Cross-Layer Performance Study of Cooperative Diversity System With ARQ

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***Abstract*—In this paper, a cross-layer design of a wireless communication system is proposed by considering a quadrature signaling (QS)-based cooperative diversity (CD) system employing truncated stop-and-wait automatic repeat request (ARQ) for error control. The proposed CD-ARQ scheme employs selection relaying at the partner, and all the transmission channels are assumed to exhibit Nakagami-m fading. To analyze the cross-layer performance of the proposed scheme, a Markov model is developed by capturing the effects of correlated transmission errors of the Nakagami-m fading cooperative channels. Based on the analysis, the effective cooperative channel of QS-CD-ARQ is uncorrelated when the normalized Doppler shift of at least one of the user-to-destination channels is higher than 0.2. Performance metrics (e.g., channel efficiency, packet loss rate, throughput, average delay, and jitter) are taken into account in the study. Our numerical results show that the QS-CD-ARQ scheme outperforms both an incremental-relaying-based CD system and a non-cooperative system if the average of the received signal is higher than the receiver sensitivity and if the channel between users is better than the direct transmission channel. In addition, QS-CD-ARQ provides the lowest packet loss rate with the lowest delay among all the schemes for any number of maximum retry limits. Moreover, compared with a scheme that employs incremental relaying, the proposed QS-CD-ARQ scheme is less complex to implement.**

***Index Terms*—Automatic repeat request (ARQ), cooperative diversity (CD), cooperative systems, cross-layer design, diversity methods, Markov model, performance study.**

I. Introduction

COOPERATIVE diversity (CD) is a promising candidate for emulating multiple-input–multiple-output (MIMO) systems in which each mobile device only has a single antenna. The cooperation between two or more users in a wireless communication system can yield diversity gain [1]–[3]. User cooperation means that when the sender transmits to the destination, it also sends the same signal to other users, called partners, to be relayed to the destination. The antennas of the sender and the partners together form a multiple-transmit antennas situation. In a CD system, the cooperating partners are geographically separated. Therefore, the spacing between any pair of users and, hence, their antennas is wider than that of a conventional MIMO system. In other words, CD systems are immune not only against small-scale channel fading but also against large-scale channel fading, i.e., if the source experiences shadowing, the partner without any shadowing can be selected for cooperation.

In general, the CD systems reported in the literature are based on different techniques that maintain orthogonality between the signals that were transmitted by the sender and the partners [1] to process (combining) all received signals at the destination, optimizing the power allocation [3], and selecting the best partners for cooperation [4]. Depending on the method used for forwarding at the partners, CD systems can be classified as amplify and forward or regenerate and forward. In addition, the CD systems may employ fixed or adaptive relaying at the partner [1]. In fixed relaying, the relay always forwards the received signals to the destination, regardless of whether they are erroneous [2]. For adaptive relaying, it can be selection relaying or incremental relaying. Selection relaying forwards the information if the received signal strength is higher than a given threshold for errorfree reception (amplify and forward) or by checking the correctness of cyclic redundancy checksum (CRC) of a frame of information bits (regenerate and forward). On the other hand, in incremental relaying, the partner forwards the information if any request is made from the destination, whereas the received signal is higher than the threshold, or the received frame is error free.

From an information-theoretic point of view, incremental relaying is more bandwidth efficient than selection relaying [1]. On the other hand, incremental relaying has implementation problems in CD systems based on orthogonal transmission. If retransmission is requested by the destination, the radio resources should efficiently be allocated for the partner-to-destination link for short durations, i.e., one period of a frame. It costs a lot of overhead and delays in the relaying. On the other hand, incremental relaying can be applied to distributed space-time coded (DSTBC) systems. However, a DSTBC system has its own implementation problems such as synchronization of carrier phase and symbol of all the partners, power distribution, and code distribution. In addition, for incremental relaying, an automatic repeat request (ARQ) scheme is necessary at the link level, and all cooperating users should be aware of it. In contrast, for selection relaying, the partner-to-destination channel could be assigned by partner-selection algorithms [4]

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for the duration of a cooperative session, which is less complex than resource allocation for a very short duration. Even though ARQ is equipped at the link level, the partners do not have to be aware of it. Thus, this will reduce the signaling overhead and the complexity at the partner's device and eliminate the delay and transmission errors due to feedback. Therefore, there is performance-complexity tradeoff among the relaying schemes in CD systems, and it is important to thoroughly study and understand the performance of a CD system with ARQ (CD-ARQ) in various wireless networking environments.

In a wireless communication system, the channels between individual users to the destination are independent and nonidentical to each other due to geographical location, user mobility, and natural and man-made obstacles. In addition, the signals transmitted through the individual channels are combined at the destination receiver. In such wireless environments, the communication channels can be modeled as Nakagami fading channels. The Nakagami fading model gives us the freedom to choose the individual channels with nonidentical distribution parameters. The effects of such a combined channel in the upper layers are different from those of the conventional MIMO systems. However, there are limited studies on the performance analysis of CD-ARQ schemes in the open literature [5]–[7], and all of them are considering incremental relaying at the partners. Incremental relaying is applied for DSTBC-CD-ARQ in [6]. The throughput of the system is analyzed with the assumption that perfect synchronization is available at the destination. However, the influence of power allocation and code allocation is not considered. In [5], the cooperative energy gain of a DSTBC-CD-ARQ scheme is studied with optimal power allocation and delay constraint. The effects in the upper layers due to ARQ, such as packet loss rate (PLR), average delay, and jitter are not considered. In [7], a selection combining (SC)-based CD-ARQ (SC-CD-ARQ) scheme, which was developed for ad hoc networks, selects only one branch at the destination. To the best of our knowledge, there is no study that considers the effects of selection relaying in the upper layers.

In this paper, we consider a cooperative communication system that combines the quadrature signaling (QS)-based CD (QS-CD) at the physical layer [3] and truncated stop-and-await ARQ at the link layer and employs selection relaying at the partner. In this respect, the cooperative communication system is across both the physical and the link layers. An analytical model that captures the effects of the time-correlated channels, and the user mobility in the upper layers is developed. First, we consider the Nakagami-m channel and develop a two-state Markov model that captures the frame error process in the QS-CD-ARQ scheme. Second, we derive the expressions that describe the efficiency, average PLR, and throughput of the scheme. Last, the model is verified via simulation and is used to analyze the performance of the CD system at different layers. The proposed QS-CD-ARQ scheme is compared with the existing schemes that only consider incremental relaying at the partner. From the comparative study, we show that the scheme in which the partner employs selection relaying outperforms that in which the partner employs incremental relaying. In other words, the QS-CD-ARQ scheme provides the lowest PLR and high throughput with the lowest number of retransmission. Furthermore, the effective cooperative channel for the proposed scheme is uncorrelated when the normalized Doppler shift of at least one of the user-to-destination channels is higher than 0.2. It reduces the correlated packet loss of the communication system.

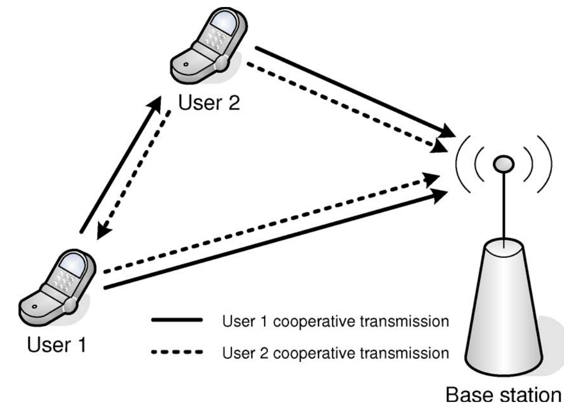

Fig. 1. Two-user cooperative diversity system.

The major contributions of this paper are twofold: 1) A selection-relaying-based QS-CD-ARQ scheme that offers less complexity in implementation and better cross-layer performance is proposed, and 2) an analytical framework is developed to evaluate the performance of CD systems for Nakagami-m fading channels. The numerical results from this study provide valuable insights for the design of partner-selection algorithms and the selection of system parameters.

The remainder of this paper is organized as follows. Section II presents the system description of the proposed QS-CD-ARQ scheme. The performance analysis of the QS-CD-ARQ scheme is given in Section III. Numerical results are presented in Section IV. In Section V, the performance of the proposed scheme is compared with existing CD-ARQ schemes. Concluding remarks are given in Section VI.

II. System Description

We consider a two-user CD system that uses regenerate and forward at the partner, in which each user has a single antenna in the physical layer, as shown in Fig. 1. With the currently available radio frequency (RF) circuitry, simultaneous transmission and reception in the same frequency is not feasible. Therefore, the orthogonality of the transmitted signals should be maintained at the partner's device to handle the transmission and reception of the uplink signal. In most of the works reported in the literature, orthogonality is achieved by dividing the available channels into subchannels in time or frequency. In this paper, we consider QS in which orthogonality can be achieved by expanding the signal constellation and transmitting in the in-phase and quadrature components of a quadrature amplitude modulation scheme. Details of the CD scheme and the advantage of QS can be found in [2] and [3]. Then, a cross-layer design is proposed by considering the QS-CD scheme at the physical layer with truncated stop-and-wait ARQ at the data link layer.

