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Cooperative Multi-Hop Transmission Protocol with Incremental Relaying Strategy over Rayleigh Fading Channel

Tran Trung Duy · Chong-Koo An

Abstract

In this paper, we propose a novel protocol called Cooperative Multi-hop transmission using Incremental Relaying (CMIR). We evaluate the performance of the CMIR protocol by deriving expressions for the average end-to-end outage probability and the average number of transmissions. Monte Carlo simulations are presented to verify the accuracy of the theoretical analyses.

Key words: Outage Probability, Multihop Transmission, Rayleigh Fading Channel, Cooperative Communication, Incremental Relaying.

Ⅰ. Introduction

Cooperative wireless communication continues to attract a great deal of interest in the research community. Cooperative diversity exploits the broadcast nature of the wireless channel and allows single-antenna radios to share their antennas to form a virtual antenna array. The current literature describes studies on various cooperative transmission protocols [1], [2] from the viewpoint of implementation issues and performance evaluations. At present, most of the work related to cooperative communication has been performed on single-hop networks. However, the multi-hop relaying in which a source communicates with a destination via a number of relays has become a promising technique for applications in current and future wireless systems.

In a conventional multi-hop transmission (CMT), each relay on the line route only processes the signal received from its immediately preceding terminal and it forwards this signal to next terminal. However, each relay on the multi-hop route can employ diversity to improve the performance. Multi-hop diversity transmission protocols have been proposed and analyzed in previous studies [3]～[5]. In these protocols, each relay on the primary route can receive the signals from all previous transmitting terminals and combine them appropriately, before forwarding the detected signals. However, these strategies require each node to restore all versions of the received signals, which requires huge storage capacity. The end-to-end delay and the power consumption, which are important criteria in multi-hop transmission, are also not also considered.

In this paper, we propose a novel protocol called cooperative multi-hop transmission using incremental relaying (CMIR) to enhance the performance in terms of average end-to-end outage probability and average number of transmissions. We assume that a route between the source and the destination is established by the network layer. Due to broadcast nature of the wireless channel, each node that lies on this route can receive the packet transmitted by all previous nodes [3]～[5]. Whenever the destination decodes the packet incorrectly, it sends a negative acknowledgment (NACK) via feedback to request a retransmission. Then, a node that has successfully decoded the signal and that has the best channel to the destination is chosen to retransmit the packet. This strategy is called incremental relaying [1]. The best relay then becomes a new source and repeats the above process. This process is repeated until the destination receives the packet correctly or until no node between the new source and the destination can decode correctly.

In this study, we evaluate the performance of the CMIR protocol by deriving mathematical expressions for the average end-to-end outage probability and the average power consumption. Monte Carlo simulations are

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Department of Electronic Engineering, University of Ulsan, Ulsan, Korea.
Corresponding Author : Chong-Koo An (e-mail : ckan@mail.ulsan.ac.kr)

presented to validate the theoretical results. The proposed protocol improves the performance when compared to the CMT protocol and it achieves full diversity order, which is equal to the number of hops.

The rest of the paper is organized as follows. The system model and the proposed scheme are described in Section Ⅱ. In Section Ⅲ, the performance of the CMIR protocol is analyzed. The simulation results are presented in Section Ⅳ. Finally, the paper is concluded in Section Ⅴ.

Ⅱ. System Model

Fig. 1 presents an *N*-hop route consisting of nodes, i.e., 0, 1, 2, ⋯ , $N-1$, *N*, where node 0 is the source, node *N* is the destination and the remaining nodes are intermediate nodes or relays.

Each node is assumed to be equipped with a single antenna and operating in a half-duplex mode. Hence, for medium access, a time-division channel allocation is occupied in order to realize orthogonal channels. In this paper, we assume that control messages such as acknowledgment (ACK) and negative acknowledgment (NACK) also use powerful error-correcting codes (ECC) for error-free reception at all of the nodes on the established route. In addition, the size of control messages is also assumed to be small compared to that of the transmitted packet. Therefore, the delay time and transmit power for transmitting them can be ignored compared with those needed for transmitting the packet.

