

Phase-Inversion Symmetric Method-Cooperative MIMO Transmission Mechanism for Clustered Ad Hoc Networks

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Abstract—Since wireless links are relatively weak, bandwidth is relatively limited and there is no support for fixed infrastructures, clustered Ad Hoc networks are easy to be disturbed by channel noises. Therefore, clustered Ad Hoc networks have poor channel transmission performance and are unable to enter the large-scale practical application stage in a short period of time. To improve the channel transmission performance of clustered Ad Hoc Networks and the practical value of the cooperative multi-input multi-output (MIMO) technology, a cooperative MIMO transmission mechanism based on phase-inversion symmetric method (PISM-CMIMO) is proposed, which absorbs the advantages of phase-inversion symmetric method and cooperative MIMO technology and makes full use of the correlation of the adjacent channel noises. This paper presents the transmission process of PISM-CMIMO system in detail. Through theoretical analysis and system simulation, it shows that the signal-to-noise ratio (SNR) gain of the proposed PISM-CMIMO transmission mechanism is 9 times greater than the traditional cooperative MIMO transmission mechanism. In addition, the proposed PISM-CMIMO transmission mechanism has larger link capacity, less bit-error rate (BER) and can reduce the distance between the cooperative MIMO mobile terminal antennas, which enhance its practical value greatly.¹

Index Terms—clustered mobile Ad Hoc networks, cooperative multi-input multi-output, phase-inversion symmetric method.

I INTRODUCTION

A mobile Ad Hoc network (MANET) is a multi-hop and temporary peer-to-peer network whose nodes act as terminals and routers. It is a network which can be quickly founded and does not need to rely on existing fixed communication infrastructures. It is self-organizing and self-healing. The control and management of a MANET are distributed to the terminals, so the nodes involved work together to communicate and exchange information (such as voice, image, video, data, etc) via a wireless link. Every node can join or exit the network dynamically, randomly or frequently, not disturbing other nodes in the network [1]-[3]. These unique characteristics suggest that mobile Ad Hoc network transmission mechanism must be specially designed.

Cooperative communication technology can be traced back to the research by Cover and Gamal in 1979 [4]. So

far, cooperative communication technology has been widely used. Its main idea is that in the multi-users' communication environment, the neighboring mobile users share each other's antenna to cooperatively transmit signals, thus generating a virtual environment similar to multi-antenna transmission environment to obtain spatial diversity gain and improve the transmission performance of the system. This theory above is very suitable for mobile Ad Hoc networks. The research of Sendonaris [5], [6] showed that the multi-node cooperative transmission mechanism could greatly increase the system capacity, and effectively resist fading effects of the wireless channels.

Dohler [7] put forward the concept of cooperative multi-input multi-output (MIMO). Ref. [8]-[11] introduced cooperative MIMO technique into energy-efficient wireless sensor networks so that the virtual cooperative transmission networks with omni-directional single antenna mobile terminal nodes would overcome the limits of the traditional MIMO and sending-receiving diversity gain and array gain collected could significantly increase the channel capacity, reduce the end-to-end transmission delay, the energy consumption of data transmission, and the received bit error rate (BER). Feng [12] have designed a weighted-node cooperative MIMO system model based on clustered Ad Hoc networks. The results of the system simulation and theoretical analysis showed that this model was able to obtain larger channel capacity and higher energy efficiency.

In the light of the phase-inversion symmetric method (PISM), this paper proposes a new cooperative MIMO transmission mechanism for clustered Ad Hoc networks, which absorbs the advantages of phase-inversion symmetric method [13] and cooperative MIMO technology. Theoretical analysis and system simulation show that this mechanism can obtain higher signal-to-noise ratio (SNR) gain and larger link capacity, lower bit-error rate (BER) and reduce the distance between the cooperative MIMO mobile terminal antennas.

II NETWORK MODEL

Mobile Ad Hoc networks can be divided into flat structure and hierarchical structure, and the latter is dealt with in this paper. As shown in Fig. 1, a certain number of nodes adjacent in position are considered as a group,

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called as a cluster. Each cluster has a head responsible for the management of this cluster. However, just as Feng *et al.* proposed in [12], each cluster is called as a virtual node (VN), the head as a kernel node (KN) and the remaining nodes as team nodes (TNs) (i.e. A_1, A_2, B_1, B_2 , etc in Fig. 1). And all the actual links corresponding between two VNs are set into a virtual link (VL). In addition, if TNs in two VNs can inter-exchange, they are known as adjacent VNs that can form a virtual backbone network via the VL. Now assuming that any nodes in a virtual backbone network can send and receive signals synchronously, all channel noises between nodes are additive white Gaussian noises (AWGN).

