On the Performance of Cooperative Multihop Communications

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Abstract—**Cooperative communications is a promising technology to improve the performance of wireless networks. In this paper, we investigate the performance of a multihop communication system with regenerative relays in terms of bit error rate (BER). We propose low complexity techniques, including a max-min cooperative approach I and II , for the relay and path selection. Simulation results indicate that when a channel in a direct link is good or high signal to noise ratio (SNR), the proposed technique achieves a lowest BER.**

Keywords-Multi-hop Relay, Space-time coding, Decode and forward, Path selection, Cooperative Communications

I. INTRODUCTION

Multihop relay transmission is likely to play an important role in future wireless communication systems since it represents an effective low cost solution for coverage extension and capacity enhancement of wireless networks. In recent years, various cooperative protocols with multiple relays have been proposed [1]. However, using more than one relay increases the implementation complexity of the system greatly, which motivates the research on relay selection. Bletsas *et al.* introduced the concept of "opportunistic relaying" in [2] where only the "best" single relay is selected for cooperation, and the work in [3] showed the outage-optimality of this method. In [4], Beres and Adve proposed another relay selection algorithm called "selection cooperation" with its focus on decode-and-forward (DF) systems and the performance of this algorithm was analyzed in [5] in details. There are also several works on the issue of relay selection in amplify-and-forward (AF) systems, e.g. [6]-[8]. ARQ is a useful technology in many wireless applications and it was integrated with relay selection first by Zhao and Valenti [9]. However, the selection criterion in [9] is location information-based, which is inappropriate for mobile networks. Aiming at this problem, [10] combined ARQ with opportunistic relaying to achieve a remarkable result.

In the wireless link layer, transmit/receive diversity is an excellent means for overcoming fading. However, in some scenarios the use of multiple antennas might be impractical because of the limited size and power of the individual nodes. Cooperative transmission has been proposed to address this problem; in this case, diversity gain can be achieved through the cooperation among many nodes by exploiting the broadcast nature of the wireless medium [11]-[12].

Although there has been a significant effort on the study of cooperative systems, there has been very little work on the cross layer design of such systems, especially on combining cooperation and routing. In [13], the problem of power allocation among transmitting nodes on a pre-selected route to maximize the network lifetime is investigated. The joint optimization of routing and power allocation is addressed in [14]-[16], either with relay-cluster-based cooperation [14] or multihop cooperation [15]-[16]. In these works, however, the communications overhead and algorithmic complexity are not considered. The work in [17] explores the benefits of cooperative communications in a networking context at different protocol layers. Distributed space-time block coding is used at the physical layer to facilitate cooperation among relay nodes. Through cooperative transmission, significant throughput enhancement can be observed at the expense of high energy consumption. How to reduce the energy penalty, which mainly comes from the overhead communications among relay nodes to coordinate the transmission, and how to deal with the multiple frequency and time offsets incurred by simultaneously transmitting from distributed relay nodes are challenging problems. In [18] the cooperative transport of packets is integrated in a proposed new architecture for next-generation mobile ad hoc networks. As pointed out in [18], selecting relay nodes with as little overhead as possible is a key problem in cooperative transport.

Routing strategies in multihop cooperative networks [19] assume no direct link from a source at a hop m to a destination at a hop $m+1$, and focus on a multihop network with multiple relays at each hop. In addition to three routing strategies are designed to achieve the full diversity gain provided by cooperation among the relays. Alamouti-based path selection strategy for multihop relay communications [20] was proposed by applying the Alamouti-based path selection (*MAPS*) strategy for multihop relay communication systems, and a system performance was investigated in comparison with the single path selection (*SPS*) and the Alamouti-based path selection (*APS*) strategies.

In this paper, we focus on the performance of cooperative protocols for mutihop ad-hoc relay communications. We consider a multihop network with multiple relays at each hop. For a sake of simplification, we consider a one-dimensional linear networks model. In particular, a generalized linear network with randomly located relay clusters, and idealized linear network with randomly located relay clusters and idealized linear network with equally spaced relay clusters are considered. The nodes within the same cluster are closely spaced, and they cooperate in signal transmission and reception. In the network, only one path is active for a source-destination pair. This type of linear model has also been used in [21]-[27].

In this paper, we also aim at the routing issue from the link layer point of view. We focus on a cooperative multihop network with multiple relays at each hop, and intend to investigate the performance of cooperative communication by reducing the transmit power by 50% compared with non-cooperative communications for a fair comparison. Moreover, we try to reduce a complexity of the path selection by proposing a low complex technique.

The paper is organized as follows. The system model is described in Section II. In Section III, we propose the path selection techniques. The simulation results are presented in Section IV. In section V, we compare the complexity of each protocol. Finally, a summary of the paper is given in Section VI.

