CQI Reporting Strategies for Nonregenerative Two-Way Relay Networks

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***Abstract*—This paper considers data exchange between two terminals in a nonregenerative two-way relay network. We first propose two efficient channel quality indicator (CQI) reporting schemes based on XOR and superposition coding for single-relay networks. These schemes allow two terminals to simultaneously estimate the CQI of the distant link without incurring additional overhead. In addition, the transmission time for CQI feedback is reduced by half while the loss of performance is negligible. Upper and lower bounds of the mean square error (MSE) of the estimated CQI are derived to analyze various effects on the performance of the proposed schemes. We then extend our MSE analysis to multi-relay networks where a low-complexity relay selection scheme is proposed based on the derived bounds. Simulation results show that, in comparison with conventional methods, this suboptimal bound-based scheme achieves satisfactory performance while reducing the complexity at least three times in case of large number of relays.**

I. Introduction

Recently, network coding (NC) [1] has been proposed to increase the system throughput in lossless networks. The principle of NC is that intermediate nodes are allowed to mix signals received from multiple links for subsequent transmissions, e.g., using XOR operator to mix two signals from two terminals. Specifically, several studies have been dedicated to investigating the application of NC to two-way single-relay network (TWSRN) [2]–[4].

In this paper, we consider a TWSRN model that includes two terminal nodes $\mathcal{T}_1$, $\mathcal{T}_2$, and a relay node $\mathcal{R}$. It is assumed that the relay works under nonregenerative protocol and there is no direct link between the terminals. In general, in order to help one terminal node decode the data sent by the other, the channel state information (CSI) of the terminal-relay links should be feedbacked to both terminal nodes. Common mechanisms for CSI feedback are via channel quality indicator (CQI) reporting [5]. Recently, a hierarchically modulated NC scheme has been proposed for asymmetric TWSRNs in which hierarchial modulations are applied at two source nodes based on the channel quality [6]. This scheme works under the assumption that the CQI information is known at all nodes. The above reasons motivate us to investigate the CQI reporting mechanism for TWSRNs where each terminal node is required to know the CQI of the distant terminal-relay link.

Most of recent work investigated CQI reporting or feedback in one-way single-relay networks only for various applications e.g., adaptive non-orthogonal cooperation [7] and adaptive utilisation of time-varying channels [8]. Extending these CQI feedback schemes to TWSRNs obviously results in doubling the signaling overhead and requiring two time slots at each relay node to forward the overhead to both terminal nodes. These drawbacks inspire us to propose a new efficient CQI reporting scheme for NC-based TWSRNs so as to reduce the number of transmissions at $\mathcal{R}$ as well as avoid the additional overhead. The NC is performed at $\mathcal{R}$ using either bitwise XOR or symbol-level superposition coding where the estimated CQIs of the two links $\mathcal{T}_1 - \mathcal{R}$ and $\mathcal{T}_2 - \mathcal{R}$ are combined to enable $\mathcal{T}_1$ and $\mathcal{T}_2$ to simultaneously estimate the CQI of the links $\mathcal{T}_2 - \mathcal{R}$ and $\mathcal{T}_1 - \mathcal{R}$, respectively. The novelty of our proposed CQI reporting scheme is that it conveys the CQIs of one terminal-relay channel to the other terminal at no additional cost in terms of bandwidth or energy. Extending to an N-relay network, it can be seen that N signalling overheads and N transmission time slots are reduced when compared with the conventional scheme. Thus, the system throughput is considerably improved, especially when N is large. Besides the advantage of our proposed scheme in improving system throughput, the other major contributions of our paper are the analysis of mean square error (MSE) of the estimated CQI and the subsequently proposed bound-based relay selection scheme, which will be described next.

Our second contribution is the derivation of the upper and lower bounds of MSE of estimated CQI in the proposed scheme over Rayleigh flat fading channel, which, to the best of our knowledge, has not been achieved before. The bounds are shown to be tight and reflect well the behaviour of the numerical MSE. It is also shown that the loss of performance and the increase of complexity of our proposed scheme are negligible compared with conventional schemes. For asymmetric broadcast channels, a better performance can be achieved with superposition coding.

Finally, we extend our proposed scheme to the case of two-way multi-relay networks (TWMRNs). Since the data exchange between two terminals can be assisted by all available relay nodes, opportunistic relay selection (RS) should be considered [4], where the best relay is chosen based on the sum of bit error rate or sum-rate. In this paper, we investigate a system where CQI is required at the transmitter and therefore

CQI reporting is a crucial performance metric for the system. This motivates us to design an efficient opportunistic RS scheme where the best relay is searched based on the sum of MSE (sum-MSE). The RS is realised by a scheduler of a coordinator node in a centralized manner, i.e., the coordinator selects the best relay based on the sum-MSE feedbacked by the relays through specific channels. Furthermore, the high complexity of relay searching in optimal schemes motivates us to propose a suboptimal bound-based relay selection scheme where the searching process will stop whenever the sum-MSE of any relay is smaller than the pre-determined upper bound. It is observed that the resulting complexity is reduced by at least three times compared with conventional selection schemes if the number of relays is sufficiently large.

