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PERFORMANCE ANALYSIS OF SELECTION COOPERATION SYSTEM WITH DYNAMICALLY CHANGING RELAY NUMBER

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Abstract. *Selection cooperation has been widely investigated as a simple but efficient strategy to improve the performance of cooperative systems. In the most of previous works, the analysis of selection cooperation has largely focused on the assumption that the number of available relays is deterministic. However, in many practical systems, one relay may be occupied by other users and thus it is unavailable for a special user (i.e., the given source) in one transmission, which will cause a change in the number of available relays for the special user. As a result, the previous analysis may not be valid in this case. In this paper, we analyze the outage performance of decode-and-forward (DF) selection cooperation system with dynamically changing relay number (DC-RN). By modeling each relay service for the given source in this proposed system as a Markov on-off chain, a close-form expression for outage probability is derived. Our numerical results verify the accuracy of the obtained analytical results.*
Keywords: Selection cooperation, Outage probability, Dynamically changing relay number, Cooperative system

1. **Introduction.** Recently, cooperative communication has attracted much attention because it can significantly provide additional spatial diversity for wireless systems and thereby further improve the system communication performance [1-4]. Among existing cooperative schemes, selection cooperation is often considered as a promising cooperation scheme due to its simplicity of implementation and excellent performance. It has been proved that the single relay selection [5], which just selects a relay with the maximum relay-destination channel value (i.e., *the best relay*) to perform cooperation, can still achieve the same full diversity order as other multiple relay selections, such as the distributed space-time-coded scheme in [6]. Based on the work of Beres and Adve in [7], various extensions to the case of selection cooperation have been investigated, e.g., [8-12].

In the literature of cooperative communication, most of the analytical results are derived based on the idealistic assumption of a fixed number of available relays. That is, each relay in the cooperative system is assumed exactly available in every transmission. Consequently, general analytical results imply that the system performance is heavily determined by the defined number of available relays. In practice, the relay may absent itself in one transmission because it may serve other users, namely, it may be preoccupied by others, and thus change the number of the available relays, especially in wireless sensor networks (WSNs). Therefore, the dynamics of number of available realys should be considered in performance analysis. In [13], an amplify-and-forward (AF) relay network with varying number of relays (RN-VR) is investigated. Each relay in RN-VR is modeled as a queueing system and follows a continuous time Markov on-off process. Then, the outage performance of RN-VR in several configurations is analyzed. It mainly studied the opportunistic relaying operates under AF in RN-VR, and hence the case of selection cooperation system with dynamically changing relay number is still an open issue.

Moreover, the direct link from source to destination is assumed to be not available, which means that it simplifies the analysis by excluding the direct transmission.

In [14], the authors propose a novel decode-and-forward (DF) selection cooperation scheme which has a remarkable performance with low complexity. This scheme is referred as lightweight selection cooperation (LSC). In this paper, we extend the LSC to DC-RN scenario with the direct transmission consideration. We still model each relay as a queuing system. Unlike the model in [13], no blocked direct link (source-destination) is assumed in our model, which should be more practical for some scenarios, such as for WSNs. Besides, the selection scheme used in this work takes full advantage of feedback to improve the spectral efficiency. Based on the model, the outage probability of the LSC with DC-RN is derived and the effects of dynamics of relay number on the cooperative system performance are analyzed via simulation, which can make great contributions to the design of practical selection cooperation systems in the future.

The rest of the paper is organized as follows. Section 2 describes the system model and the cooperation scheme. In Section 3, the outage probability analysis is given. Section 4 presents the simulation results of our method. Section 5 concludes the work.

