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DIRECTIONAL SENSITIVE MODULATION SIGNAL TRANSMITTED BY MONOPULSE CASSEGRAIN ANTENNA FOR PHYSICAL LAYER SECURE COMMUNICATION

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Abstract—The broadcast nature of the wireless medium makes the communication over this medium vulnerable to eavesdropping. In this paper, we propose a directional sensitive modulation signal transmitted by Monopulse Cassegrain antenna for physical (PHY) layer security transmission. The main idea is that the sum beam transmit communication signal, simultaneously, and two difference beams transmit artificial noise to guarantee secure transmission of the sum beam. The eavesdropper's channel is degraded by artificial noise, but the desired receiver's channel does not affect because of the spatial orthogonality between the sum beam and two difference beams. In this way, the desired receiver can demodulate the communication signal while the eavesdroppers learn almost nothing about the information from its observations. A closed-form expression of the secrecy capacity is also derived for this practical transmit scheme from the viewpoint of information theoretic. Finally, simulation results show that the proposed signal can significantly improve the performance of secure wireless communications.

1. INTRODUCTION

The Monopulse Cassegrain antenna is widely used for search-and-track purpose in modern radar system [1–4]. The sum beam and two spatially orthogonal difference beams receive the reflected signal, simultaneously, to determine the directional information of the target based on the principle of Monopulse direction-finding. The direction

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of arrival with respect to the receiver is measured via computation of a variable named Monopulse ratio, which is the ratio of the difference and sum signals [5, 6]. The Monopulse antenna is used to receive signal in the aforementioned papers, while a goal of this paper is to employ the Monopulse Cassegrain antenna as a transmit system for secure communication applications.

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. Physical (PHY) layer security is an emerging research area that explores the possibility of achieving perfect-secrecy data transmission among desired receiver without relying on upper layer data encryption. The paper to be found in this area can be clustered into two categories [7]: one deals with information theoretic aspects, and the other focuses on practical scenarios. The first category of paper provides information theoretic results for wireless PHY layer security. Papers [8–11] investigate the secrecy capacity of the multiple-input multiple-output (MIMO) system. Paper [12] gives the secrecy capacity region between a single transmitter and multiple receivers in a broadcast channel in the presence of an eavesdropper. Papers [13–15] characterize the secrecy capacity of the cooperative transmission system for different cooperative schemes. Papers [16, 17] derive a closed-form expression for the secrecy capacity by adding artificial noise which degrades the eavesdropper's channel but does not affect channel of the desired receiver. The second category of literature focuses on more practical aspects of wireless PHY layer security. Papers [18, 19] make use of channel randomness and rotation matrix, respectively, to secure orthogonal frequency division multiplexing (OFDM) system. Paper [20] proposes a space-time coding scheme for impulse radio ultra-wideband (UWB) systems. Paper [21] utilizes the random antenna array to guarantee PHY layer security in the fading channel environment.

In related work, [16, 17] present a technique by adding artificial noise in MIMO system and relay system to guarantee the PHY layer security at prerequisites of that artificial noise degrades the eavesdropper's channel but does not affect channel of the desired receiver completely. However, these papers only give the conclusion of the secrecy capacity for different communication systems from the viewpoint of information theoretic and do not concern with the practical scenarios. Determining how to add artificial noise in practical communication system to satisfy the prerequisites is a crucial problem. Papers [22, 23] describe an inverse Monopulse technique to communication and track with aerial-platform for the requirement of miniaturization receiver. These works prove that the Monopulse antenna can be used to transmit communication signal. Papers [24, 25] propose a directional modulation technique using a phased array, which transmit different constellations at different directions. The constellation points maintain their positions at the desired direction but scramble at the undesired directions. Paper [26] presents a similar directional modulation signal using an array with pattern-reconfigurable elements. Paper [27] introduces a near-field direct antenna modulation technique similar to the directional modulation technique, which forms a directional modulation signal by two transmit beams or multiple transmit beams. Papers [24–27] stand from the viewpoint of signal constellation to guarantee 1-dimensional directional PHY layer secure communication.