II. SYSTEM MODEL

We consider an idealized *M*-hop linear network model and classify a cluster as shown in Fig.1, *M-1* relay clusters are equally spaced from the source (*S*) node and the destination (*D*) node. Each relay cluster includes *L* relay nodes. We assume that the nodes in a certain relay cluster are close together and the distance between clusters is much larger than the distance between the nodes in any one cluster. Therefore, the effect of large-scale fading can be neglected and only the small-scale fading is considered. Also, each node is equipped with only one antenna and number of hop is even. Time division multiple access (*TDMA*) is adopted so that only one source/destination pair is active during each particular period. A selective decode-and-forward relaying strategy is assumed; in particular, at each cluster, only one relay node is selected to forward the packet. For the cooperation scheme, we assume a destination get signal from a source and a selected relay difference time. We also assume that the signal transmitted by a certain node can only be heard by the nodes in its neighboring relay cluster.

In this paper, we classify a network in a cluster basis as follows. Each cluster consists of a source, relay(s) and destination(s). The channel gain of the each link is modeled as a complex Gaussian random variable with zero mean and variance σ^2. That is depends on the pathloss. The average receive SNR at each relay and destination is then given by $\gamma_0 = 1/\sigma_n^2$, where σ_n^2 is the variance of the additive white Gaussian noise. Let $\gamma_{(l_1,m-1),(l_2,m)}$ represent SNR of the channel from relay l_1 to relay l_2 at hop m , $l_1,l_2 = 1,\ldots,L$ and $m = 2,\ldots,M$-1. $\gamma_{(S),(l_1,1)}$ and $\gamma_{(l_2,M),(D)}$, $l_1,l_2 = 1,\ldots,L$ are the SNRs at hops 1 and *M*, respectively. In fig.1, we have *m* hop, $m = 2,\ldots,M$-1 and each hop has relay $l = 1,\ldots,L$. So, we have $(M\text{-}2)L^2+2L$ i.i.d. links in the network. In fig.2, we have *k* cluster. Let $\gamma_{(l^*,m-1),(l,m+1)}$ represent SNR of the channel direct link in the cluster *k*, *k*=2,…,*K*-1 and *m* =3,5,7,…,*M*-1 from the destination relay l^* at cluster *k*-1 to the next destination relay *l* at cluster *k*. Hence, $\gamma_{(S),(l,2)}$ and $\gamma_{(l_2,M-1),(D)}$, $l_1,l_2 = 1,\ldots,L$ are the SNRs of the channel direct links in hops 1 and *M*, respectively. At the first cluster and the last cluster, number of direct link depend on *l* where *l*=1,…,*L*. The cluster between the first and the last hop, a number of direct link for each cluster can be calculated from L^2.

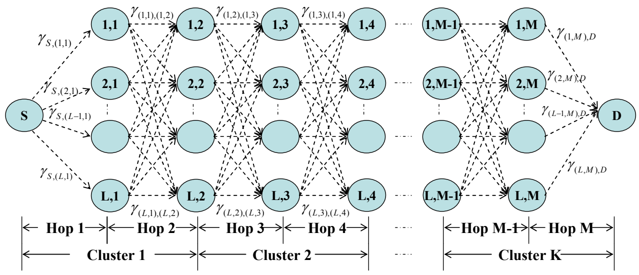

Figure 1. Linear network model with all possible path in each hop without a direct link in each cluster.

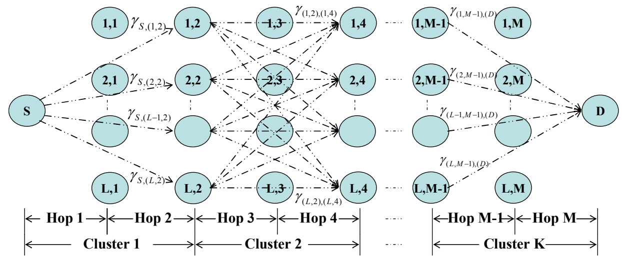

Figure 2. Linear network model with only one possible direct link in each cluster.

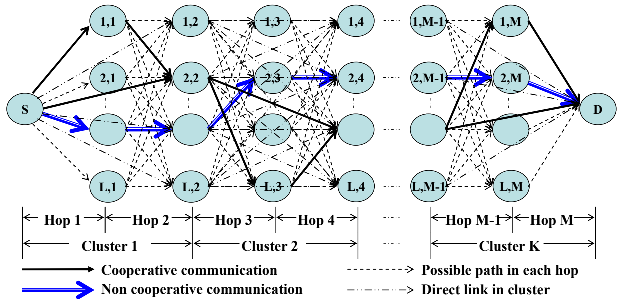

Figure 3. Linear network model that shows an example of path selection for cooperative and non cooperative communications.

