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Space-time cooperative diversity scheme using full feedback

SUN De-chun (✉), YI Ke-chu, LI Xiao-hui
State Key Laboratory of Integrated Service Networks, Xidian University, Xi'an 710071, china

Abstract
This article proposes a new space-time cooperative diversity scheme called full feedback-based cooperative diversity scheme (FFBCD). In contrast to the conventional adaptive space-time cooperative diversity schemes that utilize the feedback from only the destination node, the new scheme utilizes the feedback from both the destination node and the cooperation node. With the feedback from the destination node, the occasional successful reception of the destination node in the information distribution stage can be detected, thus avoiding unnecessary retransmissions in the information delivery stage. The feedback from the cooperation node indicates the receiving state of the cooperation node in the information distribution stage, and the source node and the cooperation node will not perform cooperative retransmission during the information delivery stage unless the cooperation node is received successfully in the information distribution stage. In this way the new scheme can reduce the number of transmission attempt and improve the channel utilization. The expressions of the average number of transmission attempt are given. Numerical approximations and simulation results both show that the new scheme performs better than the non-cooperative scheme and the conventional adaptive space-time cooperative diversity scheme.

Keywords space-time cooperative diversity, simple feedback, adaptive cooperative diversity, transmission attempt

1 Introduction
Signal fading caused by multi-path propagation is a key problem in wireless communications. Its adverse effects can be mitigated by diversity, a powerful technique. In recent years, multi-input multi-output (MIMO) systems have been studied extensively [1–2]. The space diversity provided by MIMO systems can achieve substantial diversity gain to combat signal fading [3–4]. Unfortunately, it may not always be possible to physically carry multiple antennas at a pocket terminal. An alternative way is to use antennas located on different terminals to form a distributed multi-antennas system. This method is called cooperative diversity [5] and has been attracting increasing attention [6–13]. In Ref. [7] Laneman et al. presented several cooperative diversity protocols and displayed their outage performance. Further in Ref. [8] they proposed a cooperative diversity scheme using space-time code. The conventional adaptive cooperative diversity schemes generally consist of two stages. In the first stage the source node sends information to the cooperation node(s) and this stage is called the information distribution stage. In the second stage, the source node and the cooperation node(s) cooperate to send information to the destination node and this stage is called the information delivery stage.

Because of the broadcast nature of wireless media, the destination node may hear the source node and decode it successfully during the distribution stage. This situation, however, is ignored in the fixed space-time cooperative diversity schemes. To utilize the occasional successfully reception of the destination node, several feedback schemes should be adopted. Here, the automatic repeat request (ARQ) might be an effective way [9–11]. In Ref. [9] a cross layer design that combines cooperative diversity and truncated ARQ is proposed for Ad-hoc networks. This scheme is among typical feedback-based cooperative diversity schemes. Its basic idea is to use feedback from the destination node to determine the system behavior. When the destination node receives information unsuccessfully, the source node and the cooperation node will cooperate to transmit it again. This kind of scheme indicates that the cooperation node always receives information successfully in the information distribution stage; whereas, in reality, this assumption does not always hold. When the cooperation node fails in receiving the information, the source node will retransmit it and the cooperation node will
keep inactive in the information delivery stage. As a result, no cooperation is actually implemented and the source node may waste its power. This kind of scheme is called in this article the partial feedback-based cooperative diversity scheme.

Based on the simple feedback from both the destination node and the cooperation node, a new cooperative diversity scheme is proposed in this article. With the feedback from the destination node, the occasional successful reception of the destination node in the information distribution stage can be detected to avoid unnecessary retransmission. Meanwhile, the feedback from the cooperation node indicates whether the cooperation node receives the information successfully and whether cooperation can be implemented. This new scheme is called the full feedback-based cooperative diversity scheme. Numerical approximations and simulations show that the proposed scheme can considerably improve the performance in comparison to the non-cooperative scheme. Furthermore, improvement can be gained from its comparison with the partial feedback-based cooperative diversity scheme.

