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Improved Model of the Selection with Soft and Hard Combining Decoding Strategies for Multi-User Multi-Relay Cooperative Networks

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ABSTRACT

In a wireless cooperative network, system reliability can be improved by introducing network coding (NC) for transmitting data packets from user to destination through relay nodes. At the destination, a decoding strategy is required to recover the original data packets. The use of NC in cooperative networks has been intensively studied in previous works in terms of the conventional model for two users and a single relay in a network. However, the network model cannot act as a virtual multiple-input multiple-output system, and a multi-user multi-relay network model could be used in a real system. Therefore, this paper proposes an improved model of two network decoding strategies, selection with soft combining (SSC) and selection with hard combining (SHC), for multi-user multi-relay cooperative networks. Users are classified based on their channel conditions, with better signal-to-noise (SNR) ratio sources being viewed as strong users, and others as weak or moderate users in the decoding strategies. To evaluate the performance of the proposed model, we first derive the bit error probability expressions for each strategy as a function of SNR and then evaluate the performance using numerical simulation for a Rayleigh fading channel. Simulation results show that SSC outperforms SHC. Furthermore, the improvement in network performance is achieved either by having a higher modulation level or using incremental relaying as the signal reception method at the destination.

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1. INTRODUCTION

Wireless communication technology is growing rapidly, with greater reliability, higher data rates, and more compact hardware with larger capacity. This is in line with users' communication requirements, which are no longer restricted to conventional communication methods. It has also motivated the development of new methods to satisfy these needs. However, the implementation of wireless communication systems has suffered from several weaknesses, particularly regarding communication channels as the transmission media. A wireless channel is very vulnerable to several types of disturbance, such as noise, interference, attenuation, and fading, which can degrade the performance of the system [1]. This is often known as multipath fading and is caused by the reflection of a propagated signal by diverse obstacles, thereby declining the quality of a signal arriving at a destination [2].

Diverse multiple-input multiple-output (MIMO) techniques have been introduced to overcome the effects of multipath fading, which occur frequently in wireless communication systems [2]-[4]. However, owing to the size factor, high cost, and limited hardware, MIMO technology is not effective for application in a wireless communication system, where it would be used for cellular communication. The limitations of MIMO technology have motivated research on other techniques, and in particular, on cooperative communication systems that implement relay techniques acting as virtual multiple antennas [5],[6]. A cooperative relay technique in the uplink of a cellular system is known as a multiple-access relay channel (MARC) [7]-[9].

Spatial diversity was introduced to overcome the fading problem in securing wireless data streams to some extent [10]. To achieve full transmission diversity, independent copies of signals are transmitted through multiple antennas placed at a transmitter [11]. In cooperative communication, users (multiple antennas) and relays cooperate with each other to transmit data toward a destination. At present, there has been increasing interest in applying the network coding (NC) scenario to diversify techniques in cooperative communication [12],[13]. NC was introduced in [14] to improve system throughput and the process of combining data packets. The combined packets are transmitted to all recipients, instead of each packet being forwarded individually [15].

Network decoding (ND) of user signals is a challenging problem for decoder design, where the NC-based MARC is applied at the destination [13],[16],[17]. Several previous studies have been conducted to solve this problem [16]-[19]. In [16], the performance of low-complexity ND strategies for cooperative NC in a MARC scenario was analyzed. It used selection with soft combining (SSC) strategy and majority vote ND, also known as selection with hard combining (SHC) strategy. The results have shown that the performance of the SSC strategy is similar to that of the SHC strategy for the case of two users and a single relay. Application of NC to the MARC has been studied in [18]-[20]. The previous studies considered the decoding strategies and their performance for a cooperative network with two users and a single relay. However, it is easy to conceive of many users and many relays being used in a real system. A single relay cannot act as a virtual MIMO system. Therefore, it is a motivation for introducing this concept into cooperative communications. Consequently, decoding strategies for a multi-user multi-relay cooperative network in a MARC scenario must be considered for practical implementation. An initial work for a multi-sources and multi-relay cooperative network has been presented in [21]. However, it was only for four sources and three relays network, and focused on the low complexity analysis.

In this study, we propose an improved model of SSC and SHC for multi-user multi-relay cooperative networking in a MARC scenario. To evaluate the performance of the proposed model, we derive bit error probability (BEP) expressions for each strategy as a function of the signal-to-noise (SNR) ratio in the Rayleigh fading channel. In addition, we evaluate the effects of relaying method and digital modulation type on the performance of each decoding strategy for MARC-based multi-user multi-relay cooperative networks. Our main technical contributions can be summarized as

- an improved model for multi-user multi-relay cooperative networks using the SSC and SHC decoding strategies,
- analytical expressions for the SSC and SHC decoding strategies for multi-user multi-relay cooperative networks,
- an analysis of the system performance of multi-user multi-relay cooperative networks based on the analytical expressions, and
- a study of the effect on system performance of the modulation type used with the proposed model.

2. IMPROVED SYSTEM MODEL

In previous studies [16]-[20], the conventional model is represented by two users U_1 and U_2 communicating with destination D via relay network RN with direct links from users to destination. In this section, we discuss the proposed network topology model and derive the BEP of the low-complexity SSC and SHC decoding strategies for MARC-based multi-user multi-relay cooperative NC. The network topology model analyzed in this work is shown in Figure 1. There are N-user (U_1, U_2,…, U_N), that aim to send information to a destination, D, using $N-1$ relay nodes (R_1, R_2,…, R_{N-1}), at different times. Relays are considered as fixed nodes, often called micro base stations. The relay is not limited to a fixed radio transceiver, but can also be a mobile terminal “seed” on 3rd Generation Partnership Project (3-GPP) LTE-Advanced technology [20].

