SECURE PERFORMANCE OF TIME REVERSAL PRECODING TECHNIQUE IN MISO OFDM SYSTEMS

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Abstract

Time reversal (TR) has been identified as a promising precoding technique to ensure physical layer security in wireless communications. This paper compares the secure performance of TR and maximum ratio transmission (MRT) precoding techniques in terms of achievable secrecy rate in MISO OFDM systems. Simulation results show that secrecy capacities of both precoding techniques increase with the transmit signal-to-noise ratio (SNR) and the achievable secrecy rate comparisons between them depend on the number of transmit antennas and transmit SNR. When the number of transmit antennas is small, the achievable secrecy rate of MISO TR OFDM is always better than its counterpart in MISO MRT OFDM, but the difference of the two decreases to zero as the transmit SNR increases; whereas the number of transmit antennas is large, achievable secrecy rates of the two precoding techniques become equivalent.

1 Introduction

The past two decades has witnessed a fast develop for multiple-input multiple-output (MIMO) technique. Compared with single antenna communication system, multiple antenna technique is able to increase the spectral efficiency remarkably, thus making wireless communication systems more efficient [1]. So far, the research on MIMO is restricted in flat fading channels, yet in broadband communication systems, MIMO has to cope with inter-symbol interference (ISI) due to frequency selective fading, which is quite challenging.

OFDM turns the frequency selective channel into a set of parallel flat fading channels and is, hence, a good way to deal with ISI [2]. The combination of MIMO and OFDM is very encouraging. On one hand, system capacity is increased by using MIMO; on the other hand, frequency selective fading is conquered by OFDM. Currently, MIMO OFDM has been widely accepted and is an attracting technique for the next-generation wireless local area networks (WLAN), wireless metropolitan area networks (WMAN) and fourth-generation (4G) mobile cellular wireless systems [3].

However, eavesdropping is a well known security vulnerability introduced by wireless networks due to their broadcast nature. In the MIMO OFDM systems, it is easy for the non-cooperative party Eve to wiretap and decode the confidential messages between transmitter Alice and legitimate user Bob at low cost. The regular way to realize secure communication currently is based on computationally demanding cryptographic algorithms in upper layers of communication model. Besides that, an alternative solution to guarantee confidential transmission in wireless environment is to figure out a practical method from the perspective of information-theoretic secrecy in the physical layer, i.e. physical layer security [4].

Physical layer security aims to ensure confidential communication by applying communication techniques in physical layer and exploiting spatio-temporal characteristics of wireless channels. It is stated in [5] that artificial noise can act as a way to confuse eavesdroppers and improve the secrecy performance of a system while not affecting the channel quality of main link. Furthermore, [6] applies artificial noise generation in MIMO OFDM systems and presents a quantitative analysis of the secrecy improvement. Nevertheless, the byproduct of artificial noise is the undesirable electromagnetic pollution and additional power consumption, which is quite a heavy burden in contemporary communication systems.

As a matter of fact, some well known precoding techniques are suitable to realize physical layer security owing to the spatial focusing property, such as MRT and TR precoding schemes. Lo proposed the classical MRT precoding scheme in 1999 [7], which was later proved to be equivalent to the optimal SVD precoding scheme under some normalization assumptions [8]. In that scheme, Lo moves the traditional matched filter from the receiver side to the transmitter side, so that legitimate user's receive SNR is much higher than any other surrounding users, and even a nearby receiver of similar complexity would receive noisy signals and fail to decode the confidential messages.

Aside from MRT, TR is another promising precoding technique and has been widely used in acoustics [9], ultrasonics [10], underwater communications [11] and ultra wideband communications [12], [13] due to its spatial and temporal focusing properties. Temporally speaking, TR can equivalently reduce the delay spread of multi-path channels and mitigate the negative effect of ISI, which is called 'temporal compression' [14], [15]. While spatially speaking, TR can fully exploit the multi-path propagation, recollect the broadcast signals from the wireless environment and add them coherently in the cooperative receiver, thus making legitimate user superior to illegitimate users in terms of SNR, which is called 'spatial focusing' [16]. The combination of TR and OFDM first appears in underwater acoustic communications [17][18] where the complex underwater multi-path channels have large delay spread, and TR contributes to reduce ISI, as well as enhance the secure transmission of OFDM signals in wireless channels.

Thierry Dubois et al. compare system capacity and diversity performance between TR and MRT precoding techniques in [19] and claim that MRT can exploit the full diversity while TR only exploits a half diversity. However, the secure performance of the two techniques is still unknown.

Aimed by this consideration, we will evaluate secure performance of TR by comparing it with MRT in this paper. The remainder of this paper is organized as follows. In Section 2, we introduce MISO TR OFDM and MISO MRT OFDM Model. The achievable secrecy rates of the two precoding techniques are calculated in Section 3 and corresponding simulation results are presented and analyzed in Section 4. Eventually, concluding remarks are finally made in Section 5.