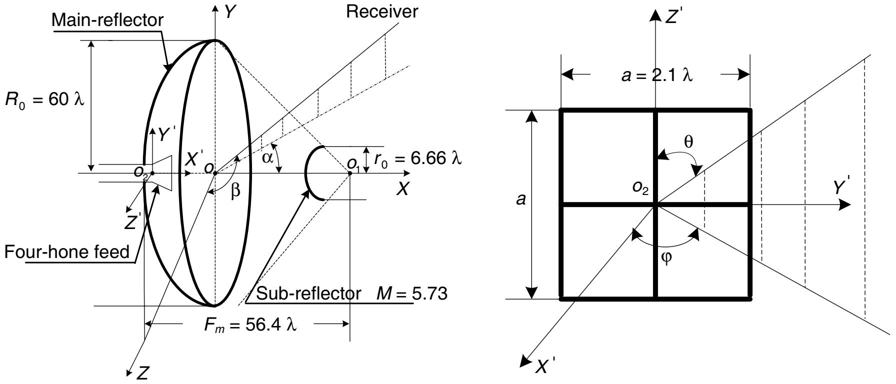
Our work in this paper is different from the aforementioned works in the following aspects: i) A practical communication system is designed for secure communication applications by adding artificial noise. ii) The Monopulse Cassegrain antenna is employed to transmit communication signal for the purpose of security communication. The sum beam transmit communication signal with the desired receiver, simultaneously, two difference beams transmit artificial noise to guarantee secure transmission of the sum beam. The prerequisites are satisfied by the characteristic of the spatial orthogonality between the sum beam and two difference beams. iii) The constellation of the transmit signal is scrambled by artificial noise at the undesired directions. Furthermore, the transmit signal guarantees 2-dimensional directional PHY layer security transmission. Therefore, this communication signal transmitted by the Monopulse Cassegrain antenna is sensitive for the direction of the receiver, so we call it directional sensitive modulation signal.

The remainder of this paper is organized as follows. Section 2 gives the geometry of the Cassegrain antenna with a four-horn feed and the excitation mode for the four-horn feed. Section 3 introduces the communication signal model. The security performance is analyzed in Section 4. Finally, the performances of the directional sensitive modulation signal are investigated by computer simulation in Section 5.

2. THE GEOMETRY OF THE CASSEGRAIN ANTENNA WITH A FOUR-HORN FEED

The geometry of the Cassegrain antenna and the four-horn feed are shown in Figures 1(a) and (b), respectively, similar to the traditional Cassegrain antenna system [4, 28, 29].

In Figure 1, φ and θ denote an azimuth angle and an elevation



(a) (b)

Figure 1. The coordinate system and the geometry of the transmit system. (a) The geometry of the Cassegrain antenna. (b) The geometry of the four-horn feed.

angle for the primary coordinate system $X'Y'Z'$. α and β denote an azimuth angle and an elevation angle for the secondary coordinate system XYZ. R_0 and r_0 are the radius of the main-reflector and sub-reflector, respectively. F_m is the focal length of the main-reflector. M is the magnification factor of the sub-reflector, and a is the total length of the four-horn feed. Similar to Monopulse radar excitation scheme, a sum beam, a H-plane difference beam and a E-plane difference beam are formed by the TE_{10} mode. The aperture field distribution of the sum beam is written as:

$$h^{\Sigma}(y',z') = h_E^{\Sigma}(y')h_H^{\Sigma}(z') = \sin\left|\left(\frac{2\pi}{a}\right)z'\right| \tag{1}$$

According to aperture antenna theory, the primary radiation pattern of the sum beam can be expressed as:

$$\begin{aligned} f_{\Sigma}(\varphi,\theta) &= \int_{-a/2}^{a/2}\int_{-a/2}^{a/2} h^{\Sigma}(y',z')e^{jky'\sin\theta\sin\varphi + jkz'\cos\theta}dy'dz' \\ &= a^2\pi\cdot\frac{\sin[(\pi a/\lambda)\sin\theta\sin\varphi]}{(\pi a/\lambda)\sin\theta\sin\varphi}\cdot\frac{1+\cos[(\pi a/\lambda)\cos\theta]}{\pi^2-[(\pi a/\lambda)\cos\theta]^2} \end{aligned} \tag{2}$$