2. **System Model and Cooperation Scheme.**

2.1. **System model.** We consider the basic system model of [14], where a source s sent a message at a rate of R to the destination d while multiple half-duplex relays (r_i, $i = 1, \cdots, M$) may help in this transmission using the same codebook as the source. The channels between s and d ($\alpha_{s,d}$), s and r_i, (α_{s,r_i}), r_i and d ($\alpha_{r_i,d}$) and the inter-relay channels (α_{r_i,r_j}) are all assumed to be flat and quasi-static independent Rayleigh fading with variance $1/\lambda_{s,d}$, $1/\lambda_{s,r_i}$, $1/\lambda_{r_i,d}$ and $1/\lambda_{r_i,r_j}$, respectively. Aside from this, we assume all the channels are reciprocity and remain constant over one information message transmission time, including possible cooperation retransmission time. We also assume that each transmission occurring in this system is performed on the orthogonal channels under the power constraint P. The noise at each node is independent, zero-mean, circularly symmetric white complex Gaussian with variance σ^2, and hence, the average signal-to-noise ratio (SNR) ρ at each receiver can be expressed as: $\rho = P/\sigma^2$. Moreover, for each relay, perfect receive-side channel state information (CSI) is assumed and can be acquired from feedback frames, namely acknowledgment (ACK) or negative acknowledgement (NACK).

Because of being preoccupied by other users, one relay may not be available for the particular user (source s) in one transmission so that it will not be involved in the cooperation. That is to say, any relay in this system can just serve only one user at a time. Consequently, as in [13], the occupancy of relay r_i can be modeled as a continuous time Markov on-off process, with unavailable and available periods exponentially distributed with means $\lambda_{r_i}^{-1}$ and generally distributed with means $\mu_{r_i}^{-1}$, respectively. According to the definition in [15], the generator matrix of relay r_i can be given by

$$Q_i = \begin{pmatrix} -\lambda_{r_i} & \lambda_{r_i} \\ u_{r_i} & -u_{r_i} \end{pmatrix} \tag{1}$$

and the stationary distribution that the relay r_i is available can be expressed as $v_{r_i}(0) = 1/(1 + \lambda_{r_i}/\mu_{r_i})$ and can be further written as $v_{r_i}(0) = 1/(1 + \eta_{r_i})$, where $\eta_{r_i} = \lambda_{r_i}/\mu_{r_i}$.

2.2. **Cooperation scheme.** In the DC-RN cooperation system, the particular source s intends to transmit information to the destination d with the help of some available relays by using LSC. For notational simplicity, we use $Ra(s)$ to denote the set of the available relays in one transmission. As illustrated in Figure 1, the whole cooperation communication process contains the following two phases.

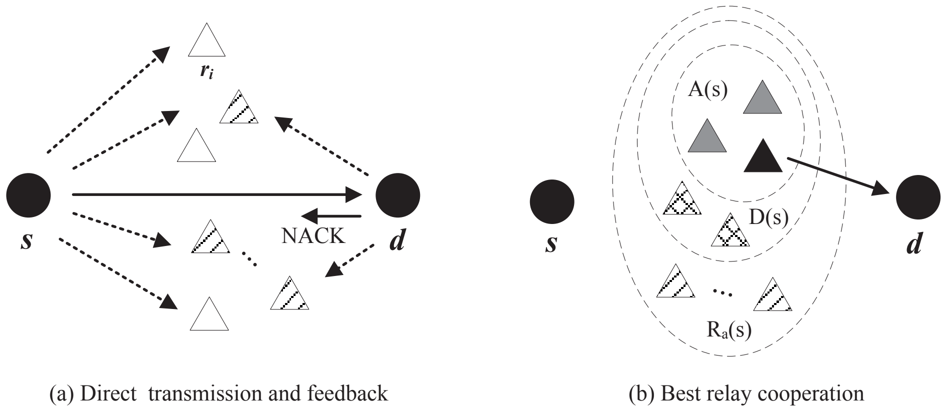

FIGURE 1. Illustration of the cooperation process of LSC with DC-RN. The nodes filled with white color are preoccupied relays while the nodes filled with lines are available relays. The nodes filled with gridding are decoding relays. The nodes filled with gray color are active relays and the nodes filled with black color is the best relay.