The remainder of the article is organized as follows: system models are described in Sect. 2. In Sect. 3, the probability of transmission failure is deduced and the expressions of the average number of transmission attempt are presented. Simulation results as well as performance comparisons are presented in Sect. 4. Conclusions are drawn in Sect. 5.

2 System model

Three nodes in the models are considered: the source node, the cooperation node and the destination node (shown in Fig. 1). The transmission is divided into time slots and each time slot consists of \( N \) symbol periods.

![Cooperative diversity system](image)

2.1 Non-cooperative model: NC

The source node sends information to the destination node only. If a transmission failure happens, the source node retransmits it. There is no cooperation between the source node and the cooperation node. The received signals are:

\[
y_d[n] = h_{s,d}[n]x[n] + z_d[n]
\]

where \( y_d \) is the signal received at the destination node, \( h_{s,d} \) is the fading coefficient of the source-destination channel, \( x \) is the transmit signal and \( z_d \) is the complex noise.

2.2 Partial feedback-based cooperative diversity (PFBCD)

This scheme uses feedback from the destination node. The source node first transmits information to the destination node and the cooperation node. This transmission is called direct transmission. At the end of the direct transmission, the receiving state of the destination node is broadcasted. If the destination node receives successfully, the source node continues to transmit new information. Otherwise, the source node and the cooperation node will cooperate to retransmit the information. This transmission is called cooperative transmission. The source node always assumes that the cooperation node has received the information successfully during the direct transmission. The source node will transmit according to the Alamouti’s space time block coding (STBC) rule. If the cooperation node has received the information successfully in the direct transmission, it will transmit in the same way as the source node; otherwise, it will do nothing. At the end of this cooperative transmission time slot, if the destination node receives successfully, the source node will start a new transmission process; otherwise, another direct transmission and cooperative transmission will be implemented to transmit the same information. The received signals in the direct transmission time slot are:

\[
y_d[n] = h_{s,d}[n]x[n] + z_d[n]
\]

If the cooperation node did not receive the information successfully in the previous direct transmission, the received signals at the destination node in the cooperative transmission time slot are:

\[
y_d[n] = \frac{\sqrt{2}}{2} h_{s,d}[n][x[n - Na] + z_d[n]]
\]

\[
y_d[n + 1] = \frac{-\sqrt{2}}{2} h_{s,d}[n][x[n - Na + 1] + z_d[n + 1]]
\]

\[
n = aN + 1, aN + 3, \ldots, (a + 1)N - 1; \quad a \geq 0
\]
\[ y_0[n] = \frac{\sqrt{2}}{2} \left( h_{s,0}[n] x[n-Na] + h_{c,0}[n] x[n-Na+1] \right) + z_0[n] \]
\[ y_0[n+1] = \frac{\sqrt{2}}{2} \left( -h_{s,0}[n] x'[n-Na] + h_{c,0}[n] x'[n-Na+1] \right) + z_0[n+1] \]
\[ n = aN + 1, aN + 3, \ldots, (a+1)N - 1; \quad a \geq 0 \tag{4} \]

In Eqs. (3)–(4), \( h_{c,0} \) is the fading coefficient of the cooperation-destination channel and \( x' \) denotes the complex conjugate of \( x \). The factor \( \sqrt{2}/2 \) indicates that the transmit power is halved when cooperation is implemented.

### 2.3 Full feedback-based cooperative diversity (FFBCD)

In this scheme, simple feedback from both the destination node and the cooperation node is utilized. At the end of a time slot, the receiving state of the destination node and the cooperation node is broadcasted. In the distribution stage, both the cooperation node and the destination node try to decode the received signals. If the destination node receives successfully not later than the cooperation node, the transmission process terminates and no more transmission attempts are needed. If the cooperation node receives successfully earlier than the destination node, the system enters into the information delivery stage. The source node and the cooperation node cooperate to transmit again.