III PISM-CMIMO TRANSMISSION PROCESSES

According to the network structure shown in Fig. 1, a virtual link which connects two adjacent virtual nodes VN_A and VN_B can be built. Then an optimal cooperative nodes selection algorithm is used to select a set of 2×2 cooperative nodes for forming a cooperative MIMO system, and a routing selection algorithm is used to search for the best path from the source node to the destination node. However, this paper mainly focuses on phase-inversion symmetric method-cooperative MIMO (PISM-CMIMO) transmission mechanism, leaving the optimal cooperative nodes selection algorithm and the routing selection algorithm aside. Now assuming that a source node A_s in VN_A transmits information to a destination node B_r in VN_B and A_1, A_2, B_1, B_2 are selected optimal cooperative nodes. The transmission process is shown in Fig. 2.

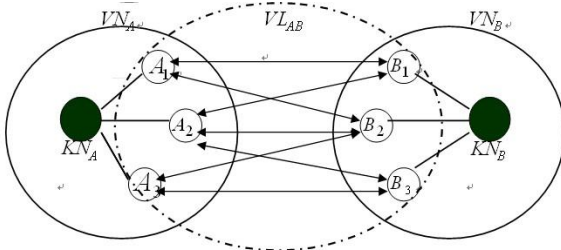


Figure 1. Virtual backbone network.

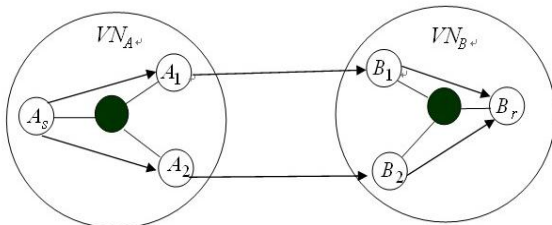


Figure 2. PISM-CMIMO transmission process.

As shown in Fig. 2, the source node A_s packages and encodes data to be sent, then transmits them to the cooperative transmit nodes A_1 and V_2 . It should be noticed here that a node whose ID number is relatively small receives the original data and the opposite receives the inverted data. Here assuming that the original is

transmitted to A_1 and the inverted data to V_2 . After modulating the received signals respectively, A_1 and A_2 send them to the cooperative receiving nodes B_1 and B_2 , thus B_1 receives the modulated original signals and B_2 receives ones after inverted. Next the signals which B_1 and B_2 received are subtracted in a sub-tractor after passing through a band-pass filter and a demodulator. Finally, the data are decoded and sent to the relay node or the destination node B_r .

In the transmission process, the cooperative nodes A_1 and V_2 send the data to two cooperative reception nodes B_1 and B_2 via an independent channel, respectively. Here we do not have to care about the distance between the two channels (the distance between the antennas must be $\geq \lambda/2$, where λ is radio wavelength), even in order to use the spatial noise correlation to improve the quality of signal transmission, the distance between the two links is as adjacent as possible.

IV MATHEMATICAL MODEL AND THEORETICAL ANALYSIS OF PISM-CMIMO [13], [14]

As for "phase-inversion symmetric method", "phase-inversion" means sending two mutually anti-phase signals synchronously at the sending terminal then transmitting them, respectively, through two independent channels in location, while "symmetric" implies that the transmission characteristics and state of the two channels should be as consistent as possible, and the two received signals through the two channels are subtracted at the receiving end. However in a real communication environment, the noises existing in two channels are strongly interrelated, which makes it possible that the noises may be eliminated.

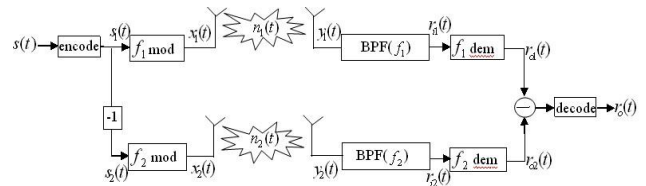


Figure 3. Sending and receiving mathematical model of PISM-CMIMO.

The sending and receiving mathematical model of PISM-CMIMO is shown in Fig. 3. The source node A_s sends the signal $s(t)$, and two signals $s_1(t)$ and $s_2(t)$ are respectively received by two cooperative transmission nodes A_1 and A_2 ($s(t) = s_1(t) = -s_2(t)$), then sent into two adjacent channels after modulated by two signal carriers of different frequencies.

