Performance analysis of ARQ cooperative diversity system with multiple two-hop relays over Rayleigh fading channels

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A R T I C L E I N F O

Article history:
Received 16 June 2011
Received in revised form 13 April 2013
Accepted 16 April 2013
Available online 21 May 2013

A B S T R A C T

Cooperative communication systems can exploit spatial diversity by opportunistically choosing relays to forward information to the destination. In this paper, we investigate the statistical performance analysis of a general cross-layer automatic repeat request cooperative diversity (ACD) system by focusing on the scenario in which decode-and-forward relaying protocol and multiple two-hop relays are employed over Rayleigh fading channel environments. To obtain the theoretical closed-form formulas for end-to-end performance parameters, we develop a time division multiple access (TDMA)-based absorbing Markov model to help find all possible transition probabilities of each transmission process. Based on this proposed model and statistical analysis, we derive two tight closed-form expressions in terms of end-to-end packet delivery failure probability and end-to-end packet delivery delay distribution. In addition, an optimal power allocation scheme under a tight power constraint for the ACD system is proposed for further enhancing the symbol error rate (SER) performance, which outperforms the equal power allocation scheme obviously. Simulation results by Monte Carlo simulations demonstrate the correctness of our analysis eventually.

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1. Introduction

Cooperative diversity has shown to play a major role in the next-generation mobile communication networks based on recent work on IEEE802.11s and IEEE802.16j [1]. With low complexity terminals, it is beneficial in enhancing data transmission performance by exploiting the broadcast nature and location dependent fading characteristics of wireless channels. Basically, a transmitting source node can be assisted by its surrounding nodes, if the direct transmission fails. By doing so, multiple copies of independent fading signal paths are provided at the destination, which brings spatial diversity [1,2].

Among the set of cooperative techniques, one most popular strategy for such cooperative diversity systems is the decode-and-forward (DF) relaying protocol [2,3] where each cooperative node decodes and re-encodes the received signal before forwarding it to the destination. The very early paper on DF cooperative diversity appeared in the single relay over physical layer [2–5]. Most of them have addressed the performance analysis in terms of symbol error rate, outage probability, and capacity. In [6], Lee et al. considered the true error probability for decode-and-forward cooperative communications with multiple relays over Nakagami-m fading channels. However, they dealt with one-layer symbol error rate analysis without considering upper layers. Recent research work [7–9] has shown that automatic repeat request (ARQ) can improve the multiplexing diversity tradeoff significantly by the retransmission round. In fact, a code division multiple access (CDMA)-based
analytical model for ARQ cooperative diversity was proposed in [7] which validated the desirable adaptive characteristics of cross-layer cooperative communication systems. But the authors focused on the system model where each source node transmitted a packet to its cluster head with its surrounding relays synchronously, if the direct transmission failed. It is not suitable for time division multiple access (TDMA) orthogonal channels, or a single channel for interference.

Motivated by all of the above, in this paper, we consider the ACD system in TDMA orthogonal channels with multiple two-hop relays and present statistical performance analysis of ACD system in terms of packet delivery failure probability and packet delivery delay distribution over Rayleigh fading channels in wireless networks. In order to take all possible transition probabilities of each transmission process into consideration, we develop an absorbing Markov model to help find their exact representations in the case of cooperative communications with retransmission round. In addition, we discuss the relationship of the power allocation scheme over different fading channels with the symbol error rate (SER) performance of the cross-layer ACD system. Based on the partial channel state information (CSI) and the analytical results developed, an optimal power allocation scheme is proposed to allocate the transmission power for further improving the performance of system. Afterward, the theoretical analysis is verified by computer Monte Carlo simulations. The numerical results show the correctness of our theoretical expressions for packet delivery failure probability and packet delivery delay distribution. It is also indicated that the performance with optimal power allocation scheme for the cross-layer ACD system is further improved compared with the equal power allocation scheme.