TABLE I
ARQ MECHANISM FOR QS-CD

Source Retry counter of each frame is initialized to zero.

1) A new frame is transmitted by the *source* to the BS and *partner* in its own multiple access channel (source's channel) with bit energy $P_S = P_1/2$.
2) In the next time slot,
   (a) if the time slot is 2 or it receives a `ACK', go to 1).
   (b) if the retry counter does not exceed the maximum retry limit L. the corrupted (`NAK' received) frame is re-transmitted in the *source's* channel with bit energy $P_P = P_2/2$, retry counter is increased by 1 and go to 2).
   (c) Otherwise, the frame is dropped and go to 1).

Partner If the *partner* receives the frame correctly, in the next time slot, received frame is forwarded using *partner's* channel with bit energy $P_P = P_2/2$. Otherwise, partner remains silent.

Destination At end of each time slot from second time slot, the message signal received from the *source* and the *partner* is combined by the BS using MRC. Depending on the received frame correctness, an `ACK' or a `NAK' is sent in the feedback channel to the source.

A. Cooperative Transmission

For cooperative transmission, the sender broadcasts a frame of bits to the destination and the partner in orthogonal subchannel 1. The partner detects the signal from the sender and detects the frame of bits to check the correctness of the bits using CRC. According to the selection mechanism, if the received frame is error free, the partner forwards the information in orthogonal subchannel 2. At the destination, the signals from the sender and the partner are combined using maximum ratio combining (MRC) to detect the frame. The correctness of the frame is checked using CRC. If the frame is error free, an acknowledgement (ACK) message is sent to the sender. Otherwise, a negative acknowledgement (NAK) message is sent to the sender. If the sender receives a NAK, it retransmits the frame if the number of retransmissions does not exceed the maximum retry limit L. In this mechanism, the partner does not need to be aware of the ARQ. This reduces the complexity of the partnering device. Details of the mechanism is described in Table I, where P_1 and P_2 denote the power transmitted in noncooperative transmission by the sender and the partner, respectively. A graphical representation of the transmission mechanism is given in Fig. 2.

For the regenerate and forward mode, it is easy to make a decision on a frame error at the partner and the destination by using CRC. To facilitate the performance study at high levels, independent of the underlying channel coding and modulation schemes, the frame error is decided upon by a signal-to-noise ratio (SNR) threshold SNR_T. SNR_T is the minimum received SNR that is required for correctly receiving a frame. Thus, if the received SNR is lower than the threshold, the received frame is considered erroneous and is dropped.

B. Channel Model

Among the available distributions that describe the statistics of wireless fading channels, the Nakagami-m distribution [8] is a generalized fading model. From this distribution, other distributions can be approximated by substituting the appropriate fading figure m. Therefore, we consider the channels between the sender and the partner $\{\mathrm{S}, \mathrm{P}\}$, the sender and the destination $\{\mathrm{S}, \mathrm{D}\}$, and the partner and the destination $\{\mathrm{P}, \mathrm{D}\}$ as exhibiting Nakagami-m fading.

The probability density function (pdf) of the Nakagami-m distribution is given by

$$f_H(h) = \frac{2m^m h^{2m-1}}{\Gamma(m)\Omega^m} e^{-\frac{mh^2}{\Omega}} \tag{1}$$

where h is the fading channel coefficient, $m = \mathbf{E}^2[h^2]/\mathrm{var}(h^2)$ is the fading figure, $\Omega = \mathbf{E}[h^2]$ is the signal power, and $\Gamma(m) = \int_0^\infty x^{m-1}e^{-x}dx$ is the Gamma function. The corresponding cumulative distribution function (CDF) can be written as

$$F_H(h) = \frac{\gamma(m, mh^2/\Omega)}{\Gamma(m)} \tag{2}$$

where $\gamma(a,b) = \int_0^b y^{a-1}e^{-y}dy$ is the incomplete gamma function.

The joint pdf of $h(t)$ and $h(t+\tau)$ can be obtained as in [8], i.e.,

$$\begin{aligned} f_{H_1,H_2}(h(t), h(t+\tau)) = &\frac{4m^{m+1}\left(h(t)h(t+\tau)\right)^m}{\Gamma(m)\Omega^{m+1}(1-\rho)\rho^{m-1}} \\ &\times \exp\left(\frac{-m}{1-\rho}\left[\frac{h(t)^2+h(t+\tau)^2}{\Omega}\right]\right) \\ &\times I_{m-1}\left(\frac{2\sqrt{\rho}mh(t)h(t+\tau)}{\Omega(1-\rho)}\right) \end{aligned} \tag{3}$$

where $H_1 = h(t)$, $H_2 = h(t+\tau)$, ρ is the correlation coefficient, and I_ν denotes the νth-order modified Bessel function. The joint cdf can be written as [14]

$$\begin{aligned} &F_{H_1,H_2}(\Delta,\Delta) \\ &\quad = \mathrm{Prob}\left(h(t) \le \Delta, h(t+\tau) \le \Delta\right) \\ &\quad = \frac{1}{2} - \frac{2}{\pi}\int_0^{\pi/2} \mathrm{Imag}\left\{\phi(-j\tan\theta) \times e^{-j\Delta^2\tan\theta}\right\}\frac{1}{\sin 2\theta}d\theta \end{aligned} \tag{4}$$

where

$$\begin{aligned} \phi(s) = &\frac{2^{2m+1}\Gamma(2m)}{\Gamma(m)\Gamma(m+1)}\frac{\left(A^2(s)m\right)^m}{\left[(1+B(s))\,B(s)\Omega\right]^m} \\ &\times {}_2F_1\left(1-m, m; 1+m; \frac{1}{2} - \frac{1}{2B(s)}\right). \end{aligned} \tag{5}$$

${}_2F_1$ is the Gauss hypergeometric function, $A(s) = (1/s)\sqrt{(m/(2\Omega(1-\rho))}$, and $B(s) = ((\sqrt{[s\Omega(1-\rho)+2m]^2-4\rho m^2})/(s\Omega(1-\rho)))$.

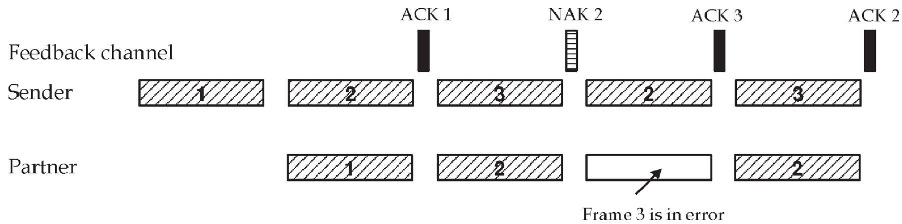

Fig. 2. QS-CD-ARQ Scheme (based on selection relaying).

III. Performance Analysis

The correlated transmission error behavior can be approximated using a discrete-time two-state Markov channel model. In this section, the performance of the proposed CD-ARQ scheme is analyzed by modeling the system as a Markov process at the frame level, considering the physical-layer parameters. From the Markov process, we derive the performance metrics at the frame level and the packet level, where a packet from the upper layer is divided into frames at the link layer.

A. Signal Reception

To model the system as a Markov process, the characteristics of the received signal at the partner's device and the destination should be known. Therefore, the signals at the individual receivers are given in this section.

1) Signal Received by the Partner: The signal that the partner's device received at time t can be written as

$$r_{S,P}(t) = \sqrt{P_S}h_{S,P}(t)x(t) + \eta_P(t) \tag{6}$$

where P_S is the transmitted power of the sender, $h_{S,P}(t)$ is the Nakagami fading channel coefficient between the sender and the partner (with fading figure $m_{S,P}$, signal power $\Omega_{S,P}$, and maximum Doppler frequency $f_{d_{S,P}}$), $x(t)$ is the symbol transmitted by the sender at time t, and $\eta_P(t)$ is the additive white Gaussian noise at the partner's device, with zero mean and two-sided power spectral density $N_0/2$.

2) Received Signal at the Destination: The transmitted signals from the sender and the partner traverse through two different Nakagami fading channels. The received signals are combined using MRC to attain diversity gain. In a cooperative situation, the channels are nonidentical but are independently distributed (non i.i.d.) due to unequal fading figures m, signal power Ω, or maximum Doppler shifts f_d. By denoting the $\{\mathrm{S,D}\}$ link by subscript 1 and the $\{\mathrm{P,D}\}$ link by subscript 2, the received signals at the destination can be written as

$$r_1(t) = \sqrt{P_S}h_1(t-T_f)x(t-T_f) + \eta_D(t) \tag{7}$$

$$r_2(t) = \sqrt{P_P}h_2(t)x(t-T_f) + \eta_D(t) \tag{8}$$

where P_P is the transmitted power of the partner, T_f is the frame duration, $\eta_D(t)$ is the additive white Gaussian noise at the destination (with zero mean and two-sided power spectral density $N_0/2$), h_1 and h_2 are the Nakagami fading channel coefficients of $\{\mathrm{S,D}\}$ (with parameters m_1 and Ω_1, maximum Doppler frequency f_{d1}) and $\{\mathrm{P,D}\}$ (with parameters m_2 and Ω_2 and maximum Doppler frequency f_{d2}), respectively.