The modulated signals are provided as:

$$x_1(t) = s_1(t) \sin \omega_1 t \quad (1)$$

$$x_2(t) = s_2(t) \sin \omega_2 t. \quad (2)$$

Two mutually-inverted signals $y_1(t)$ and $y_2(t)$ received by two cooperative receiving nodes B_1 and B_2 in the virtual node VN_B can be written as:

$$\begin{bmatrix} y_1(t) \\ y_2(t) \end{bmatrix} = \begin{bmatrix} h_{11}(x) & h_{12}(x) \\ h_{21}(x) & h_{22}(x) \end{bmatrix} \begin{bmatrix} x_1(t) \\ x_2(t) \end{bmatrix} + \begin{bmatrix} n_1(t) \\ n_2(t) \end{bmatrix}, \quad (3)$$

where $H = \begin{bmatrix} h_{11}(x) & h_{12}(x) \\ h_{21}(x) & h_{22}(x) \end{bmatrix}$ is a channel matrix, $h_{ji}(x)$ is the channel fading coefficient from the sending antenna i to the receiving antenna j ($i=1,2; j=1,2$), $n_1(t)$ and $n_2(t)$ are additive white Gaussian noises with zero average in two independent channels, and we assume two noise powers are equal ($N_1 = N_2$).

$r_{i1}(t)$ and $r_{i2}(t)$ are the output signals of two band-pass filters whose central frequencies are f_1 and f_2 respectively, then we can get the following formula:

$$\begin{bmatrix} r_{i1}(t) \\ r_{i2}(t) \end{bmatrix} = \begin{bmatrix} h_{11}(x) & 0 \\ 0 & h_{22}(x) \end{bmatrix} \begin{bmatrix} x_1(t) \\ x_2(t) \end{bmatrix} + \begin{bmatrix} n_{i1}(t) \\ n_{i2}(t) \end{bmatrix} \quad (4)$$

where $n_{i1}(t)$ and $n_{i2}(t)$ are two limited noises after passing through two band-pass filters.

The demodulated output signals are $r_{o1}(t)$ and $r_{o2}(t)$:

$$r_{o1}(t) = s_{o1}(t) + n_{o1}(t) \quad (5)$$

$$r_{o2}(t) = s_{o2}(t) + n_{o2}(t) \quad (6)$$

where $s_{o1}(t)$ and $s_{o2}(t)$ are two demodulated output phase-inversion signals; $n_{o1}(t)$ and $n_{o2}(t)$ are two demodulated output limited noise signals.

Finally, two signals $r_{o1}(t)$ and $r_{o2}(t)$ are subtracted at the receiving end, then we obtain output signal $r_o(t)$:

$$\begin{aligned} r_o(t) &= r_{o1}(t) - r_{o2}(t) \\ &= [s_{o1}(t) + n_{o1}(t)] - [s_{o2}(t) + n_{o2}(t)] \\ &= [s_{o1}(t) - s_{o2}(t)] + [n_{o1}(t) - n_{o2}(t)] \\ &= s_o(t) + n_o(t) \end{aligned} \quad (7)$$

where $s_o(t)$ is the final output signal, and $n_o(t)$ is the final noise output signal.

Let us analyze signal-to-noise ratio (SNR) gain of the sub-tractor, that is, the SNR gain of PISM-CMIMO expressed as $G_{PISM-CMIMO}$. First of all, we define two output SNRs of two demodulators as:

$$S_1 / N_1 = E[s_{o1}^2(t)] / E[n_{o1}^2(t)] \quad (8)$$

$$S_2 / N_2 = E[s_{o2}^2(t)] / E[n_{o2}^2(t)] \quad (9)$$

where S_1 and S_2 are powers of input signals, N_1 and N_2 are powers of noises.

We know $S_1 = S_2$ from $s_1(t) = -s_2(t)$, thus output signal power of the sub-tractor can be written as:

$$\begin{aligned} S_o &= E[s_o^2(t)] = E[s_{o1}(t) - s_{o2}(t)]^2 \\ &= E[2s_{o1}(t)]^2 = 4E[s_{o1}^2(t)] = 4S_1 \end{aligned} \quad (10)$$

Correspondingly, the output noise power of the sub-tractor is:

$$N_o = E[n_{o1}(t) - n_{o2}(t)]^2$$

$$\begin{aligned} &= E[n_{o1}^2(t) + n_{o2}^2(t) - 2n_{o1}(t)n_{o2}(t)] \\ &= N_1 + N_2 - 2\rho\sqrt{N_1N_2} \\ &= 2(1 - \rho)N_1 \end{aligned} \quad (11)$$

where $\rho = E[n_{o1}(t)n_{o2}(t)] / \sqrt{N_1N_2}$ is the correlation coefficient of two adjacent channel noises.

Thereby the output SNR of the sub-tractor is:

$$S_o / N_o = (4S_1) / [2(1 - \rho)N_1] = [2 / (1 - \rho)] [S_1 / N_1]. \quad (12)$$

Finally according to Eq. (12), the SNR gain of the PISM-CMIMO system is

$$G_{PISM-CMIMO} = (S_o / N_o) / (S_1 / N_1) = 2 / (1 - \rho). \quad (13)$$

Now let us consider a traditional 2x2 cooperative MIMO system as shown in Fig. 4.