The rest of this paper is organized as follows. In Section 2, we describe the system model for the cross-layer ACD system. Then, based on this model, in Section 3, two tight closed-form expressions, i.e. packet delivery failure probability and packet delivery delay distribution, are derived. Section 4 presents an optimal power allocation scheme for enhancing the system SER performance. The numerical results are used in Section 5 and the conclusions are stated in Section 6.

2. System model

In this paper, we consider an ACD system that combines DF relaying at the physical layer and truncated stop-and-await ARQ at the link layer.

2.1. Physical layer system model

A distributed wireless cooperative relaying network with one source node “S”, one destination node “D” and K relay nodes “Rk” with k = 1, . . . , K are employed over Rayleigh fading channels, as illustrated in Fig. 1. Each node is equipped with a single omni-directional antenna and operates in half-duplex mode. The source communicates with the destination through the help of the relay nodes which can fully decode the signal transmitted by node “S” in the first source-to-relay hop. Further, all the channel links are assumed to be mutually independent and the TDMA scheme is used for orthogonal channel access, i.e., only one node (the source node or relay nodes) is allowed to transmit a packet in each time slot. Therefore, the source-to-destination signal transmission via the relay nodes will occupy K + 1 time slots and the transmission procedure is fully described in Fig. 1.

Fig. 1. Diagram of transmission system.
In the first transmission hop, the received signals from the source node “S” to the destination node “D” and from the source node “S” to the kth relay node “R_k”, respectively, are denoted as

\[ y_{S,D} = \sqrt{p_S} h_{S,D} x_S + n_{S,D} \]
\[ y_{S,R_k} = \sqrt{p_S} h_{S,R_k} x_S + n_{S,R_k} \]

where \( x_S \) denotes the transmitted signal of the source node with \( x_S x_S^* = 1 \), and \( (\cdot)^* \) denotes complex conjugation; \( h_{S,D} \sim CN(0, \Omega_{S,D}) \) and \( h_{S,R_k} \sim CN(0, \Omega_{S,R_k}) \) denote the corresponding complex channel coefficients of the channel from the source node to the destination node, and from the source node to the kth relay node, respectively; \( p_S \) is the source transmission power, and \( n_{S,D} \) and \( n_{S,R_k} \) are the corresponding complex additive Gaussian noise (AWGN) power with zero mean and variance \( N_{S,D} \) and \( N_{S,R_k} \), respectively.

For the DF relaying protocol, the relay nodes which can fully decode the message of source node transmit the received signal to the destination node as helper in the second transmission hop. At the end of the lth retransmission round, the received signal of the source node and all the relay nodes at the destination is

\[ y_{K+1}^l = \sqrt{p_S} h_{S,D} x_S + n_{S,D} + \sum_{k \in D_{K+1}^l} \left( \sqrt{p_{R_k}} h_{R_k,D} x_S + n_{R_k,D} \right) \]

where \( D_{K+1}^l \) is the correctly decoding set of source node at the end of the lth retransmission round with \( l = 1, \ldots, L \); \( L \) is the maximum retransmission round (see part B of Section II in detail); \( p_{R_k} \) is the kth relay transmission power which is 0 if it cannot correctly decoded the source signal; otherwise, \( p_{R_k} = p_R \); \( h_{R_k,D} \sim CN(0, \Omega_{R_k,D}) \) is the complex channel coefficient of the kth relay node to the destination node; \( n_{R_k,D} \) is the complex additive Gaussian noise (AWGN) power of the kth relay node to the destination node channel with zero mean and variance \( N_{R_k,D} \), and for simplicity, we assume that all the noise variances are equal, i.e. \( N_{S,D} = N_{S,R_k} = N_{R_k,D} = N_0 = 1/\gamma_0 \). Here \( \gamma_0 \) can be used as a measure of the system average signal-to-noise (SNR) because it is proportional to all the SNRs [10]. After maximal ratio combing (MRC) at the destination, the received SNR can be expressed as

\[ \gamma_{K+1}^l = \frac{p_S h_{S,D}^* + \sum_{k \in D_{K+1}^l} p_{R_k} h_{R_k,D}^* h_{R_k,D}^*}{N_0} = \gamma_0 p_S |h_{S,D}|^2 + \sum_{k \in D_{K+1}^l} \gamma_0 p_{R_k} |h_{R_k,D}|^2 \]