II. System Model

Let us consider a typical TWSRN where the data exchange between two terminals $\mathcal{T}_1$ and $\mathcal{T}_2$ is assisted by a relay $\mathcal{R}$. It is assumed that there is no direct link between $\mathcal{T}_1$ and $\mathcal{T}_2$ due to power limit in each node. We focus on Rayleigh flat fading channel where channel coefficients of $\mathcal{T}_1 \to \mathcal{R}$ and $\mathcal{T}_2 \to \mathcal{R}$ links are given by h_{T_1R} and h_{T_2R}, respectively. We assume that Time-Division Duplex (TDD) is employed and all transmissions are carried out over the same frequency band. Each channel is assumed to be reciprocal (i.e., $h_{T_1R} = h_{RT_1} = h_1$ and $h_{T_2R} = h_{RT_2} = h_2$) and assumed to change every data frame, and thus the CQI reporting should be carried out every time. Pilot signals are used to initially estimate the link quality of all channels (i.e., instantaneous signal-to-noise ratio (SNR) at the receiver).

It is noteworthy that for various signal processing mechanisms in TWSRNs such as data detection or adaptive modulation [6], each terminal node $\mathcal{T}_i$ requires the channel quality information of not only its associated link $\mathcal{T}_i - \mathcal{R}$ but also that of the distant link $\mathcal{T}_j - \mathcal{R}, j \neq i$. In order to reduce the amount of feedback information, the value of channel quality, SNR, should be quantized into a finite bit sequence called CQI with different levels. The CQI reporting in TWSRNs can be divided into two phases as follows:

- First phase: $\mathcal{T}_i, i = 1, 2$, and $\mathcal{R}$ transmit pilot signals to each other to estimate the CQI of the associated link $\mathcal{T}_i - \mathcal{R}$.
- Second phase: $\mathcal{R}$ helps $\mathcal{T}_i$ estimate the CQI of the distant link $\mathcal{T}_j - \mathcal{R}, j = 1, 2, j \neq i$, which cannot be directly obtained at $\mathcal{T}_i$ since there is no direct link available between $\mathcal{T}_i$ and $\mathcal{T}_j$.

We observe that the CQI estimation in the first phase can straightforwardly follow conventional pilot-based approaches. We therefore focus on the CQI reporting in the second phase. Conventionally, a double amount of signaling overhead should be required at $\mathcal{R}$ to consecutively forward the CQIs of the links $\mathcal{T}_1 - \mathcal{R}$ and $\mathcal{T}_2 - \mathcal{R}$ to $\mathcal{T}_2$ and $\mathcal{T}_1$, respectively, in two time slots. This considerably reduces the network throughput. Therefore, we propose a new efficient CQI reporting scheme based on NC to eliminate the additional overhead and reduce the number of time slots required. By using NC, $\mathcal{R}$ can combine the estimated CQIs of two links $\mathcal{T}_1 - \mathcal{R}$ and $\mathcal{T}_2 - \mathcal{R}$ before broadcasting it to allow each terminal $\mathcal{T}_i$ to simultaneously estimate the CQI of the distant link $\mathcal{T}_j - \mathcal{R}$ $(j \neq i)$.

Let γ_i and ρ_i denote the SNR and CQI, respectively, of link h_i $(i = 1, 2)$. Assume that $\rho_i \in \mathcal{C}_i$ where $\mathcal{C}_i$ is the set of all possible CQI levels of link h_i. Let Q_i denote the cardinality of $\mathcal{C}_i$. Thus, it requires $L_i = \lceil \log_2 Q_i \rceil$ bits to represent a ρ_i level, where $\lceil . \rceil$ denotes the ceiling function of a real number. The lists of ρ_1 and ρ_2 levels are assumed to be available at $\mathcal{R}$, $\mathcal{T}_1$, and $\mathcal{T}_2$. Practically, there are multiple ways to map SNR to CQI [9]. One of the common ways is that CQI can be approximated by a linear function of SNR as follows

$$\rho_i = \lceil a\gamma_i[\text{dB}] + b \rceil, \tag{1}$$

where a and b are the constants and γ_i is calculated in dB. Assume that the range of SNR for CQI mapping is from 0 to γ_{mdB} [dB], where γ_{mdB} is positive and measured in dB. Following the above approach, we divide the range $[0 : \gamma_{mdB}]$ into Q_i levels $(1, 2, \ldots, Q_i)$ by setting $a = Q_i/\gamma_{mdB}$ and $b = 0$. As a result, we can obtain ρ_i as

$$\rho_i = \left\lceil \frac{Q_i}{\gamma_{mdB}} \gamma_i[\text{dB}] \right\rceil = \left\lceil \frac{10 Q_i \log_{10} \gamma_i}{\gamma_{mdB}} \right\rceil. \tag{2}$$

Let $\rho_{i,\mathcal{T}}$ and $\rho_{i,\mathcal{R}}$ denote the estimated values of ρ_i at $\mathcal{T}_i$ and $\mathcal{R}$, respectively, in the first phase. It can be seen that $\rho_{i,\mathcal{T}}, \rho_{i,\mathcal{R}} \in \mathcal{C}_i$. We next introduce our proposed CQI reporting schemes for TWSRNs in the second phase.

III. Proposed CQI Reporting Schemes for TWSRNs

Once two estimated CQIs $\rho_{1,\mathcal{R}}$ and $\rho_{2,\mathcal{R}}$ are available, $\mathcal{R}$ can combine them using either bit-level XOR or symbol-level superposition as follows:

Scheme A – Bit-level XOR

The bit sequences of $\rho_{1,\mathcal{R}}$ and $\rho_{2,\mathcal{R}}$ are XORed together as

$$\mathbf{b}^{(A)} \triangleq \mathbf{b}_{\rho_{1,\mathcal{R}}} \oplus \mathbf{b}_{\rho_{2,\mathcal{R}}}, \tag{3}$$

where $\oplus$ denotes the bitwise XOR operator and $\mathbf{b}_{\rho_{i,\mathcal{R}}}, i = 1, 2$, denotes the bit-level format of $\rho_{i,\mathcal{R}}$. We notice that the terms in XOR operations in (3) must have the same length. Thus, zero-padding is used to match the length of CQIs, i.e., the length of $\mathbf{b}^{(A)}$ is $\max\{L_1, L_2\} \triangleq L_m$.