2 System Model

2.1 MISO OFDM Precoding Model in Frequency Domain

As illustrated in Figure 1, suppose transmitter Alice has M_T transmit antennas, and there are N subcarriers in OFDM structure. $C_{m,n,k}$, $V_{m,n,k}$, $H_{m,n,k}$ and $N_{m,n,k}$ represent respectively the complex data, precoding factor, channel coefficient and additive white Gaussian noise associated to the m^{th} subcarrier of the n^{th} OFDM symbol in Alice's k^{th} antenna, where data $C_{m,n,k}$'s power $P_C = 1$, and the corresponding channel coefficient $H_{m,n,k}$'s module $\left|H_{m,n,k}\right|$ is assumed to follow Rayleigh distribution with parameter $\sigma^2 = 0.5$. In our research, the channel is considered as quasi-static, which means that it remains constant over several OFDM symbols. So $H_{m,n,k}$ and $V_{m,n,k}$ are abbreviated as $H_{m,k}$ and $V_{m,k}$ in the rest of the paper.

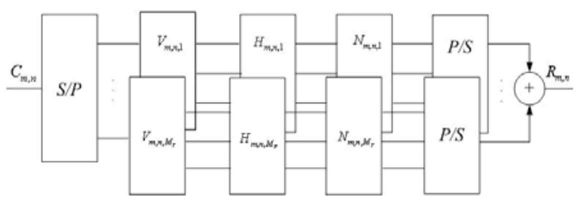

Figure 1. MISO OFDM precoding model in frequency domain

Suppose Alice transmits $C_{m,n}$, then the corresponding receive signal is

$$R_{m,n} = \sum_{k=1}^{M_T} H_{m,k} V_{m,k} C_{m,n} + N_{m,n,k} \tag{1}$$

2.2 MISO TR OFDM

MISO TR OFDM model has been studied in [20] and its precoding factor is

$$V_{m,k} = \frac{H_{m,k}^*}{\sqrt{M_T}} \tag{2}$$

Substitute (2) into (1), we can obtain the receive signal in the MISO TR OFDM

$$\begin{aligned} R_{m,n} &= \sum_{k=1}^{M_T} H_{m,k} \frac{H_{m,k}^*}{\sqrt{M_T}} C_{m,n} + N_{m,n,k} \\ &= \frac{1}{\sqrt{M_T}} \sum_{k=1}^{M_T} \left|H_{m,k}\right|^2 C_{m,n} + N_{m,n} \end{aligned} \tag{3}$$

2.3 MISO MRT OFDM

Accordingly, the precoding factor in MISO MRT OFDM model is

$$V_{m,k} = \frac{H_{m,k}^*}{\sqrt{\lambda_m}} \tag{4}$$

where

$$\sqrt{\lambda_m} = \sqrt{\sum_{k=1}^{M_T} \left|H_{m,k}\right|^2} \tag{5}$$

When the number of transmit antennas is large, and the channel coefficients are independent of each other and follow a normalized distribution, λ_m will tend towards M_T , i.e.

$$E\left[\lambda_m\right] = M_T \tag{6}$$

where $E\left[X\right]$ stands for the expectation over random variance X , and TR and MRT become equivalent at this moment.

Similarly, the receive signal in MISO MRT OFDM model is

$$\begin{aligned} R_{m,n} &= \sum_{k=1}^{M_T} \frac{\left|H_{m,k}\right|^2}{\sqrt{\lambda_m}} C_{m,n} + N_{m,n,k} \\ &= \sqrt{\sum_{k=1}^{M_T} \left|H_{m,k}\right|^2} C_{m,n} + N_{m,n} \end{aligned} \tag{7}$$

Compare equation (2) and (4), we can find that the precoding factor in MRT is more complicated than its counterpart in TR, since the denominator in MRT needs to know the channel state information for all the transmit antennas while the denominator in TR only needs to know the number of transmit antennas.

3 Secure Performance

The research on the achievable secrecy rate is essential to physical layer security and provides a theoretical guidance for the practical security scheme. In the wiretap channel, the achievable secrecy rate is a transmission rate that can be reliably supported on the primary channel, but which is undecodable on the eavesdropper's channel. For Gaussian channels, it is calculated as the difference between the mutual information on the primary and eavesdropper's channels, as

$$C_S = C_{S\_Bob} - C_{S\_Eve} \tag{8}$$

In this section, we will compare and analyze the secure performance of TR and MRT precoding techniques in the MISO OFDM systems in terms of achievable secrecy rate.

