]. Additionally, Switched architecture is considered an attractive alternative to fully adaptive arrays due to their low-cost because this switched architecture offers a drastic reduction in the amount of RF hardware (power amplifiers, mixers) required. Therefore, Switched antenna arrays are widely used for mobile 2.4 GHz ISM applications [37], wireless senor networks [38] and WIMAX [39].

Our work in this paper is different from the aforementioned works in the following aspects: i) The antenna switching scheme is controlled by a spreading sequence for the purpose of forming a RF directional modulation signal with LPI and LPD, unlike paper [25–28] for radiation pattern synthesis; ii) Fundamental frequency component and all harmonic components are used to form a RF directional modulation signal different from radiation pattern synthesis only using fundamental frequency component in paper [25–28] and direction finding application using fundamental frequency component and harmonic components in paper [35]; iii) RF directional modulation signal is associated with the spreading sequence and the direction of the receiver, unlike traditional spread-spectrum signal only depended on the spreading sequence. This advantage ensures that eavesdroppers can not demodulate the RF directional modulation signal even if eavesdroppers know the information about spreading sequence. Iv) Compared with the DM signal proposed in paper [1–4] and deliberately randomized transmit array signal proposed in paper [17], RF directional modulation signal not only has the characteristic of LPI similar to the DM signal but also has the characteristic of LPD which is benefit for physical layer secure communication.

The remainder of this paper is organized as follows. Section 2 introduces the principle of RF directional modulation signal using a switched antenna array. Section 3 explains the RF directional modulation signal from the viewpoint of frequency domain. Finally the performances of the RF directional modulation signal are investigated by computer simulation in Section 4.

2. THE PRINCIPLE OF RF DIRECTIONAL MODULATION SIGNAL USING A SWITCHED ANTENNA ARRAY

To illustrate the principle of RF directional modulation, a block diagram of the transmitter is designed as shown in Figure 1, which consists of data source, modulator, power amplifier, power splitter, CPLD module, phase shifter and a switched antenna array. The isotropic elements with equally space ($d = \frac{\lambda}{2}$) are numbered from 1 to H. Considering that each element is controlled by a high-speed RF switch, and the moving phase center technique can be implemented by high speed RF switches in the feed line of each element.

The excitation signal for this switched antenna array is $s(t) = b_n e^{j\omega_0 t}$, where $b_n \in \{+1, -1\}$ denotes the BPSK modulation symbol

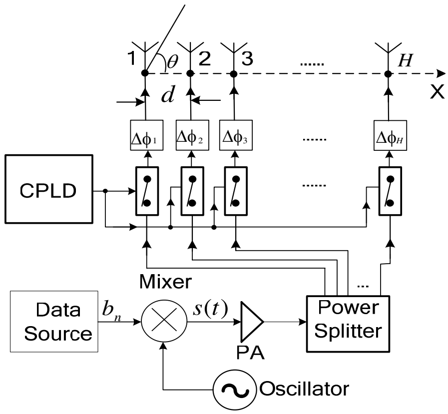

Figure 1. Block diagram of the transmitter.

and $n = 1, 2, \ldots, N$ denotes the nth BPSK modulation symbol. Considering that the spreading sequence is denoted by $q_m \in \{+1, -1\}$, where $m = 1, 2, \ldots, M$ denotes the mth chip and M is the period of the spreading sequence. We first divide the switched antenna array into $\frac{H}{V}$ antenna groups and denoted by $L_{n,m}$, $L_{n,m} \in \{1, 2, \ldots, H/V\}$, where V denotes the number of element of each antenna group. Then, we select M antenna groups as the transmit antennas from the linear array to transmit one BPSK modulation symbol. It means that each chip is correspondence with one switching antenna group. According to the spreading sequence, the antenna group switching scheme is designed as follows:

Step 1: when $q_1 = 1$, $L_{n,1} = 1$ when $q_1 = -1$, $L_{n,1} = 2$;

Step 2: $L_{n,m} = L_{n,m-1} + \frac{1}{2}(3 + q_m \cdot q_{m-1})$, $m = 2, 3, \ldots, M$.