2.2. Link layer system model

We focus on a single packet transmission from the source node with a truncated stop-and-await ARQ protocol [7,8] at the link layer and each packet consists of N symbols. To improve the multiplexing performance, the source packet is encoded into L codewords each of which is able to be fully decoded into the source message by some decoding rules and is transmitted in one retransmission round, i.e. \( K + 1 \) time slots in each retransmission round shown in Fig. 1. In the first time slot of each round, the source node broadcasts one of the message codewords to the destination and all the relay nodes. The receiving relay nodes check the correctness of it using cyclic redundancy code (CRC) and forward the information to the destination in the corresponding time slots, if they decode the packet successfully and hear a negative acknowledgment (NACK) message from the destination node. Otherwise, they keep silent in their corresponding time slots. If an acknowledgment (ACK) message is sent by the destination node, the source node and all the relay nodes do not attempt any other transmission more, which means the transmission process finished. Otherwise, the procedure is retried in the next retransmission round while the number of repetition does not exceed the maximum limit L. A graphical representation of the transmission state transition is given in Fig. 2.

3. Performance analysis

In this section, we want to investigate the end-to-end performance in terms of packet delivery failure probability and packet delivery delay distribution over Rayleigh fading channels. First, we define \( D_{K+1}^l, k = 1, \ldots, K \), i.e., the correctly decoding set of source node before the first time slot and the \((k+1)\)th time slot of the lth retransmission round, as follows:

\[ D_{K+1}^l = \{ R_i : \log_2 (1 + \gamma_0 p_S |h_{S,R_i,D}|^2) \geq 2R, i = 1, 2, \ldots, k \} \]

where \( R \) denotes the spectral efficiency in bps/Hz below which the channel is in outage [2]. Let \( D_{K+1}^l \sim j, g \) denote the gth element of the possible decoding subset of \( D_{K+1}^l \), with cardinality of which equal j. By doing so, we obtain the cumulative density function (CDF) of the achieved system SNR \( \gamma_{K+1}^l \) at the end of the \((k+1)\)th time slot of the lth retransmission round in Theorem 1.

**Theorem 1.** With reference to a cooperative diversity system as described in Section 2, the CDF of the achieved system SNR \( \gamma_{K+1}^l \) can be expressed as follows:
\[ F_{k+1}(\gamma) = \sum_{\gamma_k = 1}^{k} \left\{ \sum_{j=0}^{\gamma} \left( \int_{0}^{\omega} \left( 1 - \sum_{i=0}^{0} \frac{z_i}{n!} \left( \frac{\omega}{\Omega_{k,d}} \right)^n e^{-\frac{\omega}{\Omega_{k,d}}} \right) f_{\Omega_{k,d}}(\gamma_h) \right) \right\} \]

\[ \times d(\gamma_h)^2 (1 - e^{-\frac{\gamma_h}{\Omega_{k,d}}}) e^{-\frac{\gamma_h}{\Omega_{k,d}}} f_{\Omega_{k,d}}(\gamma_h) \]

\[ = \sum_{\gamma_k = 1}^{k} \left\{ \left[ 1 - \sum_{i=0}^{0} \frac{z_i}{n!} \left( \frac{\omega}{\Omega_{k,d}} \right)^n \int_{0}^{\omega} \left( \frac{\gamma_h P_k - \gamma}{\gamma_h P_k \Omega_{k,d}} \right)^n e^{-\frac{\gamma_h P_k \Omega_{k,d}}{\gamma_h P_k \Omega_{k,d}}} \right) \right\} \]