In MISO TR OFDM system, Bob and Eve's receive signals are

$$\begin{aligned} R_{m,n,Bob} &= \sum_{k=1}^{M_T} H_{Bob,m,k} \frac{H^*_{Bob,m,k}}{\sqrt{M_T}} C_{m,n} + N_{m,n,k} \\ &= \frac{1}{\sqrt{M_T}} \sum_{k=1}^{M_T} \left| H_{Bob,m,k} \right|^2 C_{m,n} + N_{m,n} \end{aligned} \tag{9}$$

$$\begin{aligned} R_{m,n,Eve} &= \sum_{k=1}^{M_T} H_{Eve,m,k} \frac{H^*_{Bob,m,k}}{\sqrt{M_T}} C_{m,n} + N_{m,n,k} \\ &= \frac{1}{\sqrt{M_T}} \sum_{k=1}^{M_T} H_{Eve,m,k} H^*_{Bob,m,k} C_{m,n} + N_{m,n} \end{aligned} \tag{10}$$

where $H_{Bob,m,k}$ and $H_{Eve,m,k}$ represent respectively Bob and Eve's channel coefficient associated to the m^{th} subcarrier of the n^{th} OFDM symbol in Alice's k^{th} antenna.

The corresponding receive SNR are

$$SNR_{Bob,m,TR} = E\left[\left| \sum_{k=1}^{M_T} \left| H_{Bob,m,k} \right|^2 \right|^2 \right] \frac{\rho}{M_T} \tag{11}$$

$$SNR_{Eve,m,TR} = E\left[\left| \sum_{k=1}^{M_T} H_{Eve,m,k} H^*_{Bob,m,k} \right|^2 \right] \frac{\rho}{M_T} \tag{12}$$

where ρ is transmit SNR.

Using (11) and (12), we can figure out the achievable secrecy rate for each subcarrier in an OFDM symbol, so the average achievable secrecy rate of the entire MISO TR OFDM system is

$$C_{S,TR} = \frac{1}{N} \left[\sum_{m=1}^{N} \log_2\left(1 + SNR_{Bob,m,TR}\right) - \log_2\left(1 + SNR_{Eve,m,TR}\right) \right] \tag{13}$$

Similarly, Bob and Eve's receive signals in MISO MRT OFDM system are,

$$\begin{aligned} R_{m,n,Bob} &= \sum_{k=1}^{M_T} \frac{\left| H_{Bob,m,k} \right|^2}{\sqrt{\sum_{k=1}^{M_T} \left| H_{Bob,m,k} \right|^2}} C_{m,n} + N_{m,n,k} \\ &= \sqrt{\sum_{k=1}^{M_T} \left| H_{Bob,m,k} \right|^2} C_{m,n} + N_{m,n} \end{aligned} \tag{14}$$

$$R_{m,n,Eve} = \sum_{k=1}^{M_T} \frac{H_{Eve,m,k} H^*_{Bob,m,k}}{\sqrt{\sum_{k=1}^{M_T} \left| H_{Bob,m,k} \right|^2}} C_{m,n} + N_{m,n} \tag{15}$$

And receive SNR are

$$SNR_{Bob,m,MRT} = E\left[\sum_{k=1}^{M_T} \left| H_{Bob,m,k} \right|^2 \right] \rho \tag{16}$$

$$SNR_{Eve,m,MRT} = E\left[\left| \frac{\sum_{k=1}^{M_T} H_{Eve,m,k} H^*_{Bob,m,k}}{\sqrt{\sum_{k=1}^{M_T} \left| H_{Bob,m,k} \right|^2}} \right|^2 \right] \rho \tag{17}$$

Hence, average achievable secrecy rate of the entire MISO MRT OFDM system is

$$C_{S,MRT} = \frac{1}{N} \left[\sum_{m=1}^{N} \log_2\left(1 + SNR_{Bob,m,MRT}\right) - \log_2\left(1 + SNR_{Eve,m,MRT}\right) \right] \tag{18}$$

4 Numerical Results

In this section, Monte Carlo simulations are carried out to compare the secure performance of TR and MRT precoding techniques in MISO OFDM systems. The simulated system is an OFDM system with 64 orthogonal subcarriers, using TR or MRT as a precoding technique. All the channel state information is supposed to be perfectly known at the transmitter side. Moreover, the frequency channel has 64 parallel sub-channels and the modulus of each subchannel coefficient $H_{m,n,k}$ is assumed to follow a Rayleigh distribution, independent on each subcarrier and on each antenna, with parameter $\sigma^2 = 0.5$. Fair performance comparisons are obtained under the assumption of identical transmit power whatever the precoding technique. Simulation results show that the secure performance of TR and MRT precoding techniques are slightly different and the difference depends on the number of transmit antennas. So this section is divided into two subsections as follows.

4.1 When Number of Transmit Antennas Is Small

In this subsection, we will compare the secure performance of TR and MRT precoding techniques when the number of transmit antennas is 2.

