Performance Analysis for MIMO SWIPT Systems with Space-Time Coding

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Abstract. Energy supply is a key factor affecting the normal operation of energy-constrained networks. Simultaneous wireless information and power transfer (SWIPT) technology can be used to obtain a stable and continuous energy source. But SWIPT need to take into account data transmission rate and energy harvesting performance, it is necessary to design a complex physical layer method to improve the energy efficiency of SWIPT system. The paper studies a multiple input multiple output (MIMO) SWIPT system based on space-time coding, the transmitter sends the information using the space-time encoder through multi-antenna transmission, the receiver uses the space-time decoder to decode the information and collect the energy. The expressions of channel capacity and energy harvesting under MIMO are given respectively. The energy harvesting optimization target equation under coding conditions is established. The simulation results show that the using of space-time coding can reduce the data transmission error rate of MIMO SWIPT system and improve the energy harvesting performance of the user terminals.

1. Introduction

Energy-limited networks such as wireless sensor networks and micro-nano satellite networks use the power supply method of saving batteries due to the particularity of the working environment. However, due to the limitation of volume and weight, the storage capacity of the carried savings battery is limited, which leads to great limitations in the energy and power of the communication system, so that the service performance and standby time of the system are restricted. In this regard, considering the wireless energy transmission and wireless communication mechanism, the academic community has proposed a new idea that can transmit information and energy synchronously, namely simultaneous wireless information and power transfer (SWIPT) technology.

SWIPT refers to using the same emitted electromagnetic wave to transport both energy that is harvested at the receiver, and information that is decoded by the receiver[1]. But in the wireless communication, due to channel fading and path loss, the bit error rate of data transmission will increase, and the energy transmitted through the wireless channel is also limited, so that the energy harvesting by the SWIPT receiver is also limited, it is necessary to design a complex physical layer method to improve the performance of SWIPT systems[2]. In this situation, the MIMO technology has drawn more attentions as a technology that can effectively increase the speed of wireless communication systems. The MIMO technology can merge the diversity technologies of transmitting...
and receiving together. It can take full advantage of the signal space resources through the configuration of multiple antennas to improve the system capacity.

The existing researches on MIMO SWIPT system mainly focus on the energy transmission in the MIMO channel. The energy efficiency has been studied in terms of resource allocation, power allocation, interference channel conditions etc. Reference [3] compared massive MIMO with traditional small-cell networks in the perspective of energy efficiency. It is pointed out that the former has a relatively low short circuit power, so that the energy efficiency of massive MIMO is significantly improved. The authors in [4] studied different MIMO channels and proposed an optimal transmission strategy that can maximize information and energy transmission. Reference [5] studied power allocation for energy harvesting in multi-user MIMO networks. Reference [6] investigated resource allocation in multi-user MIMO networks to maximize energy efficiency. Reference [7] studied the energy and rate of wireless energy transmission in a two-stage massive MIMO heterogeneous network. Reference [8] analyzed the energy efficiency of the cross-layer between the physical layer and the MAC layer in a MIMO network. Reference [9] analyzed the throughput in energy harvesting MIMO relay networks under fading channel conditions. The research of space-time coding is emphasized on improving channel capacity of information. Reference [10] proposed a pre-encoding method for SWIPT in a MIMO relay network, and studied the compromise area of information and energy transmission.

It can be seen that there are few researches on the performance of the SWIPT system in the MIMO system from the coding point of view. This paper studies the space-time coding method in the MIMO system and discusses steering the beam direction of the transmitted signal by coding at the transmitter. The tuning of phase and other parameters can maximize the harvested energy at the receiver while maintaining the high information transmission rate. Thereby, the performance of the MIMO enabled communication system can be improved. The energy harvesting optimization target equations are given, and the BER and energy harvesting performance of the MIMO SWIPT system with space-time block coding are analyzed by simulation. By simulation analysis, the use space-time block coding can reduce the data transmission error rate of MIMO SWIPT system and improve the energy harvesting performance of the user terminals.

2. MIMO SWIPT system model based on space-time coding

In this section, we first introduce the space-time coded MIMO SWIPT system model used in this paper, then give a mathematical description of the system, and deduce the expression of system channel capacity and energy harvested by the receiver based on the mathematical model. The system includes a transmitter and k users, the transmitter has $N_t > 1$ transmit antennas and each user has $N_r > 1$ receive antennas, as illustrated in Figure 1. The received signal is split into two independent streams by each receiver, these two streams are used separately for information decoding (ID) and energy harvesting (EH).

