Multi-Relay Cooperative Diversity Protocol with Improved Spectral Efficiency

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Abstract: **Cooperative diversity protocols have attracted a great deal of attention since they are thought to be capable of providing diversity multiplexing tradeoff among single antenna wireless devices. In the high signal–to–noise ratio (SNR) region, cooperation is rarely required; hence, the spectral efficiency of the cooperative protocol can be improved by applying a proper cooperation selection technique. In this paper, we present a simple "cooperation selection" technique based on instantaneous channel measurement to improve the spectral efficiency of cooperative protocols. We show that the same instantaneous channel measurement can also be used for relay selection. In this paper two protocols are proposed—proactive and reactive; the selection of one of these protocols depends on whether the decision of cooperation selection is made before or after the transmission of the source. These protocols can successfully select cooperation along with the best relay from a set of available M relays. If the instantaneous source–to–destination channel is strong enough to support the system requirements, then the source simply transmits to the destination as a non-cooperative direct transmission; otherwise, a cooperative transmission with the help of the selected best relay is chosen by the system. Analysis and simulation results show that these protocols can achieve higher order diversity with improved spectral efficiency, i.e., a higher diversity-multiplexing tradeoff in a slow–fading environment.**

Index Terms: **Cooperative diversity, diversity-multiplexing tradeoff, fading channel, outage probability, relay selection, spectral efficiency.**

I. INTRODUCTION

To provide transmit diversity when users cannot support multiple antennas, a cooperative diversity protocol [1] has been proposed. Various cooperative transmission protocols, implementation issues and performance and outage analysis have been studied (see [1]–[7] and the references herein). Cooperative diversity protocols can provide the powerful benefit of spatial diversity at the cost of spectral efficiency due to their half-duplex operation. For a diversity of order $M+1$, repetition-based cooperative protocols reduce the spectral efficiency by a factor of $M+1$ [5]. A distributed space-time coded (DSTC) cooperative diversity protocol that can improve spectral efficiency has been proposed in [5]. This protocol can achieve a diversity of order $M+1$, with higher spectral efficiency than repetition-based protocols for $M > 1$. However, the DSTC based cooperative diversity protocol needs a complex space–time code design and requires synchronization among the nodes. Cooperative diversity, based on network path selection proposed in [6] (termed opportunistic relaying), greatly reduces this problem. For possible M relays, opportunistic relaying selects a suitable single–relay for cooperation on the basis of the instantaneous channel state information (CSI) and always has a spectral efficiency of $1/2$ in comparison to direct transmission. The opportunistic relaying technique uses ready-to-send (RTS) and clear-to-send (CTS) packets to select an opportunistic relay. The outage optimality of the opportunistic relaying protocol has been discussed in [7]. A similar relay selection technique based on the mutual information of source and destination using relays has been proposed in [8].

Another way to improve the spectral efficiency of cooperative transmission is to use limited feedback from the destination. The incremental relaying protocol proposed in [1] showed that a single bit feedback from the destination can dramatically improve the spectral efficiency over fixed and selection relaying. The single bit feedback indicates the success or failure of the direct transmission from the source. In the incremental relaying protocol, the relay retransmits to exploit spatial diversity if the destination sends a negative acknowledgement. In [9] the idea of incremental relaying has been combined with opportunistic relaying to achieve higher order diversity with improved spectral efficiency, which is very close to the spectral efficiency in the case of direct transmission. The idea of using a relay only if it helps the source has been presented in [13] for a single relay environment. This proposal assumed that the global instantaneous CSIs of all links are known to the source node.

In this paper, we present a reactive and a proactive cooperative protocol for 'cooperation selection' (i.e., deciding whether cooperation is required or not) to achieve a higher spectral efficiency which is very close to that in the case of direct transmission. Throughout this paper, we consider only decode-and-forward based selection relaying [1] at the relays. In the proactive protocol, we show that the instantaneous channel-measurement-based relay selection procedure proposed in [6] can be used for cooperation selection. This can be done on the basis of the channel realization and the decision can be made at the source or destination. In the reactive protocol, we show that the cooperation selection procedure, like incremental relaying [1], can be used for selecting the best relay from a set of available relays. This relay selection algorithm is based on the automatic request for retransmission (ARQ) signal from the destination and the relay selection procedure is distributed as opportunistic relaying. We develop a closed-form expression for the outage probability of all protocols when the destination op-

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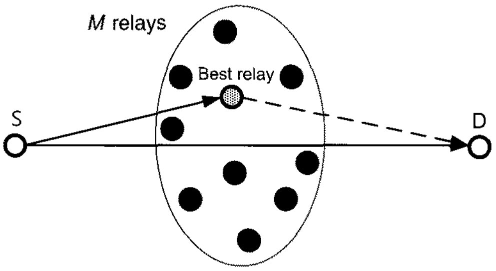

Fig. 1. System model (the dotted line indicates that the best relay transmits only if the cooperation is required).

timally combines the signals from the source and the best relay. The main contributions of this paper are summarized as follows.

- We propose two cooperation selection schemes for multi-relay wireless system to improve the spectral efficiency. The proposed cooperation selection schemes are based on the instantaneous CSI measurement. We show that the same instantaneous channel measurement can also be used for relay selection. Consequently, cooperation selection procedures are integrated with the relay selection to achieve higher diversity multiplexing tradeoff.
- The closed form expressions of outage probability, spectral efficiency and diversity multiplexing tradeoff of the proposed schemes are derived for arbitrary number of relays. Through the high SNR asymptotic outage analysis, we show that the proposed schemes achieve higher spectral efficiency and diversity multiplexing tradeoff compare to the some existing schemes for example, incremental relaying [1], DSTC [5], and opportunistic relaying [6].
- Numerical as well as simulation results are given to evaluate the performances of the proposals and to justify the arguments. Some implementation issues of the proposed schemes are also discussed.

The rest of the paper is organized as follows. In Section II, we present the system model and establish the notations. In Sections III and IV, we describe the proposed proactive and reactive protocols and analyze their outage behavior. Section V presents the diversity-multiplexing tradeoff for our proposal. Numerical and simulation results are given in Section VI. In Section VII, we compare proposed proactive and reactive protocols. Finally, we present our conclusions in Section VIII.

II. SYSTEM MODEL

We consider a system model as shown in Fig. 1, where a single source communicates with a destination and a group of M relays is available in the system to achieve cooperative diversity. The nodes transmit on orthogonal channels (e.g., TDMA, CDMA, or FDMA) which allow the destination and cooperative relays to detect each source packet without any interference. We consider a time division multiplexing for the purpose of exposition. However, our proposal does not depend on the specifics of channel access protocols. Let us consider that the channels between two nodes are subjected to flat Rayleigh fading plus additive white Gaussian noise (AWGN). Each node has a single half-duplex radio and a single antenna.