Consider the shielding effect of sub-reflector, the secondary radiation pattern can be written as:

$$\begin{aligned} F_\Sigma(\alpha,\beta) \;=\; &\int_{-R_0}^{R_0}\int_{-\sqrt{R_0^2-z^2}}^{\sqrt{R_0^2-z^2}} f_\Sigma(\varphi,\theta)e^{jky\sin\beta\sin\alpha+jkz\cos\beta}dydz \\ &-\int_{-r_0}^{r_0}\int_{-\sqrt{r_0^2-z^2}}^{\sqrt{r_0^2-z^2}} f_\Sigma(\varphi,\theta)e^{jky\sin\beta\sin\alpha+jkz\cos\beta}dydz \end{aligned} \tag{3}$$

The aperture field distributions of the H-plane and E-plane difference beams are represented by Equations (4) and (5), respectively.

$$h^{\Delta\varphi}(y',z') \;=\; h_E^{\Delta\varphi}(y')h_H^{\Delta\varphi}(z') = \sin\left[\left(\frac{2\pi}{a}\right)z'\right] \tag{4}$$

$$h^{\Delta\theta}(y',z') \;=\; h_E^{\Delta\theta}(y')h_H^{\Delta\theta}(z') = \begin{cases} \sin\left|\left(\frac{2\pi}{a}\right)z'\right|, & 0\le y'\le\frac{a}{2} \\ -\sin\left|\left(\frac{2\pi}{a}\right)z'\right|, & -\frac{a}{2}\le y'<0 \end{cases} \tag{5}$$

And the primary radiation pattern of the H-plane and E-plane difference beams are expressed as:

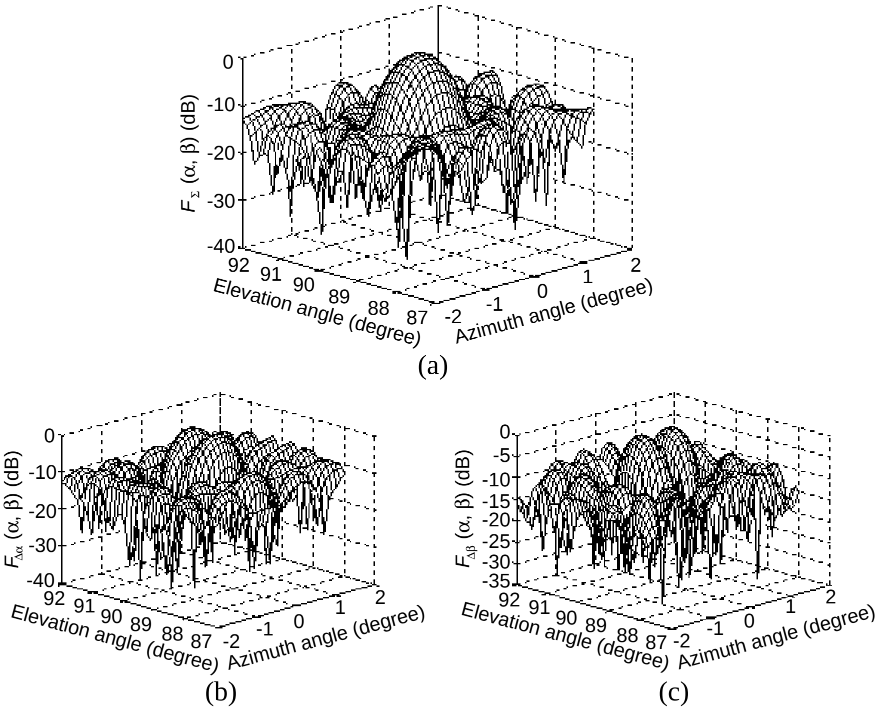
$$\begin{aligned} f_{\Delta\varphi}(\varphi,\theta) &= \int_{-a/2}^{a/2}\int_{-a/2}^{a/2} h^{\Delta\varphi}(y',z')e^{jky'\sin\theta\sin\varphi+jkz'\cos\theta}dy'dz' \\ &= a^2\pi\cdot\frac{\sin[(\pi a/\lambda)\sin\theta\sin\varphi]}{(\pi a/\lambda)\sin\theta\sin\varphi}\cdot\frac{\sin[(\pi a/\lambda)\cos\theta]}{\pi^2-[(\pi a/\lambda)\cos\theta]^2} \end{aligned} \tag{6}$$

