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Optimized Receiver Design for Decode-and-Forward Relays using Hierarchical Modulation

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***Abstract*—We consider a wireless relay network with a single source, a single destination, and multiple relays. The relays are half-duplex and use the decode-and-forward protocol. The transmit source is a layered bitstream, which can be partitioned into two layers. The source broadcasts both layers to all the relays and the destination using hierarchical 16-QAM. Each relay detects and transmits successfully decoded layers to the destination using either hierarchical 16-QAM or QPSK using orthogonal channels. We derive the optimal linear-combining receiver at the destination, where the uncoded bit error rate is minimized. We also present a suboptimal combining method with a closed-form solution, which performs very close to the optimal. Numerical results show that the two-layer scheme outperforms the classical one-layer scheme using conventional modulation.**

***Index Terms*—Relay networks, decode-and-forward relaying, layered video transmission, hierarchical modulation, maximal-ratio combining.**

I. Introduction

We consider wireless relay networks with a single source, a single destination, and multiple relays, all of which are equipped with a single antenna. In this work, we assume there is no feedback channel, and no retransmission is permitted (in order to reduce extra latency). Also, the relays cannot communicate with each other for cooperation purpose. A layered bitstream is transmitted from the source to the destination using the help of multiple relays.

In our proposed scheme, hierarchical QAM modulation is used to provide unequal error protection (UEP) for a layered video bitstream. We assume the source bitstream can be partitioned into two layers, called a base layer (BL) and an enhancement layer (EL). Generally, the BL is more important than the EL. The relays adaptively use different modulation schemes, depending on the number of successfully decoded layers. We will see later that, because of different modulation schemes used at the relays, classical maximal-ratio combining (MRC) cannot straightforwardly be applied at the destination. In [1] and [2], simple combining methods are used, however, both are suboptimal and perform significantly worse than the optimal.

In this work, we derive the optimal linear-combining weight vectors for the BL and the EL by a two-step combining method, where the optimality is in terms of minimizing the uncoded BER. For the BL, convex optimization programming [3] can be used to solve for the optimal weight vector. For the EL, only a local optimum can be guaranteed by convex optimization programming, so a global search method needs to be used. We also present a suboptimal method to find the weight for the BL by minimizing an upper-bound to the BER, which has a closed-form solution and performs very close to the optimal. Both the optimal and suboptimal methods for the BL significantly outperform the combining methods in [1], [2]. A suboptimal combining method for the EL in the second step is also presented, which performs well compared to the optimal. Numerical results show that our proposed double-layer scheme using hierarchical 16-QAM significantly outperforms a conventional single-layer scheme.

The rest of this paper is organized as follows. In Section II, we present the system model. The novel combining technique and the system performance are presented in Section III. Section IV presents numerical results, and Section V concludes the paper.

II. System Model

We consider a single source, a single destination, and N relays, all of which are equipped with a single antenna, as shown in Fig. 1. We assume the direct link is too weak and is not used. The relays are half-duplex, i.e., the relays cannot transmit and receive at the same time, and use the decode-and-forward protocol [4]. We assume the relays are not able to communicate with each other, and that the relays communicate with the destination using orthogonal channels. Similar to [2], we assume the entire bandwidth is equally divided into N sub-bands. One sub-band is allocated to each relay for communicating with the destination [2]. The broadcast channel from the source to the relays can use any one of the sub-bands, since it is transmitting in a different time slot.

A. Channel and Source Models

We assume the channels from the source to the relays and from the relays to the destination experience flat Rayleigh fading, and we use the modified Jakes' model [5] to simulate different fading rates. Due to the spatial separation, we also assume that all the channels from the source to the relays and from the relays to the destination are independent. We assume that the channel gain is constant for each symbol, and that it can be accurately estimated at the receiver. However, the channel gain is assumed to be unknown at the transmitter.