The network topology is based on consideration of a cellular communication network cell containing more than two users that aims to send information to a base station. In addition to the effects of multipath fading, the large distance between the user and the base station can cause the information received at the base station to differ from the original information (error). This limitation can be overcome by using cooperative communication in which each user sends the information through a relay node nearby. In our network topology model, N-user and $N-1$ relays are considered to represent the number of users handled by a base station in a single traffic period. This means that there are N-user active at one time and in one cell on the mobile communication network.

Figure 2 illustrates the transmission structure from transmitter to receiver nodes in the uplink scenario for a multi-user multi-relay MARC-based cooperative communication system with multi-user NC. The dashed line indicates wireless transmission of data in which the effects of channel fading and noise are excluded. However, those effects are considered in the mathematical analysis. Modulation, demodulation, and NC processes are indicated by MOD, DEMOD, and NC blocks, respectively.

The type of cooperative protocol used in this study is referred to as fixed decode-and-forward (DF), where a relay first decodes the received information from a user and then forwards it to a destination through the re-encode process. In the DF scheme, multiple users, U_1–U_N, transmit to multiple relays, R_1–R_{N-1}, and destination D simultaneously in the first time slot, and relays R_1–R_{N-1} transmit the decoded signals to destination D in the second time slot. From Figure 2, it can be seen that the users and relays transmit one symbol $m_k, (k = 1, 2, \dots, 2N - 1)$, through the link k for a particular time interval in each frame transmission.

Transmission frame is performed in three time slots for each relay node. In the first two time slots, each user transmits its own symbol towards the destination. Relay also listen to these transmissions. It decodes the received signals from users and combines these signals using bitwise XOR operation. In the third time slot, relay transmits the network coded symbol towards the destination. In Figure 2, transmitted symbol, $m_1, m_2, \dots, m_N$, denotes the set of transmitted symbols by users, while predicted symbol, $\widehat{m}_1, \widehat{m}_2, \dots, \widehat{m}_N$, is the set of detected symbols at the destination and $m_{N+1}, m_{N+2}, \dots, m_{2N-1}$ represents the network coded symbols transmitted by the relays.

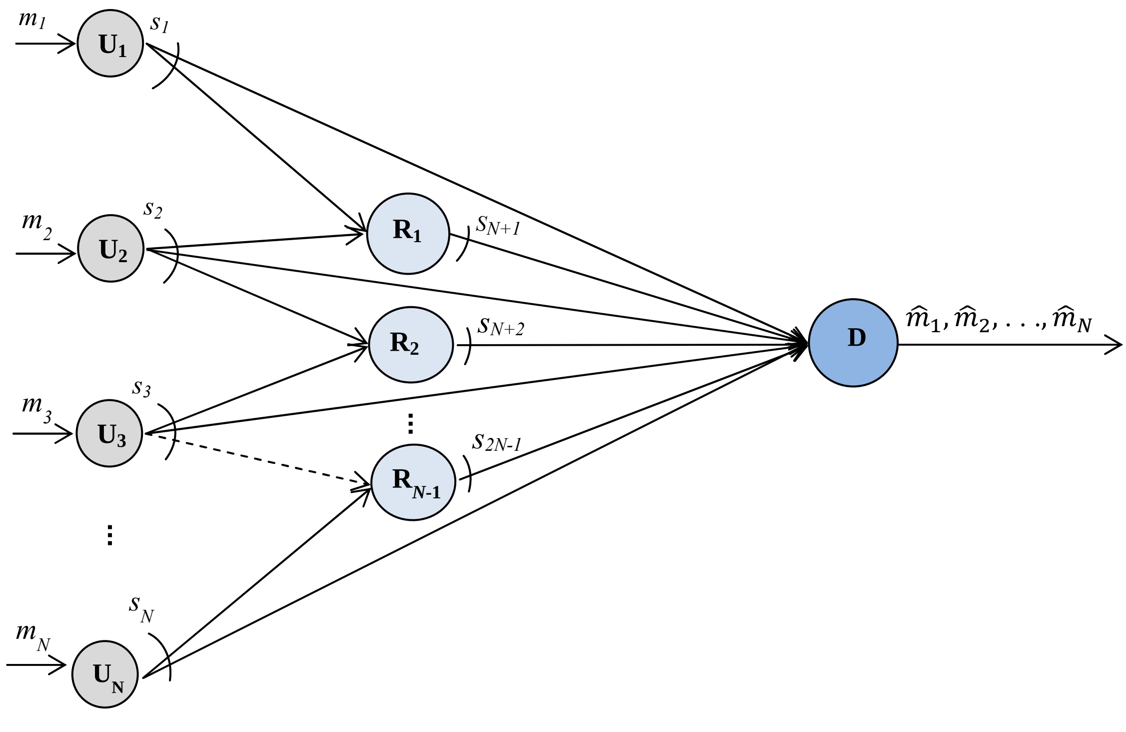

Figure 1. Proposed topology of multi-user multi-relay MARC-based cooperative communication system with NC