When the partner helps, the received signal power can be written in terms of the received signal envelopes from each user, i.e., $r_1^2(t) = \sum_{k=1}^{m_1} r_{1,k}^2(t)$, and $r_2^2(t) = \sum_{k=1}^{m_2} r_{1,k}^2(t)$

$$R^2(t) = \sum_{k=1}^{m_1} r_{1,k}^2(t) + \sum_{l=1}^{m_2} r_{2,l}^2(t) \tag{9}$$

where $r_{1,k}^2(t)$, $k = 1,\ldots,m_1$, and $r_{2,l}^2(t)$, $l = 1,\ldots,m_2$ are independent and exponentially distributed with $E\{r_{1,k}^2(t)\} = \Omega_1 P_S$ and $E\{r_{2,l}^2(t)\} = \Omega_2 P_P$, respectively. $r_{1,k}^2(t)$ and $r_{1,k}^2(t+\tau)$, $k = 1,\ldots,m_1$ are correlated, with the correlation coefficient being given by

$$\rho_1 = \frac{E\left\{r_{1,k}^2(t)r_{1,k}^2(t+\tau)\right\} - E\left\{r_{1,k}^2(t)\right\}E\left\{r_{1,k}^2(t+\tau)\right\}}{\sqrt{\mathrm{var}\left\{r_{1,k}^2(t)\right\}\mathrm{var}\left\{r_{1,k}^2(t+\tau)\right\}}} \tag{10}$$

for all k. Similarly, we can write the correlation between $r_{2,l}^2(t)$ and $r_{2,l}^2(t+\tau)$, $l = 1,\ldots,m_2$ as

$$\rho_2 = \frac{E\left\{r_{2,l}^2(t)r_{2,l}^2(t+\tau)\right\} - E\left\{r_{2,l}^2(t)\right\}E\left\{r_{2,l}^2(t+\tau)\right\}}{\sqrt{\mathrm{var}\left\{r_{2,l}^2(t)\right\}\mathrm{var}\left\{r_{2,l}^2(t+\tau)\right\}}} \tag{11}$$

for all l.

Based on the Jakes channel model, we have

$$\rho_1 = J_0^2(2\pi f_{d1}T_f) \tag{12}$$

$$\rho_2 = J_0^2(2\pi f_{d2}T_f) \tag{13}$$

where $J_0(.)$ is the zeroth-order Bessel function of the first kind.

The output of the MRC with two Nakagami channel inputs can effectively be modeled as a single Nakagami channel. Therefore, (9) can be written as

$$R^2(t) = \sum_{k=1}^{m_C} r_{C,k}^2(t) \tag{14}$$

where $r_{C,k}^2$, $k = 1,\ldots,m_C$ are independent and exponentially distributed with $E\{r_{C,k}^2(t)\} = \Omega_C$. $r_{C,k}^2(t)$ and $r_{C,k}^2(t+\tau)$, $k = 1,\ldots,m_C$ are correlated, and the correlation coefficient is given by ρ_C. The parameters m_C, Ω_C, and ρ_C can be derived as

$$m_C = m_1 + m_2 \tag{15}$$

$$\Omega_C = \sqrt{(m_1+m_2)\left(\frac{P_S^2\Omega_1^2}{m_1} + \frac{P_P^2\Omega_2^2}{m_2}\right)} \tag{16}$$

$$\rho_C = \frac{\frac{P_S^2\Omega_1^2}{m_1}\rho_1 + \frac{P_P^2\Omega_2^2}{m_2}\rho_2}{\left(\frac{P_S^2\Omega_1^2}{m_1} + \frac{P_P^2\Omega_2^2}{m_2}\right)}. \tag{17}$$

In situations where the partner does not help, the destination detects the signal as that in a conventional system, which is similar to detection at the partner's device. In this case, the received signal power is

$$R^2(t) = r_1^2(t). \tag{18}$$

B. Markov Modeling

In practice, the channel coherence time can be approximated as 42.3% of the inverse of the maximum Doppler frequency (a more conservative approximation) [9]. Therefore, it is reasonable to consider the state transitions of the Markov channel model after every frame transmission time. The next sections present the Markov modeling of the noncooperative and the cooperative channels.

1) Noncooperative Channel: The received signal $R(t)$ is sampled once in each frame interval, which is denoted as $R(nT_f)$, and it is assumed that the channel does not significantly change in a frame duration T_f. The sampled process is modeled as a two-state discrete-time Markov process [10]. If the received signal is lower than the threshold Δ, the frame is erroneous. Otherwise, the frame is error free. Therefore, the system can be categorized as in a "good" or "bad" state if the received signal envelope falls in the region (0, Δ) or (Δ, ∞). The system state is defined by $St(n)$, $n = 0, 1, 2, \ldots$, which takes the value "G" or "B" for a good or bad state, respectively.

The transition probabilities of the Markov process are given by

$$\begin{aligned} q_{GG} &= \text{Prob}\,(St(n) = G | St(n-1) = G) \\ &= \frac{\text{Prob}\,(St(n) = G, St(n-1) = G)}{\text{Prob}\,(St(n-1) = G)} \\ &= \frac{\int_{R_1=\Delta}^{\infty}\int_{R_2=\Delta}^{\infty} f_{R_1,R_2}(R_1,R_2)dR_1dR_2}{\int_{R_1=\Delta}^{\infty} f_{R_1}(R_1)dR_1} \end{aligned} \tag{19}$$

$$\begin{aligned} q_{BB} &= \text{Prob}\,(St(n) = B | St(n-1) = B) \\ &= \frac{\text{Prob}\,(St(n) = B, St(n-1) = B)}{\text{Prob}\,(St(n-1) = B)} \\ &= \frac{\int_{R_1=0}^{\Delta}\int_{R_2=0}^{\Delta} f_{R_1,R_2}(R_1,R_2)dR_1dR_2}{\int_{R_1=0}^{\Delta} f_{R_1}(R_1)dR_1} \end{aligned} \tag{20}$$

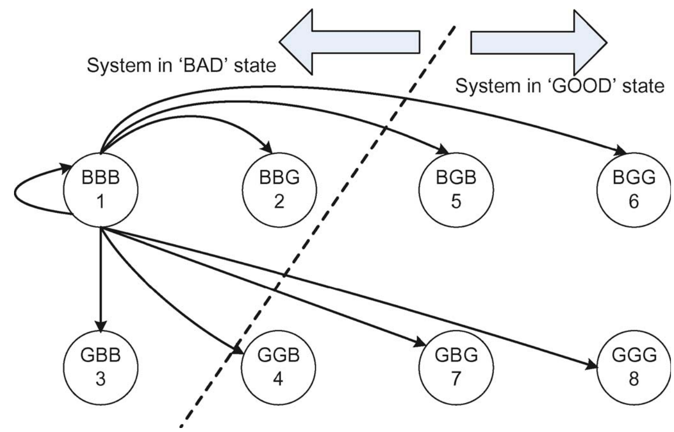

Fig. 3. Markov model of QS-CD-ARQ scheme. The system state is denoted by $\{St_{S,P}St_{S,D}St_C\}$.

where $R_1 = R(t)$, and $R_2 = R(t+T_f)$. Furthermore, q_{GG} and q_{BB} can, respectively, be simplified as

$$q_{GG} = \frac{1 - 2F_{R_1,R_2}(\Delta) + F_{R_1,R_2}(\Delta,\Delta)}{1 - F_{R_1}(\Delta)} \tag{21}$$

$$q_{BB} = \frac{F_{R_1,R_2}(\Delta,\Delta)}{F_{R_1}(\Delta)}. \tag{22}$$

Therefore, the transition probability matrix T of the steady-state Markov process is given by

$$T = \begin{bmatrix} q_{GG} & q_{GB} \\ q_{GB} & q_{BB} \end{bmatrix} \tag{23}$$

where $q_{GB} = 1 - q_{GG}$, and $q_{GB} = 1 - q_{BB}$. The steady-state probability of being in the bad state π_B and in the good state, respectively, π_G can be derived as

$$\pi_B = \frac{q_{GB}}{q_{GB} + q_{BG}} \tag{24}$$

$$\pi_G = \frac{q_{BG}}{q_{GB} + q_{BG}}. \tag{25}$$

2) Cooperative Channel: The performance of the CD system is influenced by the $\{\mathrm{S, D}\}$, $\{\mathrm{S, P}\}$, and $\{\mathrm{P, D}\}$ channels. As mentioned earlier, each channel is modeled by a two-state Markov process. The partner only helps when it has an errorfree frame. When the partner helps, the destination receives the combined signal denoted by $\{\mathrm{C}\}$. Otherwise, it receives from the sender only. This situation can be modeled by a modulated Markov process, as shown in Fig. 3, where the Markov process of the $\{\mathrm{S, P}\}$ channel triggers the resulting process at the destination by switching between the Markov process of the $\{\mathrm{S, D}\}$ and Markov process of the $\{\mathrm{C}\}$ channels. The Markov states are denoted by $\{St_{S,P}St_{S,D}St_C\}$. When the direct link is in the good state $St_{S,D} = G$, the destination decodes the frame without any error. Therefore, states 4, 5, 6, and 8 represent the overall system in the good state. When the direct link is in the bad state $St_{S,D} = B$, the destination decodes the frame without any error if and only if $St_{S,P} = G$, and $St_C = G$. Ultimately, states 1, 2, and 3 incur errors, and the system is in the bad state. The remaining five states are good states.