The baseband equivalent received signal at node j due to the transmission of node i for symbol n is given by

$$r_{ij}(n) = \alpha_{ij} s(n) + \eta_j(n) \qquad (1)$$

where $\eta_j(n)$ is the AWGN sample with variance $N_0/2$ per dimension at terminal j, α_{ij} is the fading coefficient between node i and j and $s(n)$ is the signal transmitted by node i with normalized unit transmit power (P_t). We consider flat Rayleigh fading, and hence, α_{ij} is modeled as independent samples of zero mean complex Gaussian random variables with variance σ_{ij}^2. In case of slow fading, the fading coefficients can be assumed to be constant over the channel coherent time of N symbol periods. Because of slow fading channel estimation is also possible at the receiver [10]. We assume that a perfect channel state information is available at the corresponding receivers but not at the transmitters. Another important assumption is that all control signals, introduced in this work, carry pilot symbols to estimate the fading coefficients at the corresponding receivers. We assume that the nodes measure partial CSI, in the form of channel state amplitude, from the received control signals. There are many techniques to estimate the amplitude of CSI from pilot symbols, for example [15]. The details of the channel estimation techniques are beyond the scope of this paper. We consider selection relaying [1] at relay, i.e., the relay cooperates with the source node when it successfully decodes the source message.

III. PROACTIVE PROTOCOLS

In the proactive protocols, we utilize proactive instantaneous channel-gain based relay selection for cooperation selection. We consider opportunistic relaying [6] for relay selection. We show that instantaneous channel-measurement-based relay selection protocols can be used for cooperation selection to achieve a spectral efficiency close to that of direct transmission.

A. Overview of Opportunistic Relaying

In opportunistic relaying protocol, all the relays receive a RTS packet from the source and a CTS packet from the destination. Using these two control packets all available relays in the network estimate the instantaneous CSI $\alpha_{\mathrm{S}k}$ and $\alpha_{k\mathrm{D}}$ where, $k \in \{1, 2, \cdots, M\}$. The opportunistic relaying proposed two policies to set a timer at each relay based on the minimum of $|\alpha_{\mathrm{S}k}|^2$, $|\alpha_{k\mathrm{D}}|^2$ and the harmonic mean of $|\alpha_{\mathrm{S}k}|^2$, $|\alpha_{k\mathrm{D}}|^2$ and the first policy has been observed to perform better than the second one. Throughout this paper we only consider the first policy, i.e., the relay k sets a timer with initial value

$$T_k = \frac{\Omega}{h_k} \qquad (2)$$

where $h_k = \min\{|\alpha_{\mathrm{S}k}|^2, |\alpha_{k\mathrm{D}}|^2\}$ and Ω is a constant. From (2), it is clear that the opportunistic relay reduces its timer to zero first since it starts from a small initial value. As soon as the timer of the opportunistic relay reduces to zero it transmits a flag signal to inform the other relays to back off. This protocol selects an opportunistic relay that satisfies the following condition,

$$O = \underset{k \in \{1,2,\cdots,M\}}{\operatorname{argmax}} \left(\min \left\{ |\alpha_{\mathrm{S}k}|^2, |\alpha_{k\mathrm{D}}|^2 \right\} \right). \qquad (3)$$

B. Cooperation Selection

The decision of cooperation selection can be made by either the source or destination. When the direct link between the source and the destination is strong enough to support the system requirements cooperation is not required. If cooperation is not required then there is no need to select a relay and the source transmits in the direct transmission mode. If cooperation is required, then we need to select the best relay and cooperative transmission among the source, the selected relay and the destination takes place. In direct transmission, the source transmits N symbols with a rate R bit/s/Hz during the channel coherent time. Therefore, cooperation is required if the mutual information between the source and destination is less than the target rate R. This decision can be made by calculating the mutual information between the source (S) and the destination (D), which is given by

$$I_{\mathrm{SD}} = \log(1 + \mathrm{SNR}\,|\alpha_{\mathrm{SD}}|^2) \tag{4}$$

where $\mathrm{SNR} = P_t/N_0$ is the signal–to–noise ratio without fading. The threshold value of the instantaneous channel gain for this decision is

$$|\alpha_{Th}|^2 = \frac{2^R - 1}{\mathrm{SNR}}. \tag{5}$$

If the instantaneous channel gain is greater than or equal to the threshold value then the source transmits toward the destination without selecting a relay as direct transmission. Otherwise, an opportunistic relay is selected and the source transmits with the help of the opportunistic relay as [6]. In this section, we propose two cooperation selection algorithms based on the decision taken at the source and the destination.

B.1 Source Decided Cooperation Selection

This procedure starts with RTS and CTS signal from the source and destination similar to opportunistic relaying. In the opportunistic relaying protocol proposed in [6], the authors consider these packets to be received only by the relays. But in our proposal, we allow the destination and the source to receive RTS and CTS signals respectively. The source transmits a RTS signal which the destination and all relays receive. Similarly, the CTS signal from the destination is received by the source and all relays. Upon receiving the RTS and CTS signals, all relays estimate the instantaneous channel fading $\alpha_{\mathrm{S}k}$ and $\alpha_{k\mathrm{D}}$. At the same time both the source and destination also estimate α_{SD}. Here, the subscript Sk indicates source–to–relay-k, kD indicates relay-k–to–destination and SD indicates source–to–destination channels. Assuming that the forward and backward channels between nodes are the same according to the reciprocity theorem [10], we can write $\alpha_{\mathrm{SD}} = \alpha_{\mathrm{DS}}$.

Using the value of $|\alpha_{\mathrm{SD}}|^2$ the source can decide whether cooperation is required in this instance or not. If $|\alpha_{\mathrm{SD}}|^2 \geq |\alpha_{Th}|^2$ then the source sets its timer to zero and immediately transmits a flag signal (similar to the 'best relay flag' of opportunistic relaying) toward the other relays to stop their processing. In this case, the source transmits with a rate R like direct transmission. If $|\alpha_{\mathrm{SD}}|^2 < |\alpha_{Th}|^2$ then the source remains silent and waits for receiving the best relay flag from the opportunistic relay. After receiving this flag the cooperative transmission starts with the help of the best relay.