$$\begin{aligned} f_{\Delta\theta}(\varphi,\theta) &= \int_{-a/2}^{a/2}\int_{-a/2}^{a/2} h^{\Delta\theta}(y',z')e^{jky'\sin\theta\sin\varphi+jkz'\cos\theta}dy'dz' \\ &= \frac{a^2\pi}{2}\cdot\frac{1-\cos[(\pi a/\lambda)\sin\theta\sin\varphi]}{(\pi a/\lambda)\sin\theta\sin\varphi}\cdot\frac{1+\cos[(\pi a/\lambda)\cos\theta]}{\pi^2-[(\pi a/\lambda)\cos\theta]^2} \end{aligned} \tag{7}$$

The secondary radiation pattern of the H-plane and E-plane difference beams can be written as:

$$\begin{aligned} F_{\Delta\alpha}(\alpha,\beta) \;=\; &\int_{-R_0}^{R_0}\int_{-\sqrt{R_0^2-z^2}}^{\sqrt{R_0^2-z^2}} f_{\Delta\varphi}(\varphi,\theta)e^{jky\sin\beta\sin\alpha+jkz\cos\beta}dydz \\ &-\int_{-r_0}^{r_0}\int_{-\sqrt{r_0^2-z^2}}^{\sqrt{r_0^2-z^2}} f_{\Delta\varphi}(\varphi,\theta)e^{jky\sin\beta\sin\alpha+jkz\cos\beta}dydz \end{aligned} \tag{8}$$

$$\begin{aligned} F_{\Delta\beta}(\alpha,\beta) \;=\; &\int_{-R_0}^{R_0}\int_{-\sqrt{R_0^2-z^2}}^{\sqrt{R_0^2-z^2}} f_{\Delta\theta}(\varphi,\theta)e^{jky\sin\beta\sin\alpha+jkz\cos\beta}dydz \\ &-\int_{-r_0}^{r_0}\int_{-\sqrt{r_0^2-z^2}}^{\sqrt{r_0^2-z^2}} f_{\Delta\theta}(\varphi,\theta)e^{jky\sin\beta\sin\alpha+jkz\cos\beta}dydz \end{aligned} \tag{9}$$



(a)

(b)

(c)

Figure 2. Radiation patterns of the Monopulse Cassegrain antenna. (a) Sum beam. (b) H-plane difference beam. (c) E-plane difference beam.

Figure 2 shows the radiation patterns of the sum beam, H-plane difference beam and E-plane difference beam. According to the power coverage characteristics of these beams, the sum beam is used to transmit the communication signal with the desired receiver. Simultaneously, the H-plane and E-plane difference beams are used to transmit artificial noise which cannot make the eavesdropping receiver demodulate the receive signal. It is noted that the directional information is obtained by the Monopulse Cassegrain antenna used for direction finding or a GPS module with high angular accuracy [30, 31] before the communication information transmission. Therefore, we consider that the sum beam broadside has been directed to the desired receiver.