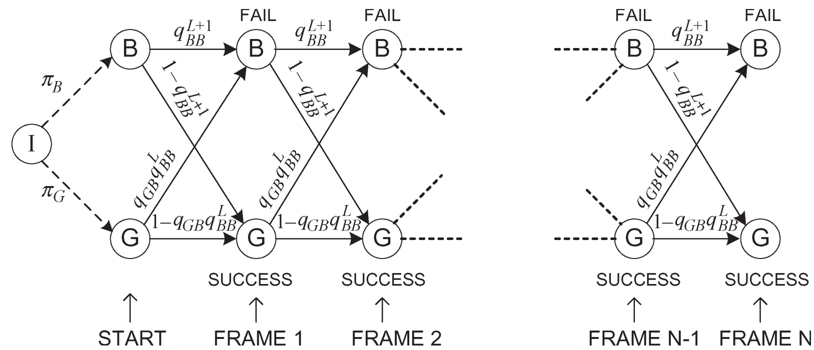

Fig. 4. State transition diagram for a packet transmission.

Therefore, this eight-state Markov process can be mapped into a two-state Markov process. The transition probabilities of the new two-state system can be expressed as

$$q_{GG} = \frac{\sum_{i=4}^{8}\sum_{j=4}^{8} Q^2[i,j]}{\sum_{i=4}^{8}\sum_{j=1}^{8} Q^2[i,j]} \tag{26}$$

$$q_{BB} = \frac{\sum_{i=1}^{3}\sum_{j=1}^{3} Q^2[i,j]}{\sum_{i=1}^{3}\sum_{j=1}^{8} Q^2[i,j]} \tag{27}$$

where Q^2 is the square of transition probability matrix Q. $Q^2[i,j]$ gives the transition probability from state i to state j after two time slots, and it can be written in terms of transition probabilities of the channels $\{\mathrm{S},\mathrm{P}\}$, $\{\mathrm{S},\mathrm{D}\}$, and $\{\mathrm{C}\}$. The square term comes into play, because the proposed CD system retransmits a particular frame in alternate slots, as shown in Fig. 2.

C. System Performance

We are interested in studying the impact of transmission techniques; therefore, we assume that a sender always has a packet to transmit (i.e., a saturated traffic model). Therefore, the effects of packet losses due to the sender's buffer overflow and the idle transmission time due to an empty buffer of the sender are not considered. The metrics of interest in the performance evaluation of the CD-ARQ and NCD-ARQ schemes are channel efficiency, throughput, and PLR.

Channel efficiency is defined in the frame level as the ratio of the sum of error free frames to the total number of frames transmitted. The packet that was generated by the source cannot be transmitted in one frame in the physical layer; therefore, the packet is usually fragmented. Similar to [7], we assume that a fixed-size packet from the upper layers is fragmented to N frames in the data link layer. Therefore, channel efficiency μ is equivalent to the probability of the system being in a good state, and it can be expressed as

$$\mu = \frac{q_{BG}}{q_{GB}+q_{BG}}. \tag{28}$$

The PLR is defined by the ratio of the sum of dropped packets to the total number of packets transmitted. To calculate the average PLR, we consider the transmission process of an arbitrary packet and focus on the instants that mark the beginning or the ending of the transmission of frames. Fig. 4 shows the state transition diagram for the packet transmission process. START marks the beginning of the packet transmission, and FRAME i, for $i = 1, 2, 3, \ldots, N$, marks the end of transmission of the ith frame of the packet. Each frame is retransmitted until it is successfully received or the number of retransmission attempts exceeds L. Therefore, at the end of frame transmission, the channel is good (G) if the transmission is successful, and it is bad (B) if the transmission fails. Consequently, the transition probabilities (see Fig. 4) from state G to state B is $q_{GB}q_{BB}^{L}$, and from state B to state B, it is q_{BB}^{L+1}. Note that the instantaneous transitions (dotted lines in Fig. 4) randomly place the channel in state B or G.

For a packet to successfully be transmitted, all the frames must successfully be transmitted. The packet success rates (PSRs) for the initial channel conditions given by B and G can be computed as $(1-q_{BB}^{L+1})(1-q_{GB}q_{BB}^{L})^{N-1}$ and $(1-q_{GB}q_{BB}^{L})^{N}$, respectively. The average PSR is given by

$$\mathrm{PSR} = \pi_B\left(1-q_{BB}^{L+1}\right)\left(1-q_{GB}q_{BB}^{L}\right)^{N-1} + \pi_G\left(1-q_{GB}q_{BB}^{L}\right)^{N}. \tag{29}$$

By considering $\mathrm{PLR} = 1 - \mathrm{PSR}$, we can write

$$\mathrm{PLR} = 1 - \left[\pi_B\left(1-q_{BB}^{L+1}\right) + \pi_G\left(1-q_{GB}q_{BB}^{L}\right) \times \left(1-q_{GB}q_{BB}^{L}\right)\right]\left(1-q_{GB}q_{BB}^{L}\right)^{N-1}. \tag{30}$$

Based on (24) and (25), we can manipulate (30) to a simpler form as

$$\mathrm{PLR} = 1 - \left(1-\pi_B q_{BB}^{L}\right)\left(1-q_{GB}q_{BB}^{L}\right)^{N-1}. \tag{31}$$

The throughput of the system is given by the ratio of the total number of packets that was successfully transmitted to the total number of slots[1] that was used. Let $Y(t)$ denote the number of packets that was successfully transmitted in time duration t. Using the renewal theorem of [17], the average throughput ζ is given by

$$\zeta = \lim_{t\to\infty}\frac{Y(t)}{t} = \frac{1-\mathrm{PLR}}{T_p}\,\text{packet/slot} \tag{32}$$

where T_p is the average time to transmit a packet.

[1]A slot corresponds to a packet transmission time.

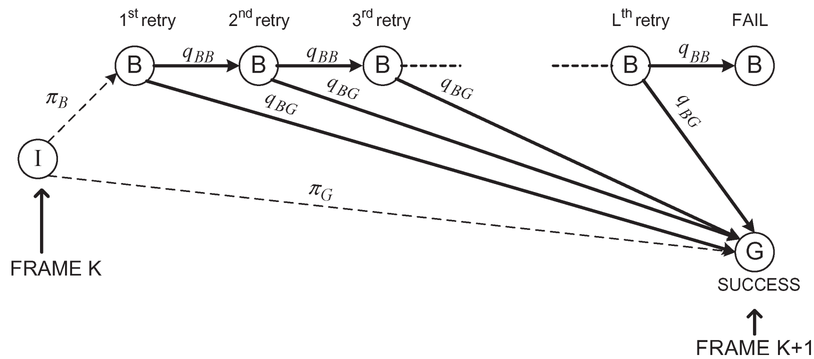

Fig. 5. State transition diagram for a frame transmission.

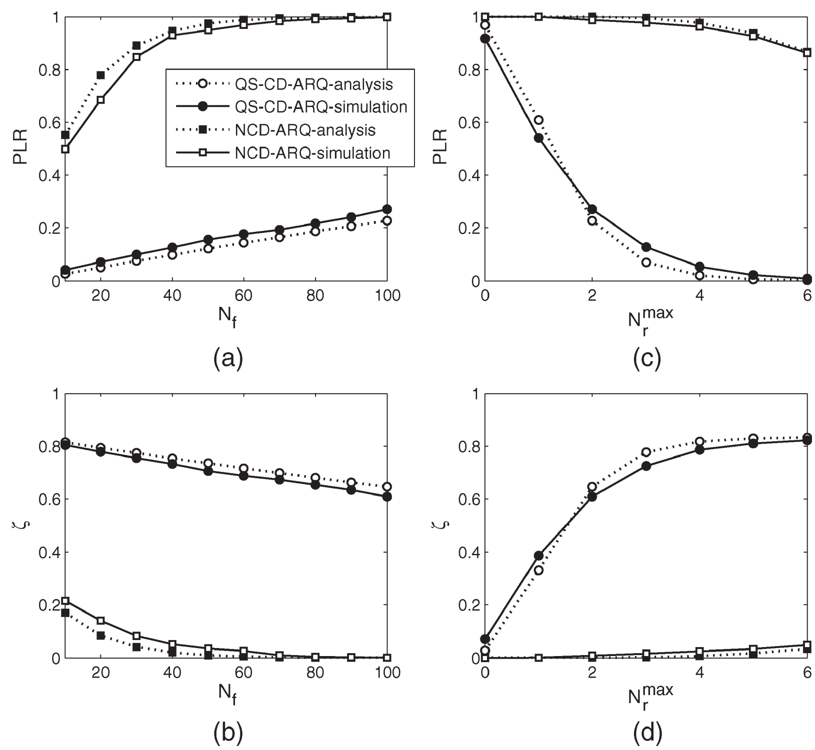

Fig. 6. PLR and throughput of the proposed scheme compared with the noncooperative scheme by varying the packet size and maximum number of retransmissions.