We consider the transmission of a layered bitstream, which can be partitioned into two layers, a BL and an EL. In practice,

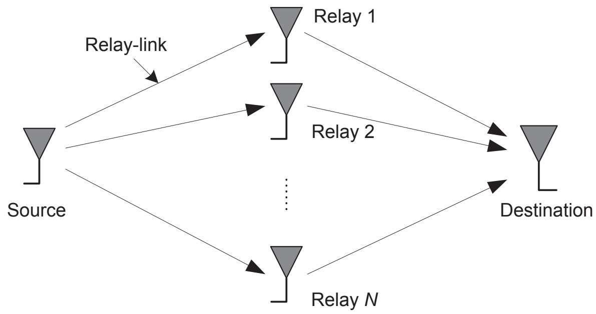

Fig. 1. Wireless relay network: a single source, a single destination, and multiple relays.

the BL is more important than the EL in terms of the quality of the reconstructed source at the receiver. Hence, the BL generally needs higher protection against transmission errors. In this work, we adopt hierarchical QAM modulation [6], [7] to provide UEP.

B. Transmission Schemes

1) Classical single-layer scheme - Baseline: In the first time slot, the source encodes and broadcasts a message using conventional 16-QAM with Gray-coded bit-mapping to all the relays and the destination. The relays separately decode the message. If successful, they re-encode and forward it to the destination using the same modulation scheme. At the destination, since the received signals use the same modulation scheme, a maximal-ratio-combining (MRC) receiver is used to combine all the received signals to decode the message.

2) Proposed double-layer scheme: In the first time slot, the source encodes and broadcasts a message consisting of both the BL and the EL (the BL/EL) using hierarchical 16-QAM to all the relays and the destination. The BL is mapped to the most significant bits (MSBs) and the EL is mapped to the least significant bits (LSBs), as shown in Fig. 2. The relays separately decode the message. If the BL is decoded successfully, an attempt is made to decode the EL. Note that a relay can successfully decode the BL/EL, only the BL, or neither. In the second time slot, the relays re-encode and forward any successfully decoded layers to the destination. Either hierarchical 16-QAM or QPSK is used depending upon if both layers or just the BL, respectively, is forwarded. In this paper, we consider optimal linear-combining methods to first detect the BL, and then to detect the EL, at the destination.

Since the mathematical representation of the single-layer scheme with conventional 16-QAM is straightforward, in the following, we focus on the double-layer scheme with hierarchical 16-QAM modulation.

C. Signal Model

We consider hierarchical 16-QAM modulation using Gray-coded bit mapping, as shown in Fig. 2. We can express a hierarchical 16-QAM symbol, denoted by A_l, as the weighted sum, or superposition, of two QPSK symbols as follows [8]:

$$A_l = \sqrt{\rho} b_l + \sqrt{\bar{\rho}} e_l \tag{1}$$

where b_l and e_l denote two QPSK-modulated symbols, which depend on the MSBs and the LSBs, respectively, of the hierarchical 16-QAM symbol. We use $\rho \in (0.5, 1]$ to denote the normalized power allocated to the MSB signal b_l, and $\bar{\rho} \triangleq 1-\rho$ to denote the normalized power allocated to the LSB signal e_l.[1]

In the following, we just consider the received signals at the destination. In the second time slot, depending on the number of successfully decoded layers at the relays, the destination can receive different signals in each sub-band. If the n-th relay transmitted the BL/EL using hierarchical 16-QAM, the received signal in the n-th sub-band at the destination is given by

$$y_{n,l}^{(d)} = \alpha_{n,l}^{rd} \sqrt{2E_r} \big(\sqrt{\rho} b_l + \sqrt{\bar{\rho}} e_l \big) + z_{n,l}^{(d)}, \tag{2}$$

or, if only the BL is transmitted (using QPSK),

$$y_{n,l}^{(d)} = \alpha_{n,l}^{rd} \sqrt{2E_r} b_l + z_{n,l}^{(d)} \tag{3}$$

where E_r denotes the average transmit symbol energy by the relays. Note that all the power is allocated to the BL when QPSK is used. In (2) and (3), similarly, we assume the $\{z_{n,l}^{(d)}\}$ are independently, identically distributed (i.i.d.), circularly symmetric, complex Gaussian noise $\mathcal{CN}(0, 2N_0)$.

Since the destination can receive two types of signals, one of which includes the BL/EL using hierarchical 16-QAM and the other includes only the BL using QPSK, the classical MRC receiver cannot be applied straightforwardly. In [1], [2], two combining methods can be used, however, they are suboptimal.

