

A Noise-Correlated Cancellation Transmission Scheme for Cooperative MIMO Ad Hoc Networks

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Abstract—A new transmission scheme based on noise-correlated cancellation (NCC) is proposed, which absorbs the advantages of phase-inversion symmetric method and cooperative MIMO technology and makes full use of the correlation of noise in the adjacent channels to reduce channel noise. This paper firstly presents the implementation process of NCC transmission scheme in detail. Further, through theoretical analysis, it is showed that the signal-to-noise ratio gain which the proposed NCC transmission scheme gets is at least 4 times greater than the signal-to-noise ratio gain which the traditional cooperative MIMO transmission scheme gets. Finally, simulation experiment results also verify that the proposed NCC transmission scheme can make the channel capacity per bandwidth of cooperative MIMO Ad Hoc networks improve significantly and bit error rate (BER) of the network reduce greatly, which will help to expand application scopes of cooperative MIMO Ad Hoc networks.

Index Terms—Mobile Ad Hoc Networks, Cooperative Multi-Input Multi-Output, Phase-Inversion Symmetric Method, Anti-Noise Performance

I. INTRODUCTION

With the continuous development of computer and communication technology, there will be a new situation that people can communicate with each other anytime. Therefore, mobile Ad Hoc networks which could be built without relying on base stations have been extensively studied by scholars. A mobile Ad Hoc network (MANET) is a multi-hop and temporary peer-to-peer network whose nodes act as terminals and routers. The control and management of a MANET are distributed to the terminals, so the terminals involved work together to communicate and exchange information (such as voice, image, video, data, etc) via a wireless link [1, 2, 3]. Since wireless links are relatively weak, bandwidth is relatively limited and there is no support of base stations, signal transmission in

mobile Ad Hoc networks is easy to be interfered by channel noises. Therefore, mobile Ad Hoc networks have relatively poor channel transmission performance which is not conducive to its large-scale practical application.

Cover and Gamal put forward to the term of “Cooperative Communication” in 1979 [4] whose main idea is that neighboring mobile users share each other’s antenna to cooperatively transmit signals in the multi-users’ communication environment, thus generating a virtual environment similar to multi-antenna transmission environment and obtaining spatial diversity gain and improving the transmission performance of the network. The research of Sendonaris [5] showed that the multi-node cooperative transmission mechanism could greatly increase the network capacity and effectively resist fading effects of the wireless channels.

Ref. [6-9] introduced cooperative multi-input multi-output (MIMO) technique into Ad Hoc networks, which showed that the virtual cooperative transmission networks with omni-directional single antenna mobile users could overcome the limits of traditional MIMO transmission networks, sending-receiving diversity gain and array gain got could significantly increase the channel capacity, reduce the end-to-end transmission delay, the energy consumption of data transmission and output bit error rate (BER).

This paper presents a new transmission scheme based on noise-correlated cancellation (NCC) for cooperative MIMO Ad Hoc networks, which absorbs the advantages of phase-inversion symmetric method [10] and cooperative MIMO technology. The scheme not only makes full use of the correlation of noise in the adjacent channels in order to achieve the purpose of resisting channel noise interference but also combines with cooperative MIMO technology in order to achieve the

purpose of enhancing the whole network transmission performance.

II. NETWORK MODEL

As shown in Fig. 1, a certain number of mobile terminals adjacent in position are considered as a cluster. Each cluster has a head responsible for the management of this cluster. However, just as Feng et al. proposed in [6], each cluster is called as a virtual node (VN), the cluster head as a kernel node (KN) and the remaining mobile terminals as team nodes (TNs). 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 which can form a virtual backbone network via the VL. Now assuming that any mobile terminals in a virtual backbone network can send and receive signals synchronously, all channel noises are additive white Gaussian noises (AWGN).