The behaviors of the source node and the cooperation node are dependent on the receiving state of the previous time slot. Use \( E_i \) to denote different system events. These events and their corresponding system behaviors are listed as follows:

**Case 1** \( (E_i) \) Neither the destination node nor the cooperation node receives successfully in the first \( k \) time slots. In the \((k+1)\)th time slot the destination node receives successfully. The received signals in these \( k+1 \) time slots are given as:
\[ y_s[n] = h_{s,0}[n] x[n-Na] + z_0[n] \]
\[ y_c[n] = h_{c,0}[n] x[n-Na] + z_c[n] \]
\[ aN + 1 \leq n \leq (a+1)N; \quad 0 \leq a \leq k \tag{5} \]

**Case 2** \( (E_i) \) Neither the destination node nor the cooperation node receives successfully in the first \( m \) time slots. In the \((m+1)\)th time slot, only the cooperation node receives successfully. After that, by using Alamouti’s STBC, the source node and the cooperation node cooperate to send the same information for \( l+1 \) times until the destination node receives it successfully. The received signals in the information delivery stage, i.e., the first \( m+1 \) time slots, are given as:
\[ y_s[n] = h_{s,0}[n] x[n-Na] + z_0[n] \]
\[ y_c[n] = h_{c,0}[n] x[n-Na] + z_c[n] \]
\[ aN + 1 \leq n \leq (a+1)N; \quad 0 \leq a \leq m \tag{6} \]

and the received signals in the information delivery stage, i.e., the second \( l+1 \) time slots, are given as:
\[ y_s[n] = \frac{\sqrt{2}}{2} \left( h_{s,0}[n] x[n-Na] + h_{c,0}[n] x[n-Na+1] \right) + z_0[n] \]
\[ y_s[n+1] = \frac{\sqrt{2}}{2} \left( -h_{s,0}[n] x'[n-Na] + h_{c,0}[n] x'[n-Na+1] \right) + z_0[n+1] \]
\[ n = aN + 1, aN + 3, \ldots, (a+1)N - 1; \quad m + 2 \leq a \leq m + 2 + l \tag{7} \]

Note that to keep the constant overall transmit power, the transmit power are all halved.

In Eqs. (1)–(7), \( a \) denotes the \( a \)th retransmission of the information block, and \( a = 0 \) denotes the first transmission. The fading coefficient \( h_{ij} \) captures the effects of path-loss, shadowing, and frequency nonselective fading, and noise \( z_i \) captures the effects of receiver noise and other forms of interference in the system. Statistically, the authors model \( h_{ij} \) as zero-mean, independent, circularly-symmetric complex Gaussian random variables with variances \( \sigma_{ij}^2 \), so that the magnitude \( |h_{ij}| \) is Rayleigh distributed (\( |h_{ij}|^2 \) is exponentially distributed with mean \( \sigma_{ij}^2 \)) and the phase \( \angle h_{ij} \) is uniformly distributed in \([0,2\pi)\). \( z_i \) is modeled as zero-mean mutually independent, circularly-symmetric, complex Gaussian random sequences with variance \( N_0 \).

### 3 Average number of transmission attempt

#### 3.1 Error probability and event probability

Assume that the binary phase shift keying (BPSK) modulation and the Raleigh fading channel model are adopted. When no cooperation is implemented, the symbol error probability of the BPSK is [12]:
\[ P_e(\overline{\gamma}_B) = 0.5 \left( 1 - \frac{\overline{\gamma}_B}{1 + \overline{\gamma}_B} \right) \tag{8} \]
where \( \overline{\gamma}_B \) is the average bit SNR over the distribution of channel coefficient \( h \). \( \overline{\gamma}_B \) is defined as
\[ \overline{\gamma}_B = \frac{\overline{\gamma}_B}{N_0} = \frac{E[|h|^2]}{N_0} \tag{9} \]

Let \( \overline{\gamma}_B^{S,0} \), \( \overline{\gamma}_B^{S,C} \) and \( \overline{\gamma}_B^{C,D} \) denote the average bit SNR of the source-destination link, source-cooperation link and cooperation-destination link, respectively, when no cooperation
is implemented.