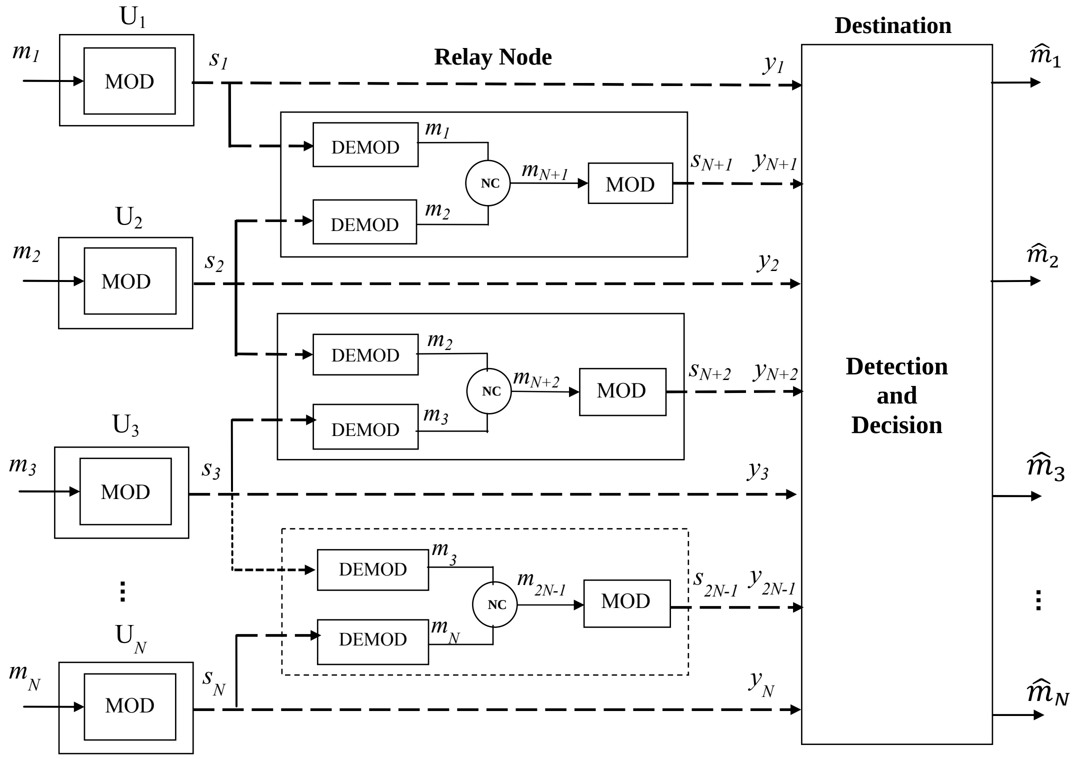

Figure 2. Generic system structure of multi-user multi-relay MARC-based cooperative communication system with NC

At the relay, all symbols are detected and encoded using NC. The NC operation is performed as a bit-wise XOR operation on symbols, where R_1 forwards the U_1 and U_2 encoded symbols, $s_{N+1} = M(m_1 \oplus m_2)$ for T_{N+1}, R_2 forwards the U_2 and U_3 encoded symbols, $s_{N+2} = M(m_2 \oplus m_3)$ for T_{N+2}, and $R_{N\text{-}1}$ forwards the U_3 and U_4 encoded symbols, $s_{2N-1} = M(m_3 \oplus m_N)$ for T_{2N-1}. Then, all encoded symbols are forwarded back to the destination.

At the destination, all symbols from users and relays are received as the signal samples y_k and decoded through the detection and error correction process. The aim of the ND strategy is to recover the original information signal from the received signal samples from each node by considering the smallest possible errors, where $\widehat{m}_i$ is the predicted symbol at the destination.

3. NETWORK DECODING STRATEGIES

This section analyzes the SSC and SHC strategies for estimating the information of a MARC-based cooperative network at the destination for N users and $N - 1$ relays in an uplink scenario.

3.1. Analysis of Selection and Soft Combining (SSC)

The receiver structure for SSC of a multi-user multi-relay MARC-based cooperative communication system with NC is illustrated in Figure 3. In this strategy, an information signal at the destination is received by selecting the best SNR, a process known as selection relaying. Users with better SNR are considered strong users, while others are considered weak users. For the weak users, signals from direct transmission and coded signals from the relay are combined to obtain a better SNR. Then, all combined symbols are forwarded back to the destination, a process known as incremental relaying.

Detection in the destination is performed using maximum likelihood (ML) detection, in which the bits received by the destination are most similar to the bits sent through the encoding process. At the destination, all alternatives are attempted using the smallest error metric to estimate the predicted symbol, $\widehat{m}_1$, $\widehat{m}_2$,…, $\widehat{m}_N$, from the transmitted symbols, $m_1, m_2, \dots, m_N$. The principle of the selection relaying method is that the transmission frames have one strong user.

Since user i can be strong or weak, with the error probabilities of the strong and weak users denoted by P_{strong} and P_{weak}, respectively, the pairwise error probability of user i can be written as follows [15]:

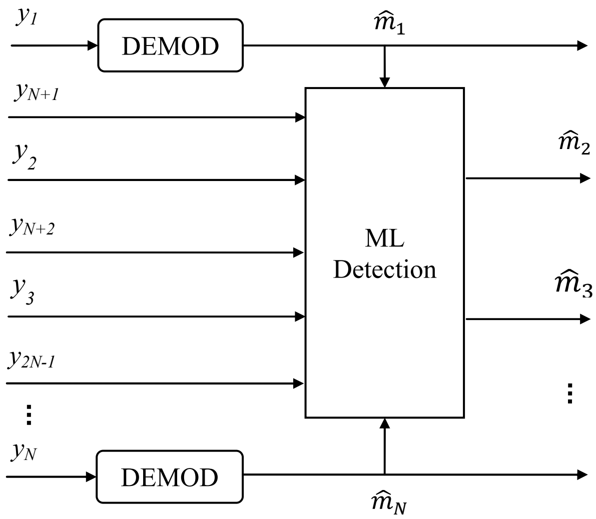

Figure 3. Receiver structure of multi-user multi-relay NC for SSC

$$P(s \to \hat{s}) = \alpha_i P_{\text{strong}} + (1-\alpha_i) P_{\text{weak}}, \tag{1}$$

where $\alpha_i = \frac{\gamma_i}{\gamma_i+\gamma_{i+1}}$ and α_i is the probability that user i is the strongest and γ_i is the average received SNR of link i, $i = 1, 2, \ldots, N$, in which N is the number of user links.