Scheme B – Symbol-level superposition

The bit sequences $\mathbf{b}_{\rho_{1,\mathcal{R}}}$ and $\mathbf{b}_{\rho_{2,\mathcal{R}}}$ are encoded into baseband signal sequences ${\mathbf{b}'}_{\rho_{1,\mathcal{R}}}$ and ${\mathbf{b}'}_{\rho_{2,\mathcal{R}}}$, respectively. Then, they are superimposed together as

$$\mathbf{b}^{(B)} = \sqrt{\theta_{\rho_1}} {\mathbf{b}'}_{\rho_{1,\mathcal{R}}} + \sqrt{\theta_{\rho_2}} {\mathbf{b}'}_{\rho_{2,\mathcal{R}}}, \tag{4}$$

where θ_{ρ_1} and θ_{ρ_2} are power allocation coefficients such that $\theta_{\rho_1}^2 + \theta_{\rho_2}^2 = 1$ and optimised as in [10].

For the CQI estimation at $\mathcal{T}_1$ and $\mathcal{T}_2$, $\mathcal{R}$ then broadcasts $\mathbf{b}^{(M)}$, $M \in \{A, B\}$, to $\mathcal{T}_1$ and $\mathcal{T}_2$. The received signal at $\mathcal{T}_i, i = 1, 2$, can be written by

$$\mathbf{y}_i^{(M)} = \sqrt{P_R} h_i \mathbf{x}^{(M)} + \mathbf{n}_i, \tag{5}$$

where P_R is the power level for the pilot signal of $\mathcal{R}$, $\mathbf{x}^{(M)}$ is the modulated version of $\mathbf{b}^{(M)}$, and $\mathbf{n}_i$ is the white Gaussian noise vector with each entry having zero mean and variance of σ_i^2.

At $\mathcal{T}_i$, $i=1,2$, it is necessary to estimate $\rho_{j,\mathcal{R}}$, $j \neq i$, of the distant link $\mathcal{T}_j - \mathcal{R}$. Based on the estimated CQI of the link $\mathcal{T}_i - \mathcal{R}$ at $\mathcal{T}_i$ (i.e., $\rho_{i,\mathcal{T}}$) in the first phase, $\mathcal{T}_i$ can create a list of all possible NC-based combinations of $\rho_{i,\mathcal{T}}$ and ρ_j using either scheme A or B as follows

Scheme A

$$\mathbf{b}_{\rho_j}^{(A)} = \mathbf{b}_{\rho_{i,\mathcal{T}}} \oplus \mathbf{b}_{\rho_j}, \tag{6}$$

where $\mathbf{b}_{\rho_{i,\mathcal{T}}}$ and $\mathbf{b}_{\rho_j}$ denote the bit-level formats of $\rho_{i,\mathcal{T}}$ and ρ_j, respectively.

Scheme B

$$\mathbf{b}_{\rho_j}^{(B)} = \sqrt{\theta_{\rho_i}}\mathbf{b'}_{\rho_{i,\mathcal{T}}} + \sqrt{\theta_{\rho_j}}\mathbf{b'}_{\rho_j}, \tag{7}$$

where $\mathbf{b'}_{\rho_{i,\mathcal{T}}}$ and $\mathbf{b'}_{\rho_j}$ denote the encoded baseband signal sequences of $\mathbf{b}_{\rho_{i,\mathcal{T}}}$ and $\mathbf{b}_{\rho_j}$, respectively.

Note that $\rho_j \in \mathcal{C}_j$ and therefore there are Q_j possible candidates of $\mathbf{b}_{\rho_j}$. $\mathcal{T}_i$ then compares the received signal $\mathbf{y}_i^{(M)}$, $M \in \{A,B\}$, given in (5) with all possible $\mathbf{b}_{\rho_j}$'s in order to choose the matched $\mathbf{b}_{\rho_j}$. Correspondingly, the matched $\rho_j \in \mathcal{C}_j$ can be found. This matched ρ_j is the estimated value of $\rho_{j,\mathcal{R}}$, which is denoted by $\hat{\rho}_{j,\mathcal{R}}$. We observe that finding $\hat{\rho}_{j,\mathcal{R}}$ can be carried out by using an exhaustive search method, where the correlation-based decision is based on the received signal $\mathbf{y}_i^{(M)}$ and the NC-based combination sample $\mathbf{b}_{\rho_j}^{(M)}$. This correlation-based decision is represented by the following correlation value:

$$\vartheta_{\rho_j}^{(M)} = \sum_{l=1}^{L_m} \mathbf{y}_i^{(M)}[l] \frac{\mathbf{x}_{\rho_j}^{(M)}[l]}{|\mathbf{x}_{\rho_j}^{(M)}[l]|^2}, \tag{8}$$

where $\mathbf{x}_{\rho_j}^{(M)}$ denotes the modulated version of $\mathbf{b}_{\rho_j}^{(M)}$. Substituting (5) into (8), we obtain as [11]