The symbol error probability of the BPSK when using the Alamouti space-time code scheme is give as [13]:

\[ P_{2\_STC}(\gamma) = 0.5 \left[ 1 - \frac{\gamma}{2 + \gamma} \left( 1 + \frac{1}{2 + \gamma} \right) \right] \]

(10)

where \( \gamma \) is the average bit SNR at the destination node and is equal to the sum of \( \gamma^{\text{SD}} \) and \( \gamma^{\text{CD}} \), which are the average bit SNR of the source-destination channel and the cooperation-destination channel, respectively, when cooperation is implemented. It is assumed that the source-destination channel and the cooperation-destination channel are identical, i.e. \( \gamma^{\text{SD}} = \gamma^{\text{CD}} \). The power level of the source node and the cooperation node are all halved, thus having:

\[ \gamma^{\text{SD}} = \gamma^{\text{CD}} = 0.5\gamma^{\text{SD}} \]

(11)

In the partial feedback-based cooperative diversity scheme, if the cooperation node has not received the information successfully during the direct transmission, in the next time slot only the source node transmits according to the Alamouti’s STBC rule. In this case, the symbol error probability of this ‘fake STC cooperative transmission’ is just like the symbol error probability of the BPSK except that the average bit SNR is halved. This symbol error probability is:

\[ P_{2\_PSTC} = P \left( \frac{\gamma}{2} \right) \]

(12)

In the full feedback-based cooperative diversity scheme, for case 1 (\( E_1 \)), the event probability is:

\[ P(E_1) = \left[ \left( 1 - P_1(\gamma^{\text{SD}}) \right)^{\frac{1}{k}} \left( 1 - P_1(\gamma^{\text{CD}}) \right)^{\frac{1}{k}} \right]^{k} \left[ \left( 1 - P_1(\gamma^{\text{SD}}) \right)^{\frac{1}{k}} \right]^{k} \]

(13)

For case 2 (\( E_2 \)), the event probability is:

\[ P(E_2) = \left[ \left( 1 - P_1(\gamma^{\text{SD}}) \right)^{\frac{1}{m}} \left( 1 - P_1(\gamma^{\text{CD}}) \right)^{\frac{1}{l}} \right]^{m} \]

(14)

\[ \left[ \left( 1 - P_1(\gamma^{\text{SD}}) \right)^{\frac{1}{m}} \right]^{l} \left[ \left( 1 - P_1(\gamma^{\text{CD}}) \right)^{\frac{1}{l}} \right]^{l} \]

3.2 Average number of transmission attempt

For the NC scheme, the destination node fails to receive in the first \( k \) time slots. In the \( (k+1) \)th time slot, the destination node receives the information successfully. The average number of transmission attempts is

\[ N_{\text{NC}} = \sum_{k=0}^{\infty} k \left[ 1 - P_1(\gamma^{\text{SD}}) \right]^k \left[ P_1(\gamma^{\text{SD}}) \right]^k \]

(15)

For the PFBCD scheme, the transmission process may terminate after a direct transmission time slot or a cooperative transmission time slot. Averaging over these cases, one can get the average number of transmission attempt:

\[ N_{\text{PFBCD}} = \sum_{k=0}^{\infty} \sum_{l=0}^{\infty} \left( k \left[ 1 - P_1(\gamma^{\text{SD}}) \right]^k \left[ P_1(\gamma^{\text{SD}}) \right]^k \right) \]

(16)

For case 1 of the FFBCD scheme, the number of transmission attempt needed to complete the transmission process is \( k+1 \). For case 2, it is \( N_{E_2} = m + l + 2 \). Averaging over these two cases, one obtains:

\[ N_{\text{FFBCD}} = \sum_{k=0}^{\infty} \left( k \left[ 1 - P_1(\gamma^{\text{SD}}) \right]^k \left[ P_1(\gamma^{\text{SD}}) \right]^k \right) \]

(17)

The relationship among Eqs. (15)–(17) can be obtained by numerical calculations.