III. Proposed Combining Methods at the Destination

Let Θ_k and Ψ_k, $k = 1, 2, \ldots, 3^N$, be sets of the received signals at the destination which include only the BL or both the BL/EL, respectively. That is, (Θ_k, Ψ_k) are subsets of the set of all relay indices $\{1, 2, \ldots, N\}$, with $\Theta_k \cap \Psi_k = \emptyset$. Note that those received signals at the destination in the sets Θ_k and Ψ_k are given in (3) and (2), respectively.

In the following, we consider both the optimal and a suboptimal method to combine the received signals in the sets Θ_k and Ψ_k at the destination to decode the base layer signal. Optimality is defined in terms of minimizing the uncoded bit error rate. We note that, if either Θ_k or Ψ_k is an empty set, i.e., only one kind of signal is received, the classical MRC receiver can be applied, which is optimal. Thus, in the following, we consider the case that both sets are nonempty.

A. Combined Signals and Optimization Problems

Let w_n represent the combining weight corresponding to the received signal from the n-th relay. We use $\mathbf{w}_\Phi$ to denote a column vector whose elements are $\{w_n\}$ for $n \in \Phi$, and similarly for $\boldsymbol{\alpha}_\Phi$, whose elements are $\{\alpha_{n,l}^{rd}\}$. The combined signal at the destination can be written as follows:

$$\begin{aligned} y_{l,bl}^{(d)} = & \sqrt{2E_r} \big[C_{\Theta_k}(\mathbf{w}_{\Theta_k}) + C_{\Psi_k}(\mathbf{w}_{\Psi_k}) \sqrt{\rho} \big] b_l \\ & + \sqrt{2E_r} \big[C_{\Psi_k}(\mathbf{w}_{\Psi_k}) \sqrt{\bar{\rho}} \big] e_l + N_{\Theta_k}(\mathbf{w}_{\Theta_k}) + N_{\Psi_k}(\mathbf{w}_{\Psi_k}) \end{aligned} \tag{4}$$

[1] Relative to the power allocation ratio in [6], we have $\alpha = d_M/d_L = (\sqrt{\rho} - \sqrt{\bar{\rho}})/\sqrt{\bar{\rho}}$ (where $\bar{\rho} = 1-\rho$), that is, e.g., if $\rho = 0.70$ then $\alpha \approx 0.528$, if $\rho = 0.80$ then $\alpha = 1.0$ (i.e., conventional constellation), and if $\rho = 0.90$ then $\alpha = 2.0$.

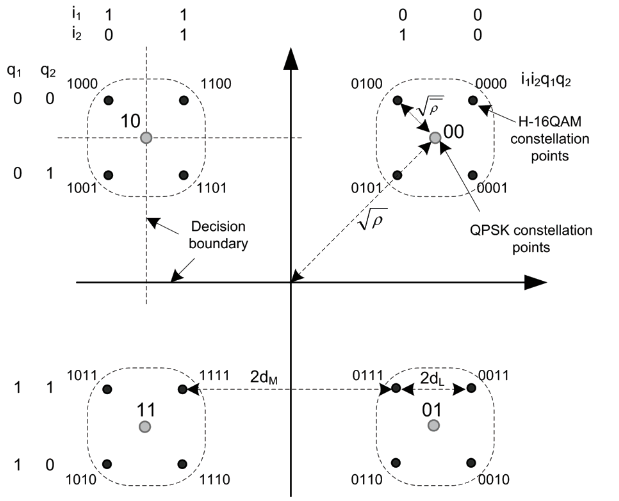

Fig. 2. Hierarchical 16-QAM symbol as superposition mapping of two QPSK symbols: $A_l = \sqrt{\rho} b_l + \sqrt{\bar{\rho}} e_l$.

where $C_\Phi(\mathbf{w}_\Phi) \triangleq \mathbf{w}_\Phi^T \boldsymbol{\alpha}_\Phi$ and $N_\Phi(\mathbf{w}_\Phi) \triangleq \mathbf{w}_\Phi^T \mathbf{z}_\Phi$ for $\Phi \in \{\Theta_k, \Psi_k\}$ (the superscript T denotes transpose).