The packet received at node *r*, $r \in \{1,2,...,N\}$, due to the transmission of node *t*, $t \in \{0,1,2,...,N-1\}$, is given by

$$y_{r,t} = \sqrt{P} h_{r,t} x + \eta_r \tag{1}$$

where, *P* is the transmitted power of node *t*, *x* is the transmitted packet, $\eta_r(n)$ is AWGN noise with variance N_0, and $h_{r,t}$, which is modeled as block and flat Rayleigh fading, is the channel between nodes *i* and *j*.

The instantaneous received Signal-to-Noise Ratio (SNR) at the node *r* is expressed by

$$\gamma_{r,t} = P |h_{r,t}|^2 / N_0 = \bar{\gamma} |h_{r,t}|^2 \tag{2}$$

where $\bar{\gamma} = P / N_0$.

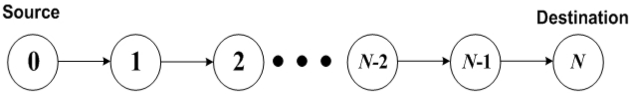

Fig. 1. An *N*-hop route established by network layer.

Because $h_{r,t}$ is the Rayleigh fading channel coefficient, $\gamma_{r,t}$ is an exponential random variable with parameter $\lambda_{r,t}$. Path loss is taken into account by expressing the parameter $\lambda_{r,t}$ as a function of distance between two nodes [6], as

$$\lambda_{r,t} = d_{r,t}^{\ \beta} \tag{3}$$

where β is path loss exponent that varies from 2 to 6 and $d_{r,t}$ is the distance between node *t* and node *r*.

The next section describes the transmission protocols applied on this route.

2-1 The CMT Protocol

In this protocol, the packet is transmitted sequentially from node *j* to node $j+1\left(0 \le j \le N-1\right)$. If node $j+1$ cannot correctly decode the packet received from node *j*, the packet will be dropped at this hop.

2-2 The CMIR Protocol

The operation of the proposed protocol is described as follows:

2-2-1 Step 1

At the first stage, the source transmits the packet, which can be received by the destination and all relays. The destination and all relays then attempt to decode the received packet. If the destination decodes successfully, the operation goes to Step 4. Otherwise, it moves to Step 2.

2-2-2 Step 2

The destination sends a NACK message to request a retransmission from one of relays. If no relays are available (between the transmitting node and destination) that can successfully decode the packet, the packet is dropped. Otherwise, the successful relay that has the best channel to the destination will become a new transmitter for the destination. The transmission of a NACK message from the destination allows estimation of the instantaneous wireless channel $h_{j,N}\left(1 \le j < N\right)$ between the destination and the successful relay *j*. Similar to an opportunistic relaying protocol [7], each successful relay sets a timer $T_j = \theta / |h_{j,N}|^2$, where θ is a constant. The successful relay that is first to have its timer reduced to zero first will then be selected for the retransmission. Now, the operation goes to Step 3.

2-2-3 Step 3

The chosen relay sends the packet to the destination and relays between it and the destination. If the destination decodes successfully, the operation goes to Step 4. Otherwise, Step 2 is repeated.

2-2-4 Step 4

The destination sends an ACK message to the source and all relays to inform. The transmission of this packet ends and the source starts to transmit a new packet.

In this paper, in order to avoid a huge storage capacity at the receivers, the received packet is removed from the relay and destination buffers after each stage.

Ⅲ. Performance Analysis

3-1 Outage Probability

In this paper, a node is considered to decode the packet successfully if the received SNR exceeds a predetermined threshold γ_{th}. Otherwise, this node is considered to have received the packet incorrectly.

Therefore, the probability that the link between nodes r and t is outage is calculated by

$$P_{out}(r,t) = \Pr\left[\gamma_{r,t} < \gamma_{th}\right] = \Pr\left[|h_{r,t}|^2 < \rho\right] \tag{4}$$

where $\rho = \gamma_{th}/\overline{\gamma}$.