The average BEP of user i can be obtained from its pairwise error probability as [15]:

$$P_b \le \frac{1}{M\log_2(M)} P(s \to \hat{s}), \tag{2}$$

where $M = 2^l$ is the modulation level, l is the number of bits per symbol and $\hat{s}$ is the estimate of the symbol s. The error probability of the strong user is based on selection diversity. Denoting by s_s the symbol of the strong user and by s_w the symbol of the weak user during a particular symbol interval, the error probability of the strong user can be written as follows [15]:

$$P_{\text{strong}}\{\varepsilon|\Gamma_{\max}\} = Q\left(\sqrt{\frac{\Gamma_{\max}\delta_s}{2}}\right), \tag{3}$$

where $\Gamma_{\max} = \max\{\Gamma_1, \Gamma_2\}$, or $\max\{\Gamma_2, \Gamma_3\}$, or…, or $\max\{\Gamma_{N-1}, \Gamma_N\}$, and $\delta_s = \frac{|s_s - \hat{s}_s|^2}{E_s}$.

In the case of Rayleigh fading channels with uncorrelated channel coefficients, the probability density function (PDF) for $\Gamma_{\max}$ can be written as follows [22]:

$$f_{max}(\gamma) = f_i(\gamma)F_{i+1}(\gamma) + f_{i+1}(\gamma)F_i(\gamma), \qquad i = 1, 2, \ldots, N \tag{4}$$

where $f_i(\gamma)$is the PDF of the instantaneous received SNR of link i (Γ_i), as given by [15]:

$$f_i(\gamma) = \frac{1}{\gamma_i} e^{-\frac{\gamma}{\gamma_i}}, \qquad \gamma \ge 0 \tag{5}$$

and $F_i(\gamma)$is the cumulative density function (CDF), as given by [15]:

$$F_i(\gamma) = 1 - e^{-\frac{\gamma}{\gamma_i}}, \qquad i = 1, 2, \ldots, N, \tag{6}$$

where $\gamma_i = E\{\Gamma_i\} = \frac{2\sigma^2 E_i}{N_o}$, and N is the number of user links.

The error probability of the strong user can therefore be obtained by averaging the expression in Eq. (3) over the PDF in Eq. (4) and is written as

$$P_{\text{strong}} = \frac{1}{2}\left[1 - \left(\sqrt{\frac{\gamma_i}{4/\delta_s + \gamma_i}}\right) - \left(\sqrt{\frac{\gamma_{i+1}}{4/\delta_s + \gamma_{i+1}}}\right) + \sqrt{\frac{\gamma_i\gamma_{i+1}\delta_s^2}{4\gamma_i\delta_s + 4\gamma_{i+1}\delta_s + \gamma_i\gamma_{i+1}\delta_s^2}}\right]. \quad (7)$$

Using $\hat{s}_s$, the estimated symbol of the strong user, the conditional error event probability for the weak user can be written as

$$P_{\text{weak}}\{\varepsilon|\Gamma_{\min}, \Gamma_r\} = Q\left(\frac{\Gamma_{\min}\delta_w + \sum_{r=N+1}^{2N-1}\frac{\Gamma_r}{E_r}(|s_r - \hat{s}_s \oplus \hat{s}_w|^2 - |s_r - \hat{s}_s \oplus s_w|^2)}{\sqrt{2\left(\Gamma_{\min}\delta_w + \sum_{r=N+1}^{2N-1}\frac{\Gamma_r}{E_r}|\hat{s}_s \oplus s_w - \hat{s}_s \oplus \hat{s}_w|^2\right)}}\right), \quad (8)$$

where $\Gamma_{min} = min\{\Gamma_1, \Gamma_2\}$, or $min\{\Gamma_2, \Gamma_3\}$, or …, or $min\{\Gamma_{N-1}, \Gamma_N\}$, Γ_r is average SNR for relay links $(\Gamma_{N+1}, \Gamma_{N+2}, \dots, \Gamma_{2N-1})$, and $\delta_w = \frac{|s_w - \hat{s}_w|^2}{E_w}$.

In above expression $s_r = s_s \oplus s_w$, and $\hat{s}_w$ is the estimate of the symbol s_w. Assuming uncorrelated Rayleigh fading channels, the PDF [15] for Γ_{min} can be written as follows [22]:

$$f_{min}(\gamma) = f_i(\gamma)\left(1 - F_{i+1}(\gamma)\right) + f_{i+1}(\gamma)(1 - F_i(\gamma)), \quad (9)$$

where $f_i(\gamma)$ and $F_i(\gamma)$ are defined as in Eqs. (5) and (6). The error event probability of the weak user can therefore be obtained by averaging the expression in Eq. (8) over the PDF in Eq. (9) and is written as

$$P_{\text{weak}} = \frac{\gamma_e\delta_w\left(1 - \sqrt{\frac{\gamma_e}{4/\delta_w + \gamma_e}}\right) - \gamma_j\hat{\delta}_j\left(1 - \sqrt{\frac{\gamma_j}{4/\hat{\delta}_j + \gamma_j}}\right)}{2(\gamma_e\delta_w - \gamma_j\hat{\delta}_j)}. \quad (10)$$

where $\delta_w = \frac{|s_w - \hat{s}_w|^2}{E_w}$, $\hat{\delta}_j = \frac{|s_j - \hat{s}_s \oplus \hat{s}_w|^2}{E_j}$, $\gamma_e = \frac{\gamma_i\gamma_{i+1}}{\gamma_i + \gamma_{i+1}}$, $j = N+1, N+2, \dots, 2N-1$, and N is number of users.