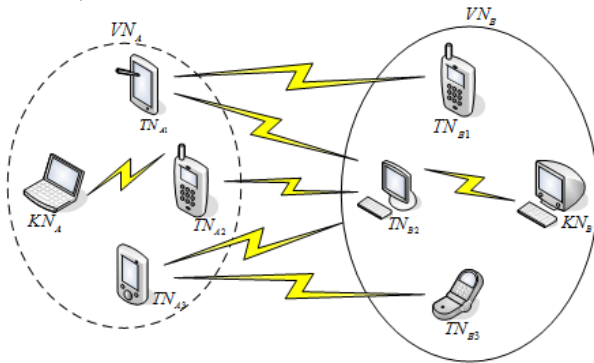


Figure 1. Network model

III. NCC TRANSMISSION SCHEME

A virtual link which connects two adjacent virtual nodes VN_A and VN_B is built in the network model shown in Fig. 1. Then an optimal cooperative terminals selection algorithm is used to select a set of 2×2 cooperative terminals for forming a cooperative MIMO wireless network, and a routing selection algorithm is used to search for the optimal path from the source terminal to the destination terminal. Now assuming that a source terminal A_s in VN_A sends information to a destination terminal B_r in VN_B and A_1, A_2, B_1, B_2 are selected as optimal cooperative terminals. The implementation process is shown in Fig. 2.

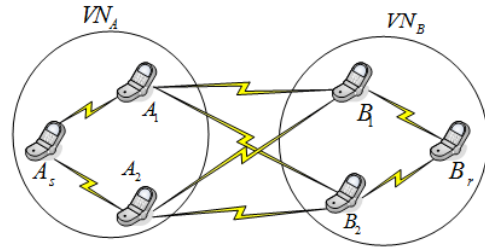


Figure 2. NCC transmission scheme

The source terminal A_s synchronously sends the original data to one cooperative sending terminal A_1 and the data which is reversed phase to another cooperative sending terminal A_2 . After modulating the received signals respectively, A_1 and A_2 send them to the cooperative receiving terminals B_1 and B_2 , thus B_1 and B_2 receive a modulated original data and a modulated inverted one respectively. Next in B_1 and B_2 the signals are subtracted in a sub-tractor after passing through a band-pass filter and a demodulator. Finally, the data is sent to the destination terminal B_r after combining processing in the receiving end.

In the implementation process, the cooperative sending terminals A_1 and A_2 respectively send the data to two cooperative receiving terminals B_1 and B_2 via two independent channels. Here we must claim that the distance between two cooperative sending/receiving antennas must be $\leq \lambda/2$ (here λ is radio wavelength), even in order to use the spatial noise correlation, the distance between the two antennas is as adjacent as possible.

IV. MATHEMATICAL MODEL AND THEORETICAL ANALYSIS OF NCC

The mathematical model of NCC transmission scheme is shown in Fig. 3. The source terminal A_s sends the signal $s(t)$, and two signals $s_1(t)$ and $s_2(t)$ are respectively received by two cooperative sending terminals A_1 and A_2 ($s(t) = s_1(t) = -s_2(t)$), then sent after modulated by two modulators who use different carriers frequencies (f_1, f_2).

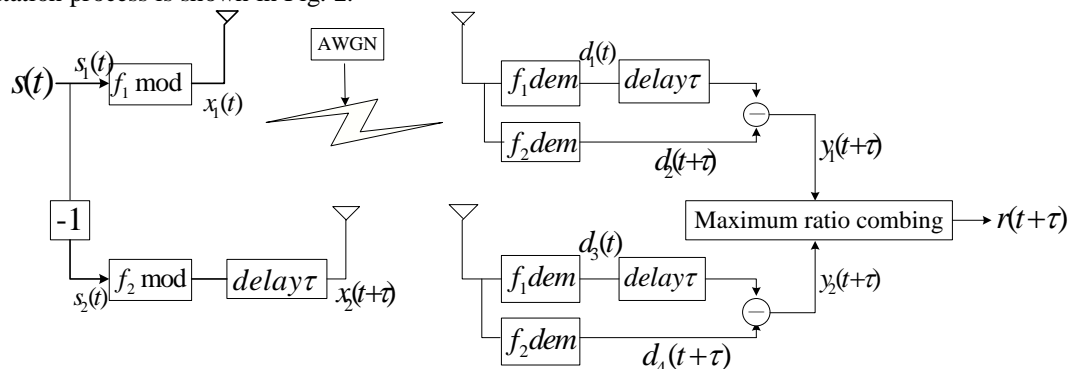


Figure 3. The mathematical model of NCC transmission scheme

Two cooperative receiving terminals B_1 and B_2 respectively receive and demodulate an original signal and a signal after reversed phase.