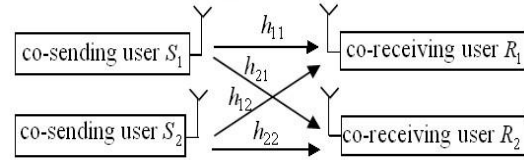


Figure 4. Traditional 2x2 cooperative MIMO system model.

Assuming that two cooperative sending users S_1 and S_2 simultaneously and respectively send a complex signal $s_1(t)$ or $s_2(t)$ at a given time t , then at the receiving end, the received signals of two cooperative receiving nodes R_1 and R_2 can be written as:

$$\begin{bmatrix} r_1(t) \\ r_2(t) \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix} \begin{bmatrix} s_1(t) \\ s_2(t) \end{bmatrix} + \begin{bmatrix} n_1(t) \\ n_2(t) \end{bmatrix} \quad (14)$$

where $H = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix}$ is a channel matrix, $h_{ji}(x)$ is the channel fading coefficient from the sending antenna i to the receiving antenna j ($i=1,2; j=1,2$), $n_1(t)$ and $n_2(t)$ are additive white Gaussian noises with zero average received by two cooperative receiving nodes R_1 and R_2 .

Assuming that channel state information (CSI) has been known at the receiving end, thus using a diversity combining technique can estimate the sending signal, it is

$$\hat{s}(t) = \alpha_1(t)r_1(t) + \alpha_2(t)r_2(t) \quad (15)$$

where $\alpha_1(t)$ and $\alpha_2(t)$ are weights, if combining Eq. (14) and Eq. (15), we can get a new formula:

$$\begin{aligned} \hat{s}(t) &= \alpha_1(t)[h_{11}s_1(t) + h_{12}s_2(t) + n_1(t)] + \\ &\quad \alpha_2(t)[h_{21}s_1(t) + h_{22}s_2(t) + n_2(t)] \\ &= \alpha_1(t)h_{11}s_1(t) + \alpha_1(t)h_{12}s_2(t) + \alpha_1(t)n_1(t) + \\ &\quad \alpha_2(t)h_{21}s_1(t) + \alpha_2(t)h_{22}s_2(t) + \alpha_2(t)n_2(t) \\ &= [\alpha_1(t)h_{11} + \alpha_2(t)h_{21}]s_1(t) + \\ &\quad [\alpha_1(t)h_{12} + \alpha_2(t)h_{22}]s_2(t) + \\ &\quad \alpha_1(t)n_1(t) + \alpha_2(t)n_2(t). \end{aligned} \quad (16)$$

To facilitate the analysis, we set $h_1 = h_{11} = h_{21}$, $h_2 = h_{12} = h_{22}$. Thus Eq. (16) can be simplified as

$$\hat{s}(t) = [\alpha_1(t) + \alpha_2(t)]h_1s_1(t) + [\alpha_1(t) + \alpha_2(t)]h_2s_2(t) + \alpha_1(t)n_1(t) + \alpha_2(t)n_2(t) \quad (17)$$

It is known from [15] that the effect of maximal ratio combining (MRC) technique is the best in three typical receiving combining techniques (maximal ratio combining, equal gain combining, and selection combining), so MRC is used in this paper. We set $\alpha_1(t) = \beta h_1$, $\alpha_2(t) = \beta h_2$, then the estimated value of the total sending signal can be obtained

$$\begin{aligned} \hat{s}(t) &= [\beta h_1 + \beta h_2]h_1s_1(t) + [\beta h_1 + \beta h_2]h_2s_2(t) + \\ &\quad \beta h_1n_1(t) + \beta h_2n_2(t) \\ &= \beta[h_1 + h_2]h_1s_1(t) + \beta[h_1 + h_2]h_2s_2(t) + \\ &\quad \beta h_1n_1(t) + \beta h_2n_2(t) \\ &= \beta[(h_1^2 + h_1h_2)s_1(t) + (h_1h_2 + h_2^2)s_2(t) + h_1n_1(t) + h_2n_2(t)] \end{aligned} \quad (18)$$

Assuming that the channel fading coefficient $h_1 = 2h_2$, then Equation (18) can further be simplified as:

$$\begin{aligned} \hat{s}(t) &= \beta\{6h_2^2s_1(t) + 6h_2^2s_2(t) + h_2[2n_1(t) + n_2(t)]\} \\ &= 6\beta h_2^2[s_1(t) + s_2(t)] + \beta h_2[2n_1(t) + n_2(t)] \\ &= \hat{s}_i(t) + \hat{n}(t) \end{aligned} \quad (19)$$

where $\hat{s}_i(t)$ is the estimated value of the original transmitting data; $\hat{n}(t)$ is the estimated value of the total receiving noises.