$$\vartheta_{\rho_j}^{(M)} = \begin{cases} \sqrt{P_R}h_i L_m + \sqrt{L_m}\sigma_i N_{\rho_j}, & \text{if } \rho_{i,\mathcal{R}}=\rho_{i,\mathcal{T}} \text{ and } \rho_j=\rho_{j,\mathcal{R}}, \\ \sqrt{P_R}h_i\left(\sqrt{\frac{L_m}{2}}\omega_1 + \sqrt{-\frac{L_m}{2}}\omega_2\right) + \sqrt{L_m}\sigma_i N_{\rho_j}, & \text{otherwise,} \end{cases} \tag{9}$$

where ω_1 and ω_2 are independent Gaussian random numbers with zero mean and unit variance, and N_{ρ_i} is the independent complex-valued random number [11]. It can be seen that L_m is almost surely greater than $(\omega_1\sqrt{L_m/2} + \omega_2\sqrt{-L_m/2})$ when $L_m \geqslant 2$. Therefore, we can conclude that $\vartheta_{\rho_j}^{(M)}$ is almost surely upper bounded by $(\sqrt{P_R}h_i L_m + \sqrt{L_m}\sigma_i N_{\rho_j})$ when $\rho_{i,\mathcal{R}} = \rho_{i,\mathcal{T}}$ and $\rho_j = \rho_{j,\mathcal{R}}$, i.e., the estimated ρ_i and ρ_j at $\mathcal{R}$ should be equal to the estimated ρ_i and the required ρ_j at $\mathcal{T}_i$, respectively.

Thus, the estimated value of $\rho_{j,R}$ is chosen from $\mathcal{C}_j$ to maximize $\vartheta_{\rho_j}^{(M)}$ as follows

$$\hat{\rho}_{j,\mathcal{R}} = \arg\max_{\rho_j \in \mathcal{C}_j} \vartheta_{\rho_j}^{(M)}. \tag{10}$$

Note that the estimation of $\rho_{2,\mathcal{R}}$ at $\mathcal{T}_1$ and the estimation of $\rho_{1,\mathcal{R}}$ at $\mathcal{T}_2$ are carried out simultaneously.

Remark 1. The required condition $\rho_{i,\mathcal{R}} = \rho_{i,\mathcal{T}}$ in order to maximize $\vartheta_{\rho_j}^{(M)}$ causes a loss in the performance of our proposed scheme when compared with the conventional scheme[1] in terms of the MSE of the estimated $\rho_{j,R}$ at $\mathcal{T}_i$. This condition may not be achieved due to the imperfect estimation of ρ_i at $\mathcal{R}$ and $\mathcal{T}_i$. Thus, the overall performance of our proposed CQI reporting scheme depends on the pilot-based CQI estimation in the first phase.

Remark 2. Scheme B would be preferable if asymmetric broadcast channel is considered, e.g., the SNR of $\mathcal{R} \to \mathcal{T}_i$ link is much higher than the SNR of $\mathcal{R} \to \mathcal{T}_j$, $j \neq i$, link. In this case, the reliability of the estimation of ρ_i at $\mathcal{T}_j$ is significantly reduced while the estimation of ρ_j at $\mathcal{T}_i$ can be carried out with an insignificant error. However, using scheme B, the estimation of ρ_i at $\mathcal{T}_j$ can be improved with an increased θ_{ρ_i} and a reduced θ_{ρ_j}. Note that the loss in the performance of the estimation of ρ_j at $\mathcal{T}_i$ caused by the reduced θ_{ρ_j} is not significant since the $\mathcal{R} \to \mathcal{T}_i$ link is at high quality.

IV. Analysis of MSE of Estimated CQI

In this section, we derive the MSE expression of estimated CQI of scheme B. The MSE analysis of scheme A can be similarly carried out. For simplicity, we study the CQI estimation at $\mathcal{T}_2$ only. The analysis of the CQI estimation at $\mathcal{T}_1$ can be similarly obtained. The estimation error occurs if the estimated $\rho_{1,\mathcal{R}}$ at $\mathcal{T}_2$ in the second phase (i.e., $\hat{\rho}_{1,\mathcal{R}}$) is different from the value of ρ_1 estimated at $\mathcal{R}$ in the first phase (i.e., $\rho_{1,\mathcal{R}}$). Thus, the MSE of estimated CQI can be computed by

$$\mathrm{MSE} = E\left\{[\hat{\rho}_{1,\mathcal{R}} - \rho_{1,\mathcal{R}}]^2\right\}, \tag{11}$$

where $E\{.\}$ denotes the expectation.

In order to deduce the MSE, we observe that it is difficult to derive $\hat{\rho}_{1,\mathcal{R}}$ and $\rho_{1,\mathcal{R}}$ for any arbitrary characteristics of two links $\mathcal{T}_1 \to \mathcal{R}$ and $\mathcal{R} \to \mathcal{T}_2$ simultaneously, however, it is still useful to understand the behaviour of the MSE in an asymptotic case and gain some insights from it. Thus, for simple analysis, let us assume that the link $\mathcal{T}_1 \to \mathcal{R}$ at a high SNR[2], i.e., $\gamma_1[dB] = \gamma_{mdB}$, and thus from (2), we can approximate $\rho_{1,\mathcal{R}}$ by Q_1. From (5), the SNR γ_2 of $\mathcal{R} \to \mathcal{T}_2$ link can be expressed as

$$\gamma_2 = \frac{P_R\theta_{\rho_1}|h_2|^2}{\sigma_2^2}. \tag{12}$$

Note that, in the second phase, $\mathbf{x}^{(B)}$ in (5) is constructed by both $\rho_{1,\mathcal{R}}$ and $\rho_{2,\mathcal{R}}$. We assume that $\rho_{2,\mathcal{R}} \approx \rho_{2,\mathcal{T}}$. Since $\rho_{2,\mathcal{T}}$ is known at $\mathcal{T}_2$, it can be removed from the received signal.