\[ \times e^{\frac{(\gamma_h P_k - \gamma_h P_k \Omega_{k,d})}{\gamma_h P_k \Omega_{k,d}}} \int_{0}^{\omega} \left( \frac{\gamma_h P_k - \gamma}{\gamma_h P_k \Omega_{k,d}} \right)^n e^{-\frac{\gamma_h P_k \Omega_{k,d}}{\gamma_h P_k \Omega_{k,d}}} \right\} \]

\[ \times e^{-\frac{\gamma_h P_k \Omega_{k,d}}{\gamma_h P_k \Omega_{k,d}}} \int_{0}^{\omega} \left( \frac{\gamma_h P_k - \gamma}{\gamma_h P_k \Omega_{k,d}} \right)^n e^{-\frac{\gamma_h P_k \Omega_{k,d}}{\gamma_h P_k \Omega_{k,d}}} \right\} \]

Fig. 2. State transition of transmission system.
Proof. With regard to DF relaying protocol and the independence of decoding subset $DS_{k+1}^j \sim j$, g, the CDF of $Y_{k+1}$ can be calculated as

$$F_{Y_{k+1}}(\gamma) = \Pr(Y_{k+1} \leq \gamma) = \sum_{j=0}^{k} \sum_{g=1}^{j} \Pr(Y_{k+1} \leq \gamma | DS_{k+1}^j \sim j, g) \Pr(DS_{k+1}^j \sim j, g)$$  \hspace{1cm} (12)

According to [3], Eq. (6) we have

$$\Pr(DS_{k+1}^j \sim j, g) = \prod_{i \in DS_{k+1}^j} \left(1 - e^{-\frac{x}{\eta_{DS,k}}}\right) \prod_{i \in \Delta_{DS_{k+1}^j}} e^{-\frac{x}{\eta_{DS,k}}}$$  \hspace{1cm} (13)

Thus, with [3], Eq. (30), we can obtain the conditional probability in (12) as

$$\Pr(Y_{k+1} \leq \gamma | DS_{k+1}^j \sim j, g) = \int_{0}^{\gamma} \Pr\left(\sum_{i \in DS_{k+1}^j} |H_{k,i}|^2 \leq \frac{\gamma - \gamma_0 P_0 |H_{S,D}|^2}{\gamma_0 P_k}\right)$$

$$\times \int_{0}^{\gamma} (h_{i,0}^2 |H_{S,D}|^2 |h_{S,D}|^2)^{d|h_{S,D}|^2}$$

$$= \int_{0}^{\gamma} \left(1 - \sum_{i=1}^{\phi} \sum_{z=1}^{\phi} \sum_{n=0}^{z} \frac{z!}{n!} \frac{(\frac{\omega}{\Omega_{k,i}})^n}{\frac{x}{\eta_{DS,k}}} \right)^{d|h_{S,D}|^2}$$

$$= \int_{0}^{\gamma} \left(1 - \sum_{i=1}^{\phi} \sum_{z=1}^{\phi} \sum_{n=0}^{z} \frac{z!}{n!} \frac{(\frac{\omega}{\Omega_{k,i}})^n}{\frac{x}{\eta_{DS,k}}} \right)^{d|h_{S,D}|^2}$$

If all relay-destination channels are i.i.d., i.e. $\Omega_{k,i} = \Omega_{k,D}$, we can rewrite (14) as

$$\Pr(Y_{k+1} \leq \gamma | DS_{k+1}^j \sim j, g) = \int_{0}^{\gamma} \left(1 - \sum_{i=1}^{\phi} \sum_{n=0}^{z} \frac{z!}{n!} \frac{(\frac{\omega}{\Omega_{k,D}})^n}{\frac{x}{\eta_{DS,k}}} \right)^{d|h_{S,D}|^2}$$

Taking (13)–(15) into (12), the CDF of $Y_{k+1}$ is obtained. □

3.1. Cross-layer analyzing model

To formulate performance parameters of the above cross-layer ACD system as shown in Fig. 2, an absorbing Markov chain model is developed in this section. After each transmission, a packet may be in “transmission process”, “Success”, or “Fail” states. If one retransmission round fails, the protocol will retransmit the packet in the next retransmission round until either the destination node has successfully received it or L retry limit has been reached.