Figure 2 illustrates Bob and Eve's information transmission rate, respectively. For Bob, the rate of TR system is better than the rate of MRT system in low SNR regime, whereas the rate of MRT system is better than the rate of TR system in high SNR regime. It means that TR is more efficient in low SNR area while MRT is more efficient in high SNR area. For Eve, the rate of MRT system is always better than the rate of TR system whatever the value of SNR. It means that the MRT radiates more power to the eavesdropper than TR.

Figure 3 demonstrates the achievable secrecy rate of TR and MRT. Observing the two curves, we can know that the achievable secrecy rate of TR is better than the achievable secrecy rate of MRT, but the difference of the two decreases to null as the SNR increases. Therefore the secure performance of TR outperforms MRT when the number of transmit antennas is 2.

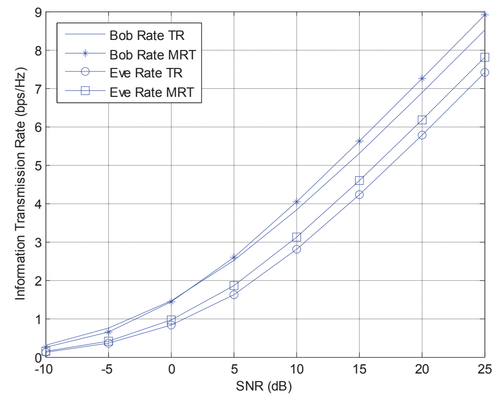

Figure 2. Bob and Eve's information transmission rate (when number of transmit antenna is 2)

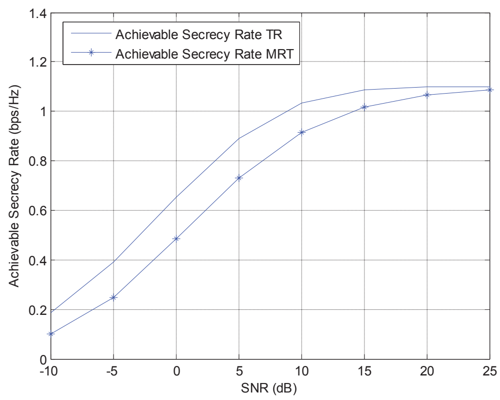

Figure 3. Achievable secrecy rate (when number of transmit antenna is 2)

4.2 When Number of Transmit Antennas Is Large

In this subsection, we will compare the secure performance of TR and MRT precoding techniques when the number of transmit antennas is 16.

Figure 4 and 5 clearly show that the secure performance of TR and MRT are almost identical when the number of transmit antennas is 16. This is primarily due to the fact that the two systems become equivalent when the number of transmit antennas is large, which is consistent with the aforementioned theoretical analysis.

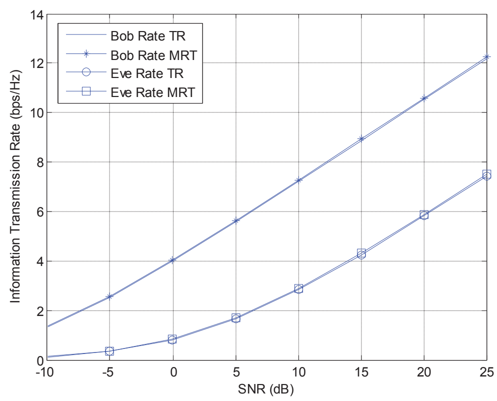

Figure 4. Bob and Eve's information transmission rate (when number of transmit antenna is 16)

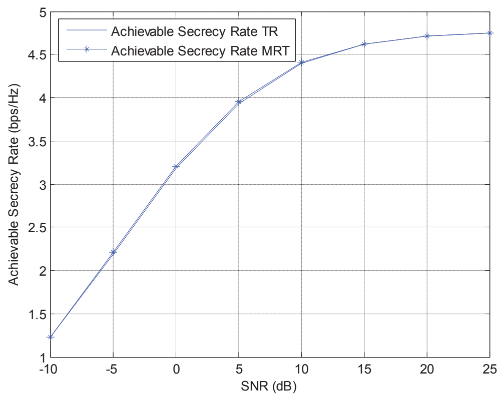

Figure 5. Achievable secrecy rate (when number of transmit antenna is 16)

5 Conclusions

This paper presents and analyzes the secure performance of TR and MRT precoding techniques in MISO OFDM system in terms of achievable secrecy rate. Numerical results show that achievable secrecy rate comparisons between TR and MRT depend on the number of transmit antennas and transmit SNR. Secure performance of TR system is superior to the secure performance of MRT when the number of transmit antennas is small, while the secure performance will be almost identical when the number of transmit antennas is large. Considering reliable communication, MRT is the optimal precoding scheme, but TR seems to be a better option from the perspective of confidential communication with less complexity.

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