In the cooperative mode, an opportunistic relay is selected and the source transmits over $N/2$ symbols with rate $2R$. The selected best relay receives this transmission and tries to decode the source information. If the decoding is successful at the best relay then it forwards the decoded symbols to the destination in the remaining $N/2$ symbol period of the channel coherent time. We consider decoding at relay is successful, when the mutual information between the source and the opportunistic relay is less than the target rate. The mutual information between the source (S) and the opportunistic relay (O) is given by

$$I_{\mathrm{SO}} = \frac{1}{2}\log\left(1 + \mathrm{SNR}\,|\alpha_{\mathrm{SO}}|^2\right). \tag{6}$$

Therefore, the opportunistic relay forwards the received signal if it satisfies the condition,

$$|\alpha_{\mathrm{SO}}|^2 \geq \frac{2^{2R} - 1}{\mathrm{SNR}}. \tag{7}$$

B.2 Destination Decided Cooperation Selection

In this protocol, the destination checks the threshold of Eq. (5) after receiving the RTS signal from the source and estimates α_{SD} to make a decision on whether or not cooperation is needed. And, to notify this decision, we consider two types of CTS signals from the destination. If the cooperation is not required, the CTS signal contains only a single bit to notify this event, otherwise, it transmits a CTS signal similar to the opportunistic relaying. If $|\alpha_{\mathrm{SD}}|^2 \geq |\alpha_{Th}|^2$, then all relays stop their processing and the source transmits with a rate R like a direct transmission. Otherwise a cooperative transmission starts.

C. Outage Analysis

For both source- and destination-decided cooperation selection, the outage probability is zero when cooperation is not required (direct transmission), provided the channel estimation is perfect. Therefore, the overall system outage probability can be generalized as the outage probability of cooperative transmission:

$$\begin{aligned} P_P^{\mathrm{Out}} = &\Pr\left[\frac{1}{2}\log\left\{1+\mathrm{SNR}\left(|\alpha_{\mathrm{SD}}|^2+|\alpha_{\mathrm{OD}}|^2\right)\right\}<R\right]\Pr(\varepsilon) \\ &+\Pr\left[\frac{1}{2}\log\left\{1+\mathrm{SNR}\left(|\alpha_{\mathrm{SD}}|^2\right)\right\}<R\right]\Pr(\bar{\varepsilon}) \end{aligned} \tag{8}$$

where the subscript P denotes the proactive protocol, $\Pr(\bar{\varepsilon})$ is the probability that the opportunistic relay decodes the source information incorrectly that can be written as

$$\begin{aligned} \Pr(\bar{\varepsilon}) = &\Pr\left[\frac{1}{2}\log\left(1+\mathrm{SNR}\,|\alpha_{\mathrm{SO}}|^2\right) < R\right] \\ = &\Pr\left[|\alpha_{\mathrm{SO}}|^2 < \frac{2^{2R}-1}{\mathrm{SNR}}\right] = \Pr\left[|\alpha_{\mathrm{SO}}|^2 < \gamma_P\right] \end{aligned} \tag{9}$$

where $\gamma_P = (2^{2R} - 1)/\mathrm{SNR}$. The exact probability density function (pdf) and cumulative distribution function (CDF) of the random variable (RV) $|\alpha_{\mathrm{SO}}|^2$ are difficult to obtain, but we can easily approximate this RV as

$$|\alpha_{\mathrm{SO}}|^2 \leq \max_{k\in\{1,2,\cdots,M\}}\{\min(|\alpha_{\mathrm{S}k}|^2, |\alpha_{k\mathrm{D}}|^2)\}. \tag{10}$$

In this paper, we consider that M relays are selected by a higher layer protocol on the basis of the average SNR of the source-to-relay and relay-to-destination links. Under this assumption, RVs $|\alpha_{\mathrm{S}k}|^2$ and $|\alpha_{k\mathrm{D}}|^2$ are exponentially distributed with parameters σ_1^{-2} and σ_2^{-2}, respectively, i.e., $\sigma_{\mathrm{S}k}^{-2} = \sigma_1^{-2}$ and $\sigma_{k\mathrm{D}}^{-2} = \sigma_2^{-2}$, for all k. The minimum of two exponentially distributed RVs with parameters σ_1^{-2} and σ_2^{-2} is another exponential RV with parameter $\left(\sigma_1^{-2} + \sigma_2^{-2}\right)$ [12]. Considering this fact, we can rewrite (9) using the CDF of $|\alpha_{\mathrm{SO}}|^2$ given in fact 1 of the Appendix, with $\lambda_y = \left(\sigma_1^{-2} + \sigma_2^{-2}\right)$ and $n = M$ as

$$\Pr(\bar{\varepsilon}) \leq \left(1 - e^{-\left(\sigma_1^{-2}+\sigma_2^{-2}\right)\gamma_P}\right)^M. \tag{11}$$

Now, it is easy to find the probability that the opportunistic relay is successful in decoding the source message as

$$\Pr(\varepsilon) = 1 - \Pr(\bar{\varepsilon}) \geq 1 - \left(1 - e^{-\left(\sigma_1^{-2}+\sigma_2^{-2}\right)\gamma_P}\right)^M. \tag{12}$$

Let

$$\begin{aligned} P_1 &= \Pr\left[\frac{1}{2}\log\left(1 + \mathrm{SNR}\,|\alpha_{\mathrm{SD}}|^2\right) < R\right] \\ &= \Pr\left[|\alpha_{\mathrm{SD}}|^2 < \gamma_P\right] \\ &= \left(1 - e^{-\sigma_{\mathrm{SD}}^{-2}\gamma_P}\right) \end{aligned} \tag{13}$$

and

$$\begin{aligned} P_2 &= \Pr\left[\frac{1}{2}\log\left\{1 + \mathrm{SNR}\left(|\alpha_{\mathrm{SD}}|^2 + |\alpha_{\mathrm{OD}}|^2\right)\right\} < R\right] \\ &= \Pr[|\alpha_{\mathrm{SD}}|^2 + |\alpha_{\mathrm{OD}}|^2 < \gamma_P]. \end{aligned} \tag{14}$$

Here, the closed-form expression of P_1 is derived considering $|\alpha_{\mathrm{SD}}|^2$ is an exponential RV with parameter σ_{SD}^{-2}. Similarly to (10), $|\alpha_{\mathrm{OD}}|^2$ can be approximated as

$$|\alpha_{\mathrm{OD}}|^2 \leq \max_{k\in\{1,2,\cdots,M\}}\{\min(|\alpha_{\mathrm{S}k}|^2, |\alpha_{k\mathrm{D}}|^2)\}. \tag{15}$$

Utilizing Lemma 1 of the Appendix with $n = M$, $x = |\alpha_{\mathrm{SD}}|^2$, $y = |\alpha_{\mathrm{OD}}|^2$, $\lambda_x = \sigma_{\mathrm{SD}}^{-2}$, and $\lambda_y = \left(\sigma_1^{-2} + \sigma_2^{-2}\right)$, we can approximate (14) as

$$\begin{aligned} P_2 \leq &\sum_{i=1}^{M-1} (-1)^i \binom{M-1}{i} \frac{M\sigma_{\mathrm{SD}}^{-2}\left(\sigma_1^{-2} + \sigma_2^{-2}\right)}{(i+1)\left(\sigma_1^{-2} + \sigma_2^{-2}\right) - \sigma_{\mathrm{SD}}^{-2}} \\ &\cdot \left[\frac{\left(1 - e^{-\sigma_{\mathrm{SD}}^{-2}\gamma_P}\right)}{\sigma_{\mathrm{SD}}^{-2}} - \frac{\left(1 - e^{-2(i+1)\left(\sigma_1^{-2}+\sigma_2^{-2}\right)\gamma_P}\right)}{(i+1)\left(\sigma_1^{-2}+\sigma_2^{-2}\right)}\right]. \end{aligned} \tag{16}$$

Finally, by combining (11), (12), (13) and (16) we can approximate the outage probability of the proactive protocol given in (8) as

$$P_P^{\mathrm{Out}} \leq P_1 \Pr(\bar{\varepsilon}) + P_2 \Pr(\varepsilon). \tag{17}$$

This approximation is an upper bound because in (16), the expression of P_2 is an upper bound.