4 Simulation results

In this section, the authors first make numerical approximations of Eqs. (15)–(17), and then simulate different transmission schemes and present the simulation results.

The number of symbols in one time slot is \( N=16 \). Let \( R_{5,6,5,6} = 10 \log_{10} \left[ \frac{E(h_{5,6}^T)}{E(h_{5,6}^T)} \right] \) denote the relationship of the source-cooperation channel and the source-destination channel. A large \( R_{5,6,5,6} \) indicates that the quality of the source-cooperation channel is much better than the source-
destination channel.

The average number of transmission attempt of different schemes is shown in Fig. 2. Both numerical approximations and simulation results are demonstrated. The two match well, which verifies the analytical expressions of Eqs. (15)–(17). It can be seen that in the region of low SNR, the PFBCD scheme performs worse than the NC scheme. Only in the region of higher SNR, the PFBCD scheme performs better. The cross point is at about 3 dB. In other words, the PFBCD scheme is only preferred in the region of higher SNR. In contrast, the FFBCD scheme performs better in the whole SNR region. The performance is improved by about 4 times at 0 dB and 2 times at 2 dB. The improvement decreases when the bit SNR increases. This indicates that when the source-destination channel is good enough, the significance of cooperative diversity will be diminished.

The difference between Fig. 2 and Fig. 3 lies in that $R_{s,c,s,d}$ is enlarged. It can be seen that with a bigger value of $R_{s,c,s,d}$, the PFBCD scheme performs better than the NC scheme when SNR is even smaller. Here the cross point is at about 1 dB.

This shows that when the source-cooperation link is getting better, the performance of the PFBCD is getting better, too. Though the receiving state of the cooperation node is not considered in the direction transmission, a better source-cooperation link will definitely increase the probability of implementing STC cooperation, hence decreasing the average number of transmission attempt.

Fig. 4 shows the average number of transmission attempt improvement of the FFBCD scheme versus $R_{s,c,s,d}$ when Bit SNR is fixed to 0 dB. It can be seen from Fig. 3 that the improvement increases with the rise of $R_{s,c,s,d}$. Whereas, this improvement is almost unchanged when $R_{s,c,s,d}$ is sufficiently large. This happens because when $R_{s,c,s,d}$ is small, statistically the source node will try more times to share the information with the cooperation node. The system needs more transmission attempts to enter into the STC cooperation state. While $R_{s,c,s,d}$ increases, the number of time slot needed to enter into the cooperation state decreases. Hence, the performance improvement increases. However, when $R_{s,c,s,d}$ is sufficiently large, the cooperation node will receive information successfully in the first direct transmission time slot with the probability of almost 1. Therefore, the system will enter into the cooperation state immediately. And the improvement is almost fixed no matter what $R_{s,c,s,d}$ is.

5 Conclusions

This article, based on simple feedback, proposes a practical space-time cooperation diversity scheme called full feedback-based cooperative diversity scheme. This scheme utilizes the feedback from both the destination node and the cooperation node to determine system behaviors. With the feedback from the destination node, one can utilize the occasional successful reception of the destination node in the information distribution stage. As a result, the transmission
process stops and no more retransmissions are needed, hence improving the channel utilization. With the feedback from the cooperation node, the system can determine whether the cooperation node receives the information successfully and whether cooperation can be implemented. Simulations indicate the proposed scheme performs better than the NC scheme in the whole SNR region. It also performs better than the conventional partial feedback-based cooperative diversity scheme, which performs better than the NC scheme only in the region of higher SNR. The effect of the quality of the source-cooperation link is also studied. Bad quality requires urgent improvement, while for sufficiently high quality, no improvement is demanded.

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References


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