Thus the estimated SNR of the total sending signals can be written as:

$$\begin{aligned} \frac{\hat{S}_i}{\hat{N}} &= \frac{E[6\beta h_2^2(s_1(t) + s_2(t))]^2}{E[\beta h_2(2n_1(t) + n_2(t))]^2} \\ &= \frac{[2\beta h_2^2]^2 E[|s_1(t) + s_2(t)|^2]}{[\beta h_2]^2 E[|n_1(t) + n_2(t)|^2]} \\ &= \frac{36\beta^2 |h_2|^4 E[|s_1(t) + s_2(t)|^2]}{\beta^2 |h_2|^2 E[|2n_1(t) + n_2(t)|^2]} \\ &= \frac{36|h_2|^2 S}{E[4n_1^2(t) + n_2^2(t) + 4|n_1(t)||n_2(t)|]} \\ &= \frac{36|h_2|^2 S}{4N_1 + N_2 + 4\rho\sqrt{N_1N_2}} \end{aligned} \quad (20)$$

where $S = E[|s_1(t) + s_2(t)|^2]$ is the total power of actual sending signals; $N_1 = E[|n_1(t)|^2]$ is the power of actual

noise signal $n_1(t)$; $N_2 = E[|n_2(t)|^2]$ is the power of actual noise signal $n_2(t)$; $\rho = E[n_1(t)n_2(t)]/(N_1N_2)^{1/2}$ is the correlation coefficient of noise signals received by two cooperative receiving nodes.

Suppose the digital features of noises in two adjacent channels should be similar, i.e., $N = N_1 = N_2$, and all signals pass through the channels without fading, that is $h_2 = 1$, then Eq. (20) can be further simplified as:

$$\frac{\hat{S}_i}{\hat{N}} = \frac{4S}{2(1+\rho)N} = \frac{2}{(1+\rho)} \cdot \frac{S}{N}. \quad (21)$$

SNR gain of the 2×2 cooperative MIMO system can be obtained as

$$G_{CMIMO} = (\hat{S}_i / \hat{N}) / (S / N) = 2 / (1 + \rho). \quad (22)$$

Further,

$$G_{PISM-CMIMO} / G_{CMIMO} = (1 + \rho) / (1 - \rho). \quad (23)$$

From Eq. (15), we can get $G_{PISM-CMIMO} / G_{CMIMO} = 1$ when $\rho = 0$, which means the SNR gain of PISM-CMIMO is the same as that of traditional cooperative MIMO. Thus PISM-CMIMO does not apply to the environment where noises in adjacent channels have no correlation, i.e., the traditional cooperative MIMO transmission mechanism is sufficient to achieve the desired results. However, the noises in a real adjacent channel is strongly relative, that is, $\rho > 0$ (if the distance of antennas is less than three meters, the correlation coefficient of noise in adjacent channels can be up to 0.8 [16]), then $G_{PISM-CMIMO} / G_{CMIMO} = 9$, which implies that cooperative MIMO using phase-inversion symmetric method can obtain 9 times SNR gain as much as traditional cooperative MIMO.

V APPLICATION RANGE OF PISM-CMIMO TRANSMISSION MECHANISM

Shannon [17] gave the well-known Shannon formula:

$$C = B \log_2(1 + (S/N)) \quad (24)$$

where B is the channel bandwidth, S is the signal power, N is the noise power. If the channel bandwidth B is increased to 2 times, that is $B' = 2B$, then $N' = 2N$ (i.e., the power of AWGN is proportional to the channel bandwidth). Thus, the channel capacity becomes:

$$\begin{aligned} C' &= B' \log_2(1 + (S/N')) \\ &= 2B \log_2(1 + (S/2N)) \\ &= B \log_2(1 + (S/2N))^2 \\ &= B \log_2(1 + S/N + (S/2N)^2) \\ &= B \log_2(1 + S'/N'). \end{aligned} \quad (25)$$

Then the SNR of system can be written as:

$$S'/N' = S/N + (S/2N)^2. \quad (26)$$

Therefore, if the traditional way of doubling the channel bandwidth is used to improve the SNR of a system, the SNR gain is as follow:

$$G = (S'/N')/(S/N) = 1 + \frac{1}{4}(S/N). \quad (27)$$

From Eq. (13), if the phase-inversion symmetric method is used, the SNR gain is $G_{PISM-CMIMO} = (S_o/N_o)/(S_i/N_i) = 2/(1-\rho)$.