The modulated signals in B_1 are shown as

$$d_1(t) = h_{11}s_1(t) + n_{11}(t). \quad (1)$$

$$d_2(t + \tau) = h_{12}s_2(t + \tau) + n_{12}(t + \tau). \quad (2)$$

The modulated signals in B_2 are shown as

$$d_3(t) = h_{21}s_1(t) + n_{21}(t). \quad (3)$$

$$d_4(t + \tau) = h_{22}s_2(t + \tau) + n_{22}(t + \tau). \quad (4)$$

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 ($i=1,2; j=1,2$),

$N_{ji} = \begin{bmatrix} n_{11}(t) & n_{12}(t) \\ n_{21}(t) & n_{22}(t) \end{bmatrix}$ is additive white Gaussian noise(AWGN) in the independent channel of the sending antenna i to the receiving antenna j at time t , τ is delay time.

Two demodulated signals in the cooperative receiving terminal B_1 are sent into a sub-tractor, so are two demodulated signals in the cooperative receiving terminal B_2 . The two output signals are:

$$y_1(t + \tau) = d_1(t + \tau) - d_2(t + \tau) \quad (5)$$

$$= h_{11}s_1(t + \tau) - h_{12}s_2(t + \tau) + n_{11}(t + \tau) - n_{12}(t + \tau).$$

$$y_2(t + \tau) = d_3(t + \tau) - d_4(t + \tau) \quad (6)$$

$$= h_{21}s_1(t + \tau) - h_{22}s_2(t + \tau) + n_{21}(t + \tau) - n_{22}(t + \tau).$$

$$s(t) = s_1(t) = -s_2(t), \text{ so } s(t + \tau) = s_1(t + \tau) = -s_2(t + \tau).$$

Thus $y_1(t + \tau)$ and $y_2(t + \tau)$ can be simplified as:

$$y_1(t + \tau) = (h_{11} + h_{12})s(t + \tau) + n_{11}(t + \tau) - n_{12}(t + \tau). \quad (7)$$

$$y_2(t + \tau) = (h_{21} + h_{22})s(t + \tau) + n_{21}(t + \tau) - n_{22}(t + \tau). \quad (8)$$

As we have already stated that the distance between two cooperative sending/receiving antennas must be $\leq \lambda/2$ (here λ is radio wavelength), so can set $h_1 = h_{11} = h_{21}$, $h_2 = h_{12} = h_{22}$ in order to facilitate the analysis. Thus:

$$y_1(t + \tau) = (h_1 + h_2)s(t + \tau) + n_{11}(t + \tau) - n_{12}(t + \tau). \quad (9)$$

$$y_2(t + \tau) = (h_1 + h_2)s(t + \tau) + n_{21}(t + \tau) - n_{22}(t + \tau). \quad (10)$$

Assuming that the channel state information (CSI) in the receiving end has been known, the final output signal gained through using receiving combining technology is

$$r(t + \tau) = \alpha_1(t + \tau)y_1(t + \tau) + \alpha_2(t + \tau)y_2(t + \tau) \quad (11)$$

$$= [\alpha_1(t + \tau) + \alpha_2(t + \tau)](h_1 + h_2)s(t + \tau) + \alpha_1(t + \tau)[n_{11}(t + \tau) - n_{12}(t + \tau)] + \alpha_2(t + \tau)[n_{21}(t + \tau) - n_{22}(t + \tau)].$$

Ref. [11] showed that the performance 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 here. Set $\alpha_1(t + \tau) = \beta h_1$ and $\alpha_2(t + \tau) = \beta h_2$, then the final output total signal can be written as:

$$r(t + \tau) = \beta(h_1 + h_2)^2 s(t + \tau) + \beta h_1 [n_{11}(t + \tau) - n_{12}(t + \tau)] + \beta h_2 [n_{21}(t + \tau) - n_{22}(t + \tau)] = s_o(t + \tau) + n_o(t + \tau). \quad (12)$$

where $s_o(t + \tau)$ is the final output signal including the whole sending information, and $n_o(t + \tau)$ is the final output noise signal.

Assuming that S_o represents the power of $s_o(t + \tau)$, and N_o represents the power of $n_o(t + \tau)$. Now discussing the output signal-to-noise ratio separately in two different environments:

(1) First, we consider an absolutely ideal case. Of course it can not be really achieved. Assuming that the noise in the different independent channels of the different sending antennas i to the same receiving antenna j is the same absolutely ($n_{11}(t + \tau) = n_{12}(t + \tau)$, $n_{21}(t + \tau) = n_{22}(t + \tau)$), thus getting $r(t + \tau) = \beta(h_1 + h_2)^2 s(t + \tau) = s_o(t + \tau)$. However $n_o(t + \tau) = 0$, so $S_o/N_o = E[|s_o(t + \tau)|^2] / E[|n_o(t + \tau)|^2] \rightarrow +\infty$. It means that the output noise is fully offset so that the signal is transmitted without interference.