From Eq. (3), we can calculate Eq. (4) as

$$P_{out}(r,t) = 1 - \exp\left(-\lambda_{r,t}\rho\right) \tag{5}$$

For the CMT protocol, we consider an N-hop route as presented in Fig. 1, where all hops are independent. Hence, the end-to-end outage probability this route can be given as

$$\begin{aligned} P_{out}^{CMT} &= 1 - \prod_{j=0}^{N-1}\left(1 - P_{out}(j, j+1)\right) \\ &= 1 - \exp\left(-\sum_{j=0}^{N-1}\lambda_{j,j+1}\rho\right) \end{aligned} \tag{6}$$

For the proposed protocol, the average end-to-end outage probability for an N-hop route can be expressed by a recursive expression as follows:

$$\begin{aligned} P_{out}^{\mathrm{CMIR}}(0,N) &= P_{out}(0,N) \\ &\times \left[\begin{aligned} &\prod_{k=1}^{N-1} P_{out}(0,k) \\ &+ \sum_{D_0} P(D_0)\left(\sum_{k=1}^{n_0=|D_0|} P_{out}^{\mathrm{CMIR}}\left(D_0(k),N\right)\right)\end{aligned}\right] \end{aligned} \tag{7}$$

where D_0 is set of nodes decoding successfully the packet received from the source 0 and $n_0 =| D_0 |$ is the number of nodes in set D_0 and $D_0(k)$ is node which belongs to set D_0 and has the best channel to the destination.

In addition, the term $\prod_{k=1}^{N-1} P_{out}(0,k)$ in Eq. (7) presents the case where all relays between the source and the destination cannot correctly decode the packet received from the source. Consider the set D_0, we can see that there are $2^{N-1}-1$ possible cases for each set D_0 and the probability for each one is calculated by

$$\begin{aligned} P(D_0) &= \prod_{k\in D_0}\left(1 - P_{out}(0,k)\right)\prod_{k\notin D_0} P_{out}(0,k) \\ &= \prod_{k\in D_0}\exp\left(-\lambda_{0,k}\rho\right)\prod_{k\notin D_0} 1 - \exp\left(-\lambda_{0,k}\rho\right) \end{aligned} \tag{8}$$

The term $P_{out}^{\mathrm{CMIR}}\left(D_0(k),N\right)$ in Eq. (7) can also be expressed by a recursive form as follows:

$$\begin{aligned} P_{out}^{\mathrm{CMIR}}\left(D_0(k),N\right) &= P_{out}^{best}\left(D_0(k),N\right) \\ &\times \left[\begin{aligned} &\prod_{k=D_0(k)+1}^{N-1} P_{out}\left(D_0(k),k\right) + \\ &\sum_{D_1} P(D_1)\left(\sum_{k=1}^{n_1=|D_1|} P_{out}^{\mathrm{CMIR}}\left(D_1(k),N\right)\right)\end{aligned}\right] \end{aligned} \tag{9}$$

where D_1 is set of nodes decoding successfully the packet received from the relay $D_0(k)$ and $n_1 =| D_1 |$ is the number of nodes in set D_1.

Next, we calculate the outage probability for the $D_0(k) - N$ link. At first, we assume that $D_0 = \{s_1, s_2, ..., s_n\}$ and $D_0(k) = s_j$ where $\{j,n\} \in \{1,2,...,N-1\}$, $1 \le j \le n$ and $1 \le s_1 < s_2 < ... < s_n \le N-1$. Because the node s_j belongs to set D_0 and has the best channel to the destination, hence we have $\gamma_{s_j,N} \ge \max\left(\gamma_{s_i,N}\right)$, where $i \in \{1,2,...,n\}$, $i \ne j$. If we denote $Y = \max\left(\gamma_{s_i,N}\right)$, the cumulative density function (CDF) of the random variable Y is given by