From the switching scheme, we obtain the transmit antenna group number set $\{L_{n,m}\}$, $m = 1, 2, \ldots, M$ for the nth BPSK modulation symbol. The switching frequency f_p equals to the symbol rate of the BPSK modulation signal and the duration of "on" times is the same for all switching antenna groups. Therefore, the duration of "on" times for the mth switching antenna group is written as:

$$\tau_{L_{n,m}} = \tau = \frac{1}{M} T \tag{1}$$

where: $T = \frac{1}{f_p}$ is the switching period. For example, V equals to 1 and the spreading sequence q_m is selected as $\{+1, -1, -1, +1, +1, +1, -1\}$. According to the switching scheme, the transmit antenna group number set $\{L_{n,m}\}$ is $\{1, 2, 4, 5, 7, 9, 10\}$. The schematic diagram of the antenna switching is shown in the Figure 2.

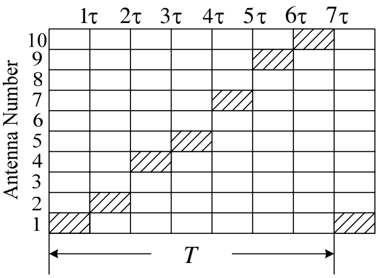

Figure 2. The schematic diagram of the antenna group switching.

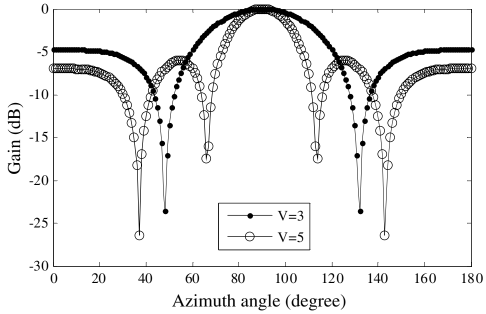

Figure 3. Amplitude radiation pattern of the switched antenna array.

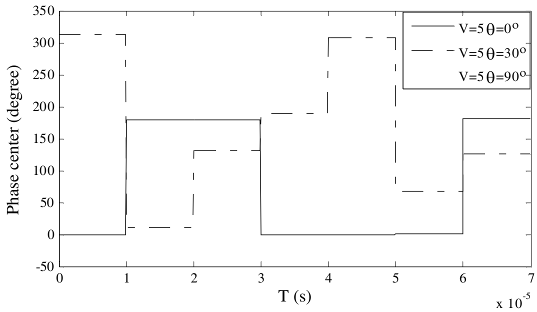

Figure 4. Phase center of the switched antenna array.

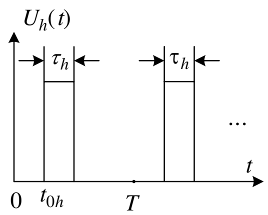

Figure 5. Schematic diagram of the switching function.

Considering that BPSK modulation symbol period equals to 7×10^{-5} s, $b_1 = +1$ and m-sequence is selected as the spreading sequence with the period $M = 7$. Figure 3 shows the amplitude radiation pattern of the switched antenna array alone with $V = 3$ and $V = 5$, respectively, and Figure 4 shows phase center locus of the switched antenna array when the receiver at different azimuth angles. We can find that the amplitude radiation pattern of the switched antenna array does not vary with antenna switching while the phase center locus of the switched antenna array motion in the direction of X-axis by controlling of the spreading sequence. For the receiver at $\theta = 0°$, the phase center locus is the same as the m-sequence which is useful for the desired receiver to demodulate the receive signal. However, the phase center locus is scrambled for the undesired receiver at $\theta = 30^\circ$ and $\theta = 90^\circ$, respectively, which is difficulty extract any useful data from the receive signal.