Let the transmission time slot counter $k + 1$, $k = 0, 1, \ldots, K$, and the retransmission round counter $l$, $l = 1, \ldots, L$, denote the transient states of the absorbing discrete-time Markov chain (DTMC), and we combine the “Success” and “Fail” as absorbing states. Hence the transition probability matrix of the cross-layer DTMC can be expressed as

$$P = \begin{bmatrix} T & S & F \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$ \hspace{1cm} (16)

where $T$ denotes transition probability matrix of order $(K + 1) \times (K + 1)$ of the “transmission process” state in Fig. 2. $S$ and $F$ denote transition probability matrix of order $(K + 1) \times 1$ from the transmission process to the absorbing “success” and “fail” states, respectively. $0$ is an all-zero matrix.

Based on the proposed state transition matrix, we can obtain the condition transition probability as

$$T((k + 1)(l - 1) + k + 1, (k + 1)(l - 1) + k + 2) = \Pr((k + 1, l) \rightarrow (k + 2, l)) = \text{PER}_{k+1}^l$$

$$S((k + 1)(l - 1) + k + 1, 1) = \Pr((k + 1, l) \rightarrow \text{Success}) = 1 - \text{PER}_{k+1}^l$$

where $k = 0, 1, \ldots, K - 1; l = 1, 2, \ldots, L; T[m, n]$ and $S[m, n]$ denote the element for $m$th row and $n$th column of transition probability matrix $T, S$, respectively; $\text{PER}_{k+1}^l$ denotes the packet error rate at the end of $(k + 1)$th time slot of the $l$th retransmission round; $(m, n)$ denotes transient states of DTMC with time slot counter and retransmission round counter equal $m$, and $n$, respectively; (Success) denotes the “Success” transient states; $\Pr(\cdot)$ denotes the probability of events.

$$T((k + 1)(l - 1) + K + 1, (k + 1)(l + 1)) = \Pr((k + 1, l) \rightarrow (1, l + 1)) = \text{PER}_{k+1}^l$$

$$S((k + 1)(l - 1) + K + 1) = \Pr((k + 1, l) \rightarrow \text{Success}) = 1 - \text{PER}_{k+1}^l$$

$$T((k + 1)(l - 1) + K + 1, (k + 1)(l + 1)) = \Pr((k + 1, l) \rightarrow (1, l + 1)) = \text{PER}_{k+1}^l$$

$$S((k + 1)(l - 1) + K + 1) = \Pr((k + 1, l) \rightarrow \text{Success}) = 1 - \text{PER}_{k+1}^l$$
where \( l = 1, 2, \ldots, L - 1 \).
\[
S(K + 1|L, 1) = Pr\{(K + 1, L) \rightarrow \text{(Success)}\} = 1 - PER_{x_l}, \quad \text{(21)}
\]
\[
F(K + 1|L, 1) = Pr\{(K + 1, L) \rightarrow \text{(Fail)}\} = PER_{y_l}, \quad \text{(22)}
\]
where \( F(m, n) \) denotes the corresponding element of “Fail” transient states (Fail).