$$\begin{aligned} F_Y(x) &= \prod_{i=1, i\ne j}^{n_0-1}\Pr\left[\gamma_{s_i,N} < x\right] = \prod_{i=1,i\ne j}^{n_0-1}\left(1 - \exp\left(-\lambda_{s_i,N}x\right)\right) \\ &= 1 - \sum_{i=1,i\ne j}^{n_0-1}(-1)^i \sum_{\substack{m_1,...,m_i=1,\ne i \\ m_1<...<m_i}}^{n_0-1}\exp\left(-\omega_i x\right) \end{aligned} \tag{10}$$

where $\omega_i = \sum_{l=1}^{i}\lambda_{s_l,N}$.

Hence, the probability that the direct transmission from node s_j to the destination is an outage is calculated by

$$P_{out}^{best}\left(s_j,N\right)=\Pr\left[Y\le\gamma_{s_j,N}<\rho\right]$$
$$=\int_0^{\rho}f_{\gamma_{s_j,N}}\left(y\right)\int_0^{y}f_Y\left(x\right)dxdy \tag{11}$$

where $f_{\gamma_{s_j,N}}\left(y\right)$ and $f_Y\left(x\right)$ are probability density function (pdf) of the random variables $\gamma_{s_j,N}$ and Y, respectively. Note that $\gamma_{s_j,N}$ has exponential distribution with parameter $\lambda_{s_j,N}$ as mentioned above. Therefore, using Eq. (10) and Eq. (11), it can be calculated as

$$P_{out}^{best}\left(s_j,N\right)=1-\exp\left(-\lambda_{s_j,N}\rho\right)-$$
$$\sum_{i=1}^{n_0-1}\left(-1\right)^i\sum_{\substack{m_1,\ldots,m_i=1,\neq j\\ m_1<\ldots<m_i}}^{n_0-1}\frac{\lambda_{s_j,N}}{\lambda_{s_j,N}+\omega_i}\left[1-\exp\left(-\left(\lambda_{s_j,N}+\omega_i\right)\rho\right)\right] \tag{12}$$

Similarly, in case where the link s_j-N is not in outage, the probability for this event is calculated by

$$P_{sucess}^{best}\left(s_j,N\right)=\Pr\left[\gamma_{s_j,N}\ge Y,\ \gamma_{s_j,N}\ge\rho\right]$$
$$=\int_{\rho}^{+\infty}f_{\gamma_{s_j,N}}\left(y\right)\int_0^{y}f_Y\left(x\right)dxdy$$
$$=\exp\left(-\lambda_{s_j,N}\rho\right)$$
$$-\sum_{i=1}^{n_0-1}\left(-1\right)^i\sum_{\substack{m_1,\ldots,m_i=1,\neq j\\ m_1<\ldots<m_i}}^{n_0-1}\frac{\lambda_{s_j,N}\exp\left(-\left(\lambda_{s_j,N}+\omega_i\right)\rho\right)}{\lambda_{s_j,N}+\omega_i} \tag{13}$$

3-2 Average Number of Transmissions

In this subsection, we derive the average power consumption required for a successful delivery from the source to the destination.

In the CMT protocol, the source and all relays must transmit the packet to the destination; hence, the number of transmissions for a successful delivery is always equal to the number of hops of the established route, i.e., N.

For the CMIR protocol, let us first denote $\Pr_{x,y}(t)$ as the probability that the packet is transmitted successfully from node x to node y under the condition where t nodes are between node x and node y to transmit the packet, and where $x<y,\ t\le y-x, x\in\{0,1,\ldots,N-1\}$, $y\in\{1,\ldots,N\}$. Considering the probability $\Pr_{0,N}\left(t\right)$, this probability is calculated as

$$\Pr_{0,N}(t)=\begin{cases}0; & N<t\\ 1-P_{out}\left(0,N\right); & t=1\\ P_{out}\left(0,N\right)\times & \\ \left[\sum_{D_0}P\left(D_0\right)\sum_{k=1}^{n_0=|D_0|}\Pr_{D_0(k),N}\left(t-1\right)\right]; & t\ge2\end{cases} \tag{14}$$