B. Combining Methods

Since $\{\alpha_{n,l}^{rd}\}$ are all non-negative, we can show that all the elements of the optimal weight vectors $\mathbf{w}_{\Theta_k}$ and $\mathbf{w}_{\Psi_k}$ must be non-negative, which we denote by $\mathbf{w}_{\Theta_k} \succeq 0$ and $\mathbf{w}_{\Psi_k} \succeq 0$ [9]. Thus, $C_{\Theta_k}(\mathbf{w}_{\Theta_k}), C_{\Psi_k}(\mathbf{w}_{\Psi_k}) \geq 0$, and the combined signal in (4) is a noisy hierarchical 16-QAM symbol. For $\mathbf{w}_{\Theta_k}, \mathbf{w}_{\Psi_k} \succeq 0$, and which are not equal to the zero vector, we can write

$$\mathbf{w}_{\Theta_k} = a_{\Theta_k} \tilde{\mathbf{w}}_{\Theta_k}, \quad \mathbf{w}_{\Psi_k} = a_{\Psi_k} \tilde{\mathbf{w}}_{\Psi_k} \tag{5}$$

for $a_{\Theta_k}, a_{\Psi_k} > 0$, $\tilde{\mathbf{w}}_{\Theta_k}, \tilde{\mathbf{w}}_{\Psi_k} \succeq 0$, and $\|\tilde{\mathbf{w}}_{\Theta_k}\| = \|\tilde{\mathbf{w}}_{\Psi_k}\| = 1$.

The BER for the BL can be written as [6], [7], [9]

$$\begin{aligned} &BER_{BL}(a_{\Theta_k}, a_{\Psi_k}, \tilde{\mathbf{w}}_{\Theta_k}, \tilde{\mathbf{w}}_{\Psi_k}) \triangleq BER_{BL}(a_{\Theta_k}\tilde{\mathbf{w}}_{\Theta_k}, a_{\Psi_k}\tilde{\mathbf{w}}_{\Psi_k}) \\ &= \frac{1}{2} Q\left(\frac{\sqrt{E_r} a_{\Theta_k} C_{\Theta_k}(\tilde{\mathbf{w}}_{\Theta_k}) + \sqrt{E_r} a_{\Psi_k} C_{\Psi_k}(\tilde{\mathbf{w}}_{\Psi_k}) \big(\sqrt{\rho} - \sqrt{\bar{\rho}}\big)\big]}{\sqrt{(a_{\Theta_k}^2 + a_{\Psi_k}^2) N_0}} \right) \\ &+ \frac{1}{2} Q\left(\frac{\sqrt{E_r} a_{\Theta_k} C_{\Theta_k}(\tilde{\mathbf{w}}_{\Theta_k}) + \sqrt{E_r} a_{\Psi_k} C_{\Psi_k}(\tilde{\mathbf{w}}_{\Psi_k}) \big(\sqrt{\rho} + \sqrt{\bar{\rho}}\big)\big]}{\sqrt{(a_{\Theta_k}^2 + a_{\Psi_k}^2) N_0}} \right) \end{aligned} \tag{6}$$

Similarly, the BER for the EL can be written as

$$\begin{aligned} &BER_{EL}(b_{\Theta_k}, b_{\Psi_k}, \tilde{\mathbf{v}}_{\Theta_k}, \tilde{\mathbf{v}}_{\Psi_k}) = Q\left(\frac{\sqrt{E_r} b_{\Psi_k} C_{\Psi_k}(\tilde{\mathbf{v}}_{\Psi_k}) \sqrt{\bar{\rho}}}{\sqrt{(b_{\Theta_k}^2 + b_{\Psi_k}^2) N_0}} \right) \\ &+ \frac{1}{2} Q\left(\frac{\sqrt{E_r} \big[2 b_{\Theta_k} C_{\Theta_k}(\tilde{\mathbf{v}}_{\Theta_k}) + b_{\Psi_k} C_{\Psi_k}(\tilde{\mathbf{v}}_{\Psi_k}) \big(2\sqrt{\rho} - \sqrt{\bar{\rho}}\big)\big]}{\sqrt{(b_{\Theta_k}^2 + b_{\Psi_k}^2) N_0}} \right) \\ &- \frac{1}{2} Q\left(\frac{\sqrt{E_r} \big[2 b_{\Theta_k} C_{\Theta_k}(\tilde{\mathbf{v}}_{\Theta_k}) + b_{\Psi_k} C_{\Psi_k}(\tilde{\mathbf{v}}_{\Psi_k}) \big(2\sqrt{\rho} + \sqrt{\bar{\rho}}\big)\big]}{\sqrt{(b_{\Theta_k}^2 + b_{\Psi_k}^2) N_0}} \right) \end{aligned} \tag{7}$$

where $b_{\Theta_k}, b_{\Psi_k} > 0$, $\tilde{\mathbf{v}}_{\Theta_k}, \tilde{\mathbf{v}}_{\Psi_k} \succeq 0$, and $\|\tilde{\mathbf{v}}_{\Theta_k}\| = \|\tilde{\mathbf{v}}_{\Psi_k}\| = 1$.