[1]The conventional scheme is referred to as a scheme where $\mathcal{R}$ sequentially transmits $\rho_{i,\mathcal{R}}$ and $\rho_{j,\mathcal{R}}$ to $\mathcal{T}_j$ and $\mathcal{T}_i$, respectively, in two time slots.

[2]This high-SNR assumption is for analysis purpose only. Our proposed CQI reporting algorithm is actually for a general case and valid for any SNR value of uplink.

Thus, it can be approximated that γ_2 determines the mapping of $\rho_{1,\mathcal{R}}$, i.e.,

$$\hat{\rho}_{1,\mathcal{R}} \approx \left\lceil \frac{10\log_{10}(\gamma_2)}{\gamma_{mdB}/Q_1} \right\rceil . \quad (13)$$

Substituting (13) into (11) with $\rho_{1,\mathcal{R}} \approx Q_1$, we have

$$\text{MSE} \approx E\left\{ \left(Q_1 - \left\lceil \frac{10\log_{10}(\gamma_2)}{\gamma_{mdB}/Q_1} \right\rceil \right)^2 \right\}. \quad (14)$$

Let $\alpha = e^{-\gamma_m/\bar{\gamma}}$, $\beta = e^{-1/\bar{\gamma}}$, $\gamma_m = 10^{\gamma_{mdB}/10}$, $Q_1' = 10Q_1/(\gamma_{mdB}\text{ln}10)$, $Q_1'' = Q_1 - Q_1'\text{ln}(\theta_{\rho_1})$ where $\bar{\gamma}$ is average SNR, $\text{ln}x$ is natural logarithm of x, $E_i(\cdot)$ is exponential integral, and $\mathfrak{G}^{m,n}_{p,q}\left({a_1,\ldots,a_p \atop b_1,\ldots,b_q}|z\right)$ is Meijer G function [12]. We have the following finding:

Theorem 1. The MSE given in (14) is upper-bounded and lower-bounded by MSE_u and MSE_l, respectively, where

$$\text{MSE}_u = \lambda_1 + \lambda_2 A + \lambda_3 B, \quad (15)$$

$$\text{MSE}_l = \lambda_1' + \lambda_2' A + \lambda_3 B, \quad (16)$$

$$\lambda_1 = [Q_1'' - Q_1'\text{ln}\bar{\gamma}]^2(\beta-\alpha), \lambda_2 = -2Q_1'[Q_1'' - Q_1'\text{ln}\bar{\gamma}], \lambda_3 = Q_1'^2,$$

$$\lambda_1' = [Q_1'' - 1 - Q_1'\text{ln}\bar{\gamma}]^2(\beta-\alpha), \lambda_2' = -2Q_1'[Q_1'' - 1 - Q_1'\text{ln}\bar{\gamma}],$$

$$A = \beta\text{ln}(-\text{ln}\beta) - \alpha\text{ln}(-\text{ln}\alpha) + E_i(\text{ln}\alpha) - E_i(\text{ln}\beta),$$

$$B = \beta\text{ln}^2(-\text{ln}\beta) - \alpha\text{ln}^2(-\text{ln}\alpha) - 2\text{ln}(-\text{ln}\alpha)\mathfrak{G}^{2,0}_{1,2}\left({1 \atop 0,0}| - \text{ln}\alpha\right) + 2\text{ln}(-\text{ln}\beta)\mathfrak{G}^{2,0}_{1,2}\left({1 \atop 0,0}| - \text{ln}\beta\right) - 2\mathfrak{G}^{3,0}_{2,3}\left({1,1 \atop 0,0,0}| - \text{ln}\alpha\right) + 2\mathfrak{G}^{3,0}_{2,3}\left({1,1 \atop 0,0,0}| - \text{ln}\beta\right).$$

Proof: We notice that $\lceil x \rceil \geqslant x \ \forall x$. Thus,

$$Q_1 \geqslant \left\lceil \frac{10\log_{10}(\gamma_2)}{\gamma_{mdB}/Q_1} \right\rceil \geqslant \frac{10\log_{10}(\gamma_2)}{\gamma_{mdB}/Q_1} \geqslant 0. \quad (17)$$

Applying (17) to (14), MSE is upper-bounded by

$$\text{MSE}_u = E\left\{ \left(Q_1 - \frac{10\log_{10}(\gamma_2)}{\gamma_{mdB}/Q_1} \right)^2 \right\}. \quad (18)$$

Let $\gamma = P_R|h_2|^2/\sigma_2^2$. (18) can be rewritten by

$$\text{MSE}_u = E\{(Q_1'' - Q_1'\text{ln}\gamma)^2\} = \int_1^{\gamma_m} (Q_1'' - Q_1'\text{ln}\gamma)^2 f_\gamma(\gamma)d\gamma, \quad (19)$$

where $f(\cdot)$ is the probability density function (pdf) of a random variable. Since the fading channel $\mathcal{R} \rightarrow \mathcal{T}_2$ is Rayleigh flat fading, $f_\gamma(\gamma)$ is given by $f_\gamma(\gamma) = 1/\bar{\gamma}\text{exp}(-\gamma/\bar{\gamma})$ [13], where $\bar{\gamma}$ is the average SNR. Thus, we have

$$\text{MSE}_u = \int_1^{\gamma_m} (Q_1'' - Q_1'\text{ln}\gamma)^2 \frac{1}{\bar{\gamma}}\text{exp}\left(-\frac{\gamma}{\bar{\gamma}}\right) d\gamma. \quad (20)$$

From [12] and after some simple algebraic manipulations, we obtain (15).