By finding the average time for each transition in the state diagram shown in Fig. 4, T_p can be computed by adopting a similar approach that was used in [16]. However, this approach may increase the computational complexity. Therefore, in this study, we use an approximation with $T_p \cong N \times \bar{T}_f$, where $\bar{T}_f$ is the average time to transmit a frame.

Moving further to Fig. 4, Fig. 5 shows a state transition diagram for the $(K+1)$th frame transmission process. Based on Fig. 5, $\bar{T}_f$ can be computed as

$$\begin{aligned}\bar{T}_f =& \pi_G + 2\pi_B q_{BG} + 3\pi_B q_{BB} q_{BG} + 3\pi_B q_{BB}^2 q_{BG} \\ &+ L\pi_B q_{BB}^{L-2} q_{BG} + (L+1)\pi_B q_{BB}^{L-1} q_{BG} \\ &+ (L+1)\pi_B q_{BB}^{L} q_{BG}. \end{aligned} \tag{33}$$

$q_{BG} + q_{BB} = 1$, so (33) can be written as

$$\bar{T}_f = \pi_G + \pi_B + \pi_B q_{BB} + \pi_B q_{BB}^2 + \ldots + \pi_B q_{BB}^{L-1} \tag{34}$$

It can further be simplified to

$$\bar{T}_f = 1 + \pi_B \frac{1 - q_{BB}^L}{1 - q_{BB}}. \tag{35}$$

By substituting (31) and (35) in (32), the throughput can be written as

$$\zeta = \frac{\left(1 - \pi_B q_{BB}^L\right)\left(1 - q_{GB} q_{BB}^L\right)^{N-1}}{N\left(1 + \pi_B \frac{1 - q_{BB}^L}{1 - q_{BB}}\right)} \text{packet/slot}. \tag{36}$$

IV. Numerical Results

In this section, the analysis of the proposed QS-CD-ARQ scheme is validated by numerical results. In addition, the performance of the QS-CD-ARQ is compared with that of the NCD-ARQ (conventional stop-and-wait ARQ) scheme. A detailed description of the stop-and-wait ARQ scheme can be

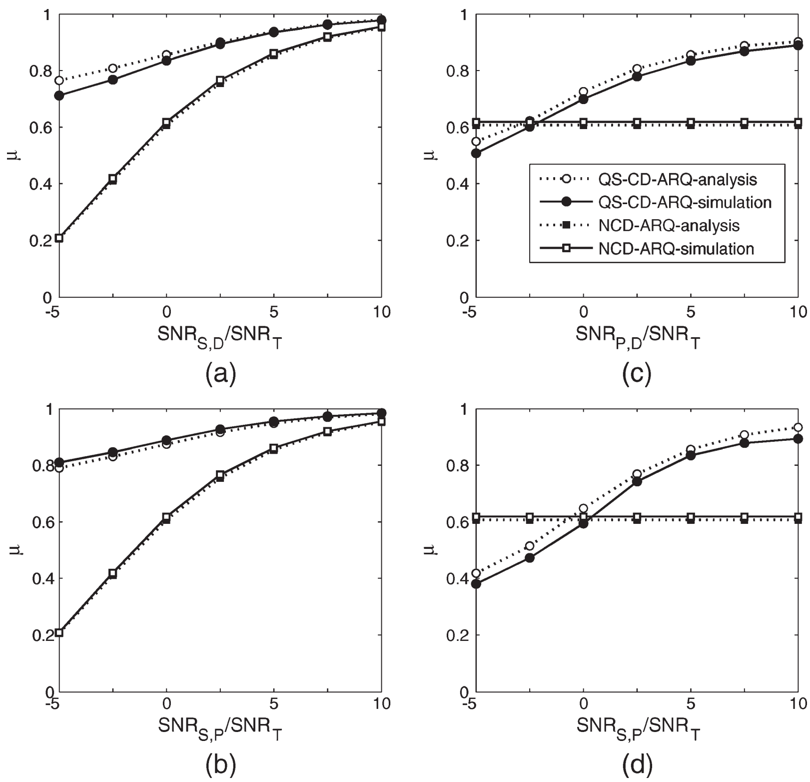

Fig. 7. Efficiency of the proposed scheme compared with the noncooperative scheme. [For (b), $m_{P,D}$ is changed to 2.]

found in [11]. For the simulation, we first utilize an improved Jakes' simulator, as proposed in [12], to generate correlated Rayleigh fading traces and then use the efficient method proposed in [13] to generate correlated Nakagami-m fading envelope from the generated Rayleigh traces.

We simulate independent nonidentical time-correlated fading envelopes and use these according to the CD-ARQ schemes. To obtain accurate results, we use a sampling interval $T_f = 10^{-3}$ s and collect 10^5 samples for each random seed. The simulation results are obtained by considering the carrier frequency $f_c =$ 900 MHz. For a given $f_d T_f$, the relative velocity v of the $\{\mathrm{S, P}\}$, $\{\mathrm{S, D}\}$, and $\{\mathrm{P, D}\}$ links is given by $v = f_d c/f_c$, where c is the velocity of light. To generalize the performance study, the average signal power of each link and the signal threshold Δ are written in terms of the average SNR and SNR threshold SNR_T, respectively. By defining the noise power spectral density $N_0 = 1$, the average signal powers can be written as $P_S \Omega_{S,P} = \mathrm{SNR}_{S,P}$, $P_S \Omega_1 = \mathrm{SNR}_{S,D}$, $P_P \Omega_2 = \mathrm{SNR}_{P,D}$, and $\mathrm{SNR}_T = \Delta^2$.

Unless explicitly stated, the system parameters that were used to generate the results presented in Figs. 6–10 are the Nakagami fading figures $m_1 = 1$, $m_2 = 1$, and $m_{S,P} = 2$, normalized Doppler frequency $f_d T_f = 0.1$ for all links, normalized average SNRs $\mathrm{SNR}_{S,P}/\mathrm{SNR}_T = 5$ dB, $\mathrm{SNR}_{S,D}/\mathrm{SNR}_T = 5$ dB, and $\mathrm{SNR}_{P,D}/\mathrm{SNR}_T = 5$ dB, number of frames per packet $N = 100$, and a retry limit of a frame $L = 4$.

A. Effects of ARQ Parameters

In this section, we study the impact of ARQ protocol parameters on performance by considering the packet size N and the maximum number of retransmissions L. The PLR and the throughput of the QS-CD-ARQ scheme are compared with those of the NCD-ARQ scheme in Fig. 6. Based on Fig. 6, we can observe that the overall performance of the QS-CD-ARQ is much better than the NCD-ARQ. In other words, cooperation yields a smaller PLR and higher throughput to the communication system. As expected, the performance of both QS-CD-ARQ and NCD-ARQ degrades in terms of PLR and throughput as the packet size increases, which is shown in Fig. 6(a) and (b). The rate of change of QS-CD-ARQ is slower than that of NCD-ARQ. This means that a variable packet size system is more robust with QS-CD-ARQ than NCD-ARQ. In Fig. 6(c) and (d), the maximum number of retries is varied from 0 to 6. Based on the results, the NCD-ARQ scheme keeps improving as L increases. However, the performance improvement of the QS-CD-ARQ scheme is not significant beyond $L = 4$. In addition, the analytical and simulation results coincide for both schemes when $N = 100$. Therefore, we use $L = 4$ and $N = 100$ to study the effects of other parameters on the system performance.

B. Effects of Channel Condition

In this section, we study the effects of channel conditions with respect to the normalized SNRs, fading figures, and normalized Doppler frequencies.

The channel efficiency μ, PLR, and throughput ζ of both QS-CD-ARQ and NCD-ARQ are presented in Figs. 7–9, respectively, for four different scenarios. In these figures, the $\mathrm{SNR}_{S,D}/\mathrm{SNR}_T$ is varied from -5 dB to 10 dB for $m_2 = 1$ and $m_2 = 2$, respectively, whereas $\mathrm{SNR}_{P,D}/\mathrm{SNR}_T$

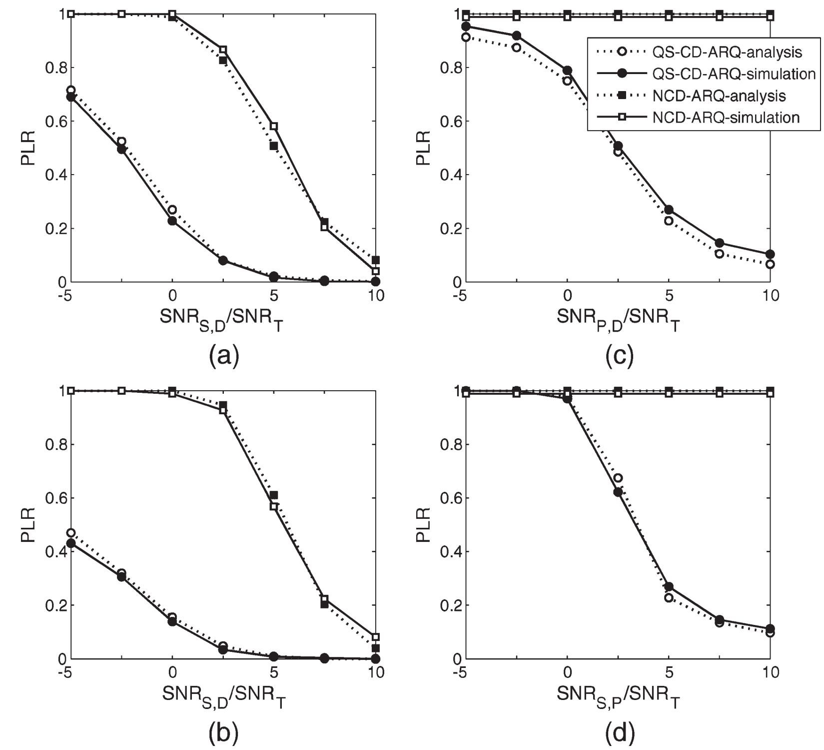

Fig. 8. PLR of the proposed scheme compared with the noncooperative scheme. [For (b), $m_{P,D}$ is changed to 2.]