3.2. Analysis of Selection and Hard Combining (SHC)

Similarly to SSC, signal reception at the destination for SHC also uses selection relaying. The SHC receiver structure of a multi-user multi-relay MARC-based cooperative communication system with NC is illustrated in Figure 4. Links with better SNR are considered strong links, links with second strongest SNR are considered moderate links, and the others with weakest SNR are considered weak links.

In this strategy, the weakest link symbol is decoded based on symbols detected for the stronger link and the relayed signal. Hence, XOR-based ND is performed using the signals of the strong link and the relay for obtaining the symbols of the weakest link. This detection scheme has lower complexity than the other two detection schemes, as it always ignores the weakest link during detection. Here, P_{strong}, P_{mod}, and P_{weak} are the error probabilities when source i has the strongest, second strongest or moderate, and weakest link, respectively. The pairwise error probability of link k can be written as follows [15]:

$$P(s \to \hat{s}) = \alpha_k P_{\text{strong}} + \beta_k P_{\text{mod}} + (1 - \alpha_k - \beta_k)P_{\text{weak}}, \quad (11)$$

where α_k is the probability that link k is the strongest, and β_k is the probability that link k is the second strongest, $k = 1, 2, \dots, 2N-1$.

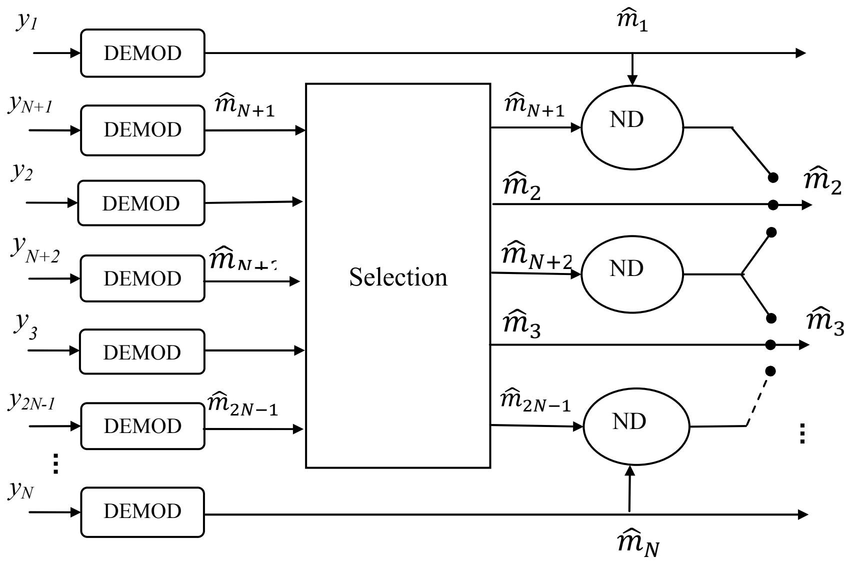

Figure 4. Receiver structure of multi-user multi-relay NC for SHC

3.3. Error probability for strong link

This sub-subsection evaluates the error probability for the strongest link in a multi-user and multi-relay MARC-based cooperative communication system with NC. Similarly to SSC, this strategy assumes that each transmission frame has one strong user. Moreover, P_{strong} can be obtained as follows [15]:

$$P_{\text{strong}} = \int_0^{+\infty} Q\left(\sqrt{\frac{\Gamma_s \delta_s}{2}}\right) f_{\text{strong}}(\gamma) d\gamma, \tag{12}$$

where $\Gamma_s = \frac{|h_s|^2 E_s}{N_0}$, and $\delta_s = \frac{|s_s - \hat{s}_s|^2}{E_s}$.

Considering uncorrelated Rayleigh fading channels, the PDF for Γ_s can be written as follows [22]:

$$f_{\text{strong}}(\gamma) = f_i(\gamma) F_{i+1}(\gamma) F_j(\gamma) + f_{i+1}(\gamma) F_i(\gamma) F_j(\gamma) + f_j(\gamma) F_i(\gamma) F_{i+1}(\gamma) \tag{13}$$

where $f_j(\gamma)$ and $F_j(\gamma)$ are the same as $f_i(\gamma)$ and $F_i(\gamma)$ in Eqs. (5) and (6). The error event probability of the strong source can therefore be obtained by averaging the expression in Eq. (12) over the PDF in Eq. (13) and is written as

$$P_{\text{strong}} = \frac{1}{2}\left(1 - \sum_{k=1}^{2N-1} \sqrt{\frac{\gamma_k}{4/\delta_s^2 + \gamma_k}} + \sqrt{\frac{\gamma_{ik}}{4/\delta_s^2 + \gamma_{ik}}} + \sqrt{\frac{\gamma_{ij}}{4/\delta_s^2 + \gamma_{ij}}} - \sqrt{\frac{\gamma_{ijk}}{4/\delta_s^2 + \gamma_{ijk}}}\right), \quad \text{for } i \neq k \tag{14}$$

where $\gamma_{ij} = \frac{\gamma_i \gamma_j}{\gamma_i + \gamma_j}, \gamma_{ij} = \frac{\gamma_i \gamma_j}{\gamma_i + \gamma_j}$, and $\gamma_{ijk} = \frac{\gamma_i \gamma_j \gamma_k}{\gamma_i \gamma_j + \gamma_i \gamma_k + \gamma_j \gamma_k}$ for $i = 1, 2, \ldots, N$, $j = N+1, N+2, \ldots, 2N-1$, and $k = 1, 2, \ldots, 2N-1$.