1) Combining Methods – Step I: Closed form for BL/EL: The optimization problem is given as follows:

$$\begin{aligned} BER_{BL}^* &= \underset{\substack{a_{\Theta_k}, a_{\Psi_k} > 0, \tilde{\mathbf{w}}_{\Theta_k}, \tilde{\mathbf{w}}_{\Psi_k} \succeq 0 \\ \|\tilde{\mathbf{w}}_{\Theta_k}\| = \|\tilde{\mathbf{w}}_{\Psi_k}\| = 1}}{\text{minimize}} BER_{BL}(a_{\Theta_k}, a_{\Psi_k}, \tilde{\mathbf{w}}_{\Theta_k}, \tilde{\mathbf{w}}_{\Psi_k}) \\ &= \min_{a_{\Theta_k}, a_{\Psi_k} > 0} \min_{\substack{\tilde{\mathbf{w}}_{\Theta_k}, \tilde{\mathbf{w}}_{\Psi_k} \succeq 0 \\ \|\tilde{\mathbf{w}}_{\Theta_k}\| = \|\tilde{\mathbf{w}}_{\Psi_k}\| = 1}} BER_{BL}(a_{\Theta_k}, a_{\Psi_k}, \tilde{\mathbf{w}}_{\Theta_k}, \tilde{\mathbf{w}}_{\Psi_k}) \end{aligned}$$

where the superscript $*$ denotes the optimal value for the corresponding quantity.

The solution of the inner optimization problem for the BL is given by

$$(\tilde{\mathbf{w}}_{\Theta_k}^*, \tilde{\mathbf{w}}_{\Psi_k}^*) = (\boldsymbol{\alpha}_{\Theta_k}/\|\boldsymbol{\alpha}_{\Theta_k}\|, \boldsymbol{\alpha}_{\Psi_k}/\|\boldsymbol{\alpha}_{\Psi_k}\|) \triangleq (\tilde{\boldsymbol{\alpha}}_{\Theta_k}, \tilde{\boldsymbol{\alpha}}_{\Psi_k}) \tag{8}$$

A similar result was shown to hold for the EL, i.e.,

$$(\tilde{\mathbf{v}}_{\Theta_k}^*, \tilde{\mathbf{v}}_{\Psi_k}^*) = (\tilde{\boldsymbol{\alpha}}_{\Theta_k}, \tilde{\boldsymbol{\alpha}}_{\Psi_k}) \tag{9}$$

2) Combining Methods – Step II: Optimal Solution: Without loss of generality, we can assume $a_{\Theta_k} = 1$, and the BER for the BL, as a function of a_{Θ_k}, can be written as

$$BER_{BL}(a_{\Psi_k}) = \frac{1}{2} Q\left(\frac{A + B a_{\Psi_k}}{\sqrt{1 + a_{\Psi_k}^2}} \right) + \frac{1}{2} Q\left(\frac{A + C a_{\Psi_k}}{\sqrt{1 + a_{\Psi_k}^2}} \right) \tag{10}$$

where we define $A \triangleq \frac{\sqrt{E_r} C_{\Theta_k}^*}{\sqrt{N_0}}$, $B \triangleq \frac{\sqrt{E_r} C_{\Psi_k}^*}{\sqrt{N_0}} (\sqrt{\rho} - \sqrt{\bar{\rho}})$, $C \triangleq \frac{\sqrt{E_r} C_{\Psi_k}^*}{\sqrt{N_0}} (\sqrt{\rho} + \sqrt{\bar{\rho}})$ for $A \geq 0$ and $C \geq B \geq 0$, and $C_\Phi^* \triangleq C_\Phi(\tilde{\boldsymbol{\alpha}}_\Phi) = \|\tilde{\boldsymbol{\alpha}}_\Phi\|$. We note that $BER_{BL}(a_{\Psi_k})$ in (10) is *not* convex. However, for $a_{\Psi_k} > 0$, we define