![Figure 1. A MIMO SWIPT system with Space-Time coding](image-url)
In the space-time coded MIMO SWIPT systems, bit stream is mapped into symbol set $\{ \tilde{v}_i \}_{i=1}^{N}$, As depicted in Figure 1, a symbol stream, which size is $N$, is encoded into $\{ \tilde{x}_i^{(t)} \}_{i=1}^{N}$, $t = 1, 2, \cdots, T$ with space-time coding, where $t$ is the symbol time index and $i$ is the antenna index. Then the equation of the complex baseband transmitted signal at the transmitter is

$$x = \sum_{i=1}^{K} v_i \tilde{x}_i^{(t)}$$

(1)

Where $v_i$ denotes the beamforming vector at the transmitter for user $k$, $k \in \{1, 2, \cdots, K\}$.

In the paper, we use the flat fading channel and define the channel matrix from the transmitter to the $k$ th user is $H_k \in \mathbb{C}^{N_c \times N_t}$. So the equation of signal received by the $k$ th user is:

$$y_k = H_k x + n_k$$

(2)

Where $n_k \sim \mathbf{c}(0, \delta_k^2)$ denotes the antenna noise of the $k$ th user.

After power split, the equation of signal used for energy harvesting is:

$$y_k^{EH} = \sqrt{1 - \rho} (H_k \sum_{j=1}^{K} v_j \tilde{x}_j^{(t)} + m_k), \forall k$$

(3)

The signal used for information decoding is expressed as:

$$y_k^{ID} = \sqrt{\rho} (H_k \sum_{j=1}^{K} v_j \tilde{x}_j^{(t)} + m_k), \forall k$$

(4)

Correspondingly, the equation of SNR of information decoding and energy harvesting of $k$ th user is:

$$SNR_k = \frac{\rho \left| H_k x_k \right|^2}{\rho \left| \sum_{j=2}^{K} H_k x_j \right|^2 + \rho \sigma_k^2 + \delta_k^2}, \forall k$$

(5)

$$E_k = \eta (1 - \rho) (\sum_{j=1}^{K} \left| H_k x_j \right|^2 + \delta_k^2), \forall k$$

(6)

Where $\eta \in (0,1]$ denotes the $k$ th user’s energy conversion efficiency.

3. Performance Analysis

In this section, we derive the system capacity and the user collect energy expression based on the mathematical description of the space-time MIMO SWIPT system model, and obtain the energy harvesting optimization formula. The simulation compares the information error rate and energy efficiency performance of the space-time block case for different number of antennas.

3.1. System capacity and energy harvesting expression

In the paper, we assume that the receiver can accurately know the channel state information, and assume that the noise is independent of each other, resulting in a channel capacity and energy harvesting expressions of user terminal.
\[ C_k = \log_2(1 + \frac{\rho_k |H_kx_k|^2}{\rho^2 \sum_{j=1}^{K} |H_jx_j|^2 + \rho^2 \sigma^2_k + \delta^2_k}), \forall k \]

\[ = \log_2(1 + \frac{\rho_k \text{Tr}(HH^HXX^H)}{\rho^2 \text{Tr}(HH^HXX^H) + \rho^2 \sigma^2_k + \delta^2_k}), \forall k \]

\[ = \log_2(1 + \frac{\rho_k \text{Tr}(HQ)}{\rho^2 \text{Tr}(HQ) + \rho^2 \sigma^2_k + \delta^2_k}), \forall k \]

\[ E_k = \eta(1 - \rho_k)(\sum_{j=1}^{K} |H_jx_j|^2 + \delta^2_k) \]

\[ = \eta(1 - \rho_k)(|HX|^2 + \delta^2_k) \]

\[ = \eta(1 - \rho_k)(Tr(HH^HXX^H) + \delta^2_k) \]

\[ = \eta(1 - \rho_k)(Tr(HQ) + \delta^2_k) \]

Where \( H = H_k^H \), \( Q = \sum_{i=1}^{K} E(x_i x_i^H) \), \( E(x_i x_i^H) \) denotes the covariance matrix of transmit signals.