Another inequality concerning with ceiling function is that $\lceil x \rceil < x + 1, \forall x$. Thus,

$$0 \leqslant \left\lceil \frac{10\log_{10}(\gamma_2)}{\gamma_{mdB}/Q_1} \right\rceil < \frac{10\log_{10}(\gamma_2)}{\gamma_{mdB}/Q_1} + 1. \quad (21)$$

The lower bound of MSE is then given by

$$\text{MSE}_l = E\left\{ \left(Q_1 - 1 - \frac{10\log_{10}(\gamma_2)}{\gamma_{mdB}/Q_1} \right)^2 \right\}. \quad (22)$$

We observe that the expression of MSE_l has the same form of MSE_u in (18). Thus, MSE_l in (16) can be similarly obtained. ■

Remark 3. MSE bounds increase as a function of Q_1^2. From Theorem 1, λ_1, λ_2, λ_1', λ_2', and λ_3 depend on Q_1, whereas A and B are independent of Q_1. We observe that MSE_u and MSE_l can be rewritten as a function of Q_1^2, i.e., $\text{MSE}_u = \zeta Q_1^2$ and $\text{MSE}_l = \zeta' Q_1^2$, where ζ and ζ' are non-negative constants.

V. Extension to TWMRNs

Let us consider a TWMRN including N relay nodes $\{\mathcal{R}_1, \ldots, \mathcal{R}_N\}$. In the proposed relay selection scheme, only one best relay is opportunistically selected to perform the network coding between two terminal nodes. Specifically, an optimal scheme is proposed where the relay is chosen to minimize the sum-MSE given by $\text{SMSE}(n) \triangleq \text{MSE}_1(n) + \text{MSE}_2(n)$, where $\text{MSE}_i(n)$ denotes the MSE of the estimated CQI_i at $\mathcal{T}_j$, $i, j \in \{1, 2\}$, $i \neq j$, in a TWSRN using $\mathcal{R}_n$, $n \in \{1, \ldots, N\}$. Thus, the optimal relay selection is represented by

$$n^* = \arg\min_n \text{SMSE}(n). \quad (23)$$

However, the computation complexity of this scheme is high. Let us consider a suboptimal relay selection scheme based on the maximum of MSE or max-MSE. In fact, it is well-known that minimizing the sum can be approximated to minimizing the maximum. Therefore, the relay can be approximately determined by

$$n^*_{sub} = \arg\min_n \text{MMSE}(n), \quad (24)$$

where $\text{MMSE}(n) \triangleq \max\{\text{MSE}_1(n), \text{MSE}_2(n)\}$.

Due to the quantization carried out in the mapping process as explained for TWSRNs, we can derive the upper bound and lower bound of $\min \text{MMSE}(n)$ or $\text{MSE}(n^*_{sub})$. For simple analysis, we assume that scheme A is applied at each relay, Q_1 and Q_2 are equal, and, $\gamma_1(n)$ and $\gamma_2(n)$ have the same probability density function. Letting $\alpha_N = e^{-2\gamma_m/\bar{\gamma}}$, $\beta_N = e^{-2/\bar{\gamma}}$, $Q = Q_1 = Q_2$, and $Q' = 10Q/(\gamma_{mdB}\text{ln}10)$, we have the following finding:

Theorem 2. $\text{MSE}(n^*_{sub})$ is upper-bounded and lower-bounded by $\text{MSE}_u(n^*_{sub})$ and $\text{MSE}_l(n^*_{sub})$, respectively, where

$$\text{MSE}_u(n^*_{sub}) = \lambda_{1N} + \lambda_{2N}A_N + \lambda_{3N}B_N, \quad (25)$$

$$\text{MSE}_l(n^*_{sub}) = \lambda_{1N}' + \lambda_{2N}'A_N + \lambda_{3N}B_N, \quad (26)$$

$$\lambda_{1N} = [Q - Q'\text{ln}(\bar{\gamma}/2)]^2 \left[(1-\alpha_N)^N - (1-\beta_N)^N\right],$$

$$\lambda_{2N} = -2Q' \left[Q - Q'\ln(\bar{\gamma}/2)\right], \lambda_{3N} = Q'^2,$$
$$\lambda'_{1N} = \left[Q - 1 - Q'\ln(\bar{\gamma}/2)\right]^2 \left[(1-\alpha_N)^N - (1-\beta_N)^N\right],$$
$$\lambda'_{2N} = -2Q' \left[Q - 1 - Q'\ln(\bar{\gamma}/2)\right],$$

and, A_N and B_N are given by Eqs. (27) and (28), respectively.

Proof: From (24), n^*_{sub} can be written by $n^*_{sub} = \arg\min_n \max\{\mathrm{MSE}_1(n), \mathrm{MSE}_2(n)\}$, where $\mathrm{MSE}_i(n)$ is given by (14). Since $Q_1 = Q_2$, n^*_{sub} can be obtained as $n^*_{sub} = \arg\max_n \min\{\gamma_1(n), \gamma_2(n)\}$. Let us denote $\gamma^* = \max \gamma_{\min}(n)$ where $\gamma_{\min}(n) = \min\{\gamma_1(n), \gamma_2(n)\}$. $\mathrm{MSE}(n^*_{sub})$ can be calculated by

$$\mathrm{MSE}(n^*_{sub}) = E\left\{\left(Q - \left\lceil \frac{10\log_{10}\gamma^*}{\gamma_{mdB}/Q} \right\rceil\right)^2\right\}. \tag{29}$$