IV. REACTIVE PROTOCOLS

In the reactive protocol, both relay and cooperation selections are done after the information is transmitted by the source. This transmission is received by the destination and all relays. If the destination can successfully decode the source message then cooperation is not needed; indeed, there is no need to select a relay. In this protocol, only one control signal, negative acknowledgment (NACK), is used to measure the relays to destination CSIs and select both the cooperation and the best relay. In contrast, the proposal in [9] uses the RTS & CTS signals for relay selection and a feedback signal for cooperation selection; hence, this proposal needs to measure the corresponding CSIs from the RTS, CTS, and NACK signals. Moreover, this hybrid protocol [9] always selects a relay without considering whether or not the cooperation is needed. On the other hand, our proposal (both proactive and reactive) selects the best only when cooperation is required.

In this section, we present a reactive cooperative protocol for both cooperation selection and relay selection. First, the source transmits N symbols with a rate R bit/s/Hz during the channel coherent time without considering the relay selection. The destination and all available relays receive this signal and try to decode. If the decoding at the destination is successful then there is no need to select a relay. If the destination fails to decode the received signal, then the best relay is selected from the decoding set of relays (set of relays that successfully decode the source message) for cooperation.

A. Cooperation Selection

This protocol works on the basis of a request for cooperation, which is similar to a conventional ARQ. In conventional ARQ protocols, the destination sends a feedback signal to the source for more information. In this proposal, the destination sends a feedback signal toward a group of relays for more information, i.e., for cooperation. Conventional ARQ protocols exploit time diversity, whereas, our proposal exploits spatial diversity. This proposal works in two phases: A mandatory phase and an on-demand phase.

In the mandatory phase, the source transmits N symbols with a rate R bit/s/Hz during the channel coherent time. Owing to the broadcast nature of the wireless transmission, the destination and all available relays are able to receive this transmission. If the destination can decode the source message block successfully then the transmission for this message block ends with a positive acknowledgement (ACK) from the destination. If the destination fails to decode the source information in the mandatory phase then the on-demand phase of our proposed protocol starts with a NACK signal from the destination. In the on-demand phase, the best relay is selected by using the NACK signal and the selected best relay forwards the message during the next N symbol period at rate R bit/s/Hz. At the end of the on-demand phase, the destination optimally combines the signal from the source and the best relay.

B. Reactive Relay Selection

Consider, among M available relays a set of K ($K \leq M$) relays that have successfully decoded the source information in the mandatory phase. The NACK signal from the destination is received by all K relays. Using this NACK signal relay k can estimate the destination-to-relay channel condition α_{dk}, where $k \in \{1, 2, \cdots, K\}$. According to the reciprocity theorem [10], we can write $\alpha_{\mathrm{D}k} = \alpha_{k\mathrm{D}}$. Therefore, all relays know their instantaneous CSI along with the destination. For relay selection, we use the distributed approach of setting a timer at each relay, which is explained in the previous section. All K relays set their timer with an initial value T_k, which is inversely proportional to $|\alpha_{k\mathrm{D}}|^2$ as

$$T_k = \frac{\Omega}{|\alpha_{k\mathrm{D}}|^2}. \tag{18}$$

Let $|\alpha_{\mathrm{BD}}|^2 = \max\{|\alpha_{k\mathrm{D}}|^2\}$ then, $T_B = \min\{T_k\}$ for $k \in \{1, 2, \cdots, K\}$. Hence, the timer of the relay that has the best channel condition with the destination reduces to zero first. As soon as the timer of the relay b reaches zero, it transmits a best relay flag to the other relays to stop their processing. For $K = \phi$, i.e., when all the relays fail to decode the received signal, the source will not receive any best relay flag and start a new phase after a predefined time interval. The collision probability of this kind of scheme i.e., the probability of two or more relay timers expiring within the same time interval has been discussed in [6] and was found to be very small.

C. Outage Probability

The outage probability of our proposed proactive protocol can be generalized as the outage probability after the on-demand phase, because it includes the mandatory phase when the destination optimally combines the received signal of both mandatory and on-demand phases. The exact outage event is dependent on the number of relays that successfully decode the source information in the mandatory phase. Now the probability that k relays have decoded the source information correctly is

$$\Pr(K) = \begin{pmatrix} M \\ K \end{pmatrix} p^{M-K}(1-p)^K \tag{19}$$

where p is the probability of wrong decoding at each relay independently which can be given as

$$\begin{aligned} p &= \Pr\left[\log\left(1 + \mathrm{SNR}\,|\alpha_{\mathrm{S}k}|^2\right) < R\right] \\ &= \Pr\left[|\alpha_{\mathrm{S}k}|^2 < \frac{2^R - 1}{\mathrm{SNR}}\right] \\ &= 1 - e^{-\sigma_1^{-2}\gamma_R} \end{aligned} \tag{20}$$

where $\gamma_R = (2^R - 1)/\mathrm{SNR}$ and the subscript R denotes the reactive protocol. Similar to Section III, we assume $\sigma_{\mathrm{S}k}^{-2} = \sigma_1^{-2}$ and $\sigma_{k\mathrm{D}}^{-2} = \sigma_2^{-2}$ for all k.