Now, if $G_{PISM-CMIMO} \geq 2G$, in order to improve the SNR of a system, the PISM-CMIMO, a better way than the traditional one, is used to increasing channel bandwidth. Thus, we can get the following constraints:

$$\begin{aligned} 2/(1-\rho) &\geq 2[1 + \frac{1}{4}(S/N)] \\ S/N &\leq (4\rho)/(1-\rho). \end{aligned} \quad (28)$$

From Eq. (28), the smaller the SNR of the original system is, the better the effect of PISM-CMIMO transmission mechanism is. From Eq. (27), when the original system has a very small SNR, the effect of increasing bandwidth to improve SNR is not obvious. For example, if $S/N=1/2$ in an original system, then $G=1.12$, that is the SNR is improved by 12.5% through doubling the bandwidth. Thereby PISM-CMIMO transmission mechanism is more suitable for a network which has a small SNR.

With the absence of support for fixed communication infrastructure, the wireless links in clustered mobile Ad Hoc networks are variable and instable, thus there are strong noises existing. Therefore using PISM-CMIMO transmission mechanism in clustered Ad Hoc networks can significantly improve the quality and SNR of the transmitted signals.

VI SIMULATION AND ANALYSIS OF PISM-CMIMO [18][19]

A. Analysis of the SNR Gain of PISM-CMIMO

According to Eq. (13) and Eq. (22), the PISM-CMIMO system is simulated by MATLAB software. Compared with the SNR gain of traditional cooperative MIMO system, the simulation result is shown in Fig. 5.

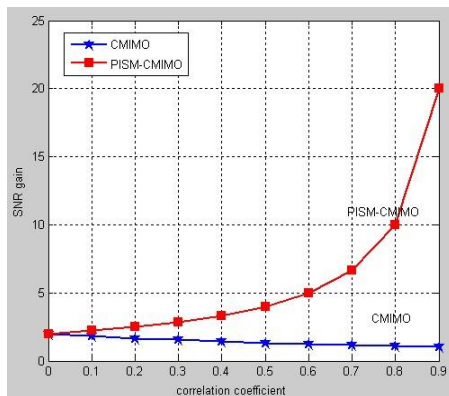


Figure 5. Comparison result of SNR gains of PISM-CMIMO and cooperative MIMO.

In Fig. 5, the x -axis represents the correlation coefficient ρ of noises between two adjacent channels, which is increasing with decreasing of the distance between the mobile terminal antennas, and by measuring if the distance between antennas is less than three meters, the correlation coefficient ρ of noises in adjacent channels can be up to 0.8; the y -axis represents the SNR gain of different systems. The result in Fig. 5 shows when the cooperative mobile terminals are at a distance with each other and make their channel noises tend to less correlation, the PISM-CMIMO transmission mechanism is not superior to the traditional way. However, with the distance between the mobile terminals shrinking, PISM-CMIMO can be able to obtain a higher SNR gain, and thus improve the quality of the receiving signals and the anti-noise performance of the system.

Further, let us see the well-known Shannon formula $C = B \log_2(1 + (S/N))$. With the increase of S/N , thus the channel capacity C will be improved in the case of the same channel bandwidth.

B. Analysis of Channel Capacity of PISM-CMIMO

Considering Shannon formula again:

$$C = B \log_2(1 + S/N). \quad (29)$$

In order to compare with the traditional 2×2 cooperative MIMO, set $SNR = S/N$, $SNR = 10 \log_{10} A$, then get $A = 10^{(SNR/10)}$. Thus, the channel capacity per bandwidth can be changed into

$$C = \log_2(1 + A). \quad (30)$$

which is also the channel capacity of single-input single-output (SISO) system.

Traditional cooperative MIMO system is the same as distributed MIMO system in essence, so they have the same channel capacity [20]:

$$C = W \log_2 \det \left(I_m + \frac{P}{n_r \sigma^2} Q \right) \quad (31)$$

where W is the bandwidth of each sub channel, thus the channel capacity per bandwidth can be modified as

$$C = \log_2 \det \left(I_m + \frac{P}{n_r \sigma^2} Q \right) \quad (32)$$

where n_r is the total number of the receiving antennas, n_T is the total number of the sending antennas, I_m is a $\min(n_r, n_T)$ -order unit matrix, R is a $n_R \times n_T$ -order random matrix which follows a normal distribution. If $n_R < n_T$, then $Q = HH^H$; if $n_R \geq n_T$, thus $Q = H^H H$. P is the total power of all sub-channels, and σ^2 is the noise power of every receiving antenna, then P/σ^2 is the SNR at the receiving end.

So the channel capacity per bandwidth can be further presented as:

$$C = \log_2 \det \left(I_m + \frac{A}{n_T} Q \right) \quad (33)$$

where $SNR = 10 \log_{10} A$, and $A = 10^{(SNR/10)}$.