Supposing that the desired receiver is at the azimuth angle θ_1. To direct main beam to the desired receiver and synthesize the phase center locus at the desired azimuth angle, the phase value for each phase shifter can be calculated as follows:

$$\varphi_h = -(h-1)\beta d \cos\theta_1 + \pi \left[ceil\left(\frac{h}{V}\right) - 1 \right],\ h = 1, 2, \ldots\ldots, H \quad (2)$$

where: $\beta = \frac{2\pi}{\lambda}$ denotes the propagation constant and h denotes hth antenna. Therefore, the receive signal at the azimuth angle θ is expressed as follows:

$$r(t) = b_n \sum_{h=V(L-1)+1}^{h=V(L-1)+V} U_h(t) e^{j[\beta(h-1)d\cos\theta + \phi_h]} e^{j\omega_0 t} \quad (3)$$

where: $\omega_0 = 2\pi f_0$ denotes the carrier radian frequency, f_0 is the carrier frequency and $U_h(t)$ is switching function of the antenna. The expression of the switching function is expressed by Equation (4) and its schematic diagram is shown in Figure 5.

$$U_h(t) = \begin{cases} 1, & t_{0h} \le t \le (t_{0h} + \tau_h) \\ 0, & 0 \le t \le t_{0h},\ (t_{0h} + \tau_h) \le t \le T \end{cases} \quad (4)$$

where: t_{0h} denotes the switch-on time instant of the hth antenna, τ_h is the duration of "on" times, $T = \frac{1}{f_p}$ is the switching period and f_p is the switching frequency.

This RF directional modulation signal modulated both in the baseband and the antenna level is benefit for the physical layer secure communication because one of the important objectives of physical layer design is to guarantee wireless transmissions with LPI. In next section, we will explain the RF directional modulation signal with LPD from the viewpoint of frequency-domain.

3. FREQUENCY DOMAIN ANALYSIS OF RF DIRECTIONAL MODULATION SIGNAL

Considering that the amplitude spectrum of the BPSK modulation signal b_n is denoted by $E(j\omega)$ with modulation bandwidth $2\omega_b$. The spectrum function of the switching function is a series of impulse function, which appear at different harmonic frequencies because the switching function $U_h(t)$ is a periodic function. The expression of the spectrum function is written as:

$$S(j\omega) = \sum_{i=-\infty}^{i=+\infty} \pi \dot{A}_i \delta(\omega - i\omega_p) \tag{5}$$

$$\dot{A}_i = \frac{2\tau}{T} Sa\left(\frac{i\omega_p \tau}{2}\right) \tag{6}$$

$$\omega_p = 2\pi f_p = \frac{2\pi}{T} \tag{7}$$

where: $\dot{A}_i$ denotes the amplitude of the ith harmonic component, ω_p denotes the angular frequency of the fundamental harmonic and $Sa(x) = \frac{\sin x}{x}$. According to the convolution theorem in frequency-domain and Equation (3), the receive signal in frequency-domain can be expressed as follows:

$$\begin{aligned} R(j\omega) &= \frac{1}{2\pi} E(j\omega) * S(j\omega) = \frac{1}{2\pi} E(j\omega) * \sum_{i=-\infty}^{i=+\infty} \pi \dot{A}_i \delta(\omega - i\omega_p) \\ &= \sum_{i=-\infty}^{i=+\infty} \frac{\dot{A}_i}{2} E\left[j(\omega - i\omega_p)\right] = \frac{\tau}{T} \sum_{i=-\infty}^{i=+\infty} Sa\left(\frac{i\omega_p \tau}{2}\right) E[j(\omega - i\omega_p)] \end{aligned} \tag{8}$$

The amplitude spectrum of the RF directional modulation signal due to the switching function is illustrated in Figure 6, which is a repetition of the modulation spectrum centered at the carrier radian frequency ω_0. The envelope of the harmonic components follows the function $Sa(x)$, which is determined from the Fourier transform of the switching function. The amplitude spectrum of the RF directional modulation signal not only appears at the carrier radian frequency ω_0 (fundamental component) but also removal the fundamental component to the radian frequencies $\omega_0 \pm \omega_p$, $\omega_0 \pm 2\omega_p$, $\ldots$, and $\omega_0 \pm i\omega_p$ (harmonic components), respectively, unlike using a single antenna array to radiate BPSK modulation signal directly. To avoid the aliasing effects (overlapping of the modulation spectrum), the minimum switching frequency is determined by the Nyquist sampling theory, which is satisfied by:

$$f_p \geq \frac{2\omega_b}{2\pi} = \frac{\omega_b}{\pi} \tag{9}$$

The harmonic components contain the same data as the fundamental component only different at power levels. Paper [28–30] consider that these harmonic components are harmful for the pattern synthesis, which need to minimize its power levels and filter by a low-pass filter. However, we utilize these harmonic components to form the RF directional modulation signal for secure communication applications. Considering that m-sequence is selected as the spreading sequence with the period $M = 15$, $M = 31$ and $M = 63$, respectively. According to the Equations (5) and (6), the power of the fundamental and harmonic components for the RF directional modulation signal is shown in Figure 7. Compared with the power level of the BPSK modulation signal transmitted by a single antenna array (regarded