$$\phi = \tan^{-1}(a_{\Psi_k}), \quad \phi \in (0, \pi/2) \tag{11}$$

Substituting $a_{\Psi_k} = \tan(\phi)$, we have

$$\begin{aligned} BER_{BL}^{(a)}(\phi) &\triangleq BER_{BL}(\tan(\phi)) \\ &= \frac{1}{2} Q\left(A \cos\phi + B \sin\phi\right) + \frac{1}{2} Q\left(A \cos\phi + C \sin\phi\right) \end{aligned} \tag{12}$$

which is convex [9], and can be solved by convex optimization programming [3].

Similarly, the optimal weights in the second step for the EL are given by [9]

$$b_{\Theta_k}^* = \tan\theta^*, \quad b_{\Psi_k}^* = 1 \tag{13}$$

for

$$\begin{aligned} \theta^* = \arg \min_{\theta \in (0, \pi/2)} & Q\left(D \cos\theta\right) + \frac{1}{2} Q\left(E \sin\theta + F \cos\theta\right) \\ & - \frac{1}{2} Q\left(E \sin\theta + G \cos\theta\right) \end{aligned} \tag{14}$$

where $D \triangleq \sqrt{\frac{E_r}{N_0}} C_{\Psi_k}^* \sqrt{\bar{\rho}}, E \triangleq 2\sqrt{\frac{E_r}{N_0}} C_{\Theta_k}^*, F \triangleq \sqrt{\frac{E_r}{N_0}} C_{\Psi_k}^* (2\sqrt{\rho} - \sqrt{\bar{\rho}})$, and $G \triangleq \sqrt{\frac{E_r}{N_0}} C_{\Psi_k}^* (2\sqrt{\rho} + \sqrt{\bar{\rho}})$.

3) Combining Methods – Step II: Suboptimal, Closed-form: An upper bound for the BER of the BL is twice the dominant term:

$$BER_{BL}(a_{\Psi_k}) \leq Q\left(\frac{A + Ba_{\Psi_k}}{\sqrt{1 + a_{\Psi_k}^2}}\right) \triangleq BER_{BL}^{ub}(a_{\Psi_k}) \quad (15)$$

By minimizing the upper bound BER, we can show that [9]

$$a_{\Psi_k}^{\dagger} = B/A = \frac{C_{\Psi_k}^*}{C_{\Theta_k}^*}(\sqrt{\rho} - \sqrt{\bar{\rho}}) = \frac{\|\boldsymbol{\alpha}_{\Psi_k}\|}{\|\boldsymbol{\alpha}_{\Theta_k}\|}(\sqrt{\rho} - \sqrt{\bar{\rho}}) \quad (16)$$

In summary, the closed-form suboptimal weight vectors for the BL:

$$\mathbf{w}_{\Theta_k}^{\dagger} = \boldsymbol{\alpha}_{\Theta_k}, \quad \mathbf{w}_{\Psi_k}^{\dagger} = (\sqrt{\rho} - \sqrt{\bar{\rho}})\boldsymbol{\alpha}_{\Psi_k} \quad (17)$$

Simple suboptimal weight vectors for the EL are given by

$$\mathbf{v}_{\Theta_k}^{\dagger} = \mathbf{0}, \quad \mathbf{v}_{\Psi_k}^{\dagger} = \boldsymbol{\alpha}_{\Psi_k} \quad (18)$$

That is, we only combine the received signals that consist of the BL/EL to decode the EL.

IV. Numerical Results

In the numerical results, we assume the channel gains of all links experience independent flat Rayleigh fading with normalized Doppler frequency $f_{dn} = 10^{-3}$ and second moment Ω_0. The channel state information is perfectly known at the receiver. The transmit symbol energy by a relay is $E_r = E_s/N$ where E_s is the transmit symbol energy by the source. We define the received signal-to-noise ratio (at a relay) as $SNR = E_s\Omega_0/N_0$.