3.2. Energy harvesting optimization formula

Here, we assume that the channel is a flat fading channel, the energy harvesting expression from the precious section can be expressed as:

\[ E_k = (1 - \rho_k)\eta \text{Tr}(H_kH_k^H \sum_{k=1}^{K} E(x_kx_k^H) + \delta^2_k) \]

Under the condition of guaranteeing the information transmission rate of the receiver and the power constraint of the transmitter, the energy value obtained by the user receiver is maximized, and the optimized formula of energy harvesting is obtained. Its optimization formula is as follows:

\[ \max \{E_k\}_{k \in K} \]

\[ s.t. \log_2(1 + \frac{\rho_k \text{Tr}(HQ)}{\rho^2 \text{Tr}(HQ) + \rho^2 \sigma^2_k + \delta^2_k}) \geq n \]

\[ \text{Tr}(\sum_{k=1}^{K} E(x_kx_k^H)) \leq P_T \]

\[ 0 \leq \rho_k \leq 1, \forall k \in K \]

Where \( n \) denotes the threshold of the information transmission rate of the receiver; \( P_T \) \( n \) denotes the maximum transmission power constraint value of transmitter.

3.3. Simulation and analysis

This section simulates the BER performance of the space-time coding and the energy values harvested at the receiver for different transmit antenna \( (N_T) \) and receive antenna \( (N_R) \) numbers. Simulation parameters are shown in Table 1.
| Parameters                  | Value          |
|-----------------------------|----------------|
| Transmit antenna number     | 2/4/8          |
| Receive antenna number      | 2/4/8          |
| Modulation                  | 16QAM          |
| Channel model               | Gaussian       |
| Antenna spacing             | λ/2            |
| Noise of receiver(dB)       | 5              |
| Path loss model/(l in km)   | 128.1+37.6 lg(l) |
| Carrier frequency(GHz)      | 2.4            |
| Transmission power constraint value(W) | 1             |

We compare the BER of space-time coding in three cases: \( N_T = 4, N_R = 4 \), \( N_T = 2, N_R = 4 \), \( N_T = 2, N_R = 2 \), and the Figure 2 shows the BER performance curve. It can be seen that with the same number of transmit antennas, the increase in the number of receive antennas can reduce the BER of space-time coding, at the same time, as the transmit antennas number and the receive antennas number increases, the bit error rate of space-time coding also decreased.

According to the energy harvesting formula of the receiver, based on the known channel parameter information, the value of the harvested energy is related to the trace of the covariance of the transmitted signal without exceeding the maximum power constraint if the transmitter, and the trace of covariance is related to the sum of the diagonal elements, that is the number of transmit antennas. Here we take \( \rho_k = 0.5, k = 1, 2, \ldots, K \), that is 50% of the power received by the receiving antenna is used to collect energy; take \( \eta_k = 0.3, k = 1, 2, \ldots, K \), that is the energy conversion efficiency of the receiver is 30%. From this we can get the curve of the energy value harvested by the receiver as shown in Figure 3. It can be seen that the energy value harvested by the receiver increases with the number if transmitting antennas. The SISO system and the MIMO SWIPT system using the number of transmitting antenna \( N_T = 8 \) is compared. The curve of the relationship between the energy value harvested by the receiver and the information rate is shown in Figure 4. It can be seen that the energy value at the receiver is declining with the increases of the information rate, but the MIMO SWIPT system’s drop speed is lower than that of the SISO system.

![Figure 2. The BER curve of Space-time coding for different number of transmit/receive antennas](image-url)
In summary, the use of MIMO technology and space-time coding in the SWIPT system can reduce the data transmission error rate, and can increase the energy value harvested by the user terminal, thereby improving the performance of the SWIPT system.

4. Conclusion
In this paper, the MIMO SWIPT system with space-time coding is studied. Firstly, the scheme of MIMO SWIPT system used space-time coding is given, and the system model is described in detail. Secondly, the system channel capacity and energy harvesting expression are given based on the space-time coding principle. Then the optimization formula for the user to harvest the maximum energy is analyzed. Finally the performance of the MIMO SWIPT system with different number of transmit antennas is analysed by the space-time block coding simulation. According to the simulation results, the use of space-time block coding in the MIMO SWIPT system can reduce the data transmission error rate, and increase the performance of energy harvesting by the user terminal.

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