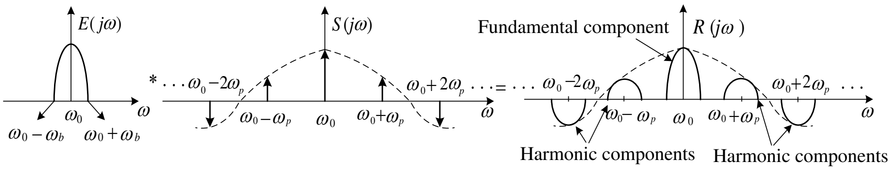

Figure 6. Removal procedure of the amplitude spectrum.

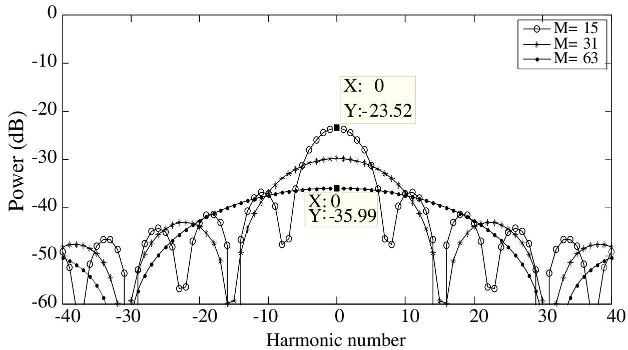

Figure 7. The power of the fundamental and harmonic components for the RF directional modulation signal.

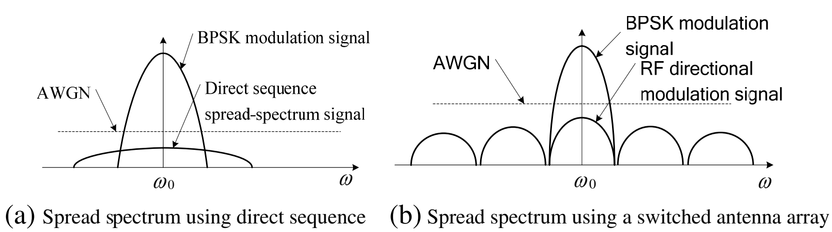

Figure 8. Comparison diagram of the spread-spectrum between the direct sequence spread-spectrum signal and the RF directional modulation signal.

as 0 dB), the power level of the fundamental component reduce to −23.52 dB and −35.99 dB, alone with the period of m-sequence $M = 15$ and $M = 63$, respectively. Figure 8 shows the comparison diagram of the spread-spectrum between the direct sequence spread-spectrum signal and the RF directional modulation signal. The RF directional modulation signal is formed by switching the antenna array, unlike the direct sequence spread-spectrum signal which is mixed of the data with a spreading sequence directly before the final carrier modulation. This spread-spectrum signal generated by a switching antenna array is benefit for the physical layer secure communication because this transmit signal is not only with LPI but also with the LPD as traditional spread-spectrum signal.

4. SIMULATION RESULTS

The simulation conditions are supposed as follows:

(1) The desired receiver is at the direction $\theta_1 = 60°$. Five adjacent antennas ($V = 5$) are regarded as an antenna group to radiate transmit signal.

(2) In order to compare the bit error ratio (BER) performances between traditional spread-spectrum signal and RF directional modulation signal, amplitude radiation pattern of the switched antenna array is used to radiate traditional spread-spectrum signal.

(3) The transmit signal at $\theta = 60°$ (mainlobe direction) as standard signal is used to calculate the adding power of AWGN. For other directions, the adding power of AWGN is the same as the direction $\theta = 60°$. It means that the adding power of AWGN is the same for all directions.