(2) The noise in real adjacent channels is correlated strongly. Ref. [12] has proved that the correlation coefficient ρ of two adjacent channel noises is up to 0.8 or more through actual measurement when the physical distance of two adjacent channels is less than three meters. Thereby, the output noise of the different independent channels of the different sending antennas i to the same receiving antenna j is extremely similar. Thus the output noise of the sub-tractor in the cooperative receiving terminal B_1 is $n_1(t + \tau) = n_{11}(t + \tau) - n_{12}(t + \tau)$, $n_1(t + \tau) < n_{12}(t + \tau) < n_{11}(t + \tau)$ and that of the sub-tractor in the cooperative receiving terminal B_2 is $n_2(t + \tau) = n_{21}(t + \tau) - n_{22}(t + \tau)$, $n_2(t + \tau) < n_{22}(t + \tau) < n_{21}(t + \tau)$.

$$\text{So } r(t + \tau) = \beta(h_1 + h_2)^2 s(t + \tau) + \beta h_1 n_1(t + \tau) + \beta h_2 n_2(t + \tau) = s_o(t + \tau) + n_o(t + \tau).$$

the total output signal-to-noise ratio (SNR) can be written as:

$$\begin{aligned}
S_o/N_o &= E\left[|s_o(t+\tau)|^2\right] / E\left[|n_o(t+\tau)|^2\right] \\
&= E\left[|\beta(h_1+h_2)s(t+\tau)|^2\right] / E\left[|\beta h_1 n_1(t+\tau) + \beta h_2 n_2(t+\tau)|^2\right] \quad (13) \\
&= |\beta(h_1+h_2)|^2 E\left[|s(t+\tau)|^2\right] / |\beta|^2 E\left[|h_1 n_1(t+\tau) + h_2 n_2(t+\tau)|^2\right].
\end{aligned}$$

Set $h = h_1 = h_2$, then:

$$\begin{aligned}
S_o/N_o &= |4\beta h^2|^2 E\left[|s(t+\tau)|^2\right] / |\beta h|^2 E\left[|n_1(t+\tau) + n_2(t+\tau)|^2\right] \\
&= 16|h|^2 S / E\left[|n_1(t+\tau)|^2 + |n_2(t+\tau)|^2 + 2|n_1(t+\tau)||n_2(t+\tau)|\right] \\
&= (16|h|^2 S) / \{N_1 + N_2 + 2E[|n_1(t+\tau)||n_2(t+\tau)|]\} \\
&= (16|h|^2 S) / (N_1 + N_2 + 2\rho\sqrt{N_1 N_2}). \quad (14)
\end{aligned}$$

where S represents the total power $E[|s(t+\tau)|^2]$ of signal in the sending end, N_1 represents the power $E[|n_1(t+\tau)|^2]$ of the output noise $n_1(t+\tau)$ of the sub-tractor in B_1 , N_2 represents the power $E[|n_2(t+\tau)|^2]$ of the output noise $n_2(t+\tau)$ of the sub-tractor in B_2 , and $\rho = E[n_1(t+\tau)n_2(t+\tau)] / \sqrt{N_1 N_2}$ represents the correlation coefficient of the noise received by the two cooperative receiving terminals.

In order to compare with traditional cooperative MIMO system, considering $h=1$ which means each channel has no attenuation and $N = N_1 = N_2$ which means the noise in the output ends of the two sub-tractors is the same. Get $N < N_i$ (N_i is the noise power in the channel i) from $n_i(t+\tau) < n_{i2}(t+\tau) < n_{i1}(t+\tau)$ and $n_2(t+\tau) < n_{22}(t+\tau) < n_{21}(t+\tau)$. Thus the output signal-to-noise ratio (SNR) can be further transformed into:

$$S_o/N_o = (16S) / [2(1+\rho)N] > \frac{8}{(1+\rho)} \cdot \frac{S}{N_i}. \quad (15)$$

Finally, the SNR gain of NCC transmission scheme is:

$$G_{NCC} = (S_o/N_o) / (S/N_i) > \frac{8}{1+\rho}. \quad (16)$$

The SNR gain of the traditional cooperative MIMO system is [12]:

$$G_{CMIMO} = 2 / (1+\rho). \quad (17)$$

Therefore,

$$G_{NCC} / G_{CMIMO} > 4. \quad (18)$$

Equation (18) shows that the SNR gain which the proposed NCC transmission scheme gets is at least 4 times greater than the SNR gain which the traditional cooperative MIMO transmission scheme gets.