Direct Transmission: The source s distributes its data directly, and then the destination d and every available relay in $Ra(s)$ (rather than all the relays) attempt to decode this message. If the direct transmission succeeds, the destination feeds back ACK and the current transmission is finished. Otherwise, the destination feeds back NACK. And the cooperative transmission will be performed in the second phase.

Best Relay Cooperation: The available relays (i.e., relays in $Ra(s)$) that successfully decode the message from the source compose the decoding set $D(s)$. The relays belonging to $D(s)$ that also correctly decodes the NACK will form a new set called active set $A(s)$. Each of the relay in $A(s)$ will compete for the best relay. The relay with the best instantaneous relay-destination channel will be selected as the best relay. Then the selected best relay will forward the message to the destination immediately.

By using the feedback scheme in the LSC and modelling each relay as a queueing system, both the direct transmission link and the dynamics of relay number will be fully considered in the outage analysis, which will be discussed in the next section detailedly. In addition, it is the utilization of feedbacks (i.e., ACK/NACK frames) that reduces both the complicated message which exchanges between relays and the destination and the radio complexity (since the radios of nodes do not need to perform any combining reception). This is the reason why the protocol is named as LSC.

3. **Outage Probability Analysis.** In this section, we analyze the outage probability of selection cooperation with DC-RN. According to the protocol description in Section 2, one successful information message transmission only occurs in two cases: 1) The destination correctly decodes the message from source; 2) the direct transmission fails but the cooperative retransmission succeeds, that is, there is at least one available relay that joins in $A(s)$ and can afford a high enough relay-destination channel to support cooperative retransmission. Hence, it is easy to see that the typical outage event occurs only when the direct transmission fails and $A(s)$ is empty. Let β denote the cooperation failure. Then, the outage probability is given by

$$P_{out} = \Pr\{I_C < R/2|\beta\} \Pr\{\beta\} \tag{2}$$

where I_C denotes the mutual information between the source s and the destination d for cooperation.

When the event occurs, no available relay can support the cooperative retransmission, so the first term of (2) can be given by [14]

$$\Pr\left\{I_C < \frac{R}{2}\middle|\beta\right\} = \Pr\left\{\frac{1}{2}\log\left(1+\rho|\alpha_{s,d}|^2\right) < \frac{R}{2}\right\} = 1 - e^{-\lambda_{s,d}\cdot g} \tag{3}$$

where $g = \left(2^R - 1\right)/\rho$.

Then, we consider the second term of (2). Since each relay may be busy in serving in one transmission, namely being preoccupied by other users. So the number of available relays for the particular source s is not the same in each transmission, and thus, $Ra(s)$ is a random set. Besides, the decoding set $D(s)$ is formed based on $Ra(s)$ and is also a random set. According to the total probability law in [10], the probability of event β can be written as

$$\begin{aligned}\Pr\{\beta\} &= \sum_{R_a(s)\subseteq R}\sum_{D(s)\subseteq R_a(s)} \Pr\{\beta, D(s), R_a(s)\}\Pr\{R_a(s)\} \\ &= \sum_{R_a(s)\subseteq R}\sum_{D(s)\subseteq R_a(s)} \Pr\{\beta, D(s)|R_a(s)\}\Pr\{R_a(s)\} \\ &= \sum_{R_a(s)\subseteq R}\sum_{D(s)\subseteq R_a(s)} \{\Pr\{\beta|D(s), R_a(s)\}\times\Pr\{D(s)|R_a(s)\}\Pr\{R_a(s)\}\}\end{aligned} \tag{4}$$

where $R = \{1, 2, \cdots, M\}$ is the set of the all relays in the cooperation system.

In order to solve (4), we first calculate the probability of available relay set. For a relay available for the source s, we have

$$\Pr\{r_i \in R_a(s)\} = v_{r_i}(0) = \frac{1}{1+\eta_{r_i}} \tag{5}$$

where $\eta_{r_i} = \lambda_{r_i}/\mu_{r_i}$ represents the traffic intensity in a queueing system [15].