3. SECURE COMMUNICATION SIGNAL MODEL

According to [23], the receive signal can be expressed by Equation (10), when multiple beams are used to transmit the communication signal.

$$r(k,\alpha,\beta)=\left[F_{\Sigma}(\alpha,\beta)\quad F_{\Delta\alpha}(\alpha,\beta)e^{-j\psi_1}\quad F_{\Delta\beta}(\alpha,\beta)e^{-j\psi_2}\right]\begin{bmatrix} s(k)\\ x_\alpha(k)\\ x_\beta(k)\end{bmatrix} +w(k) \tag{10}$$

where $s(k)=c_{11}(k)+j\cdot c_{12}(k)$ denotes the communication signal with power σ_s^2. $x_\alpha(k)=c_{21}(k)+j\cdot c_{22}(k)$ denotes the azimuth artificial noise transmitted by $F_{\Delta\alpha}(\alpha,\beta)$ with power σ_x^2. $x_\beta(k)=c_{31}(k)+j\cdot c_{32}(k)$ denotes the elevation artificial noise transmitted by $F_{\Delta\beta}(\alpha,\beta)$ with power σ_x^2. Therefore, the total power of the transmit signal $P_0=\sigma_s^2+2\sigma_x^2$. ψ_1 and ψ_2 are the random error phases between the sum beam with the two difference beams which are caused by the excitation channel of these multiple beams, and $w(k)$ is Additive White Gaussian Noise (AWGN) samples with variance σ_n^2. From Equation (10), the baseband signal can be written as:

$$\begin{bmatrix} X(k)\\ Y(k)\end{bmatrix}=\begin{bmatrix} c_{11}(k) & c_{21}(k) & c_{22}(k) & c_{31}(k) & c_{32}(k)\\ c_{12}(k) & c_{22}(k) & -c_{21}(k) & c_{32}(k) & -c_{31}(k)\end{bmatrix}\begin{bmatrix} F_{\Sigma}(\alpha,\beta)\\ F_{\Delta\alpha}(\alpha,\beta)\cos\psi_1\\ F_{\Delta\alpha}(\alpha,\beta)\sin\psi_1\\ F_{\Delta\beta}(\alpha,\beta)\cos\psi_2\\ F_{\Delta\beta}(\alpha,\beta)\sin\psi_2\end{bmatrix} \tag{11}$$

where $X(k)$ and $Y(k)$ denote the in-phase baseband component and the quadrature baseband component of the receive signal, respectively. The complex baseband signal $Z(k)$ equals $X(k)+jY(k)$. In [16, 17], AWGN signal is selected as the artificial noise $x_\alpha(k)$ and $x_\beta(k)$ from the viewpoint of information theoretic, because these papers do not

Table 1. Design of the artificial noise.

Communication information	QPSK symbol	Azimuth artificial noise $x_\alpha(k)$	Elevation artificial noise $x_\beta(k)$
$c_{11}=1$, $c_{12}=1$	$1+j$	$c_{21}=1$, $c_{22}=-1$	$c_{31}=-1$, $c_{32}=1$
$c_{11}=1$, $c_{12}=-1$	$1-j$	$c_{21}=1$, $c_{22}=1$	$c_{31}=-1$, $c_{32}=-1$
$c_{11}=-1$, $c_{12}=-1$	$-1-j$	$c_{21}=-1$, $c_{22}=1$	$c_{31}=1$, $c_{32}=-1$
$c_{11}=-1$, $c_{12}=1$	$-1+j$	$c_{21}=-1$, $c_{22}=-1$	$c_{31}=1$, $c_{32}=1$