3.4. Error Probability for Moderate Link

This sub-subsection evaluates the error probability for the second strongest (moderate) link in a multi-user multi-relay MARC-based cooperative communication system with NC. Here, symbols from relay nodes are considered moderate links, while the symbols from users are considered weak links. For the weak links, the signal from direct transmission and the coded signal from a relay are combined to obtain a better SNR. Then, all combined symbols are forwarded back to the destination, through the process of incremental relaying. Then, P_{mod} can be obtained as follows [15]:

$$P_{\text{mod}} = \int_0^{+\infty} Q\left(\sqrt{\frac{\Gamma_m \delta_m}{2}}\right) f_{\text{mod}}(\gamma) d\gamma, \quad (15)$$

where $\Gamma_m = \frac{|h_m|^2 E_m}{N_0}$ and $\delta_m = \frac{|s_m - \hat{s}_m|^2}{E_m}$.

Considering uncorrelated Rayleigh fading channels, the PDF for Γ_m can be written as follows [22]:

$f_{\text{mod}}(\gamma) = f_i(\gamma)\left[F_{i+1}(\gamma)(1 - F_j(\gamma)) + F_j(\gamma)(1 - F_{i+1}(\gamma))\right] + f_{i+1}(\gamma)\left[F_i(\gamma)\left(1 - f_j(\gamma)\right) + F_j(\gamma)(1 -$
Fiγ)+fjγFiγ1−Fi+1γ+Fi+1γ(1−Fiγ), (16)

where $f_i(\gamma)$ and $F_i(\gamma)$ are as defined in Eqs. (5) and (6). The error probability of the moderate source can therefore be obtained by averaging the expression in Eq. (15) over the PDF in Eq. (16) and is written as

$$P_{\text{mod}} = \frac{1}{2}\left(1 - \sqrt{\frac{\gamma_{ik}}{4/\delta_m^2 + \gamma_{ik}}} - \sqrt{\frac{\gamma_{ij}}{4/\delta_s^2 + \gamma_{ij}}} + 2\sqrt{\frac{\gamma_{ijk}}{4/\delta_m^2 + \gamma_{ijk}}}\right). \quad (17)$$

where $\gamma_{ik} = \frac{\gamma_i \gamma_k}{\gamma_i + \gamma_k}$, $\gamma_{ij} = \frac{\gamma_i \gamma_j}{\gamma_i + \gamma_j}$, and $\gamma_{ijk} = \frac{\gamma_i \gamma_j \gamma_k}{\gamma_i \gamma_j + \gamma_i \gamma_k + \gamma_j \gamma_k}$.

3.5. Error Probability for Weak Link

Using the two obtained symbols $\{\hat{s}_s, \hat{s}_w\}$, the user symbols $\{s_1, s_2, \ldots, s_N\}$ can be obtained either directly, if the relay links are the weakest links, or via ND, when the relay links are the strongest or the second strongest. When the relay links are the weakest, an error will occur if and only if an error has occurred in the strongest or second strongest symbol. Hence, the error probability of the weakest link can be written as follows [15]:

$$P_{\text{weak}} = P_{\text{strong}} + P_{\text{mod}} - \left(1 + \frac{1}{(M-1)}\right) P_{\text{strong}} \times P_{\text{mod}}. \quad (18)$$

With this expression for P_{weak}, the pairwise error probability in Eq. (11) can be rewritten as

$$P(s \to \hat{s}) = (1 - \beta_k) P_{\text{strong}} + (1 - \alpha_k) P_{\text{mod}} - (1 - \alpha_k - \beta_k)\left(1 + \frac{1}{(M-1)}\right) P_{\text{strong}} \times P_{\text{mod}}. \quad (19)$$

where α_k is the probability that link k is the strongest and β_k the probability that link k is the second strongest (moderate link). Moreover, the BEP for SHC is equal to the BEP in Eq. (2) for SSC.

Table 1. Simulation Parameters of Decoding Strategies Performance

Parameters	Remarks
Modulation types	BPSK, QPSK, and 8PSK
Relay protocol	Decode and forward
Channel	Rayleigh fading
No. of sources	N
No. of relays	$N - 1$
SNR vector	0–30 dB

Table 2. BEP Comparison of Decoding Strategies

Decoding Strategies	BEP
SSC	$P_b \le \frac{1}{M\log_2(M)} \sum_{i=1}^{N} \left(\alpha_i P_{\text{strong}} + (1 - \alpha_i) P_{\text{weak}}\right)$
SHC	$P_b \le \frac{1}{M\log_2(M)} \sum_{k=1}^{2N-1} \left(\alpha_k P_{\text{strong}} + \beta_k P_{\text{mod}} (1 - \alpha_k - \beta_k) P_{\text{weak}}\right)$

4. NUMERICAL RESULTS

4.1. Performance of MARC-based cooperative network

In this section, we evaluate the performance of two low complexity ND strategies for multi-user multi-relay cooperative networks using SSC and SHC. The simulation parameters for the performance evaluation are presented in Table 1. All of the simulations were conducted using computer simulation. The analytical expressions derived in the previous section for the respective decoding strategies are used to evaluate the performance of the different decoding strategies under different SNR conditions on the links. The SSC performance is analyzed based on the difference in the values of the user and relay SNRs. This means that there are selection processes, the relaying selection method, for the user that transmits the information to the destination. This is because detection of user and relay symbols is based on the SNR value used to verify the strong and weak users. During the simulation, α_i, $i = 1,3,\ldots,N$ where N is odd number, (respective probabilities that U_1, U_3,…, and U_N are strong users) is set to the same value, as the SNR values of the user and relay are assumed to be equal ($\gamma_1 = \gamma_2 = \cdots = \gamma_{2N-1}$). However, the SNR of the relay node varies (same as or greater than the user SNR).