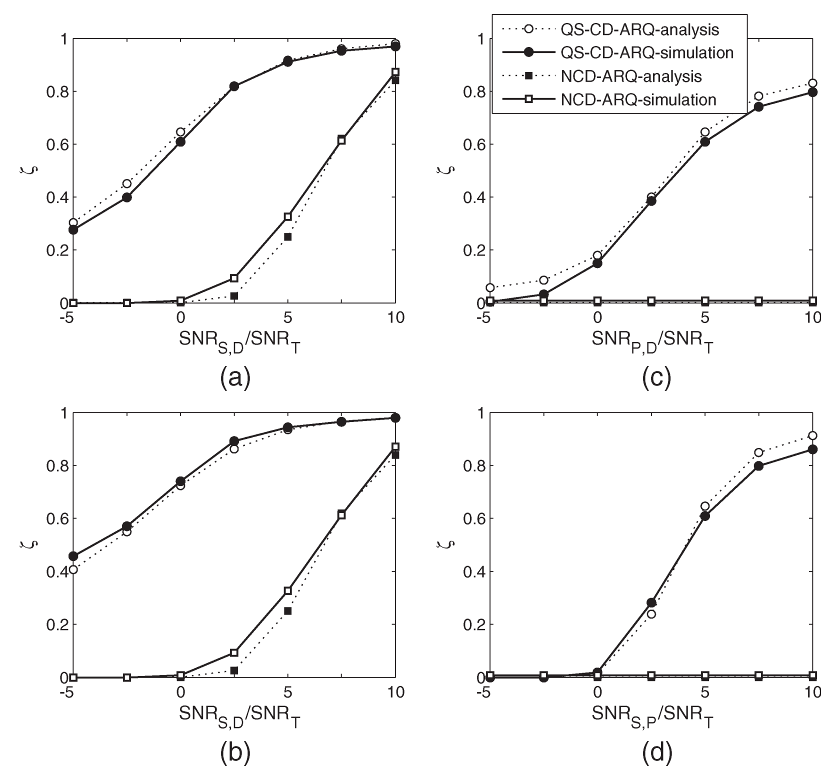

Fig. 9. Throughput of the proposed scheme compared with the noncooperative scheme. [For (b), $m_{P,D}$ is changed to 2.]

and $\mathrm{SNR}_{S,P}/\mathrm{SNR}_T$ are varied from -5 dB to 10 dB, respectively.

In Fig. 7, the channel efficiency of QS-CD-ARQ increases as the normalized SNRs increases. In Fig. 7(a) and (b), the channel efficiency of QS-CD-ARQ is better than that of NCD-ARQ and improves when the fading figure of the $\{\mathrm{P}, \mathrm{D}\}$ channel is changed from 1 to 2. This is because the frame error rate decreases with improving cooperative channels. In Fig. 7(c) and (d), the QS-CD-ARQ scheme outperforms the NCD-ARQ scheme when the normalized SNRs are greater than 0 dB, which

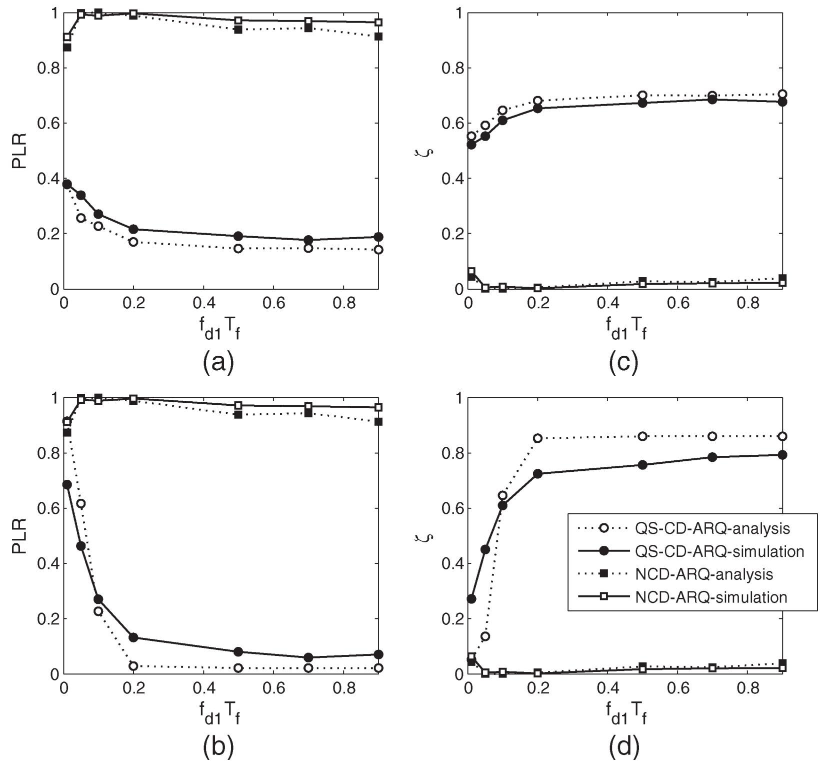

Fig. 10. PLR and throughput of the proposed scheme compared with the noncooperative scheme for various speed of the users.

means that the average received signal power at the receivers should be higher than the SNR_T.

The PLR is presented in Fig. 8. In all cases, the proposed QS-CD-ARQ gives a lower PLR than NCD-ARQ, and the PLR decreases as the normalized SNRs increases. In Fig. 8(a) and (b), it can be seen that increasing the fading figure of the $\{\mathrm{P}, \mathrm{D}\}$ channel significantly improves the PLR performance. In addition, the throughput of the QS-CD-ARQ scheme given in Fig. 9 exhibits similar performance characteristics as PLR in Fig. 8. This behavior of the QS-CD-ARQ is due to the diversity provided by cooperation and improved channel quality with SNR.

Based on Figs. 7–9, we can conclude that increasing the normalized SNRs improves the QS-CD-ARQ performances. The fading figure of the $\{\mathrm{P}, \mathrm{D}\}$ channel significantly affects the upper layer performance. When the average received SNRs of all the channels are higher than the SNR_T, the proposed QS-CD-ARQ scheme outperforms the NCD-ARQ scheme. Finally, it can be observed in these figures that the analytical results closely follow those of the simulations.

In Fig. 10, the PLR and throughput are plotted for various values of normalized Doppler frequencies $f_d T_f$. The normalized Doppler frequency of the $\{\mathrm{S}, \mathrm{D}\}$ channel $f_{1,b} T_f$ is varied from 0.01 to 0.9 in Fig. 10(a) and (c). On the other hand, in Fig. 10(b) and (d), the normalized frequencies of all the channels are simultaneously changed from 0.01 to 0.9. Even though the NCD-ARQ poorly performs for the given system parameters in terms of PLR and throughput, the QS-CD-ARQ scheme performs better in all cases. When the normalized frequency is larger than 0.2, the PLR of the QS-CD-ARQ is almost saturated to 0.2 for Fig. 10(a) and to 0.05 for Fig. 10(b). This is also reflected in the throughput performance in Fig. 10(c) and (d), which means that the throughput is saturated when the normalized frequency is larger 0.2. The normalized Doppler frequency of all the channel are equal in Fig. 10(b) and (d); therefore, the effective channel is more uncorrelated than the effective channel in the case of Fig. 10(a) and (c). Therefore, the QS-CD-ARQ scheme provides lower PLR and higher throughput for Fig. 10(b) than Fig. 10(a), respectively. Similar to Fig. 10(a) and (c), the effects of individual channel correlation can be studied.

Based on Figs. 6–10, the analytical study is validated by simulation not only for the proposed QS-CS-ARQ scheme but also for NCD-ARQ. The proposed scheme can outperform the conventional noncooperative ARQ scheme by selecting a good partner for cooperation.

V. Related Work and Comparative Study

In this section, the performance of the DSTBC-CD-ARQ, SC-CD-ARQ, and NCD-ARQ schemes are compared with our proposed QS-CD-ARQ scheme. In all cases, we use a two-user-based CD and stop-and-wait ARQ mechanism. The description of each scheme is given in the following section.

A. System Description

In the DSTBC-CD-ARQ scheme, the relay is equipped with incremental relaying, and the destination combines the signals according to the space–time block coding employed. This scheme is similar to the scheme proposed in [5] and [6]. The mechanism of DSTBC-CD-ARQ is given in Table II and is illustrated in Fig. 11. The SC-CD-ARQ is similar to

TABLE II
ARQ MECHANISM FOR DSTBC-CD

Source Flag=New frame; retry counter of each frame initialized to zero.