The outage probability of our proposed reactive protocol can be calculated using the total probability theorem as

$$P_R^{\mathrm{Out}} = \sum_{K=0}^{M} \Pr(K) \Pr(\mathrm{Out}\,|K). \tag{21}$$

The conditional outage probability of (21) is given by

$$\begin{aligned} \Pr(\mathrm{Out}\,|K) &= \Pr\left[\log\left\{1 + \mathrm{SNR}\left(|\alpha_{\mathrm{SD}}|^2 + |\alpha_{\mathrm{BD}}|^2\right)\right\} < R\right] \\ &= \Pr\left[\left(|\alpha_{\mathrm{SD}}|^2 + |\alpha_{\mathrm{BD}}|^2\right) < \gamma_R\right] \end{aligned} \tag{22}$$

where $|\alpha_{\mathrm{SD}}|^2$ is the exponential random variable with parameter $\sigma_{\mathrm{SD}}^{-2}$ and $|\alpha_{\mathrm{BD}}|^2$ is the channel gain of the best relay to destination which is the maximum of k exponential random variables with parameter σ_2^{-2}. We can calculate the conditional outage probability of (22) for $k > 0$ by using the CDF developed in Lemma 1 of the Appendix considering $|\alpha_{\mathrm{SD}}|^2 = x$, $|\alpha_{\mathrm{BD}}|^2 = y$, $\lambda_x = \sigma_{\mathrm{SD}}^{-2}$ and $\lambda_y = \sigma_2^{-2}$ as

$$\begin{aligned} \Pr(\mathrm{Out}\,|K) = \sum_{i=1}^{K-1} (-1)^i \begin{pmatrix} K-1 \\ i \end{pmatrix} \frac{K\sigma_{\mathrm{SD}}^{-2}\sigma_2^{-2}}{(i+1)\sigma_2^{-2} - \sigma_{\mathrm{SD}}^{-2}} \\ \cdot \left[\frac{\left(1 - e^{-\sigma_{\mathrm{SD}}^{-2}\gamma_R}\right)}{\sigma_{\mathrm{SD}}^{-2}} - \frac{\left(1 - e^{-(i+1)\sigma_2^{-2}\gamma_R}\right)}{(i+1)\sigma_2^{-2}}\right]. \end{aligned} \tag{23}$$

For $K = 0$,

$$\Pr(\mathrm{Out}\,|K = 0) = 1 - e^{-\sigma_{\mathrm{SD}}^{-2}\gamma_R}. \tag{24}$$

Using (19), (20), (23), and (24), we can calculate the outage probability of (21).

V. DIVERSITY-MULTIPLEXING TRADEOFF

If the system is not in outage, the spectral efficiency of our proposal is R when cooperation is not required and $R/2$ when cooperation is required. Therefore, if $|\alpha_{\mathrm{SD}}|^2 \geq |\alpha_{Th}|^2$, then the spectral efficiency is R otherwise it is $R/2$. The average spectral efficiency of the system over many coherent intervals can be given as

$$\begin{aligned} \bar{R} &= \left(1 - P^{\mathrm{Out}}\right)\left(\Pr\left[|\alpha_{\mathrm{SD}}|^2 \geq \frac{2^R - 1}{\mathrm{SNR}}\right] R \right. \\ &\quad \left. + \Pr\left[|\alpha_{\mathrm{SD}}|^2 < \frac{2^R - 1}{\mathrm{SNR}}\right] \frac{R}{2}\right) \\ &= \left(1 - P^{\mathrm{Out}}\right)\left[1 + \exp\left(-\sigma_{\mathrm{SD}}^{-2}\frac{2^R - 1}{\mathrm{SNR}}\right)\right]\frac{R}{2}. \end{aligned} \tag{25}$$

At high SNR, $P^{\mathrm{Out}} \to 0$ and (25) can be approximated as

$$\lim_{\mathrm{SNR}\to\infty} \bar{R} = (1 + 1)\frac{R}{2} = R. \tag{26}$$

Fig. 2 shows the average spectral efficiency as a function of the average SNR. It is clear from Fig. 2 that the average spectral efficiency of our proposal is very close to R at high SNR as is evident from (26). In this figure, we also compare the spectral efficiencies of different protocols. Fig. 2 shows the average spectral efficiency of our proposed protocol is higher than that of the opportunistic relaying and greater than or equal to direct transmission at the SNR region of interest.

The standard definition for diversity gain (δ) and multiplexing gain (ρ) as a function of SNR is given in [11] as

$$\begin{aligned} \delta &= -\lim_{\mathrm{SNR}\to\infty} \frac{\log\left(P^{\mathrm{Out}}(\mathrm{SNR})\right)}{\log(\mathrm{SNR})}, \\ \rho &= \lim_{\mathrm{SNR}\to\infty} \frac{\log(R(\mathrm{SNR}))}{\log(\mathrm{SNR})}. \end{aligned} \tag{27}$$

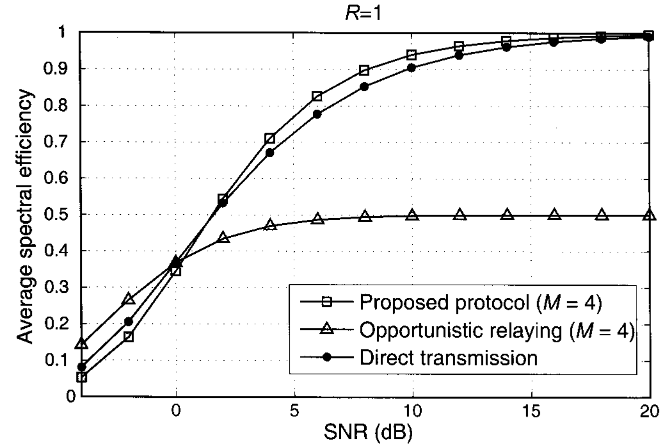

Fig. 2. Spectral efficiency of different protocols.

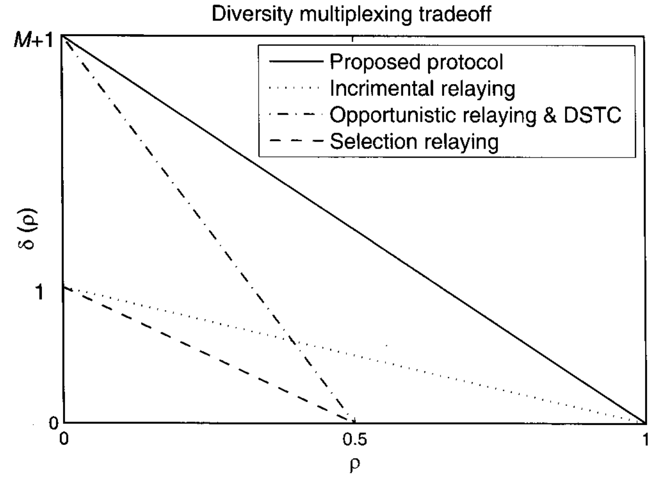

Fig. 3. Diversity-multiplexing tradeoff of different protocols.