Figure 9 shows BER comparison diagram of the traditional spread-spectrum signal and RF directional modulation signal versus azimuth angle when M equals to 7 and SNR equals to 0 dB. We can find that BER performance of RF directional modulation signal varies rapidly with azimuth angle compared with the traditional spread-spectrum signal. It means that undesired receiver can not extract any useful information from the receive signal when undesired receiver off of the desired direction. This characteristic is benefit for physical layer secure transmission.

Figure 10 shows BER comparison diagram of the traditional spread-spectrum signal and RF directional modulation signal versus SNR when desired receiver and undesired receiver at 60° and 55°, respectively, and the period of the spreading sequence M equals to 7. For traditional spread-spectrum signal, BER performance of the desired receiver at the direction 60° is almost the same as the undesired receiver at the direction 55°. It means that eavesdropper can extract the information data from the receive signal when eavesdropper knows the information about the spreading sequence, which is harmful for secure wireless communication. For RF directional modulation signal, BER performance of the desired receiver at the direction 60° is the same as traditional spread-spectrum signal while undesired receiver at the direction 55° can not extract any useful information from the

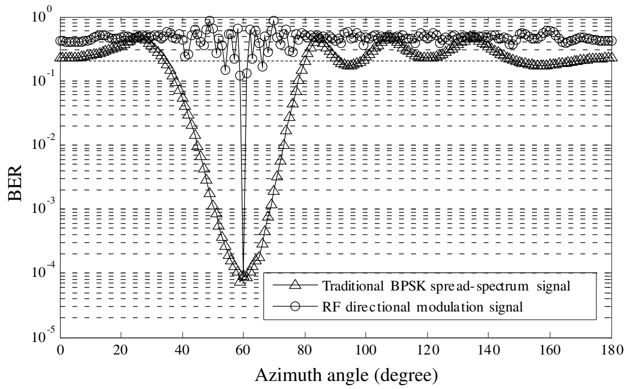

Figure 9. BER performance versus azimuth angle when signal-to-noise ratio (SNR) equals to 0 dB and the period of the spreading sequence M equals to 7.

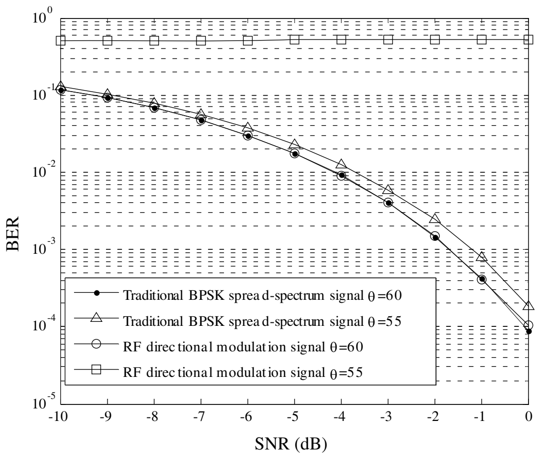

Figure 10. BER performance versus SNR when desired receiver and undesired receiver at 60° and 55°, respectively, and M equals to 7.

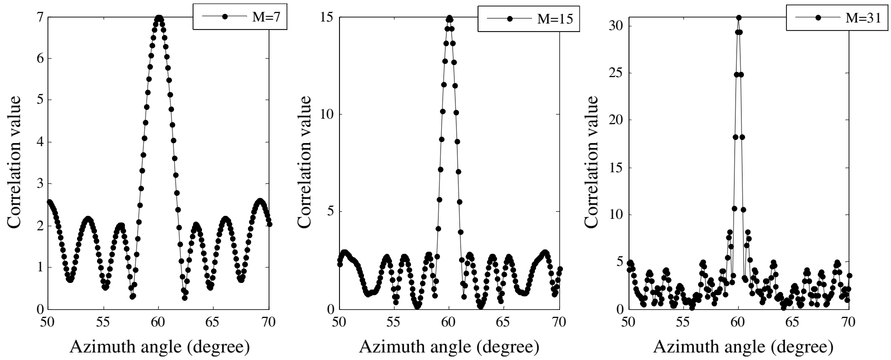

Figure 11. The correlation value of the spreading sequence versus the receiver at different directions when $M = 7$, $M = 15$ and $M = 31$, respectively.