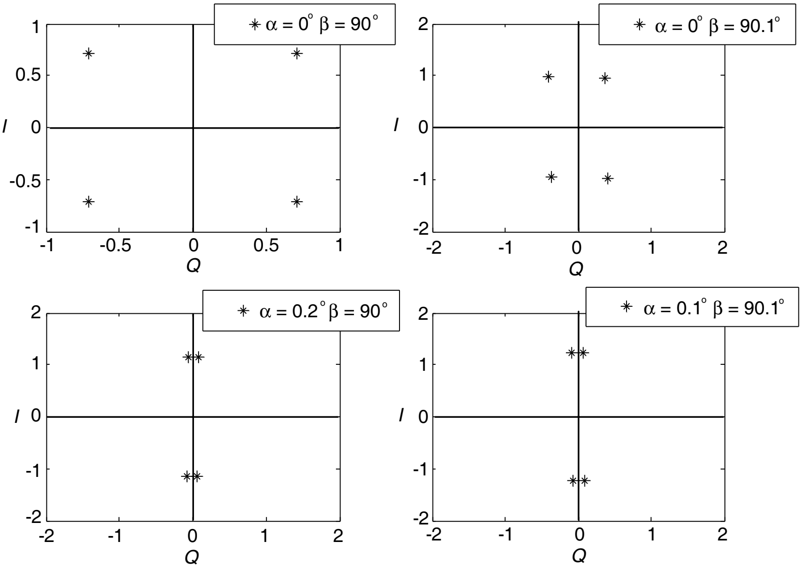


Figure 3. Constellation diagrams of the signal when the receiver at different directions.

concern practical communication signal form and transmit scheme. According to the Monopulse Cassegrain antenna transmit scheme and QPSK signal of this study, we design the artificial noise $x_\alpha(k)$ and $x_\beta(k)$ as shown in Table 1.

Figure 3 shows the constellation diagrams of the receive signal, alone with the receiver at ($\alpha = 0°$, $\beta = 90°$), ($\alpha = 0°$, $\beta = 90.2°$), ($\alpha = 0.2°$, $\beta = 90°$) and ($\alpha = 0.2°$, $\beta = 90.2°$), respectively. We can find that the constellation diagram is the same as the traditional QPSK modulation when the receiver is at ($\alpha = 0°$, $\beta = 90°$), while the constellation points become distorted when the receiver is out of the direction ($\alpha = 0°$, $\beta = 90°$).

4. ANALYSIS OF SECURITY PERFORMANCE

The receive signal for the desired receiver and the eavesdropping receiver can be denoted by $r(k, \alpha_0, \beta_0)$, $(\alpha_0, \beta_0) = (0°, 90°)$ and $r(k, \alpha_1, \beta_1)$, (α_1, β_1), respectively. For the desired receiver, the sum beam transmitting the communication signal can reach the maximum gain in the direction of (α_0, β_0). Simultaneously, the two difference beams transmitting the artificial noise can reach null steering in the direction of (α_0, β_0). Therefore, the receive signal $r(k, \alpha_0, \beta_0)$ can be demodulated as the ordinary QPSK signal. Compared with the desired receiver, the eavesdropping receiver receives the communication signal and the artificial noise in the direction of (α_1, β_1) simultaneously. The interference to signal ratio (ISR) can be written as:

$$\text{ISR (dB)} = 10 * \log_{10} \frac{\left|F_{\Delta\alpha}(\alpha_1, \beta_1)\right|^2 \sigma_x^2 + \left|F_{\Delta\beta}(\alpha_1, \beta_1)\right|^2 \sigma_x^2}{\left|F_{\Sigma}(\alpha_1, \beta_1)\right|^2 \sigma_s^2} \tag{12}$$

From the viewpoint of information theoretic [16], the secrecy capacity C_{sec}^a of this scheme is expressed below by the difference in mutual information between the transmitter and the desired receiver versus the transmitter and the eavesdropping receiver:

$$\begin{aligned} C_{\text{sec}}^a &= I(R;U) - I(E;U) \\ &= \log_2\left(1 + \frac{\left|F_{\Sigma}(\alpha_0, \beta_0)\right|^2 \sigma_s^2}{\sigma_{n0}^2}\right) \\ &\quad - \log_2\left(1 + \frac{\left|F_{\Sigma}(\alpha_1, \beta_1)\right|^2 \sigma_s^2}{\left|F_{\Delta\alpha}(\alpha_1, \beta_1)\right|^2 \sigma_x^2 + \left|F_{\Delta\beta}(\alpha_1, \beta_1)\right|^2 \sigma_x^2 + \sigma_{n1}^2}\right) \end{aligned} \tag{13}$$