In (14), $\Pr_{D_0(k),N}\left(t-1\right)$ is determined recursively by

$$\Pr_{D_0(k),N}\left(t-1\right)=$$
$$\begin{cases}0; & N-D_0\left(k\right)<t-1\\ P_{sucess}^{best}\left(D_0\left(k\right),N\right); & t=2\\ P_{out}^{best}\left(D_0\left(k\right),N\right)\times & \\ \sum_{D_1}\left[P\left(D_1\right)\sum_{k=1}^{n_1=|D_1|}\Pr_{D_1(k),N}^{\text{CMIR}}\left(t-1\right)\right]; & t\ge3\end{cases} \tag{15}$$

where, $P_{sucess}^{best}\left(D_0\left(k\right),N\right)$ and $P_{out}^{best}\left(D_0\left(k\right),N\right)$ are given in (12) and (13), respectively.

Finally, the average number of transmissions of the CMIR protocol is given as

$$Num_{CMIR}=\frac{\sum_{k=1}^{N}\Pr_{0,N}\left(k\right)}{1-P_{out}^{CMIR}} \tag{16}$$

Ⅳ. Simulation Results

In this section, we use a Monte-Carlo simulation to verify our theoretical results. We assume that the transmit power P is the same for every transmitting node, including the source and all relays. We also consider the line network where all the nodes are on the same line and that the distance between two adjacent nodes is equal to 1.

In Figs. 2, 3, we present the average end-to-end outage probability as a function SNR $\left(\bar{\gamma}\right)$ in dB. The simulation in Fig. 2 is implemented on the 3-hop networks with path loss exponent $\beta=3$ and threshold $\gamma_{th}=1$. The theoretical results and simulation results match very well. In addition, the CMIR protocol obtains a better performance at high SNR value compared to the CMT protocol. Similarly, in Fig. 3, we set the parameters as follows: $N=4$, $\beta=4$ and $\gamma_{th}=1$. Again, the theoretical and simulation results are in good agreement and the proposed protocol outperforms the CMT protocol at high SNR region.

Fig. 4 presents the outage probability of the CMT and CMIR protocols based on the theoretical results, in order to determine the diversity order of each protocol. In this simulation, we assume that $\beta=3$, $\gamma_{th}=1$ and N equals

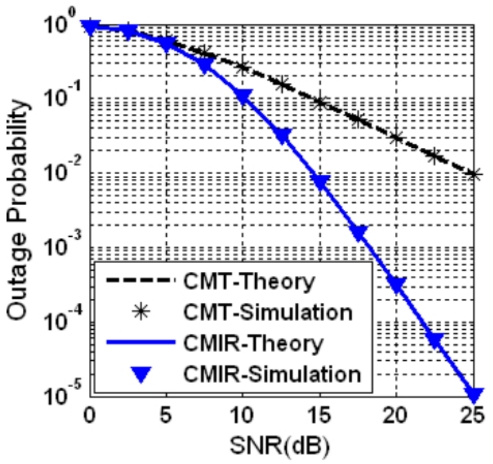

Fig. 2. Outage probability as a function of SNR (dB) when $N=3$; $\beta=3$ and $\gamma_{th}=1$.

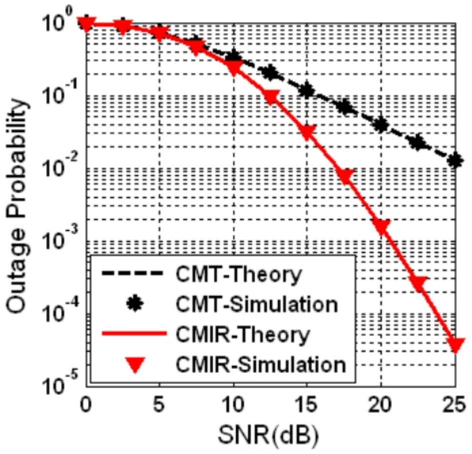

Fig. 3. Outage probability as a function of SNR (dB) when $N=4$; $\beta=4$ and $\gamma_{th}=1$.