Similarly to the SSC strategy, the performance of SHC is also analyzed based on the difference in the values of the user and relay SNRs. In this strategy, the worst channel condition (lowest SNR value) is considered a weak link, while the other users with better channel conditions are considered strong and moderate links. During the simulation, α_k and β_k (respective probabilities that the k^{th} link is a strong or moderate link) are set to the same value, as the SNR values of the user and relay are assumed to be equal ($\gamma_1 = \gamma_2 = \cdots = \gamma_{2N-1}$). Then, numerical simulation is conducted using the derived analytical upper bounds. Two cases are considered in the simulation, as follows:

- Case 1: all links (users and relays) are assumed to have equal average SNRs, $\gamma_1 = \gamma_2 = \cdots = \gamma_{2N-1} = 10$ dB.
- Case 2: average SNRs of relays is assumed to be higher than that of users, with $\gamma_1 = \gamma_2 = \cdots = \gamma_N = 10$ dB and $\gamma_{N+1} = \gamma_{N+2} = \cdots = \gamma_{2N-1} = 20$ dB, because the system is using incremental relaying as the signal reception method at the destination.

The performance of the two low complexity decoding strategies, compared using the average BEP plotted as a function of SNR in the two cases, is shown in Figure 5. The BEP expressions, considered as measures of the tightness of the analytical upper bound for both strategies, are presented in Table 2. In the simulation, the number of users (N) is set to 5 and then the number of relays is 4. For SSC, P_{strong} and P_{weak} are calculated using Eqs. (7) and (10), respectively, while for SHC, P_{strong} and P_{mod} are calculated using Eqs. (14) and (17), respectively. Here, binary phase shift keying (BPSK) is assumed to be used at the nodes, with one bit per symbol, and the BEP of the links over Rayleigh fading channels is plotted.

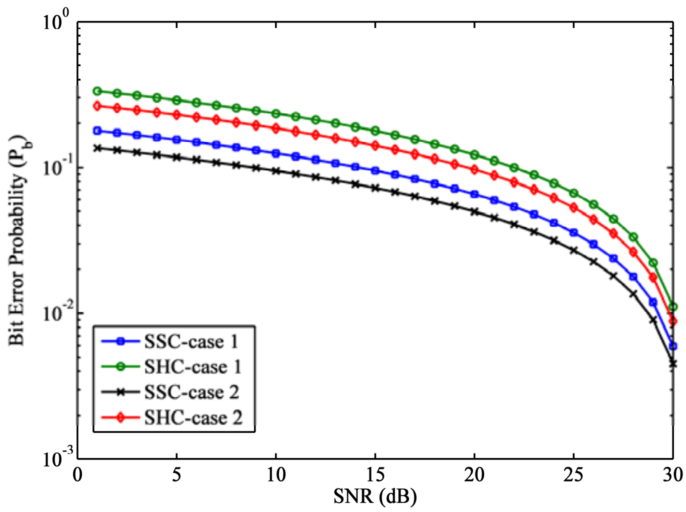

Figure 5. Performance of different decoding strategies

Based on Figure 5, the BEP performance decreases as the SNR value increases for both decoding strategies. In general, SSC performs better than SHC in both cases. As an example, at SNR = 15 dB, the SSC performances for Cases 1 and 2 are 9.5 × 10^{-2} and 7.0 × 10^{-2}, respectively. In Case 2 of SSC, the incremental relaying method is used at the relay at which the SNR is first combined to find the better SNR, with the result that its performance shows a better BEP than in Case 1. At the same SNR of 15 dB for SHC, the performances of Cases 1 and 2 are 1.7 × 10^{-1} and 1.5 × 10^{-1}, respectively. Hence, the performance is better as the SNR for each node increases. Furthermore, the BEP performance for Case 2 is also better than that for Case 1.

4.2. Performance of two-user single-relay and multi-user multi-relay NC

Figure 6 shows a performance comparison for a conventional of two-user [16]-[20] and the proposed multi-user multi-relay MARC-based cooperative communication system with NC using SSC and SHC. In the conventional model, MARC with NC is a cooperative relay technique in which data of two or more users are first processed at a relay and then forwarded to the destination to reduce the complexity of transmission paths. The conventional model is represented by two users communicating with a destination via a relay network with direct links from users to destination. It is assumed that the link between the users and the relay node is ideal and the data are always correctly received by the relay network. The simulation result refers to Cases 1 and 2 with $N = 2$ for conventional model and $N = 5$ for the proposed model. The BEP performance of a single relay cooperative network (conventional model) is better than that of a multi-user multi-relay cooperative network for both strategies. This is a result of multi-user interference in the network, which has contributed to performance degradation. It is also a common phenomenon in communication systems where system performance decreases as the number of users in the network increases. For SSC strategy, the error propagation phenomenon from strong users with better SNR to weak users with lower SNR is starting to fade when users have the better SNR than the relay link. As a result, it makes the curve coincide with each other eventually. While for SHC strategy, the information provided by the weakest user is not considered by the destination, therefore the performance is gradually decreased. Therefore, SSC provides better performance not only for both cases but also for both two-user and multi-user networks.