where σ_{n0}^2 denotes the noise power for the desired receiver, and σ_{n1}^2 denotes the noise power for the eavesdropping receiver. From Equation (13), C_{sec}^a is associated with the direction of the eavesdropping receiver and the power of the artificial noise. The worst case situation would occur if $|F_{\Delta\alpha}(\alpha_1, \beta_1)| \to 0$ and $|F_{\Delta\beta}(\alpha_1, \beta_1)| \to 0$ (e.g., $(\alpha_1, \beta_1) \to (\alpha_0, \beta_0)$). The minimum secrecy capacity is close to zero ($C_{\text{sec}}^a \to 0$) in this situation. The best case situation would occur if $\sigma_x^2 \gg \sigma_s^2$ or $|F_{\Sigma}(\alpha_1, \beta_1)|^2 \to 0$. The maximum secrecy capacity can reach AWGN channel capacity ($C_{\text{sec}}^a \to \log_2(1 + \frac{|F_{\Sigma}(\alpha_0, \beta_0)|^2 \sigma_s^2}{\sigma_{n0}^2})$).

5. SIMULATION RESULTS

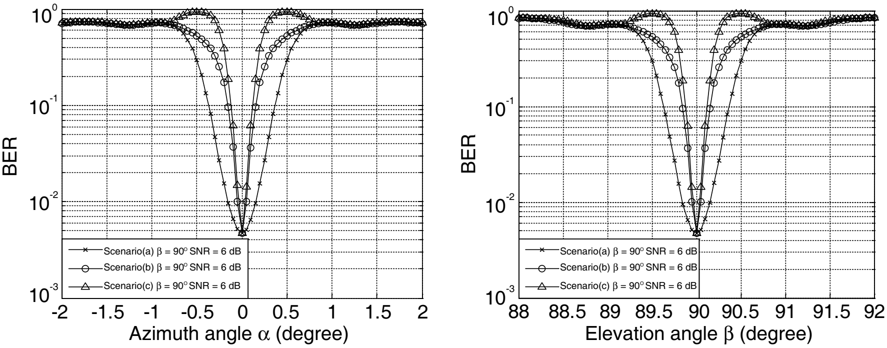
The simulation conditions are supposed as follows:

(1) Consider three cases: (a) the sum beam is used to transmit the communication signal (as the traditional transmitter); (b) the sum beam is used to transmit the communication signal; the two difference beams are used to transmit the artificial noise; AWGN signal is selected as the artificial noise; (c) the transmit scheme is the same as (b), but the design signal shown in Table 1 is selected as the artificial noise.

(2) In order to compare the bit error ratio (BER) performances of these cases, the communication signal transmitted by the sum

beam at (0°, 90°) as a 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 (0°, 90°). It means that the adding power of AWGN is the same for all directions.

Figure 4 shows the BER performance versus direction information for three different scenarios as the desired receiver is at (0°, 90°) and other eavesdropping receivers from (−2°, 88°) to (2°, 92°). We can find that scenario (b) and scenario (c) offer a more rapid decay rate of BER over the scenario (a) not in reducing the pattern beam-width but rather by reducing the information beam-width. Furthermore, the artificial noise designed in Table 1 can achieve a better jamming effect for the eavesdropping receiver.



(a) (b)

Figure 4. BER performance versus direction information when SNR equals to 6 dB and $\sigma_s^2 = \sigma_x^2$. (a) BER performance versus azimuth angle. (b) BER performance versus elevation angle.

Figure 5 shows the BER performance versus the signal to noise ratio (SNR) as the desired receiver is at (0°, 90°), simultaneously, other eavesdropping receivers at (0.05°, 90.05°) and (0.1°, 90.1°). The BER performance for the eavesdropping receivers reduces about three and five orders of magnitude compared with the desired receiver when SNR equals 10 dB.