A. Uncoded Bit Error Rate

In the following, we compare the uncoded BER performances of the BL and the EL for the different combining methods above. For simplicity, we assume there are two relays. One is always sending the BL using QPSK, and the other is always sending the BL/EL using hierarchical 16-QAM. For the BL, we plot the uncoded BER performances for the combining methods in [1], [2], and our optimal and suboptimal methods. For the EL, we plot our simple combining method, the locally suboptimal method, and the lower bound.

First, we consider the performances for the BL, as shown in Fig. 3, for the power allocation parameter $\rho = 0.72$, a value which will be of interest below. We note that the combining method in [2] does not perform as well as the other methods, since it only uses the QPSK received signal to detect the BL, and thus results in just the QPSK BER performance (with diversity order 1). Our suboptimal combining method of minimizing an upper-bound BER significantly outperforms the combining method used in [1]. We can observe approximately 1dB gain in the medium and high SNR region, i.e., say, the channel $SNR \geq 8$dB. Our suboptimal method performs almost as well as the optimal in the medium and high SNR region. For a higher value of ρ, say, $\rho = 0.8$ (i.e., conventional constellation), as shown in Fig. 4, our suboptimal combining method performs almost identical to the optimal one over the range of SNR in the plot. The gain compared to the combining

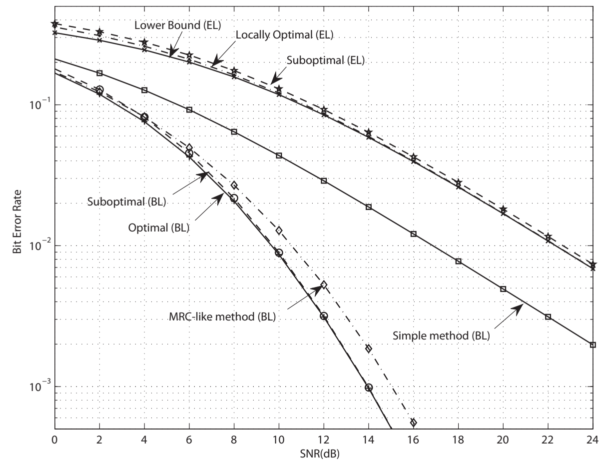

Fig. 3. Comparison of uncoded BER performance for the BL and the EL with $\rho = 0.72$.

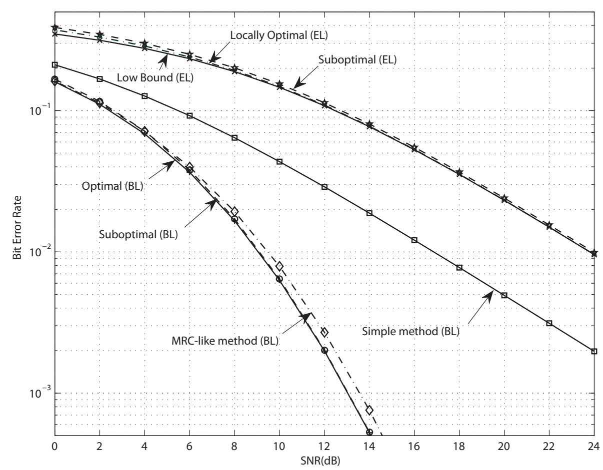

Fig. 4. Comparison of uncoded BER performance for the BL and the EL with $\rho = 0.80$.

method in [1] reduces for a high value of ρ, but the proposed method is still much better than the method in [2], as can be seen in Fig. 4.

Next, we consider the performance for the EL. In Fig. 3, we observe that the suboptimal combining method performs very close to the locally optimal and the lower bound performances. For smaller ρ, the performance loss slightly increases. For higher values of ρ, say $\rho = 0.8$, the performance loss is almost negligible, as seen in Fig. 4. We note that in all cases, the locally optimal performance is almost identical to the lower bound for, say, the channel $SNR \geq 8$dB, which suggests that the local optimum is very close, if not identical, to the global optimum in this SNR region.