The diversity-multiplexing tradeoff (DMT) of our proposed proactive protocol is the same as the opportunistic relaying with single round feedback proposed in [9] and given as

$$\delta_P(\rho) = (M+1)(1-\rho). \tag{28}$$

To derive the DMT of the reactive protocol, assume that the channels are identically independent, i.e., $\sigma_{\mathrm{SD}}^{-2} = \sigma_2^{-2} = \sigma^{-2}$. For this high SNR DMT analysis, we are interested in the diversity gain, which is not dependent on this assumption. To derive the DMT, we need to approximate the outage probability of the reactive protocol at high SNR. At SNR $\to \infty$, $K \to M$; hence, the outage probability of (21) becomes

$$\begin{aligned} P_R^{\mathrm{Out}}(\mathrm{SNR}) &\approx \Pr(\mathrm{Out}\,|M) \\ &= \Pr\left[\left(|\alpha_{\mathrm{SD}}|^2 + |\alpha_{\mathrm{BD}}|^2\right) < \frac{2^R-1}{\mathrm{SNR}}\right] \end{aligned} \tag{29}$$

where $|\alpha_{\mathrm{BD}}|^2$ is the channel gain of the best relay to the destination which is the maximum of M exponential random variables with parameter σ^{-2}. The outage probability at SNR $\to \infty$ can be calculated using the CDF of Lemma 2 of the Appendix as

$$P_{RP}^{\mathrm{Out}}(\mathrm{SNR}) \approx \frac{(\sigma^{-2})^{M+1}}{M+1}\left(\frac{2^R-1}{\mathrm{SNR}}\right)^{M+1}. \tag{30}$$

From (30) it is clear that the proposed reactive protocol achieves a diversity of order $(M+1)$. Using the definitions of (27) and the outage probability of (30), we can easily obtain the DMT as

$$\delta_R(\rho) = (M+1)(1-\rho). \tag{31}$$

Therefore, both reactive and proactive protocols afford the same DMT. Fig. 3 shows the DMT of our proposal compare to the other protocols proposed in [1], [5], and [6]. A similar DMT analysis of different relaying protocols for single relay ($M = 1$) environment has been shown [1]. In this paper, we consider M relays which involves relay selection along with cooperation selection algorithm. Consequently, the maximum diversity order in Fig. 3 is $M+1$.

VI. NUMERICAL AND SIMULATION RESULTS

The main contributions of the proposed schemes are improving the spectral efficiency and diversity multiplexing tradeoff. The comparisons among the proposed scheme and other well-known relaying schemes, in terms of spectral efficiency and diversity-multiplexing tradeoff, are presented in Figs. 2 and 3. Figs. 2 and 3 show that the proposed schemes operate on higher spectral efficiency than other relay selection schemes. In this paper, we avoid the comparison with other relay selection schemes, in terms of outage probability, because of this different spectral efficiency of the protocols. In this section, we provide some numerical results for the outage probabilities developed in Sections III and IV and verify these results with simulations. We show the outage probabilities of both proactive and reactive protocols as a function of the average SNR without fading. We consider a symmetric source to relays and relays to destination channel. We assume, $\sigma_1^2 = 1.5$, $\sigma_2^2 = 1$, $\sigma_{\mathrm{SD}}^2 = 0.75$, and $R = 1$ bps/Hz for all cases of our simulation. The variance of channel coefficient reflects the channel quality. The assumed values of the channel variances indicate that the average quality of the source-to-relay and relay-to-destination channels is better than the source-to-destination channel. Also, the quality of the source-to-relay channel is better than the relay-to-destination channel.

Fig. 4 shows the outage probability as a function of the SNR for proactive protocols with different numbers of relays. In the proactive protocol the outage probability developed in (17) is an upper bound as depicted in Fig. 4. Fig. 5 shows the outage probabilities of the reactive protocol with different numbers of relays as a function of the SNR. In this case the analytical outage probability of (21) is an exact expression therefore, the simulation and numerical results match very well. Both simulation and numerical results clearly indicate the improvement of the diversity order as the number of relays increases for both the proactive and reactive protocol.

In Fig. 6, we compare the outage probabilities of the proactive and reactive protocols through simulation. These results show that the reactive protocol performs better than the proactive protocol and this improvement increases as the number of

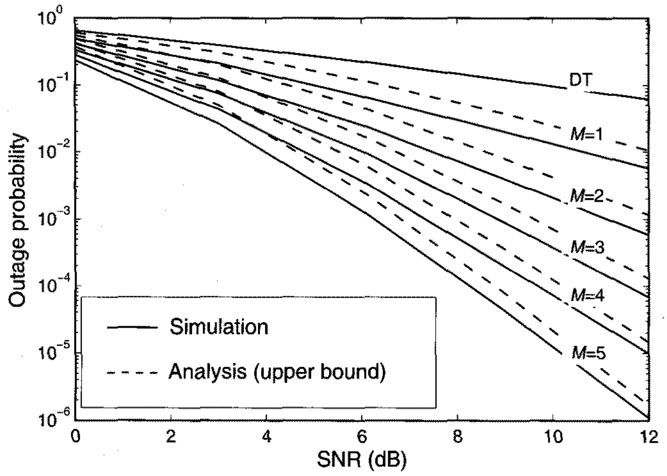

Fig. 4. Outage probability of the proactive protocol as a function of the SNR.

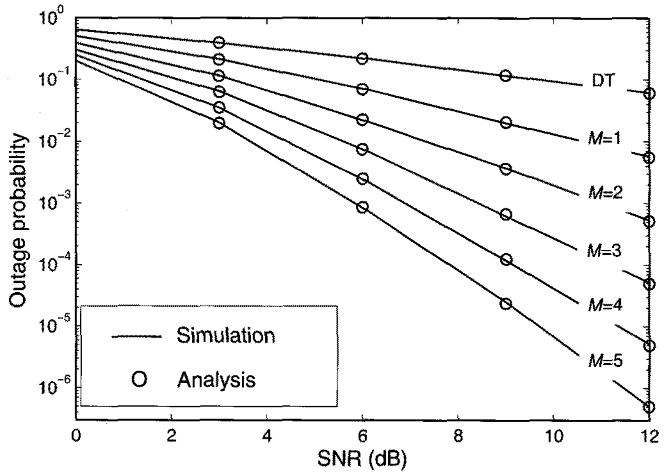

Fig. 5. Outage probability of the reactive protocol as a function of the SNR.

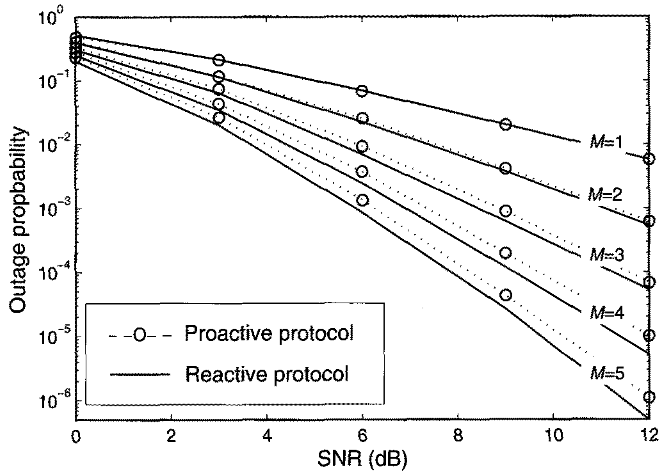

Fig. 6. Outage probability comparison of the proactive and reactive protocols.

relays increase. This result suggests that the reactive relay selection policy is better than the proactive one. Bletsas *et. al.* in [7] showed that opportunistic relaying is outage optimal when only cooperative links are considered, i.e., the destination decodes the signal received from the best relay. In this paper, we consider that the destination optimally combines the signals received from the source and the best relay. Therefore, the best relay-to-destination channel does not necessarily require carrying the whole information because the source-to-destination channel carries a portion of the information. Hence, when the destination optimally combines two links, our proposed reactive relay selection performs better than opportunistic relaying.