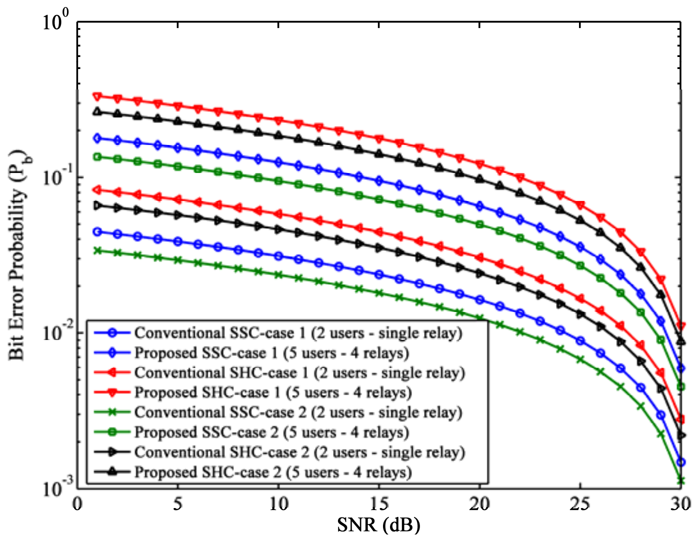

Figure 6. Performance comparison of two-user single relay and multi-user multi-relay cooperative networks

4.3. Impact of modulation on the performance of SSC and SHC in cooperative networks

The impact of using different types of modulation for SSC and SHC based on the Case 1 with $N = 5$ is shown in Figure 7. For SSC at a 10^{-2} BEP performance, there is a difference 4 dB of SNR for the QPSK and BPSK modulations. Moreover, there is a difference 15 dB of SNR for the 8PSK and QPSK modulations. For SHC strategy, there is a difference 2 dB of SNR for the QPSK and BPSK modulations. While for the 8PSK and QPSK, there is a difference 8 dB of SNR. Therefore, there are the differences 10, 3 and 1 dB of SNR with the same modulation type for SSC and SHC, respectively. These indicate that the network performance of SSC is better than that of SHC for the same modulation type. This is a result of the fact that the error propagation phenomenon from strong to weak sources for SSC begins to vanish at these SNR values. On the other hand, SHC does not use the information provided by the weakest links, hence a slight degradation in its performance can be observed as compared to SSC, when the SNR of the users from direct transmission is better than the relay SNR. The trend of the BEP curves is similar for the SSC and the SHC strategy, as a result of the fact that SHC uses incremental relaying for information signal reception at the destination. This indicates that using incremental relaying improves the performance of the two ND strategies.

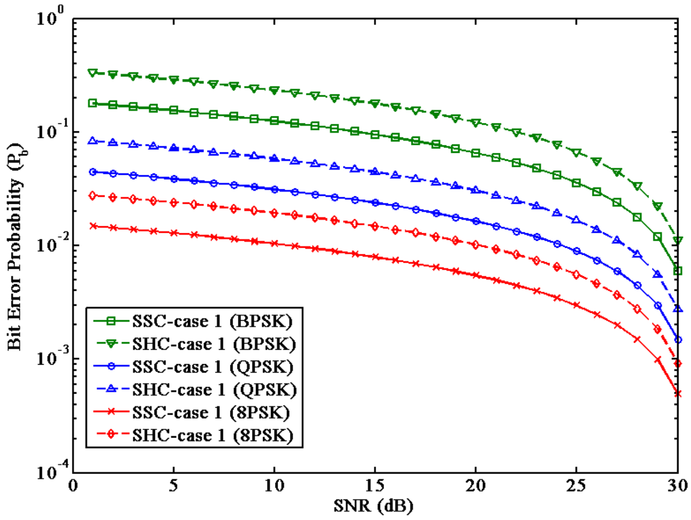

Figure 7. Effect of modulation type on the performance of different decoding strategies

Figure 7 also shows a comparison of the performance of the two ND strategies with different modulation levels. For instance, assuming that quadrature phase shift keying (QPSK) is used at the nodes, the curve for average symbol error probability at the same SNR conditions, is that of BPSK. It is interesting to note that using higher modulation levels increases the performance of the two ND strategies. For example, a 15 dB SNR for SSC results in BEPs of 9.5×10^{-2}, 2.2×10^{-2} and 8.0×10^{-3} for BPSK, QPSK and 8PSK modulation, respectively, while SHC at the same SNR results in BEPs of 1.8×10^{-1}, 4.0×10^{-2} and 1.5×10^{-2} for BPSK, QPSK and 8PSK modulation, respectively. The higher modulation level for both decoding strategies performs better performance than those of lower modulation levels. Moreover, the SSC performance is better than that of SHC in all different modulation levels.

From this analysis, it can be seen that system performance improves with higher modulation level ($M = 2^l$). If we assume an incorrect detection of a bit from the relay node for one of the symbols for BPSK modulation with one bit per symbol ($l = 1$), then the error detection probability at the destination is 50%. For QPSK modulation with two bits per symbol ($l = 2$), with the signal decoding process of each user using two symbols, then the symbols of the signal from both the direct transmission and the relay nodes are involved. Hence, the error detection probability at the destination is 25%. Similarly for 8PSK ($l = 3$), the error detection probability at the destination is 12.5%. Thus, the error detection probability at the destination decreases as the level of modulation increases and then the system performance increases as well.

5. CONCLUSION

This paper proposed an improved model of the SSC and SHC decoding strategies for a multi-user multi-relay cooperative network. To evaluate the performance of the proposed model, we derived analytical expressions for BEP performance as a function of SNR in a Rayleigh fading channel. Moreover, two different cases were considered in a performance evaluation of the proposed model. The simulation results showed that BEP performance decreases as the SNR value increases for both decoding strategies, and that SSC performs better than SHC in both cases. This is because the SSC performance is obtained using incremental relaying as the information signal reception method, where the weak users from direct transmission and the coded signal from the relay are combined to obtain a better SNR at the destination. Furthermore, SSC and SHC performance both decrease as the number of users and relays increase. We also studied the impact of different modulation levels on the performance of the ND strategies for multi-user multi-relay cooperative network using BPSK, QPSK and 8PSK modulation. The results showed that the performance of both the SSC and the SHC ND strategies is improved by using a high modulation level in the multi-user multi-relay cooperative network. For future work, a multi-user multi-relay with multi-destination network should be considered. Applying network coding error correction and different relay protocols in the network are also crucial to improve the system performance.

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