B. Packet Error Rate

In this subsection, we simulate the packet error rate (PER) for the system with 4 relays. We use a convolutional code of rate $r_{\text{fec}} = 1/2$ with soft Viterbi decoding for the forward error correction (FEC) on all links. The convolutional code

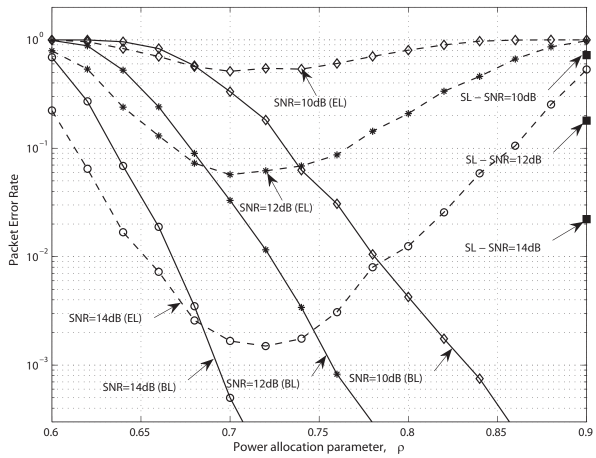

Fig. 5. Packet error rate of the double-layer and single-layer scheme.

has constraint length 7, and generator polynomial (133,171) in octal. We use a frame length of $2\text{x}400/r_{\text{fec}} = 1600$ bytes, half of which carries the BL packet and the other half carries the EL packet. Because of the hierarchical 16-QAM modulation, we need the same number of bits in the two priority classes. The BL is mapped into the MSBs and the EL is mapped into the LSBs of the hierarchical 16-QAM symbols. In this simulation, we use a pair of block bit interleavers of size 80x80 bits each (i.e., 800 bytes) for the BL and the EL separately to partially decorrelate the channel fading correlation. Note that to reduce the computational complexity, in the following, we use the proposed suboptimal combining methods that have the closed-form weights, instead of numerically solving for the optimal (or locally optimal) weights.

In Fig. 5, we plot the packet error rate (PER) for both the single-layer and double-layer scheme, where an i.i.d. bitstream was sent. The abscissa is the power allocation parameter, ρ, for the double-layer scheme. The PERs of the BL and the EL packets are plotted separately. As the single-layer scheme uses the classical 16-QAM with no distinction among the input bits, the single-layer scheme only depends on channel SNR, and not ρ. It is plotted on the right hand edge as a single point for each channel SNR for comparison. For each channel SNR, we observe that the PER of the BL monotonically decreases as ρ increases, because the BL is allocated more power. For the EL performance, the plot shows that the PERs of the EL are not a monotonic function of ρ. This can be explained as follows: For $\rho \geq 0.72$, the BL is successfully decoded most of the time, and so the EL performance mainly depends on the power allocated to it; thus, the PER of the EL monotonically increases as $\bar{\rho} = 1 - \rho$ decreases. In contrast, for $\rho \leq 0.70$, as ρ decreases, the relays are not able to reliably detect the BL (because of the decreased SINR of the BL), and thus they frequently keep silent. At some point, the destination does not receive enough signal power because too few signals are being relayed; hence, both the PER of the BL and the PER of the EL become worse.

We note that for many values of ρ (e.g., $\rho \in [0.68, 0.78]$ for channel $SNR = 12$dB), both the BL and the EL PER of the double-layer scheme are better than the PER of the single-layer scheme. This is because a relay that might fail to decode a packet if the single-layer scheme is used during a deep fade might still be able to decode the BL portion if the double-layer scheme is used, and thus might be able to forward it to the destination, which enhances the probability that the BL is successfully decoded at the destination. Note that for $\rho \in [0.68, 0.78]$, the EL performance is also enhanced, because $\rho < 0.8$. As a result, at the destination, both the BL and the EL are favored in terms of received power; therefore, the PERs of both the BL and the EL can be simultaneously better than that of a single-layer scheme.

V. Conclusions

In this paper, we consider decode-and-forward wireless relay networks using both hierarchical 16-QAM and QPSK. The source broadcasts a message consisting of two layers to all the relays and the destination. Depending on the number of successfully decoded layers, a relay can use either hierarchical 16-QAM or QPSK to transmit both layers or just the BL, respectively, to the destination. We proposed a relaying protocol and novel combining methods for the received signals at the destination. We derived the optimal linear-combining solution in terms of minimizing the uncoded BER. We also presented suboptimal combining methods for both the BL and the EL, which have closed-form solutions and perform very close to the optimal. Both our optimal and suboptimal methods significantly outperform other combining methods in the literature. Simulation results showed that the double-layer scheme using hierarchical 16-QAM significantly outperforms the classical single-layer scheme using conventional 16-QAM.

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