Performance of multi-antenna wireless systems based on time reversal

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Abstract. 5G wireless mobile communication system is faced with massive equipment access, information security and effective transmission is worth paying attention to. Wireless physical layer security mainly uses encryption principle to enhance the security of information transmission, while time reversal technology combines its electromagnetic characteristics and physical channel characteristics to improve the security performance of wireless communication system. In this paper, a signal transmission model of wireless multi-antenna communication system based on time reversal cavity is proposed and white Gaussian noise is introduced. The simulation results show that the space-time focusing characteristics of time reversal cavity can make the signal energy more concentrated on the target user, which can not only effectively alleviate the communication quality problems caused by multipath effect, but also ensure the security of information transmission process.

1. Introduction

Wireless communication is closely related to People's Daily life, involving people's food, clothing, housing, transportation and other aspects. People can enjoy the speed and convenience brought by wireless communication. With the rapid development of technology, 5G wireless networks have spawned a host of new services. However, security issues in wireless networks also involve national security, financial security, information security, personal privacy and so on, which has been concerned by people.

Ensuring the security of wireless communication is a challenging task. In fact, network security protocol design is a frequently referenced approach in layered communication systems, but security protocols are different at different layers. People tend to overlook the most basic communication layer, the physical layer, which encodes and modulates information. Because the most basic information coding and modulation are ignored, it means that the security of modern communication system is actually incomplete. The physical layer is unique in wireless communication. In a typical multipath wireless scenario, the channel response corresponding to the propagation path is frequency selective and is determined by the spatial location [1]. The unique spatial and frequency characteristics of the physical layer of wireless communication provide a solid foundation for the establishment of new security services in the physical layer.
1.1. Background
At present, the research of physical layer security has made great progress in source coding, key extraction algorithm, cooperative interference, message authentication, artificial noise, direction modulation and so on. Artificial noise and directional modulation techniques are briefly introduced below.

Artificial noise technology [2],[3]: Artificial noise technology is a common physical layer security technology. The main principle of this technology is to add artificial noise to the signal of the transmitter. The information will produce great interference to eavesdroppers, but will not have any impact on the legitimate users. Although the signal consumes some power during transmission, it is worth it in terms of information security and confidentiality. In the process of information transmission, artificial noise will interfere the channel of eavesdroppers, but has no impact on legitimate users, which ensures the security of wireless information transmission.

Directional modulation technology [4]: Directional modulation technology is an advanced technology for secure transmission at the physical layer. Its main principle is to combine beamforming technology with artificial noise, to improve the security of communication system. Different from the traditional beamforming technology, it can ensure that the directional signal can be transmitted as expected. However, the traditional directional modulation technology has the problem of Angle dependence, which makes it difficult to achieve accurate communication.

2. Time Reversal
Time Reversal (TR) is a technique derived from the detection of target media in optics. In recent years, TR technology has attracted much attention due to its unique space-time focusing characteristics. With the in-depth study of this technology, time reversal technology has been widely applied in ultrasonic lithotriptic, underwater acoustic communication and other aspects. In 2004, Professor M.Fink introduced TR technology to the electromagnetic field. Through the operation of time reversal of electromagnetic wave or electromagnetic signal, many novel phenomena are generated. Thus, many new techniques based on time-reversal electromagnetics are derived, such as nondestructive testing, large-capacity wireless communication, super-resolution imaging and detection, localized energy transmission and power synthesis, etc.