Since each relay performs independent service, then, we further obtain

$$\begin{aligned}\Pr\{R_a(s)\} &= \prod_{r_k\in R\backslash R_a(s)} (1-\Pr\{r_k\in R_a(s)\})\times\prod_{r_j\in R_a(s)}\Pr\{r_j\in R_a(s)\} \\ &= \prod_{r_j\in R_a(s)}\frac{1}{1+\eta_{r_j}}\times\prod_{r_k\in R\backslash R_a(s)}\frac{\eta_{r_k}}{1+\eta_{r_k}}\end{aligned} \tag{6}$$

Next, we consider the term, the decoding set probability conditioned on the available relay set. Same as in [14], a relay r_i is not in the decoding set D(s) if the s-r_i channel satisfies the condition below:

$$\Pr\{r_i \notin D(s)\} = \Pr\left\{\log\left(1+\rho|\alpha_{s,r_i}|^2\right) < R\right\} = 1 - e^{-\lambda_{s,r_i}\cdot g} \tag{7}$$

Then, we have

$$\Pr\{D(s)|R_a(s)\} = \prod_{r_v\in R_a(s)\backslash D(s)}\left(1-e^{-\lambda_{s,r_v}\cdot g}\right)\times\prod_{r_i\in D(s)} e^{-\lambda_{s,r_i}\cdot g} \tag{8}$$

From [14], for a relay r_i in $D(s)$, the probability which fails to join $A(s)$ is $\mathrm{P}_{rr} = 1 - e^{-\lambda_{r_i,d}\cdot g}$. Using this result, we get

$$\Pr\{\beta|D(s), R_a(s)\} = \prod_{r_i\in D(s)}\left(1-e^{-\lambda_{r_i,d}\cdot g}\right) \tag{9}$$

After that, substituting (6), (8) and (9) into (4), we obtain the probability of event β. Finally, by substituting this result and (3) into (2), the total outage probability is obtained

$$\begin{aligned} P_{out} = \left(1 - e^{-\lambda_{s,d} \cdot g}\right) \sum_{R_a(s) \subseteq R} \sum_{D(s) \subseteq R_a(s)} & \left[\prod_{j \in R_a(s)} \frac{1}{1+\eta_j} \times \prod_{k \in R \backslash R_a(s)} \frac{\eta_k}{1+\eta_k} \right. \\ & \left. \times \prod_{r_i \in D(s)} \left(e^{-\lambda_{s,r_i} \cdot g} - e^{-\left(\lambda_{s,r_i} + \lambda_{r_i,d}\right) \cdot g} \right) \times \prod_{r_v \in R_a(s) \backslash D(s)} \left(1 - e^{-\lambda_{s,r_v} \cdot g}\right) \right] \end{aligned} \tag{10}$$

As a special case, where both the unavailable and available periods for every relay r_i are identically distributed, namely, $\lambda_{r_i} = \lambda$ and $\mu_{r_i} = \mu$, then the total outage probability can be further simplified as

$$\begin{aligned} P_{out} = \left(1 - e^{-\lambda_{s,d} \cdot g}\right) \sum_{R_a(s) \subseteq R} \sum_{D(s) \subseteq R_a(s)} & \left[\left(\frac{1}{1+\eta} \right)^{|R_a(s)|} \times \left(\frac{\eta}{1+\eta} \right)^{|R| - |R_a(s)|} \right. \\ & \left. \times \prod_{r_i \in D(s)} \left(e^{-\lambda_{s,r_i} \cdot g} - e^{-\left(\lambda_{s,r_i} + \lambda_{r_i,d}\right) \cdot g} \right) \times \prod_{r_v \in R_a(s) \backslash D(s)} \left(1 - e^{-\lambda_{s,r_v} \cdot g}\right) \right] \end{aligned} \tag{11}$$

where $\eta = \lambda/\mu$.