1) broadcast mode: The sender transmits a frame (depending on Flag) to the destination, the partner in the user-1 channel with bit energy $P_S = P_1$,
   - (a) if it receives an `ACK', Flag=New frame; go to 1).
   - (b) if it receives a `NAK' and the retry counter does not exceed the retry limit, go to 2).
   - (c) otherwise, drop the frame; Flag=New frame; go to 1).
2) cooperation mode: The sender retransmits the same frame in the user-1 channel with bit energy $P_S = P_1/2$, increase the retry counter of the frame by 1, and
   - (a) if it receives an `ACK', Flag=New frame; go to 1).
   - (b) if it receives a `NAK' and the retry counter does not exceed the retry limit, Flag=current frame; go to 1)
   - (c) otherwise, drop the frame; Flag=New frame; go to 1).

Partner

1) listening mode: The partner listens the transmission and decodes it, and
   - (a) if the received frame is in error, stay in 1).
   - (b) otherwise, go to 2).
2) transmission mode:
   - (a) if it receives a `NAK' from the destination, transmits with the sender simultaneously in user-1 channel with power $P_P = P_2/2$ and go to 1).
   - (b) otherwise, go to 1).

Destination

1) conventional mode: The destination decodes the signal from sender and check for correctness, and
   - (a) if the received frame is error, send a 'NAK' in the reverse channel and go to 2).
   - (b) otherwise, send an 'ACK' in the feedback channel and stay in 1).
2) cooperation mode: do the signal processing according to the DSTBC, decode the signal from sender and check for correctness, and
   - (a) if the received frame is in error, send a 'NAK' in the feedback channel and go to 1).
   - (b) otherwise, send an 'ACK' in the feedback channel and go to 1).

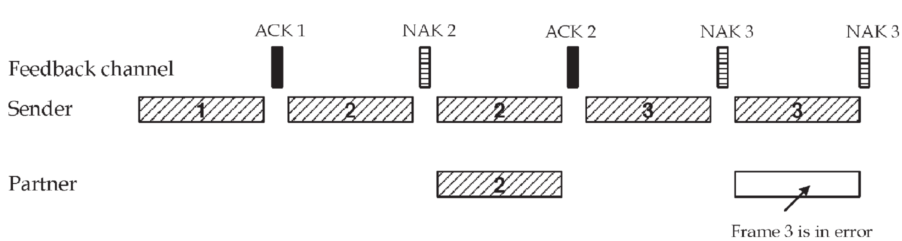

Fig. 11. DSTBC-CD-ARQ scheme (based on incremental relaying).

DSTBC-CD-ARQ, except that the relays forward without any coding technique (decode and repeat), and the destination uses SC instead of DSTBC. This scheme is equivalent to the node cooperative ARQ scheme proposed in [7]. NCD-ARQ is a conventional stop-and-wait ARQ scheme without cooperation.

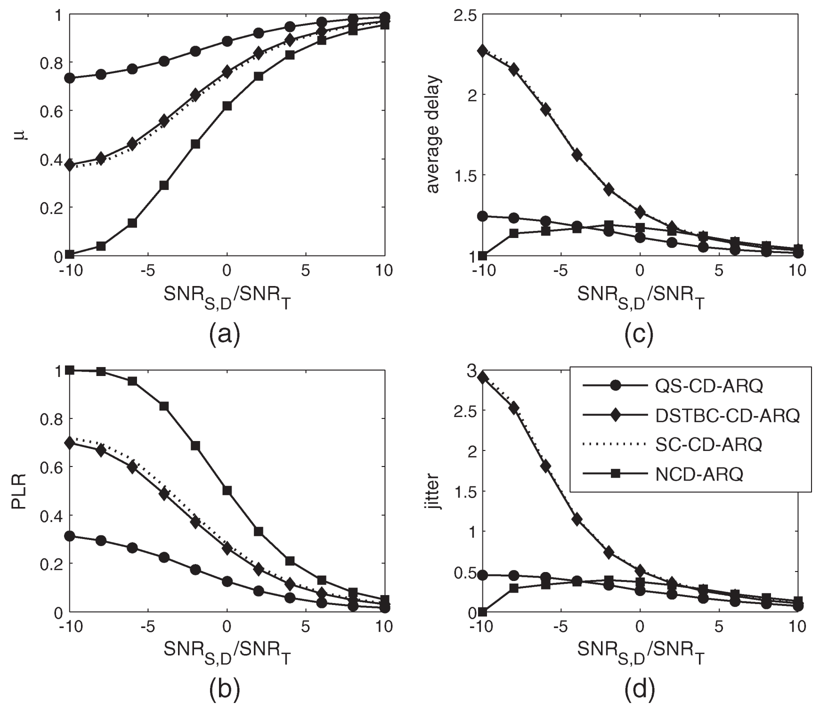

Fig. 12. Performance of the CD-ARQ scheme with varying $\mathrm{SNR}_{S,D}/\mathrm{SNR}_T$ from -10 to 10 dB.

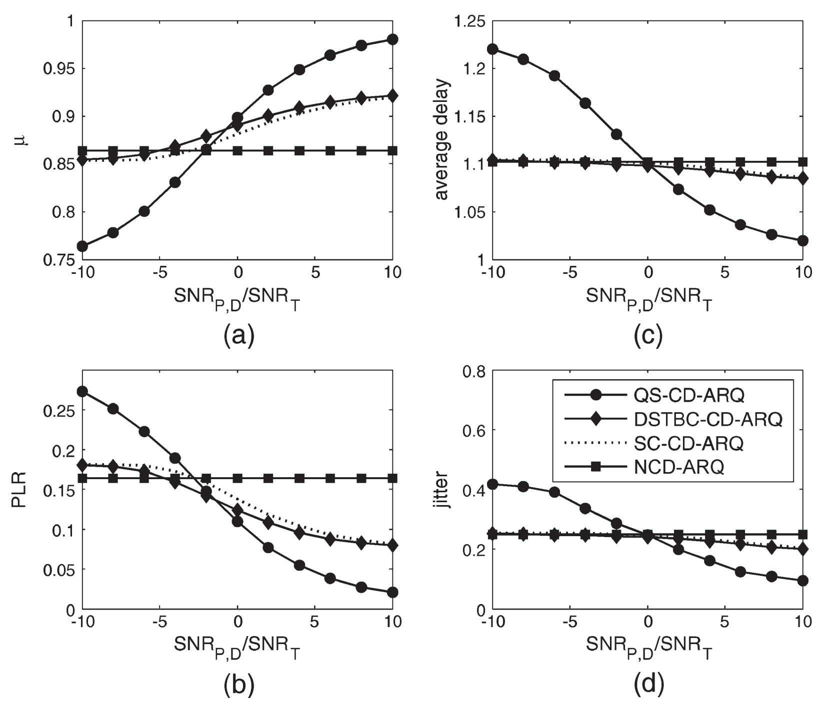

Fig. 13. Performance of the CD-ARQ scheme with varying $\mathrm{SNR}_{P,D}/\mathrm{SNR}_T$ from -10 to 10 dB.

A comparative study is performed based on simulations. Due to space limitations, we only show the results for $m_1 = m_2 = 1$ and $m_{S,P} = 2$. To obtain accurate results, we use a sampling time of 10^{-3} s and collect 10×10^5 samples for each random seed. In the simulation study, we consider the following system parameters. The carrier frequency f_c is equal to 900 MHz. The relative velocity of the $\{\mathrm{S,P}\}$, $\{\mathrm{S,D}\}$, and $\{\mathrm{P,D}\}$ links are 10 km/hr, 30 km/hr, and 30 km/hr, respectively. Unless explicitly stated, the parameters used are the normalized SNRs $\mathrm{SNR}_{S,P}/\mathrm{SNR}_T = 15$ dB, $\mathrm{SNR}_{S,D}/\mathrm{SNR}_T = 5$ dB, and $\mathrm{SNR}_{P,D}/\mathrm{SNR}_T = 5$ dB, number of frames per packet $N = 10$, and retry limit of a frame $L = 9$.

The metrics of interest in evaluating the performance of the CD-ARQ schemes are efficiency, PLR, average delay, and delay jitter. The efficiency and PLR have been defined earlier. The average delay of the packet is given by the ratio of the total number of successful packets to the total number of slots used. Jitter is the variance of the packet delay.