2.1. Time Reversal theory
Wave equation is a mathematical definition describing the motion of electromagnetic waves, which is mainly derived from Maxwell's equations. The propagation of electromagnetic waves follows the wave equation. The wave equation is also the mathematical basis of time reversal. Assuming $\phi(r, t)$ is a scalar function of the electromagnetic field, then the scalar wave equation of the passive field can be denoted as [5]

$$\nabla^2 \phi(r, t) - \frac{1}{v^2} \frac{\partial^2}{\partial t^2} \phi(r, t) = 0 \quad (1)$$

The general solution to this equation is

$$\phi(r, t) = \frac{g_1\left(\frac{t-r}{v}\right)}{r} + \frac{g_2\left(\frac{t+r}{v}\right)}{r} \quad (2)$$

Where, $v^2 = \frac{1}{\mu \varepsilon}$, $g_1(x)$ and $g_2(x)$ are any functions. The solution of the wave equation can be expressed as

$$\phi(r, t) = \frac{g_1\left(\frac{t-r}{v}\right)}{r} \quad (3)$$
\[ \phi \left( r, t \right) = g \left( t + \frac{r}{v} \right) \]  
(4)

It can be seen from the above equation that \( \phi \left( r, t \right) \) are two types of waves propagating towards each other. By time reversal operation for \( \phi \left( r, t \right) \), we can get

\[ \phi \left( r, -t \right) = g \left( -t + \frac{r}{v} \right) \]  
(5)

It can be inferred that the \( \phi \left( r, -t \right) \) after time reversal is also the solution of the wave equation.

Similarly, \( \phi_{2} \left( r, -t \right) \) after time reversal of \( \phi_{2} \left( r, t \right) \) also satisfies the solution of the wave equation. \( \phi \left( r, -t \right) \) is also a solution to the wave equation. If \( T - t \) is replaced by \( t \) (\( T \) is a constant), then \( \phi \left( r, T - t \right) \) is also a solution to the wave equation.

If it is in a homogeneous and dispersion-free passive field, the electromagnetic field \( \vec{E}, \vec{H} \) should also satisfy the homogeneous vector wave equation, so it is denoted as:

\[ \nabla^{2} \vec{E} \left( r, t \right) - \mu \epsilon \frac{\partial^{2}}{\partial t^{2}} \vec{E} \left( r, t \right) = 0 \]  
(6)

\[ \nabla^{2} \vec{H} \left( r, t \right) - \mu \epsilon \frac{\partial^{2}}{\partial t^{2}} \vec{H} \left( r, t \right) = 0 \]  
(7)

Where, \( \epsilon \) is the dielectric constant, \( \mu \) is the permeability, and both are related to the spatial position \( r \). \( \vec{E} \left( r, t \right) \) is the solution of the vector wave equation, and it can be inferred that \( \vec{E} \left( r, -t \right) \) should also be the solution of the vector wave equation. Similarly, \( \vec{H} \left( r, t \right) \) is the solution of the vector wave equation, and \( \vec{H} \left( r, -t \right) \) is also the solution of the vector wave equation. If the time reversal does not replace \( t \) with \( -t \), but replaces \( t \) with \( T - t \) (\( T \) is a constant), then \( \vec{E} \left( r, T - t \right) \) or \( \vec{H} \left( r, T - t \right) \) is also the solution of the wave equation.

2.2. Characteristics of time reversal,

Time reversal (TR) technology has great potential in wireless communication systems [6]. For example:

- strong anti-interference capability: In the non-line of sight complex environment, the spatial focusing effect of time reversal is more obvious. In the rich multipath scattering environment, time reversal views the multipath channel as a distributed antenna. Therefore, time reversal can effectively eliminate inter-symbol Interference (ISI), inter-user Interference (IUI) [7], etc. Due to its unique characteristics, it can effectively capture the energy of multipath propagation signal, so the SNR of the system is effectively improved.
Scalability of network density: When the distance exceeds a certain range, communication may fail. In TR wireless communication systems, different users will have different resonance effects, which are caused by impulse response rather than distance. In TR wireless communication systems, new access points can effectively receive signals from base stations, and the same spectrum will not cause too much interference. Therefore, TR technology provides more scalability for wireless communication and improves the security of communication system [8].