### 3.2. Performance measures

According to [5], Eq. (22), [10], Eq. (14), and [11–15], we can further obtain the average system SER, using (6) of the Theorem 1, as follows,
\[
SER_{k+1}^l = \alpha Q\left(\frac{\sqrt{p_{x_l}^l}}{\sqrt{\beta_{y_l}^l}}\right) = \alpha E\left(Pr\left\{X > \frac{\sqrt{p_{x_l}^l}}{\sqrt{\beta_{y_l}^l}}\right\}\right)
\]
\[
= \alpha E\left[F_{x_l}^l(k^2/\beta)\right] = \alpha \int_0^\infty F_{x_l}^l(k^2/\beta) \frac{1}{\sqrt{2\pi}} e^{-\frac{k^2}{2}} dk
\]
\[
= \frac{\alpha}{\sqrt{2\pi}\Omega_{x_l}D_l} \int_0^\infty \sum_{j-0}^k \sum_{g-1}^k \left[ \prod_{i=g+1}^l \left(1 - e^{-\frac{x^2}{(\gamma_{0})^2}}\right) \prod_{i=g+1}^l e^{\frac{x^2}{(\gamma_{0})^2}}\right]
\]
\[
\times \left\{ \int_0^{\frac{2\pi}{\Omega_{x_l}D_l}} \left(1 - \sum_{i-1}^l \sum_{n-0}^l \frac{\gamma_{i,l}^2}{n!} \frac{(\gamma_{0})^2}{\Omega_{x_l}D_l}\right) \frac{e^{-\frac{x^2}{(\gamma_{0})^2}}}{\Omega_{x_l}D_l} dx\right\} e^{-\frac{x^2}{2}} dx
\]
where \( SER_{k+1}^l \) denotes the average SER at the end of \((k + 1)\)th time slot of the \(l\)th retransmission round; \( Q(x) \) denotes Gaussian Q function; \( \alpha, \beta \) are determined by specific constellations [10], such as, for Binary-PSK modulation, \( \alpha = 1, \beta = 2 \); for M-PSK modulation, \( \alpha = 1, \beta = 2\sin^2(\pi/M) \); \( E\{\} \) denotes the expectation.

Thus we obtain system average PER as
\[
PER_{k+1}^l = 1 - \left(1 - SER_{k+1}^l\right)^N
\]
Based on the characteristics of absorbing DTMC [12], \( B = (I - T)^{-1} \) is the basic matrix of the absorbing DTMC \( P \) and the elements in this matrix are average transition times between the “transmission process” states. The elements in matrix \( C_1 = BS \) and \( C_2 = BF \) denote the average transition probabilities from “transmission process” states to absorbing states of “Success” and “Fail”, respectively. We can obtain the packet delivery success probability \( P_s \) and the packet delivery failure probability \( P_f \), respectively, as
\[
A = [1 \quad 0 \quad \ldots \quad 0]^{(K-1)l}
\]
\[
P_s = AC_1, \quad P_f = AC_2
\]
where \( A \) is the initial probability row vector. Then, we obtain the average packet success delivery time slot and the average packet failure delivery time slot, respectively, as
\[
T_s = A(I - T)^{-2}S, \quad T_f = A(I - T)^{-2}F
\]
Finally, the packet delivery delay distribution can be expressed as
\[
D = (T_s + T_f)T_{slot}
\]
where \( T_{slot} \) is the time for one time slot.

### 4. Optimal power allocation

In this section, a power allocation scheme is proposed for the cross-layer ACD system based on the above analysis. Similar to [6], only partial CSI is required for the distributed network framework on how much power is allocated to the source node and relay nodes. For ease of exposition, we assume all relay-destination channel conditions are the same as \( \Omega_{l,D_l} \), i.e. all relay nodes which are in the decoding set of source node would use the same transmission power \( p_R \).

From the foregoing context, our analytical performance parameters are determined by the SER performance. Instead of allocating power equally among the source and relays, we could decrease the system SER by allocating power optimally.
To have a fair comparison between the equal power allocation scheme and optimal power allocation scheme, we assume that the total power for each scheme is subject to a limitation of $p_{\text{tot}}$ with $DS_{k+1} \sim j, g$, i.e.,

$$p_k = \frac{p_{\text{tot}} - p_S}{j}$$

We substitute (11) into (19) and modify it to

$$SER_{k+1} = \frac{2}{\sqrt{2\pi}} \sum_{j=0}^{k} \binom{k}{j} \left(1 - e^{-\frac{1}{2\sigma^2}}\right)^{k-j} e^{-\frac{j}{2\sigma^2}} \left\{ \int_{0}^{\infty} e^{-\frac{x^2}{2\sigma^2}} \left[ 1 - e^{-\frac{x^2}{\sigma^2}} - \sum_{n=0}^{j-1} (-1)^n \frac{(-1)^j}{n!\sigma^{2n}2^n} \int_{0}^{\infty} \left( \frac{j_0 p_S^2 x - x^2}{j_0 p_S^2 \Omega_x} \right)^n \right] dx \right\}$$