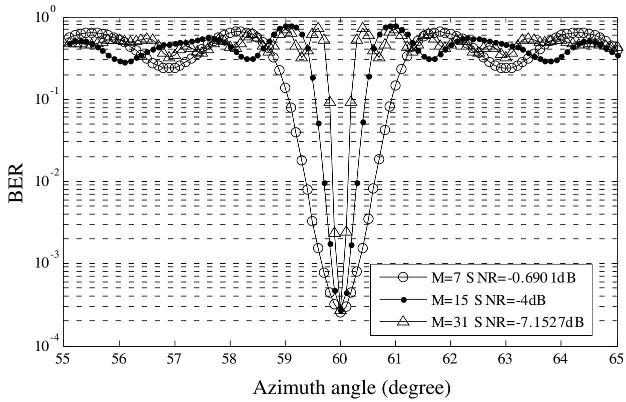

Figure 12. BER performance versus azimuth angle when M equals to 7, 15 and 31, respectively.

receive signal even if eavesdropper knows the information about the spreading sequence. Furthermore, BER performance of the undesired receiver does not vary with the SNR.

Figure 11 shows the correlation value of the spreading sequence versus the receiver at different directions when the period of the spreading sequence M equals to 7, 15 and 31, respectively. The resolution of the azimuth angle equals to 0.1° for the azimuth angle. We can find that the capture range of the RF directional modulation signal get smaller with the period of the spreading sequence increasing. It means that the directional of the RF directional modulation signal improve with the period of the spreading sequence which is benefit for the secure communication applications.

Figure 12 shows BER performance versus azimuth angle when M equals to 7, 15 and 31, respectively. According to the period of the spreading sequence, the spreading gains are 8.4510 dB, 11.7609 dB and 14.9136 dB, respectively, when $M = 7$, 15 and 31. In order to compare the BER performance of these cases, SNR are set -0.6901 dB, -4 dB and -7.1527 dB, respectively. We can find that demodulation range of RF directional modulation signal get smaller with the period of the spreading sequence increasing. We can control the demodulation range by the period of the spreading sequence.

5. CONCLUSION

Traditionally, spread spectrum is the most widely used technique for LPI and LPD at physical layer. However, LPI and LPD of traditional spread-spectrum signal depend on that eavesdroppers have no information about the spreading sequence of the transmit signal. A RF directional modulation signal has been demonstrated using a switched antenna array in this paper. This signal is modulated both in the baseband and the antenna level different from traditional spread spectrum only in the baseband. Compare with the DM signal, RF directional modulation signal not only has the advantage of directional but also has the characteristic of LPD. It means that RF directional modulation signal combines the advantage of DM signal and traditional spread spectrum signal which is benefit for physical layer secure communication. It is noted that this switched antenna array is similar to smart antenna array, which need more antenna number than traditional transmitter. However, this technique offer a more secure transmission method for wireless communication and can be apply to military and homeland security applications. Future work on the problem such as apply this RF directional modulation signal to secure cooperation communication system is required.

ACKNOWLEDGMENT

This work was supported by the Aeronautic Science Foundation of China under Grant No. 20095152026, and by the Natural Science Foundation of Jiangsu Province under Grant No. BK2009367.