We define $u = \frac{\sigma_x^2}{\sigma_s^2}$ to denote the artificial noise power to the communication signal power ratio (ACR). Figure 6 shows the BER performance versus ACR when SNR equals 6 dB. The curves show that the BER performance is not affected by the desired receiver while BER performance decays rapidly with the artificial noise power increasing for the eavesdropping receivers at (0.05°, 90.05°) and (0.1°, 90.1°), respectively.

Figure 7 shows that the secrecy capacity of this system varies with the SNR when the eavesdropping receivers are at (0°, 90°), (0.1°, 90.1°) and (0.2°, 90.2°), respectively. The worst case situation would occur if the eavesdropping receiver is at (0°, 90°) the same direction of the desired receiver. The secrecy capacity equals zero for this worst case situation. Figure 8 shows the secrecy capacity versus the SNR, alone with $u = 1$, $u = 2$, $u = 3$, and $u \to \infty$, respectively, when a eavesdropping receiver is at (0.05°, 90.05°). The secrecy capacity increases with the artificial noise power even if the eavesdropping receiver is very close to the desired receiver.

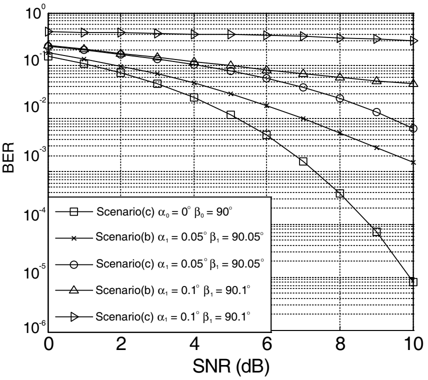


Figure 5. BER performance versus SNR when $\sigma_s^2 = \sigma_x^2$.

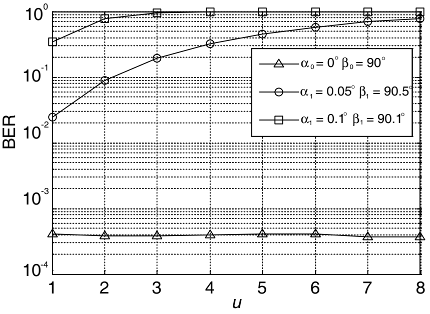


Figure 6. BER performance versus ACR when SNR equals to 6 dB.

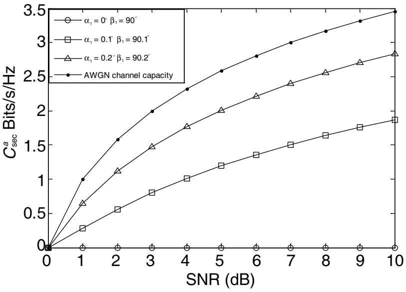


Figure 7. Secrecy capacity versus SNR when the eavesdropping receivers in different directions.

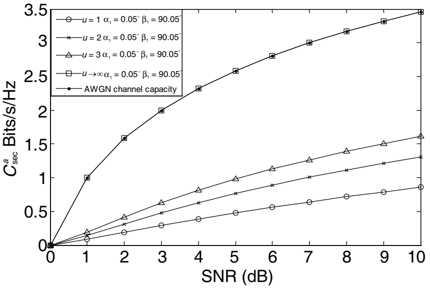


Figure 8. Secrecy capacity versus SNR when $u = 1$, $u = 2$, $u = 3$, and $u \to \infty$, respectively.

6. CONCLUSION

This paper considers the problem of PHY layer secure communication by adding artificial noise in practical scenario. The Monopulse Cassegrain antenna is employed to transmit the directional sensitive modulation signal, which utilizes the characteristic of the spatial orthogonality between the sum beam and two difference beams to guarantee the secure communication of the sum beam. The closed-form expression of the secrecy capacity is also derived for this practical transmit scheme from the viewpoint of information theoretic. The PHY security communication by adding artificial noise wastes the transmit power of the transmitter. However, this scheme can also be applied to same special applications, especially in military and homeland security applications such as secure communication with satellite and airplane. Future studies on the problem such as design a practical relay system by adding artificial noise are required.

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