We substitute (29) into above expression (30) and obtain a formula about source node transmission power $p_S$. Note that the above expression would be expressed as a function of $p_S$. It is convex with respect to $p_S$ which is within the range between 0 and $p_{\text{tot}}$ by $\frac{\partial^2 SER_{k+1}}{\partial p_S^2} > 0$. Accordingly, it is possible to minimize the $SER_{k+1}$ performance in (30) by varying $p_S$ properly. In this work, we adopt the KKT method to find the optimal $p_S$ and the details can be found in [13,14,16–18], which are omitted due to the length constraint. By this way, a smaller SER of each retransmission round can be obtained compared to the equal power allocation scheme.

5. Simulation results

In this section, we numerically validate the correctness of performance analytical results with regard to the packet delivery failure probability and packet delivery delay distribution for the ACD system. For ease of exposition, we also provide the numerical SER of each retransmission round. After that, we compare the effect of power allocation control with our optimal power allocation and equal allocation according to the total power constraint.

We set all the channel variance parameters and transmission power equal one [19,20], and Monte Carlo simulations are sampled by 1,000,000 times. Fig. 3 gives the simulation results and theoretical analysis for SER performance of each retransmission round at the end of time slot 1, 2, 3 and 4, respectively, i.e. $K = 3$, and $L = 3$. It can be seen that the theoretical analysis are valid for a practical system SNR. Meanwhile, the SER performance rapidly decreases as the time slot increases, which shows the spatial diversity of cooperative diversity system.

Figs. 4 and 5 show the packet delivery failure probability and packet delivery delay distribution with different relay nodes and number of retransmission round, i.e. $K = 2$, 3, 5 and $L = 3$, 4, respectively. The packet delivery failure probability is equal
to one minus packet delivery success probability. From these figures, we can see that our cross-layer analyzing model is correct for evaluating the performance parameters of a general cross-layer ACD system. The packet delivery failure probability decreases as $K$, $L$, and the system SNR. However, the packet delivery delay increases as the number of $K$ and $L$ in low system SNR region. This is because that more relay node and retransmission round need more time slot, which is needless when achieving enough packet delivery success probability and quality of service (QoS). Also, we find that the larger $K$ and $L$, the more abrupt decreasing as the system SNR increases. However, the packet delivery delay increases as the number of $K$ and $L$ in large system SNR region. This is because more relay node and retransmission round need more time slot. These results indicate that we should efficiently utilize the parameters in the ARQ cooperative diversity system design.

Fig. 6 shows the SER performance by the proposed optimal power allocation scheme at the end of each retransmission round with $K = 3$, and $L = 3$. In these experiments, we set to equal to 1.5, 2, and 4, respectively, and the total power equal to
From the figure, it can be observed that the optimal power allocation scheme outperforms the equal power allocation scheme obviously. The results demonstrate that our power control design is suitable to be utilized in general cross-layer ACD systems with all kinds of channel conditions.

6. Conclusion

This paper has analyzed the performance of a general cross-layer ACD system with multiple two-hop relays over Rayleigh fading channels. Through the theoretical analysis, the tight closed-form expressions of two important performance metrics, i.e. packet delivery failure probability and packet delivery delay distribution, were derived. Both the theoretical analysis and simulation results demonstrate the effectiveness of our analytical derivations. Additionally, simulation results also show that the optimal power allocation scheme proposed as application outperforms the equal power allocation scheme greatly.

Acknowledgments

The authors would like to thank the anonymous reviewers for their arduous working. They would also like to thank the Natural Science Foundation of China (61201255, 61201256, 61002012), Natural Science Foundation of Guangdong (S2012040007462, S201110005586), and Foundation for Distinguished Young Talents in Higher Education of Guangdong, China (No. LYM11101).

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