Similarly, applying the inequalities (17) and (21) to (29), $\mathrm{MSE}(n^*_{sub})$ has an upper bound and a lower bound given by

$$\mathrm{MSE}_u(n^*_{sub}) = E\left\{\left(Q - \frac{10\log_{10}\gamma^*}{\gamma_{mdB}/Q}\right)^2\right\}, \tag{30}$$

$$\mathrm{MSE}_l(n^*_{sub}) = E\left\{\left(Q - 1 - \frac{10\log_{10}\gamma^*}{\gamma_{mdB}/Q}\right)^2\right\}, \tag{31}$$

respectively. Observing that (30) and (31) have the same form, we will derive the expression of $\mathrm{MSE}_u(n^*_{sub})$. The derivation for $\mathrm{MSE}_l(n^*_{sub})$ can be carried out similarly.

In order to derive $\mathrm{MSE}_u(n^*_{sub})$, let us calculate the pdf of γ^*. Note that $\gamma_1(n)$ and $\gamma_2(n)$ have the same pdf and cumulative density function (cdf) of Rayleigh fading given by $f_\gamma(\gamma) = 1/\bar{\gamma}\exp(-\gamma/\bar{\gamma})$ and $F_\gamma(\gamma) = 1 - \exp(-\gamma/\bar{\gamma})$ [13], respectively, where $\bar{\gamma}$ is the average SNR. Applying order statistics [14], the pdf of γ^* can be calculated by $f_{\gamma^*}(\gamma) = N f_{\gamma_{\min}}(\gamma) F^{N-1}_{\gamma_{\min}}(\gamma)$, where $f_{\gamma_{\min}}(\gamma) = 2f_\gamma(\gamma)[1 - F_\gamma(\gamma)]$ and $F_{\gamma_{\min}}(\gamma) = 1 - [1 - F_\gamma(\gamma)]^2$ denote the pdf and cdf of $\gamma_{\min}$, respectively. Thus, $f_{\gamma^*}(\gamma) = 2N/\bar{\gamma}\exp(-2\gamma/\bar{\gamma})[1 - \exp(-2\gamma/\bar{\gamma})]^{N-1}$.

Following the same proof as in Theorem 1 with [12] and by using some simple algebraic manipulations, we obtain (25) and (26). ■

Remark 4. The MSE performance of the suboptimal scheme converges to zero when the number of relays is large. It can be seen that $\lambda_{1N} \to 0$, $\lambda'_{1N} \to 0$, $A_N \to 0$, and $B_N \to 0$ as $N \to \infty$. Thus, $\mathrm{MSE}_u(n^*_{sub}) \to 0$ and $\mathrm{MSE}_l(n^*_{sub}) \to 0$. Since $\mathrm{MSE}_u(n^*_{sub}) \geqslant \mathrm{MSE}(n^*_{sub}) \geqslant \mathrm{MSE}_l(n^*_{sub})$, we can deduce that $\mathrm{MSE}(n^*_{sub}) \to 0$ as $N \to \infty$. We can also deduce that the bounds are tighter as N increases.

Based on the bounds of $\mathrm{MSE}(n^*_{sub})$ given in Theorem 2 and their characteristics discussed in Remark 4, we propose a so-called suboptimal bound-based relay selection scheme to reduce the complexity of the searching method in (24). Note that if the previously mentioned suboptimal relay selection scheme (i.e., (24)) is used, N relays would be verified to choose the best one to minimize the MMSE. Instead, the proposed suboptimal bound-based relay selection will stop the searching when finding out a relay with MMSE being smaller than $\mathrm{MSE}_u(n^*_{sub})$. As the result, the number of iterations is significantly reduced, especially with larger N (i.e., when $\mathrm{MSE}_u(n^*_{sub})$ decreases). The complexity reduction will be shown and further discussed in the simulation results.

VI. Numerical Results

Let us first consider the TWSRNs where the CQI estimation is carried out at $\mathcal{T}_2$. The estimation error occurs if the estimated CQI_1 at $\mathcal{T}_2$ is different from the CQI_1 estimated at $\mathcal{R}$. For comparison, the conventional scheme is applied to the same relay model (i.e., two-way data exchange between two terminals through one relay). Using the conventional scheme, CQI_1 of the link $\mathcal{T}_1 \to \mathcal{R}$ is fed back to $\mathcal{T}_2$ through one feedback link, and CQI_2 is separately fed back to $\mathcal{T}_1$ through another link, which results in heavy overhead. Using our proposed schemes, combined data broadcasted from relay $\mathcal{R}$ enables each terminal to estimate the required CQI. This process utilises only one time slot and requires no additional overhead.

As shown in Fig. 1, the MSE of estimated CQI_1 of various schemes is drawn against the SNR of $\mathcal{R} \to \mathcal{T}_2$ link with the assumption that $Q_1 = Q_2 = 8$ and $\gamma_{mdB} = 20$ dB. The SNRs of the $\mathcal{T}_1 \to \mathcal{R}$ and $\mathcal{T}_2 \to \mathcal{R}$ links are assumed to be 20 dB, and, the SNRs of the $\mathcal{R} \to \mathcal{T}_1$ and $\mathcal{R} \to \mathcal{T}_2$ links are subject to have sum of 20 dB. First, the upper and lower bounds given by (15) and (16) are shown to be quite tight and reflect well the behavior of the numerical MSEs. We can observe that the performance of our proposed schemes is close to the conventional scheme, especially at high SNR. The expected small loss is explained in Remark 1. Finally, comparing between scheme A and scheme B, we observe that a better performance can be achieved with scheme B when the SNR of $\mathcal{R} \to \mathcal{T}_2$ link is less than 10 dB. This confirms the explanation in Remark 2.