If $n_R = n_T = 2$, the channel capacity of 2×2 cooperative MIMO can be obtained as follows:

$$C = \log_2 \det \left(I_2 + \frac{A}{2} Q \right). \quad (34)$$

From Fig. 5, we know that the SNR gain of PISM-CMIMO is 9 times greater than that of traditional cooperative MIMO when $\rho > 0.8$. If the input SNRs of two systems are normalized, then the output SNR of PISM-CMIMO is 9 times greater than that of traditional cooperative MIMO. Thus, the channel capacity per bandwidth of 2×2 PISM-CMIMO is

$$C = \log_2 \det \left(I_2 + \frac{9A}{2} Q \right). \quad (35)$$

According to Eq. (30), Eq. (34) and Eq. (35), the channel capacities of SISO, 2×2 cooperative MIMO and 2×2 PISM-CMIMO are simulated and analyzed respectively. The result is shown in Fig. 6.

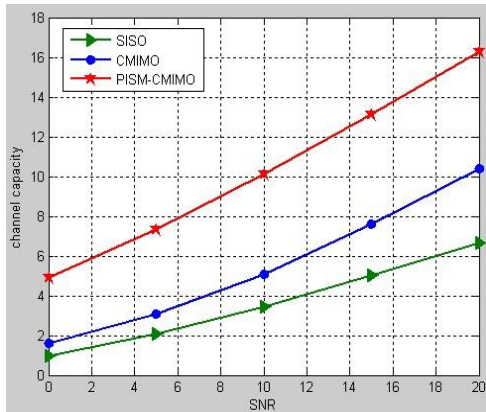


Figure 6. Relationship between the channel capacity and SNR of three systems.

Fig. 6 shows that PISM-CMIMO has relatively larger channel capacity. The reason is that PISM-CMIMO takes full advantages of the correlation of noises in adjacent channels so that the SNR gain of the system is improved and the channel capacity of the system is increased in the case of the same channel bandwidth.

Due to the limitations of clustered mobile Ad Hoc networks, the channel bandwidth of such system is very limited. Therefore, it is not suitable to increase channel capacity by increasing system bandwidth while the way of increasing SNR is relatively well. Above all, the PISM-CMIMO transmission mechanism is feasible for clustered mobile Ad Hoc networks.

Extending 2×2 PISM-CMIMO to $2n \times 2n$ PISM-CMIMO, the changes of channel capacity after simulation by MATLAB can be observed, as shown in

Fig. 7 and Fig. 8.

Fig. 7 shows that the channel capacity of PISM-MIMO is increasing with the increase of the SNR and the pairs of sending-receiving antennas, which suggests that we can improve the channel capacity and transmission rate of the system via increasing the number of cooperative mobile terminals.

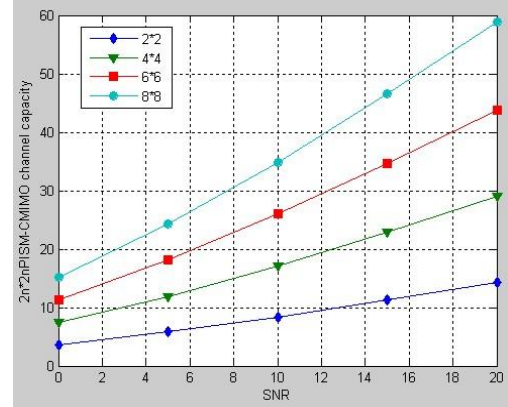


Figure 7. Relationship between the channel capacity and SNR of $2n \times 2n$ PISM-CMIMO.

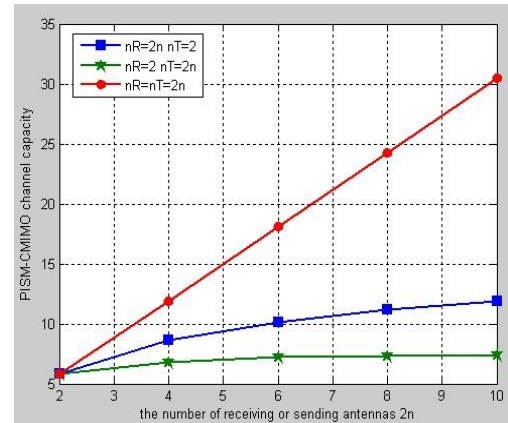


Figure 8. Relationship between the channel capacity and the number of sending and receive antennas of PISM-CMIMO.

From Fig. 8, we can observe the results as follow.

- 1) When $n_R < n_T$, channel capacity remains nearly unchanged with the increase of the number of sending antennas.
- 2) When $n_R > n_T$, channel capacity has a little increase with the increase of the number of receiving antennas.
- 3) When $n_R = n_T$, channel capacity increases linearly with the increase of the number of sending-receiving antenna pairs. Meanwhile, the system gets full diversity effect, and the space resource is utilized maximally.