V. SIMULATION AND ANALYSIS OF NCC

A. Analysis of the SNR Gain of NCC

According to Equation (16) and Equation (17), using MATLAB software for simulating NCC transmission scheme. Compared with the SNR gain of traditional cooperative MIMO (CMIMO) system, the simulation result is shown in Fig. 4.

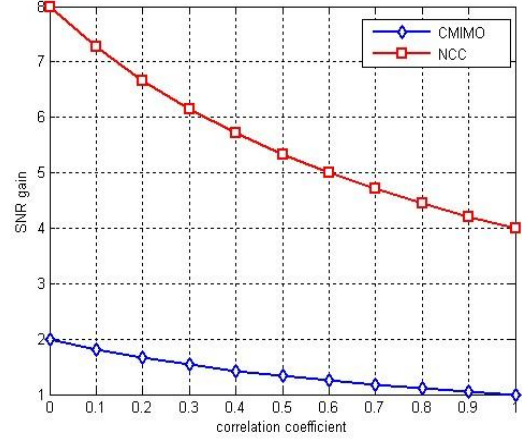


Figure 4. The comparison of SNR gains of NCC and CMIMO

In Fig. 4, the x-axis represents the correlation coefficient ρ of noise in the two adjacent channels which is increasing with decreasing of the spacing between the mobile terminal antennas. Through actually measuring, the correlation coefficient ρ of noise in adjacent channels can be up to 0.8 or more if the spacing between the mobile terminal antennas is less than three meters [12]. The y-axis represents the SNR gain of different systems. The simulation result shows that the SNR gain of cooperative MIMO system based on NCC transmission scheme is much better than that of traditional cooperative MIMO system which can contribute to boosting the anti-noise performance and signal transmission quality of the whole cooperative MIMO Ad Hoc networks.

Further, due to the increase of S/N , the channel capacity $C = B \log_2(1+(S/N))$ [13] would be improved in the case of the same channel bandwidth.

B. Analysis of Channel Capacity of NCC

C. E. Shannon gave the well-known Shannon formula [13]:

$$C = B \log_2(1 + S/N). \quad (19)$$

where B is the channel bandwidth, S is the signal power and N is the noise power.

In order to compare with the traditional $C = b \det(I_2 + \frac{4A}{2}Q)$ cooperative MIMO system, set $SNR = S/N$ and $SNR = 10 \log_{10} A$, then can get $C = \log_2 \det(I_2 + \frac{A}{2}Q)$ which is used in MATLAB simulation. Thus, the channel capacity per bandwidth of

Single-Input Single-Output (SISO) system can be changed into:

$$C = \log_2(1 + A). \quad (20)$$

The channel capacity per bandwidth of traditional cooperative MIMO system is the same as that of distributed MIMO system, so it is [14, 15]:

$$C = \log_2 \det(I_2 + \frac{A}{2}Q). \quad (21)$$

Because the SNR gain of NCC transmission scheme is at least 4 times greater than that of traditional cooperative MIMO system when $\rho > 0.8$, the output SNR of NCC transmission scheme also is at least 4 times greater than that of traditional cooperative MIMO system after normalizing the input SNRs of two systems. Therefore the channel capacity per bandwidth of 2×2 cooperative MIMO system based on NCC transmission scheme is:

$$C = \log_2 \det(I_2 + \frac{4A}{2}Q). \quad (22)$$

According to Equation (20), Equation (21) and Equation (22), the channel capacities of SISO system, 2×2 traditional cooperative MIMO system and 2×2 cooperative MIMO system based on NCC transmission scheme are simulated and analyzed respectively. The result is shown in Fig. 5.