VII. DISCUSSION

In this study cooperation selection is integrated with relay selection to reduce implementation complexity. In the proactive protocol, we show that the instantaneous channel-gain-based relay selection like the opportunistic relaying technique can be used for cooperation selection without any extra overhead. In the reactive protocol, we propose an ARQ based cooperation selection like incremental relaying and show that this cooperation selection technique can be used for the best relay selection without any extra control signal. In this section, we give some comparisons between the proactive and reactive protocols in terms of implementation issues.

a. Control signals: The proactive protocol requires two control signals (RTS and CTS) in all cases of transmission whereas the reactive protocol requires only one (ACK or NACK). In [9], a hybrid protocol has been proposed where the relay selection is proactive and the cooperation selection is reactive. This hybrid protocol requires three control signals (RTS, CTS, and NACK). The best relay flag needs to be transmitted by the selected best relay for all protocols. Here, we only consider the control signals require to measure the instantaneous CSI to implement the cooperation selection and the relay selection.

b. Coherent time: Once a relay is selected, the selection is valid over the channel coherent time which restricts the proactive and the hybrid protocols to transmit over half of the channel coherent time from the source and relay when cooperation is needed. If cooperation is not required, the source can transmit over the entire channel coherent time. The source can adjust this variable nature of channel use in two ways. a) The source can transmit in a rate-adaptive fashion (source transmits with a rate R when cooperation is not required and with a rate $2R$ when cooperation is required). In this case, nodes should be equipped with adaptive rate transmitters and receivers. Obviously, this is not a good strategy because by transmitting at a higher rate when cooperation is required, it becomes more difficult for the selected relay to decode the source transmission. b) The source can always transmit over the half of channel coherent time with a fixed rate. If cooperation is needed, the best relay forwards over the next half of the channel coherent time. If cooperation is not needed, the source starts a new phase with a new RTS message. In this case, we need to execute cooperation selection and relay selection procedures twice over the coherent time if cooperation is not needed. At high SNR cooperation

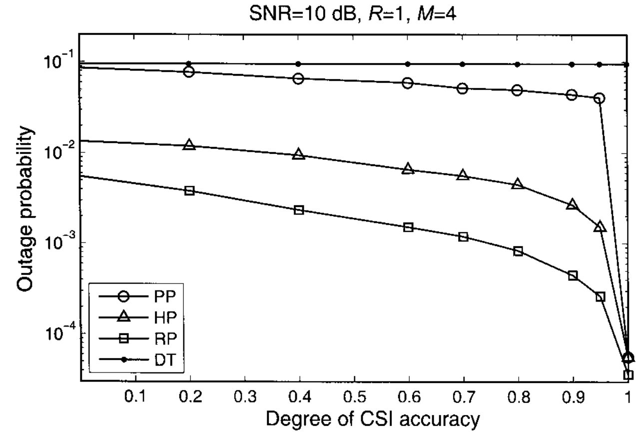

Fig. 7. Effect of inaccurate CSI on outage probability

is rarely required; therefore, the cooperation selection and the relay selection procedures must be executed almost twice the number of times in the adaptive case. On the other hand, in the reactive protocol, the source can transmit over the entire channel coherent time without considering the cooperation selection and relay selection. Hence, the reactive protocol can reduce the number of selection procedures without without the use of the rate adaptation technique.

c. Inaccurate CSI: Due to channel variation or estimation error, the measured CSI ($|\hat{\alpha}_{ij}|^2$) can differ from the actual CSI ($|\alpha_{ij}|^2$) [14]. The proactive protocol (PP) is more vulnerable to channel estimation error than the reactive protocol as both cooperation selection and relay selection are performed by using the instantaneous channel measurement. In the reactive protocol (RP), only relay selection is performed by using estimated instantaneous CSI. The cooperation selection is done after the message is transmitted by the source so other error checking techniques for example, a cyclic-redundancy-check (CRC) can be used at the destination to make this decision. The performance of the hybrid protocol [9] lies between the proactive and reactive protocols. In Fig. 7, we present the outage probabilities of the three protocols when measured CSI is inaccurate. We consider that the estimated CSI $|\hat{\alpha}_{ij}|^2$ and actual CSI $|\alpha_{ij}|^2$ are jointly Gaussian as,

$$|\hat{\alpha}_{ij}|^2 \sim N\left(c\,|\hat{\alpha}_{ij}|^2, (1-c^2)\sigma_{ij}^2\right) \tag{32}$$

where, c is the correlation coefficient between $|\hat{\alpha}_{ij}|^2$ and $|\alpha_{ij}|^2$ that represents the degree of measured CSI accuracy. Fig. 7 validates the above arguments and shows that the performance of the proactive protocol is substantially more affected by the inaccuracy of the CSI than the reactive protocol. Moreover, all these protocols require a highly accurate CSI estimation to obtain the full diversity. Importantly, all three protocols perform better than direct transmission (DT) for any value of c.

d. Overhearing: In the proactive and hybrid protocols, the best relay is selected before the source transmission. Hence, only the best relay needs to overhear the source message. In the reactive protocol the best relay is selected after the source transmission and all possible relays need to overhear the source message to participate in the relay selection procedure. Therefore, the reactive protocol provides the above mentioned advantages at the cost of this extra overhearing. This overhearing overhead is same as the DSTC but our proposal does not require the distributed space-time-coding algorithm proposed in [5].

VIII. CONCLUSION

This paper presents a new approach of instantaneous channel-measurement-based cooperation selection procedure that can greatly improve a system's spectral efficiency. We investigated this technique along with an instantaneous-channel-based relay selection procedure and showed that both cooperation selection and relay selection can be performed using the same control signals. We proposed two protocols in this paper; these protocols can select cooperation and the best relay to achieve a higher diversity-multiplexing tradeoff. We presented a method to calculate the outage probability of our proposal. We also analyzed the spectral efficiency and diversity order hence, the diversity-multiplexing tradeoff of our proposal. The approach presented in this work can be viewed as cross-layer design between the physical layer and the data-link layers. In this paper, only physical layer analysis is presented. Link layer analysis should be carried out in a future study.