4. **Simulation Results.** In this section, numerical results are provided to illustrate the theoretical analysis. We note that the system in [13] also considers the occupancy of relays, but its cooperative scheme is different from the one investigated in this paper. As for the analysis in [14], it is in fact a special case of this work, that is, the traffic intensity $\eta = 0$ in the proposed system, which means that each relay in the system is available. In this paper, we focus on analyzing the performance of selection cooperation proposed in [14] in terms of DC-RN, and thus we just present the comparisons with conventional selection cooperation in [5] for further investigation. Throughout this section, we set the rate as $R = 1$b/s/HZ and arbitrary channel undergoes Rayleigh fading.

The outage probability curves of the LSC with DC-RN for different numbers of relays ($M = 3, 4, 5, 6, 7$) at $\eta = 0.5$ are plotted in Figure 2. Meanwhile, the conventional selection cooperation which utilizes combining reception with DC-RN is also presented in the same figure. From Figure 2, it is clear that the analytical results for LSC with DC-RN well match with the simulation results so that the accuracy of the analysis is verified. Clearly, we can see that both the outage probabilities of LSC and conventional selection with DC-RN decrease as the number of relays increases. Moreover, we also observe that on the condition of the same number of relays (e.g., $M = 3$) at the given traffic intensity (i.e., $\eta = 0.5$), that is, in the case of almost fixed in number of available relays, the outage probability of convention selection is slightly higher than that of LSC because of its combining reception, which is similar to the result given in [14].

In Figure 3, we present the outage probability of the LSC with DC-RN with different traffic intensities ($\eta = 0.1, 0.3, 0.5, 0.7, 0.9$). Considering a DC-RN network with four relays, for the sake of illustration, we assume the homogeneous case, namely, $\lambda_{r_i,d} = \lambda_{r_i,d} = \lambda_{r_i,d} = 1$. As depicted in Figure 3, it is easy to see that both the outage probabilities of LSC and conventional selection with DC-RN decrease as the traffic intensity (η) decreases, which can be attributed to the fact that decreasing traffic intensity can in turn increase the probability of one relay to be available and thus afford relay more opportunities to perform cooperation so that the system performance is improved significantly. From this result, we can see that in the case of DC-RN, the performances of LSC, as well as conventional selection, are not only determined by the total number of relays, but considerably effected by the traffic intensity, which provides some significant insights into the design of furture practical systems.