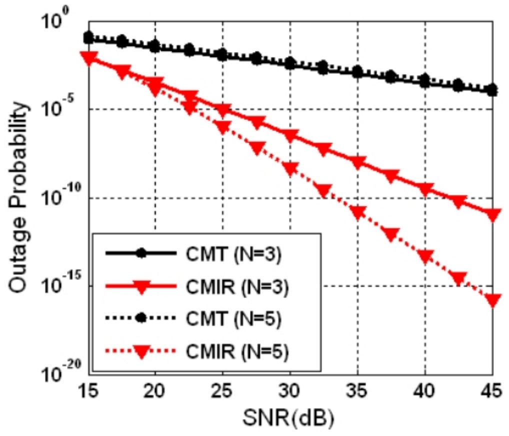

Fig. 4. Outage probability as a function of SNR (dB) when $\beta=3$ and $\gamma_{th}=1$.

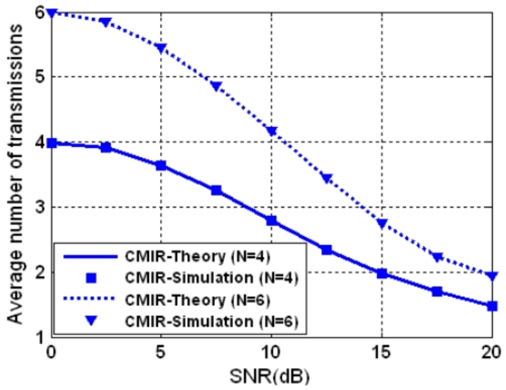

Fig. 5. Outage probability as a function of SNR (dB) when $\beta=3$ and $\gamma_{th}=1$.

3 or 5. The figure shows that the proposed protocol obtains the diversity order of 3 and 5, when the number of hops equals 3 and 5, respectively. Even when we change the number of hops, the diversity of the CMT protocol remains 1.

Fig. 5 shows the average number of transmissions as a function of the SNR in dB, when the values of β and γ_{th} are assigned as 3 and 1, respectively. The simulation and theoretical results are again in good agreement. In addition, this figure shows that the CMIR protocol utilizes fewer transmissions than the CMT protocol does, and this is equal to the number of hops.

Figs. 2～5 show that the proposed protocol not only enhances the performance of the system in terms of outage probability, but it also reduces the number of transmissions and therefore the power consumption.

Ⅴ. Conclusion

In this paper, we proposed a protocol called CMIR, which is a cooperative multi-hop transmission that uses an opportunistic relaying protocol, where the retransmission is accomplished by the best relay. In order to evaluate the performance of the proposed protocol, we derived the mathematical expressions to calculate the end-to-end outage probability and the average power consumption. We then verified the accuracy of the derivation by simulations. The simulation results show that the CMIR protocol improves the performance of the system at the high SNR region when compared to the CMT protocol. Our proposed protocol not only reduces power consumption of the system but also end-to-end transmission time, because it bypasses unnecessary relays.

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Tran Trung Duy

received Telecommunications Engineering from Ho Chi Minh City University of Te the B.E. degree in Electronics and technology, Vietnam, in 2007. He is currently working toward the Master degree in the Department of Electrical Engineering, University of Ulsan, Korea. His major research interests are mobile ad-hoc networks, wireless sensor networks, cooperative communications, cooperative routing, cognitive radio, combining techniques.

Chong-Koo An

received his Ph.D. degree in electrical engineering from the University of Texas at Austin. Currently, he is a professor at the School of Electrical Engineering, University of Ulsan, Republic of Korea. His current research interests include transmission technology (cooperative transmission tech).