Thereby, when using PISM-CMIMO transmission mechanism is introduced into clustered mobile Ad Hoc networks, the system model in which the number of sending-receiving antenna pairs is always same should be adopted as much as possible, but it also needs to consider the complexity and energy consumption of the networks.

C. Analysis of BER of PISM-CMIMO

Monte Carlo simulation method is used to simulate the real signal transmission processes of PISM-CMIMO, cooperative MIMO (using space-time block coding) and SISO systems respectively. In this process, Function randn() is used to simulate a Gaussian random channel with zero mean and unit variance (whose mean score is 0 and the variance is 1). In this channel, there is AWGN whose mean is zero and power spectral density is $N_0/2$. Besides, BPSK mapping method is used in simulation, normalizing all the receiving signals. As for 2×2 cooperative MIMO system, we use the best selection combining mechanism to simultaneously receive two signals. Finally the maximum likelihood ratio criterion is used to recover the original sending signal at the receiving end of each system. Fig. 9 and Fig. 10 present that the relationship between BER and the received SNR of each system.

Fig. 9 and Fig. 10 show that with the increase of the receiving SNR of the system, the BERs of three systems (PISM-CMIMO, cooperative MIMO and SISO) are all declining. The reason is that the transmission performance will be improved as the receiving SNR increases, thus the probability of transmitting error code will be decreased.

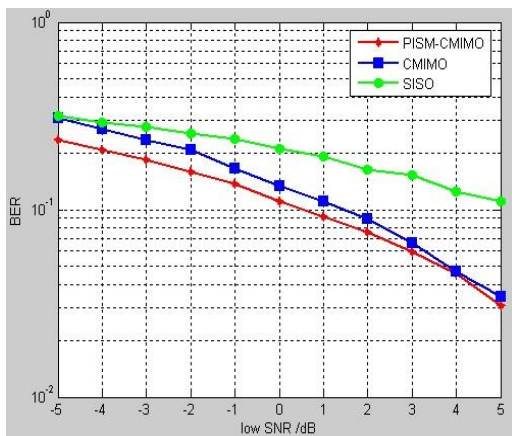


Figure 9. Relation between BER and low SNR of PISM-CMIMO, cooperative MIMO and SISO

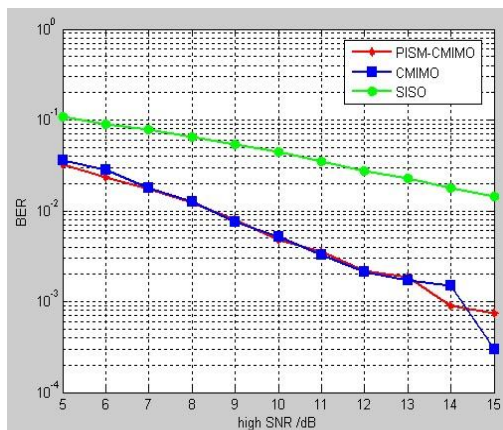


Figure 10. Relation between BER and high SNR of PISM-CMIMO, cooperative MIMO and SISO

Vertical comparison of the three curves in Fig. 8

shows that the BER of 2×2 PISM-CMIMO transmission system is the lowest, and that of SISO transmission system is the relatively highest when the receiving SNR is less than 5dB. Fig.10 shows that the BER of the 2×2 PISM-CMIMO transmission system tends to be consistent with that of the 2×2 cooperative MIMO transmission system when the receiving SNR is greater than 5dB. The above shows that the cooperative MIMO transmission mechanism combined with phase-inversion symmetric method is more suitable for the transmission network with small SNR. However, the cooperative MIMO transmission mechanism connected with space-time coding method would have good effect on the transmission network with high SNR.

Therefore, PISM-CMIMO transmission mechanism is very suitable for clustered mobile Ad Hoc networks with low SNR, which will greatly reduce the BER of the network, improve the quality of the transmitted signals, and make clustered mobile Ad Hoc networks into the stage of practical application earlier.

VII CONCLUSIONS

The noises in real adjacent channels has a strong correlation, but the traditional cooperative MIMO system claims the distance between the mobile terminal antennas should be large enough in order to avoid this correlation, restricting its application in clustered mobile Ad Hoc networks. This paper proposes a cooperative MIMO transmission mechanism based on phase-inversion symmetric method (PISM-CMIMO) in which the correlation between the adjacent channel noises is utilized as a favorable resource so that the minimum distance of the mobile terminal antennas is not limited. In addition, theoretical analysis and system simulation results show that PISM-CMIMO transmission mechanism enables Ad Hoc networks to obtain greater output SNR, improve the channel capacity per bandwidth, and reduce the BER of the system in a low SNR environment, thus overcoming its shortcomings of self-limitation and big noise, and improving the transmission performance of Ad Hoc networks.

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