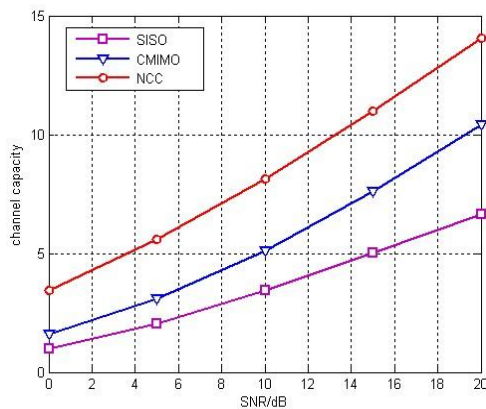


Figure 5. Relationship between the channel capacity and SNR of three systems

Fig. 5 shows that 2×2 cooperative MIMO system based on NCC transmission scheme has relatively the largest channel capacity. That is because NCC transmission scheme takes full advantages of the correlation of noise in adjacent channels to partly offset noise interference so that the SNR gain of the whole system is improved and the channel capacity of the system also is increased in the case of the same channel bandwidth.

The characteristics of cooperative MIMO Ad Hoc networks decides its limited channel bandwidth, 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 NCC transmission scheme is feasible for cooperative MIMO Ad Hoc networks.

C. Analysis of BER of NCC

Using Monte Carlo method for simulating the real signal transmission processes of the 2×2 cooperative MIMO system based on NCC transmission scheme, the 2×2 cooperative MIMO system based on space-time block coding (STBC), the 2×1 cooperative MISO system based on Alamouti coding and SISO system respectively. Function randn() is used to generate a Gaussian random channel whose mean score is 0 and variance is 1. In the channel, there is AWGN whose mean score is zero and power spectral density is $N_0/2$. Besides, BPSK mapping method is used in simulation, normalizing all the receiving signals. Finally the maximum likelihood ratio criterion is used to recover the original sending signal at the receiving end of each system. Fig. 6 presents that the relationship between BER and the output SNR of each system.

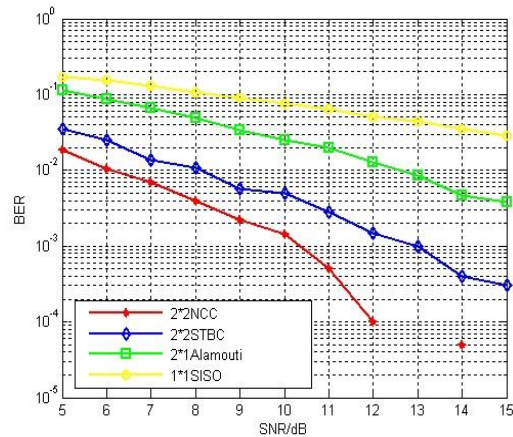


Figure 6. Relationship between BER and output SNR of NCC, STBC, Alamouti and SISO

Fig. 6 shows that the BERs of four systems (NCC, STBC, Alamouti and SISO) are all declining with the increase of the output SNR of the corresponding system. The reason is that the transmission performance will be improved with the increasing of the output SNR, thus the probability of transmitting error code will be decreased.

Vertical comparison of the four curves in Fig. 6 shows that the BER of the 2×2 cooperative MIMO system based on NCC transmission scheme is the lowest, and that of SISO transmission system is the relatively highest. The signal transmission qualities of the 2×2 cooperative MIMO system based on NCC transmission scheme and the 2×2 cooperative MIMO system based on space-time block coding (STBC) all are better than that of the 2×1 cooperative MISO system based on Alamouti coding and SISO system. That is because the Alamouti coding system only adopts transmitting diversity technique but the STBC coding system adopts transmitting diversity and receiving combining techniques, and the NCC system also adopts noise-correlated cancellation method except for transmitting diversity and receiving combining techniques.

VI. CONCLUSIONS

The traditional cooperative MIMO system claims the spacing between the mobile terminal antennas should be large enough in order to avoid the correlation of the noise in different channels, restricting its application in cooperative MIMO Ad Hoc networks. This paper proposes a transmission mechanism based on noise-correlated cancellation method (NCC) in which the correlation between noise in the adjacent channels 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 NCC transmission scheme enables cooperative Ad Hoc networks to obtain greater output SNR, improve the channel capacity per bandwidth, and reduce the BER of the system, thus overcoming its shortcomings of self-limitation and big noise, and improving the transmission performance of cooperative MIMO Ad Hoc networks.

ACKNOWLEDGEMENT

This work was supported in part by a grant from the National Natural Science Foundation Project of China (No. 61271249).

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