REFERENCES

1. Daly, M. P. and J. T. Bernhard, "Directional modulation technique for phased arrays," *IEEE Transactions on Antennas and Propagation*, Vol. 57, No. 9, 2633–2640, 2009.
2. Daly, M. P., E. L. Daly, and J. T. Bernhard, "Demonstration of directional modulation using a phased array," *IEEE Transactions on Antennas and Propagation*, Vol. 58, No. 5, 1545–1550, 2010.
3. Daly, M. P. and J. T. Bernhard, "Beamsteering in pattern reconfigurable arrays using directional modulation," *IEEE Transactions on Antennas and Propagation*, Vol. 58, No. 7, 2259–2265, 2010.
4. Babakhani, A., D. B. Rutledge, and A. Hajimiri, "Transmitter architectures based on near-field direct antenna modulation," *IEEE Journal of Solid-state Circuits*, Vol. 43, No. 12, 2674–2692, 2008.
5. Hubenko, V. P., R. A. Raines, R. F. Mills, R. O. Baldwin, B. E. Mullins, and M. R. Grimaila, "Improving the global information grid's performance through satellite communications layer enhancements," *IEEE Communications Magazine*, Vol. 44, No. 11, 66–72, 2006.
6. Debbah, M., E. Hesham, P. H. Vincent, and S. Shlomo, "Editorial: Wireless physical layer security," *Eurasip Journal on Wireless Communications and Networking*, Vol. 2009, 2009.
7. Khisti, A. and G. W. Wornell, "Secure transmission with multiple antennas I: The MISOME wiretap channel," *IEEE Transactions on Information Theory*, Vol. 56, No. 7, 3088–3104, 2010.
8. Khisti, A. and G. W. Wornell, "Secure transmission with multiple antennas — Part II: The MIMOME wiretap channel," *IEEE Transactions on Information Theory*, Vol. 56, No. 11, 5515–5532, 2010.
9. Hero III, A. O., "Secure space-time communication," *IEEE Transactions on Information Theory*, Vol. 49, No. 12, 3235–3249, 2003.
10. Kim, H. and J. D. Villasenor, "Secure MIMO communications in a system with equal numbers of transmit and receive antennas," *IEEE Communications Letters,* Vol. 12, No. 5, 386–388, 2008.
11. Csiszar, I. and J. Korner, "Broadcast channels with confidential messages," *IEEE Transactions on Information Theory*, Vol. 24, No. 3, 339–348, 2003.
12. Krikidis, I., J. Thompson, and S. Mclaughlin, "Relay selection for secure cooperative networks with jamming," *IEEE Transactions*

on Wireless Communications, Vol. 8, No. 10, 5003–5011, 2009.

13. Dong, L., Z. Han, A. P. Petropulu, and H. V. Poor, "Improving wireless physical layer security via cooperating relays," *IEEE Transactions on Signal Processing*, Vol. 58, No. 3, 1875–1888, 2010.
14. Simeone, O. and P. Popovski, "Secure communications via cooperating base stations," *IEEE Communications Letters*, Vol. 12, No. 3, 188–190, 2008.
15. Li, Z. and X.-G. Xia, "A distributed differentially encoded OFDM scheme for asynchronous cooperative systems with low probability of interception," *IEEE Transactions on Wireless Communications*, Vol. 8, No. 7, 3372–3379, 2009.
16. Ma, R., L. Dai, Z. Wang, and J. Wang, "Secure communication in TDS-OFDM system using constellation rotation and noise insertion," *IEEE Transactions on Consumer Electronics*, Vol. 56, No. 3, 1328–1332, 2010.
17. Li, X.-H. and J. Hwu, "Using antenna array redundancy and channel diversity for secure wireless transmissions," *Journal of Communications*, Vol. 2, No. 3, 24–32, 2007.
18. Hong, T., M.-Z. Song, and Y. Liu, "Directional sensitive modulation signal transmitted by monopulse cassegrain antenna for physical layer secure communication," *Progress In Electromagnetics Research M*, Vol. 17, 167–181, 2011.
19. Jing, T., S. Qiao, Z.-G. Shi, L. Peng, J. Huangfu, W.-Z. Cui, W. Ma, and L.-X. Ran, "Simulation and experimental evaluation of the radar signal performance of chaotic signals generated from a microwave colpitts oscillator," *Progress In Electromagnetics Research*, Vol. 90, 15–30, 2009.
20. Chou, H.-T., K.-L. Hung, and C.-Y. Chen, "Utilization of a Yagi antenna director array to synthesize a shaped radiation pattern for optimum coverage in wireless communications," *Journal of Electromagnetic Waves and Applications*, Vol. 23, No. 7, 851–861, 2009.
21. Kazemi, S., F. Keshmiri, and H. R. Hassani, "Amplitude distribution synthesize of unequally spaced arrays," *Journal of Electromagnetic Waves and Applications*, Vol. 23, No. 8–9, 987–997, 2009.
22. He, Q.-Q., H.-D. He, and H. Lan, "An efficient pattern synthesis method for cylindrical phased array antennas," *Journal of Electromagnetic Waves and Applications*, Vol. 23, No. 4, 473–482, 2009.