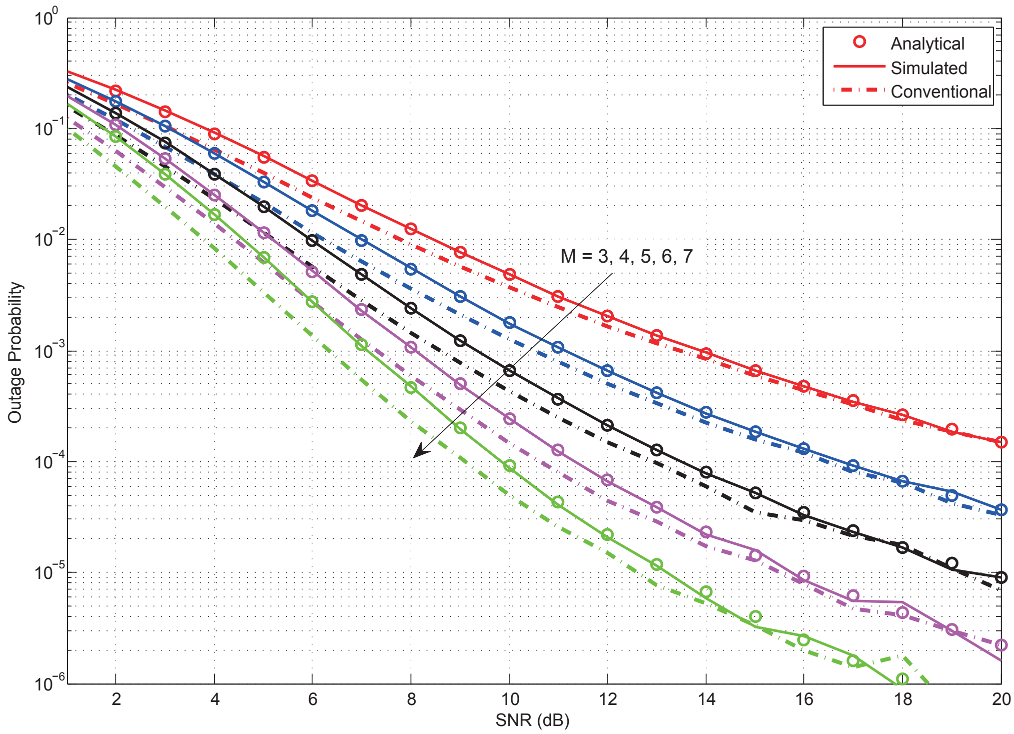

FIGURE 2. Comparison of the outage probability for LSC and the conventional selection cooperation with DC-RN for different numbers of relays (M) at $\eta = 0.5$

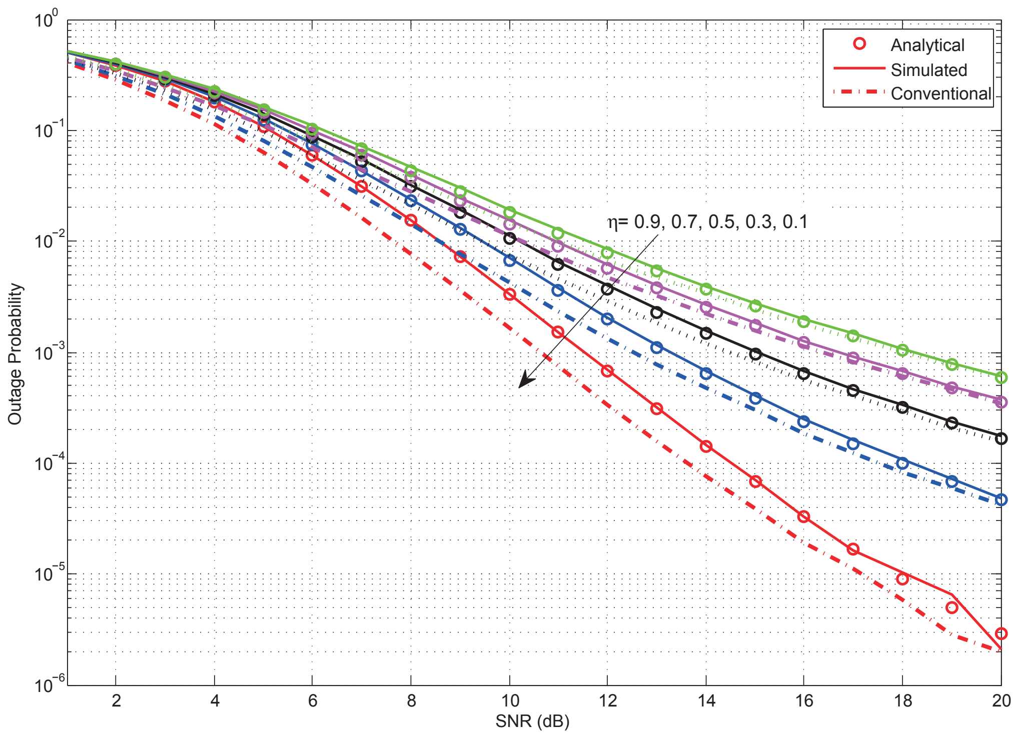

FIGURE 3. Comparison of the outage probability among simulated and analytical results of LSC as well as the conventional selection cooperation with DC-RN for different traffic intensities ($\eta = 0.1, 0.3, 0.5, 0.7, 0.9$) at $M = 4$

5. **Conclusion.** Motivated by a lack of analysis of selection cooperation with dynamically changing relay number, we have investigated the outage probability of a novel selection cooperation scheme in this scenario based on the queueing theory. Numerical results have been given as well to verify the investigation and provide insights into the outage performance of selection cooperation system affected by the dynamics of relay number.

In the future, we plan to implement the presented selection protocol in existing wireless systems and investigate its practical performance based on the system model proposed in this paper.

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