Wireless channel security: TR technology is used to focus energy in a specific time and space. Meanwhile, signals are too low to be detected outside the focus. TR technology can use multipath effect to focus energy in time domain and space domain [1],[3]. This focus of energy plays an important role in high resolution and ensuring the security of the information [9].

3. Wireless communication system based on time reversal cavity

TR technology is to reverse the order of the signal in the time domain, which is equivalent to the conjugate in the frequency domain. The resultant signal has the characteristics of compression and space-time focus. The simple description of the time reversal process is: when the time domain signal sent by the point source is received by the receiver, the receiver resends the received time domain signal to the source in the first-come-last-sent and last-to-first-sent modes. In other words, it’s time reversed and then sent back to the source.

Based on this, the main tasks of this section are:
1. Introduce time reversal cavity (TRC) [10] into wireless communication system and establish mathematical model;
2. According to the design of the model, the safety performance of the designed system model is evaluated and analyzed.

3.1. Model for multiple antenna system based on time reversal cavity

Time reversal cavity (TRC) has been studied in medical ultrasound in the past, either in shock wave therapy or imaging [11]. This section studies the principle of wireless communication signal transmission based on the time reversal cavity. The system schematic diagram is shown in Figure 1.

![Figure 1. Communication system diagram based on time reversal.](image)

In the Figure 1, it is assumed that the signal $S(t)$ is sent from the source and propagated to the receiving point $R(h_r, r_l)$ through channel 1. After the signal at the receiving point $R(h_r, r_l)$ is superposed with the local interference noise $n_r(t)$, $x_r(t)$ is output. $x_r(t)$ passes through the time reversal cavity to obtain $x_r(-t)$ and then resends. After the time reversal signal $x_r(-t)$ is transmitted through channel 2, the receiving signal $y_r(t, h, r)$ of the final receiver is obtained, and the signal is gathered at the receiver.

According to the figure 1, $x_r(t)$ is the signal at the receiving point, and the expression is

$$x_r(t, h, r_l) = s(t) \otimes h_r(t, h, r_l) + n_r(t)$$  \hspace{1cm} (8)

Where, $\otimes$ represents convolution. The output of channel 2 is

$$y_r(t, h, r) = x_r(-t) \otimes h_r(t, h, r_l) + n_r(t)$$  \hspace{1cm} (9)
Assuming that the impulse response of channel 1 and channel 2 is the same, and the noise is not considered, then
\[
y_i(t, h, r) = s(-t) \otimes h_i(-t, h, r) \otimes h_i(t, h, r)
\]  
(10)
The total impulse response of channel 1 and channel 2 is
\[
h(t, h, r) = h_i(-t, h, r) \otimes h_i(t, h, r)
\]  
(11)
When \( \tau = 0 \), the peak of the channel impulse response is obtained.
\[
y_i(t, h, r) = s(-t) h_i^2(t, h, r)dt
\]  
(12)
It can be seen from the above equation that the more channels there are, the higher the output peak value of the time reversal cavity is and the more concentrated the energy is.
Assume that the system consists of an energy transmitter consisting of \( M \) antennas and \( N \) users. Each user is configured with an antenna. The base station antenna emits energy signals to each user.

The transmission response matrix between the transmitter and receiver is represented by \( H \).

\[
H = \begin{bmatrix}
h_{11} & h_{12} & \cdots & h_{1M} \\
h_{21} & h_{22} & \cdots & h_{2M} \\
\vdots & \vdots & \ddots & \vdots \\
h_{N1} & h_{N2} & \cdots & h_{NM}
\end{bmatrix}
\]  
(13)
Where, \( h_{ij} \) \( (i=1,2,...N; j=1,2,...M) \) represents the channel transmission coefficient from the \( j \) TH energy transmitter antenna to the \( i \) TH receiver antenna.