23. Lim, S.-H., J.-H. Han, S.-Y. Kim, and N.-H. Myung, "Azimuth beam pattern synthesis for airborne SAR system optimization," *Progress In Electromagnetics Research*, Vol. 106, 295–309, 2010.
24. Shanks, H. E. and R. W. Bickmore, "Four-dimensional electromagnetic radiators," *Canad. J. Phys.,* Vol. 37, 263–275, Mar. 1959.
25. Yang, S., Y. B. Gan, and P. K. Tan, "A new technique for power-pattern synthesis in time-modulated linear arrays," *IEEE Antennas Wireless Propagat. Lett.*, Vol. 2, 285–287, 2003.
26. Li, G., S. Yang, M. Huang, and Z. Nie, "Sidelobe suppression in time modulated linear arrays with unequal element spacing," *Journal of Electromagnetic Waves and Applications,* Vol. 24, No. 5–6, 775–783, 2010.
27. Yang, S., Y. Chen, and Z.-P. Nie, "Simulation of time modulated linear antenna arrays using the FDTD method," *Progress In Electromagnetics Research*, Vol. 98, 175–190, 2009.
28. Pal, S., S. Das, and A. Basak, "Design of time-modulated linear arrays with a multi-objective optimization approach," *Progress In Electromagnetics Research B*, Vol. 23, 83–107, 2010.
29. Li, G., S. Yang, and Z. Nie, "A study on the application of time modulated antenna arrays to airborne pulsed Doppler radar," *IEEE Transactions on Antennas and Propagation*, Vol. 57, No. 5, 1578–1582, May 2009.
30. Li, G., S. Yang, and Z. Nie, "Direction of arrival estimation in time modulated linear arrays with unidirectional phase center motion," *IEEE Transactions on Antennas and Propagation*, Vol. 58, No. 4, 1105–1111, 2010.
31. Fredrick, J. D., W. Yuanxun, J. Seong-Sik, and T. Itoh, "A smart antenna receiver array using a single rf channel and digital beamforming," *2002 IEEE MTT-S International Microwave Symposium Digest*, Vol. 1, 311–314, 2002.
32. Bregains, J. C., J. Fondevila-Gomez, G. Franceschetti, and F. Ares, "Signal radiation and power losses of time-modulated arrays," *IEEE Transactions on Antennas and Propagation*, Vol. 56, No. 6, 1799–1804, 2008.
33. Yang, S., Y. B. Gan, and A. Qing, "Sideband suppression in time-modulated linear arrays by the differential evolution algorithm," *IEEE Antennas Wireless Propagat. Lett.*, Vol. 1, 173–175, 2002.
34. Rocca, P., L. Poli, G. Oliveri, and A. Massa, "Synthesis of time-modulated planar arrays with controlled harmonic radiations," *Journal of Electromagnetic Waves and Applications*, Vol. 24,

No. 5–6, 827–838, 2010.

35. Tennant, A. and B. Chambers, "A two-element time-modulated array with direction-finding properties," *IEEE Antennas Wireless Propag. Lett.*, Vol. 6, 64–65, 2007.
36. Li, G., S. Yang, Y. Chen, and Z.-P. Nie, "A novel electronic beam steering technique in time modulated antenna array," *Progress In Electromagnetics Research*, Vol. 97, 391–405, 2009.
37. Dimousios, T. D., C. D. Nikolopoulos, S. A. Mitilineos, and C. N. Capsalis, "A new low-profile and cost SPA-PIFA for mobile 2.4 GHz ISM applications," *Journal of Electromagnetic Waves and Applications*, Vol. 24, No. 7, 881–891, 2010.
38. Viani, F., L. Lizzi, M. Donelli, D. Pregnolato, G. Oliveri, and A. Massa, "Exploitation of parasitic smart antennas in wireless sensor networks," *Journal of Electromagnetic Waves and Applications*, Vol. 24, No. 7, 993–1003, 2010.
39. Soltani, S., M. N. Azarmanesh, E. Valikhanloo, and P. Lotfi, "Design of a simple single-feed dual-orthogonal-linearly-polarized slot antenna for concurrent 3.5 GHz WIMAX and 5 GHZ WLAN access point," *Journal of Electromagnetic Waves and Applications*, Vol. 24, No. 13, 1741–1750, 2010.