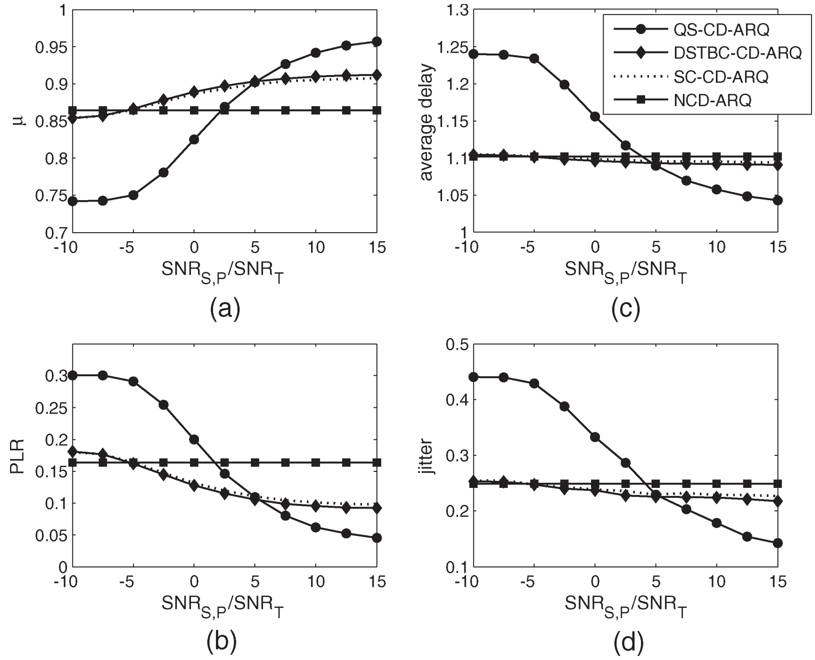

Fig. 14. Performance of the CD-ARQ scheme with varying $\mathrm{SNR}_{S,P}/\mathrm{SNR}_T$ from -10 to 15 dB.

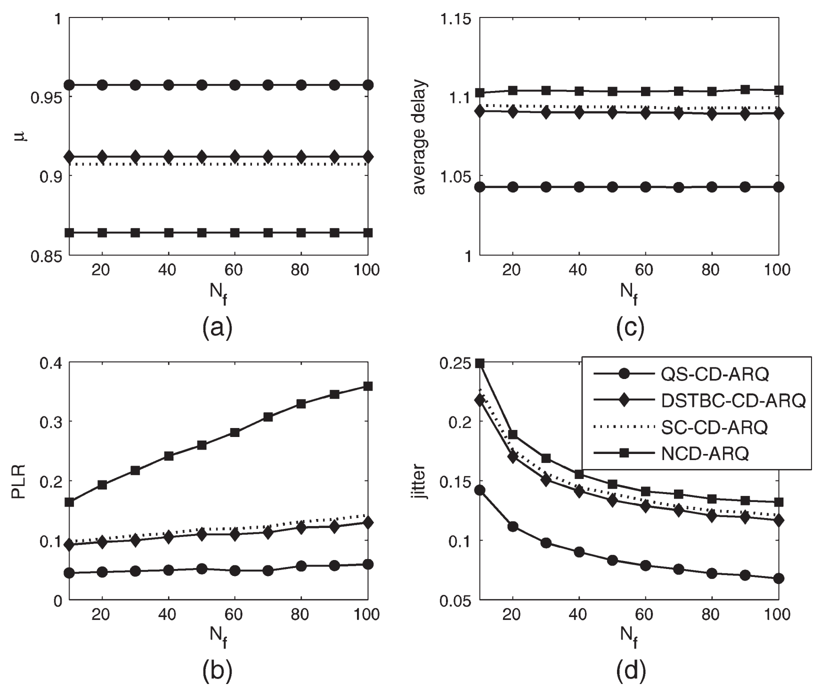

Fig. 15. Performance of the CD-ARQ scheme with varying N from 10 to 100.

B. Effects of Channel Condition

In this section, we study the effects of channel conditions by using the normalized SNRs. Figs. 12–14 are plotted as a function of $\mathrm{SNR}_{S,D}/\mathrm{SNR}_T$, $\mathrm{SNR}_{P,D}/\mathrm{SNR}_T$, and $\mathrm{SNR}_{S,P}/\mathrm{SNR}_T$, respectively. The performance metrics such as channel efficiency, PLR, average delay, and jitter are presented in Fig. 13(a)–(d), respectively.

By utilizing selection relaying in the cooperation, even though the sender to destination channel is poor, a good partner (with good interuser and partner to destination channels) helps for successful transmission in the first attempt. However, in incremental relaying-based schemes, the partner helps only if the first attempt fails. This is the reason that QS-CD-ARQ outperforms all other schemes in Fig. 12. Furthermore, NCD-ARQ has low delay and jitter compared with those of DSTBC-CD-ARQ and SC-CD-ARQ at the expense of higher PLR. The proposed QS-CD-ARQ outperforms all other schemes when $\mathrm{SNR}_{P,D}/\mathrm{SNR}_T$ is greater than 0 dB in Figs. 12 and 13, and $\mathrm{SNR}_{S,P}/\mathrm{SNR}_T$ is greater than $\mathrm{SNR}_{S,D}/\mathrm{SNR}_T$ in Fig. 14. This is because QS-CD-ARQ always gets help from the partner. Therefore, the $\{\mathrm{S}, \mathrm{P}\}$ and $\{\mathrm{P}, \mathrm{D}\}$ links should be good enough. In addition, SC-CD-ARQ closely follows the

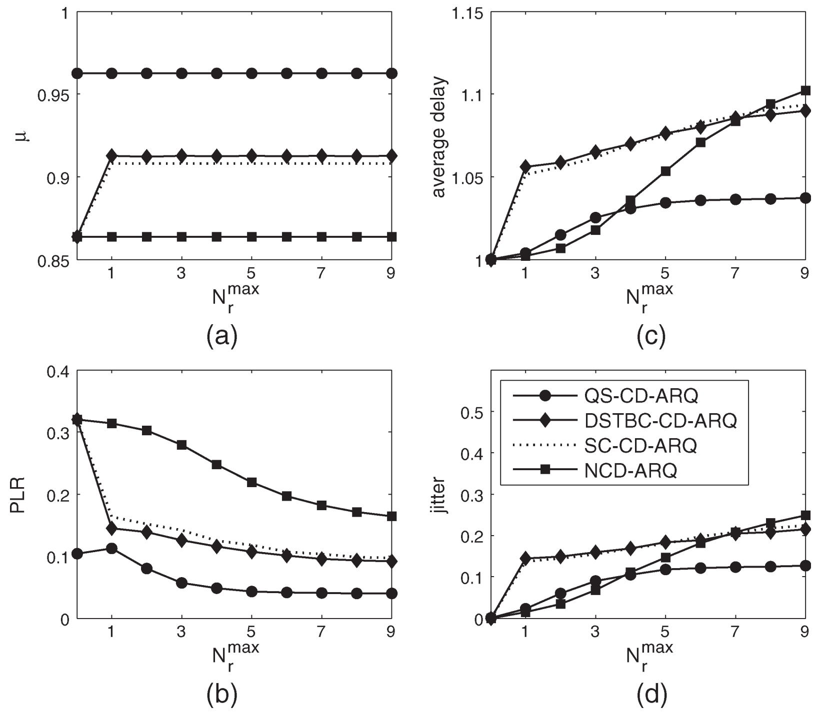

Fig. 16. Performance of the CD-ARQ scheme with varying maximum retransmission limit L from 0 to 9.

DSTBC-CD-ARQ in Figs. 12–14, since both are equipped with incremental relaying, and the effect of signal combining techniques at the destination is not significant for correlated frame losses. In other words, the performance difference between SC and DSTBC is minor in the upper layers.

C. *Effects of ARQ Parameters*

In this section, we study the impact of ARQ protocol parameters on performance by considering the number of frames N in the link layer and the maximum retry limit L.

The effects of N are shown in Fig. 15. The channel parameters are not changed, so the efficiency and average delay are not changed with the packet size. The PLR is increased with N for all schemes, but the rate of changes is the smallest for QS-CD-ARQ. In addition, the performance of QS-CD-ARQ is better than other schemes, which can be observed from all of the four performance metrics. As discussed earlier, the QS-CD-ARQ performs better due to the selection relaying mechanism.

The performance of the schemes is shown against L in Fig. 16. The efficiency of the channel that employs each scheme is similar to that in Fig. 15, except at $L = 0$. Without an ARQ mechanism $(L = 0)$, DSTBC-CD-ARQ and SC-CD-ARQ have a channel efficiency similar to that of NCD-ARQ, since there is no help from the partner. On the other hand, the efficiency of QS-CD-ARQ is better than others, even for $L = 0$, because the relay in the QS-CD-ARQ scheme always forwards if it has an errorfree frame and is unaware of any ARQ mechanism. This leads QS-CD-ARQ to have comparably very low PLR at $L = 0$. The overall performance of the QS-CD-ARQ is better than other schemes, and the rate of change of both average delay and jitter are minimal compared with other schemes when L is greater than 4. Therefore, the proposed QS-CD-ARQ scheme is more favorable for quality-of-service-guaranteed applications.

VI. Conclusion

We have introduced a common framework for analyzing the performance of adaptive relaying in CD-ARQ schemes for time-selective channels. The performance of the proposed QS-CD-ARQ scheme is compared with those of existing CD-ARQ schemes based on incremental relaying, and the complexity of the schemes is discussed. The proposed QS-CD-ARQ outperforms other schemes when the sender is cooperating with a partner who provides a good sender-to-partner and partner-to-destination link. It can be achieved by having good partner selection and power allocation algorithms. Moreover, the results of this comparative study can be applied for a best partner selection in the CD-ARQ schemes or when making a decision to switch from one CD-ARQ scheme to another, where partner selection has limitations. From the implementation point of view, QS-CD-ARQ is more favorable, since radio resources can be allocated for a long duration, and the partner does not need to be aware of the presence of ARQ.

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