Assume that the complex signal vector emitted by \( N \) user receiver antennas is \( \vec{r} = [r_1, r_2, ..., r_N]^T \). Then the signal received by the \( j \) TH antenna of the transmitter is \( t_j = \sum_{i=1}^{M} r_i h_{ij} \). In the process of signal transmission, the energy signal vector to be transmitted by the transmitter antenna is \( \vec{e} = [e_1, e_2, ..., e_N]^T \), TRC preoperation is performed on \( t_j \), and the power signal of the \( j \) TH transmitting antenna is \( e_j t_j^* \), so the received signal of the antenna of the \( k \) TH user antenna is
\[
P_k = \sum_{j=1}^{M} e_j t_j^* h_{kj} = \sum_{j=1}^{M} \sum_{i=1}^{N} e_j r_i^* h_{ij} h_{kj}
\]  
(14)
The received signals of \( N \) users are expressed as vectors, then the total energy transmission matrix is \( a_{TRC} = T_{TRC} \vec{e} \), \( T_{TRC} \in \mathbb{C}^{(N \times M)} \) and the expression is
\[
T_{TRC} = \begin{bmatrix}
\sum_{i=1}^{N} r_i^* h_{i1}^* h_{11} & \sum_{i=1}^{N} r_i^* h_{i2}^* h_{12} & \cdots & \sum_{i=1}^{N} r_i^* h_{iM}^* h_{1M} \\
\sum_{i=1}^{N} r_i^* h_{i1}^* h_{21} & \sum_{i=1}^{N} r_i^* h_{i2}^* h_{22} & \cdots & \sum_{i=1}^{N} r_i^* h_{iM}^* h_{2M} \\
\vdots & \vdots & \ddots & \vdots \\
\sum_{i=1}^{N} r_i^* h_{i1}^* h_{N1} & \sum_{i=1}^{N} r_i^* h_{i2}^* h_{N2} & \cdots & \sum_{i=1}^{N} r_i^* h_{iM}^* h_{NM}
\end{bmatrix}
\]  
(15)
Where the conjugate and transpose of the vector \( \vec{x} \) or the matrix \( X \) are correspondingly represented as \( (\vec{x})^T \) and \( (X)^T \) [5]. The above equation can be used to obtain the energy focusing in space after TRC processing.
3.2. Simulation
MATLAB will be used to simulate the method mentioned in this paper. The following numerical simulation is done: establish a single frequency rectangular pulse signal, the sampling frequency is 40KHz, the sampling number is 256, the signal frequency is 15KHz, \( M=32 \), \( N=4 \), and the channel noise is gaussian white noise.

Figure 2 shows the pulse signal after time reversal processing. It is obvious that the amplitude of the pulse signal is compressed. With the change of time, the envelope waveform is distorted and the pulse is broadened, which has the characteristics of Rayleigh fading channel. The energy of the signal will refocus and intensify at some point over time.

![Figure 2. Signal after TR.](image1)

![Figure 3. Energy Distribution after TR.](image2)

Figure 3 shows that the impulse response signal of the channel is transformed from the time domain to the frequency domain by Fourier transform for calculation, so that each frequency component is processed by phase conjugation. Since the selected signal frequency is 15KHz, the signal achieves energy focusing at the frequency of 15KHz after time reversal. Figure 3 indicates that time reversal technology can realize energy focusing.

![Figure 4. Energy Distribution 1 after TRC.](image3)

![Figure 5. Energy Distribution 2 after TRC.](image4)
Figure 4 and Figure 5 show the three-dimensional energy distribution after TRC. It can be clearly seen from the figure that the signal can be focused not only in time but also in space after time reversal processing. This temporal and spatial clustering feature enables the signal energy to be focused on the target user and improves the reception SNR. Signals in illegal user space are weak and cannot be effectively decoded.

4. Conclusion
TR technology can collect energy over multiple paths, reducing the risk of information leakage. It has unique advantages in physical layer security. In a rich multi-path environment, the signals processed by TRC will have synchronous focusing characteristics in time and space at the receiving end. Therefore, TR technology has great advantages for Wireless physical layer security.

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