Next, we consider the TWMRNs where multiple relays are taken into account. For relay selection, the optimal scheme in (23), the suboptimal max-MSE based scheme in (24), and the proposed suboptimal bound-based scheme are used. For CQI estimation, the conventional scheme for the TWSRNs is also considered. We assume that $Q_1 = Q_2 = 16$ and the SNRs of the $\mathcal{R} \to \mathcal{T}_1$ and $\mathcal{R} \to \mathcal{T}_2$ links are 4 dB. As shown in Fig. 2, the performances with different selection schemes are

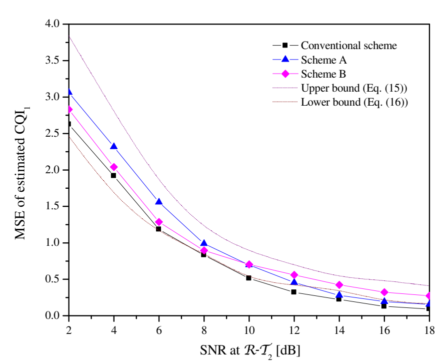

Fig. 1. MSE of estimated CQI_1 at $\mathcal{T}_2$ versus γ_{RT_2} with different schemes.

$$A_N = (-1)^{N-1} \sum_{m=1}^{N} (-1)^{m-1} \frac{\prod_{j=1}^{m-1} (N-j+1)}{(m-1)!} \{E_i [(N-m+1)\ln\alpha_N] - E_i [(N-m+1)\ln\beta_N] - \alpha_N^{N-m+1} \ln(-\ln\alpha_N) + \beta_N^{N-m+1} \ln(-\ln\beta_N)\}, \tag{27}$$

$$B_N = (-1)^{N} \sum_{m=1}^{N} (-1)^{m-1} \frac{\prod_{j=1}^{m-1} (N-j+1)}{(m-1)!} \{\alpha_N^{N-m+1} \ln^2(-\ln\alpha_N) - \beta_N^{N-m+1} \ln^2(-\ln\beta_N) + 2\ln(-\ln\alpha_N) \mathfrak{G}_{1,2}^{2,0} \left(\begin{smallmatrix}1\\0,0\end{smallmatrix}\middle| -(N-m+1)\ln\beta_N\right) - 2\ln(-\ln\beta_N) \mathfrak{G}_{1,2}^{2,0} \left(\begin{smallmatrix}1\\0,0\end{smallmatrix}\middle| -(N-m+1)\ln\beta_N\right) + 2\mathfrak{G}_{2,3}^{3,0} \left(\begin{smallmatrix}1,1\\0,0,0\end{smallmatrix}\middle| -(N-m+1)\ln\alpha_N\right) - 2\mathfrak{G}_{2,3}^{3,0} \left(\begin{smallmatrix}1,1\\0,0,0\end{smallmatrix}\middle| -(N-m+1)\ln\beta_N\right)\}, \tag{28}$$

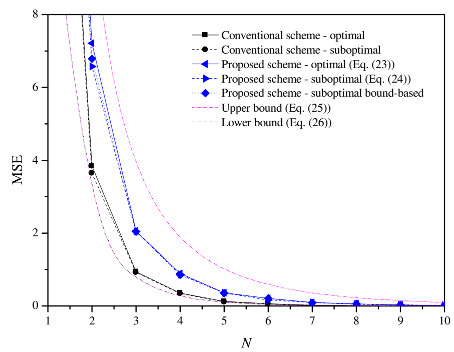

Fig. 2. MSE versus number of relays (N) with different relay selection schemes.

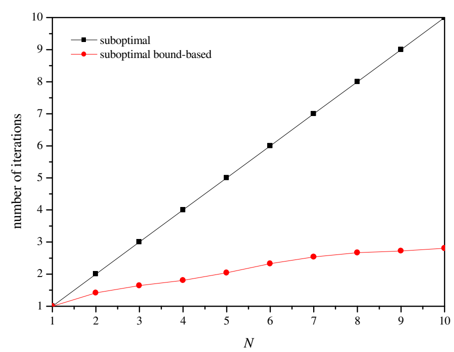

Fig. 3. Number of iterations versus number of relays (N) with suboptimal and suboptimal bound-based relay selection schemes.

close and converge to zero if the number of relays is large. That observation confirms the statement in Remark 4. Fig. 3 shows the complexity advantage of the proposed suboptimal bound-based relay selection scheme. The number of iterations is significantly reduced compared to that of the searching algorithm in (24), especially when the number of relays in TWMRNs is large. For example, the complexity is reduced by at least three times if the number of relays is larger than five.

VII. Conclusion

In this paper, we proposed and discussed two efficient CQI reporting schemes in nonregenerative TWSRNs based on XOR and superposition coding. These schemes reduce the transmission time by half while incurring no additional overhead. Significantly, these throughput advantages are obtained at the expense of negligible performance loss. In addition, the upper and lower bounds of the MSE of estimated CQI are derived. The bounds are shown to be tight and reflect well the behavior of the numerical MSE curves. Furthermore, a suboptimal bound-based relay selection scheme is proposed for TWMRNs to reduce the searching complexity of the optimal scheme. The performance of the proposed selection scheme is shown to be close to that of the optimal one while reducing the complexity by at least three times if the number of relays is larger than five. For future work, one can investigate the system model including the direct link between two terminals and consider the scenario where the channels are not completely reciprocal.

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