APPENDIX

Fact 1: Let, $y = \max(y_1, y_2, \cdots, y_n)$, where, y_1, $y_2, \cdots$, y_n are n independent exponential random variables with common parameter λ_y. The pdf and CDF of the random variable y are

$$f_y(y) = n(1-e^{-\lambda_y y})^{n-1}\lambda_y e^{-\lambda_y y} \tag{33}$$

$$F_y = \left(1-e^{-\lambda_y y}\right)^n. \tag{34}$$

Lemma 1: Let, $z = x+y$, where, x is an exponential random variable with parameter λ_x and y is defined in Fact 1. Now the pdf and CDF of z are given by

$$f_z(z) = \begin{cases} \sum\limits_{i=0}^{n-1}(-1)^i\binom{n-1}{i}\frac{n\lambda_x\lambda_y}{(i+1)\lambda_y-\lambda_x} \\ \cdot\left[e^{-\lambda_x z}-e^{-(i+1)\lambda_y z}\right],\ \lambda_x \neq \lambda_y, \\ n\lambda^2 z e^{-\lambda z}+\sum\limits_{i=1}^{n-1}(-1)^i\binom{n-1}{i} \\ \cdot\frac{n\lambda}{i}\left[e^{-\lambda z}-e^{-(i+1)\lambda z}\right],\ \lambda_x=\lambda_y=\lambda, \end{cases} \tag{35}$$

$$F_z(z) = \begin{cases} \sum\limits_{i=1}^{n-1}(-1)^i\binom{n-1}{i}\frac{n\lambda_x\lambda_y}{(i+1)\lambda_y-\lambda_x}\left[\frac{1}{\lambda_x}\left(1-e^{-\lambda_x z}\right)\right. \\ \left.-\frac{1}{(i+1)\lambda_y}\left(1-e^{-(i+1)\lambda_y z}\right)\right],\lambda_x \neq \lambda_y, \\ n\left[1-(1+\lambda z)e^{-\lambda z}\right]+\sum\limits_{i=1}^{n-1}(-1)^i\binom{n-1}{i}\frac{n}{i} \\ \cdot\left[1-e^{-\lambda z}-\frac{1}{i+1}\left\{1-e^{-(i+1)\lambda z}\right\}\right],\ \lambda_x=\lambda_y=\lambda. \end{cases} \tag{36}$$

Proof:

Case 1: $\lambda_x \neq \lambda_y$

The pdf of the summation of two random variables can be written using the approach of [12] as

$$
\begin{aligned}
f_z(z)=&\int_0^z f_x(z-y)f_y(y)dy\\
=&\int_0^z \lambda_x e^{-\lambda_x(z-y)}n(1-e^{-\lambda_y y})^{n-1}\lambda_y e^{-\lambda_y y}dy\\
=&\int_0^z n\lambda_x\lambda_y e^{-\lambda_x z}\sum_{i=0}^{n-1}(-1)^i\binom{n-1}{i}e^{-\{(i+1)\lambda_y-\lambda_x\}y}dy\\
=&\sum_{i=0}^{n-1}(-1)^i\binom{n-1}{i}\frac{n\lambda_x\lambda_y}{(i+1)\lambda_y-\lambda_x}\left[e^{-\lambda_x z}-e^{-(i+1)\lambda_y z}\right].
\end{aligned}
\tag{37}
$$

Now the CDF is given by

$$
\begin{aligned}
F_z(z)=&\int_0^z f_z(z)dz\\
=&\sum_{i=1}^{n-1}(-1)^i\binom{n-1}{i}\frac{n\lambda_x\lambda_y}{(i+1)\lambda_y-\lambda_x}\\
&\cdot\left[\frac{1}{\lambda_x}\left(1-e^{-\lambda_x z}\right)-\frac{1}{(i+1)\lambda_y}\left(1-e^{-(i+1)\lambda_y z}\right)\right].
\end{aligned}
\tag{38}
$$

Case 2: $\lambda_x = \lambda_y = \lambda$
In this case the summation of (37) is undetermined for $i = 0$. Using the fact that $\lim_{i\to 0}\frac{1}{i\lambda}(1-e^{-i\lambda z}) = z$; we can derive the pdf for this case from (37).

Now the CDF is given by

$$
\begin{aligned}
F_z(z)=&\int_0^z f_z(z)dz\\
&= n\lambda^2\int_0^z ze^{-\lambda z}dz+\sum_{i=1}^{n-1}(-1)^i\binom{n-1}{i}\\
&\cdot\frac{n\lambda}{i}\int_0^z\left[e^{-\lambda z}-e^{-(i+1)\lambda z}\right]dz\\
&= n\left[1-(1+\lambda z)e^{-\lambda z}\right]+\sum_{i=1}^{n-1}(-1)^i\binom{n-1}{i}\frac{n}{i}\\
&\cdot\left[1-e^{-\lambda z}-\frac{1}{i+1}\left\{1-e^{-(i+1)\lambda z}\right\}\right].
\end{aligned}
\tag{39}
$$

□

Lemma 2: Let, $z = x + y$, where, x is an exponential random variable with parameter λ_x and y is defined in Fact 1 and consider $\lambda_x = \lambda_y = \lambda$. Now, at $\lambda \to 0$ the pdf and CDF of z can be approximated as

$$f_z(z) \approx \lambda(1-\lambda z)(\lambda z)^n \tag{40}$$

$$F_z(z) \approx \frac{1}{n+1}(\lambda z)^{n+1}. \tag{41}$$

Proof: Using the approximation $e^\tau \approx (1+\tau)$ the second equality of (37) can be written as

$$
\begin{aligned}
f_z(z) \approx& \int_0^z n\lambda^2(1-\lambda z)(\lambda y)^{n-1}dy\\
=&n\lambda^{n+1}(1-\lambda z)\frac{1}{n}z^n\\
=&\lambda(1-\lambda z)(\lambda z)^n.
\end{aligned}
\tag{42}
$$

Now the CDF can be given as

$$
\begin{aligned}
F_z(z) &\approx \int_0^z \lambda(1-\lambda z)(\lambda z)^n dz\\
&= \frac{1}{n+1}(\lambda z)^{n+1}-\frac{1}{n+2}(\lambda z)^{n+2}\\
&= \frac{1}{n+1}(\lambda z)^{n+1}\left(1-\frac{n+1}{n+2}(\lambda z)\right)\\
&= \frac{1}{n+1}(\lambda z)^{n+1}.
\end{aligned}
\tag{43}
$$

The last approximation follows from the fact that $\lambda \to 0$. □

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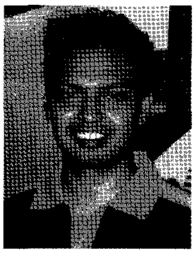

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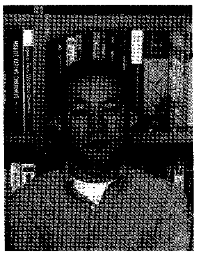

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