In an M^{th} hop with *L* relays, there are $I = L^{M-1}$ possible paths. Let $r_k^{(i)}$ represent the relay at a cluster *k* in a path *i*, where $I = 1,\ldots,I$ and $k = 1,\ldots,K$-1. Also assume $r_0^{(i)} = S$, i.e. the source, and $r_K^{(i)} = D$, i.e. the destination. Obviously each path has a different relay set $\{r_k^{(i)}\}$ and the corresponding SNR set given by $\{\gamma_{(source),(destination)}\}$.

In this paper, we apply a max-min approach (*MA*) for non-cooperative protocols to cooperative protocols by assuming the destination of each cluster can get a direct signal from a source, and combine with the signal from a relay at the receiver. For the max-min cooperative approach (*MCA*), we propose two techniques for a performance evaluation.

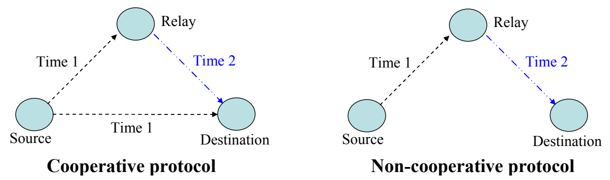

Figure 4. Illustration of cooperative and non-cooperative protocols

TABLE I. HOW EACH PROTOCOL WORK?

Approach	Time 1	Time 2
MA	Source broadcast X to relay.	Relay retransmit $\tilde{X}$ to destination.
MCA	Source broadcast X to relay and destination.	Relay retransmit $\tilde{X}$ to destination.

TABLE II. PARAMETERS SETUP FOR THREE APPROACHES

Strategy	Parameters			
	Tx power at the source	***Tx power at the relay***	***Modulation***	***Bandwidth Efficiency (bit/sec./Hz.)***
MA	1 Watt	1 Watt	BPSK	0.5
MCA I	0.5 Watt	0.5 Watt	BPSK	0.5
MCA II	0.5 Watt	0.5 Watt	BPSK	0.5

We employ a fast fading model for the communication channels so that a path selection from a source to a destination will be changed frequently in every sending packet. We transmit symbol (X) through the channel impulse response (H) with the transmit power according to table II. The n_R and n_D are additive white Gaussian noise at a receiver of the relay and a destination, respectively.

The received signal model for the non-cooperative communication at each cluster, from a source to a relay (*SR*) and from a relay to a destination (*RD*) can be expressed as

$$y_{SR} = \sqrt{P_1} H_{SR} X + n_R \tag{1}$$

$$y_{RD} = \sqrt{P_1} H_{RD} \tilde{X} + n_D \tag{2}$$

where $\tilde{X}$ is the decoded symbol from the relay, and $\tilde{X}$ will be re-transmitted to the destination.

For the cooperative communications, the signal from a source to a destination (y_{SD}), and the signal from a relay to a destination (y_{RD}) will be combined using a maximum ratio combining (MRC).

$$y_{RD} = \sqrt{P_2} H_{RD} \tilde{X} + n_D \tag{3}$$

$$y_{SD} = \sqrt{P_2} H_{SD} X + n_D \tag{4}$$

$$y_{total} = y_{SD} + y_{RD} \tag{5}$$

In order to improve the performance of MRC in this paper, we employ a cooperative maximum ratio combining (C-MRC). The concept of C-MRC is that the quality of the decoded symbols X greatly depends on the SNR of the source-to-relay link. We regard $\gamma_{eq} = \min(\gamma_{SR}, \gamma_{RD})$. If $\gamma_{SR} > \gamma_{RD}$, we place a full confidence to the source-to-relay link, if $\gamma_{SR} < \gamma_{RD}$, i.e. more error could be anticipated on X, then the confidence is reduced on the source to relay link, where the *MRC* weight could be represented by $w = (\gamma_{eq} / \gamma_{RD})$. In addition, N_0 is a noise variance. The received signal at the *C-MRC* output (y_{C-MRC}) can be express as

$$y_{C-MRC} = \frac{w\sqrt{P_2}\left|H_{RD}\right|^2 + \sqrt{P_2}\left|H_{SD}\right|^2}{N_0} \tag{6}$$

III. PATH SELECTION TECHNIQUES

In this section, we provide more details of the three techniques for multihop communications. In the max-min cooperative approach I (*MCA I*), we select a relay node and path by using a *MA* technique before the direct link is selected. The destination direct link will be determined accordingly. In contrast, the max-min cooperative approach II (*MCA II*) will select the best direct transmission first, then select relay and path using the *MA* technique. In fig.3, we show an example of two approaches in terms of routing from a source to a destination among relays and possible paths. Fig.4 shows how to transmit a symbol X from a source to a destination in the time domain, and the table *I* describes in more details.

A. Max-Min Approach (MA)

In each cluster, the system is limited by the minimum SNR of possible path (i). We assume that a destination node only receives a signal from a relay. In order to optimize technique, the path in a cluster with a maximum $\gamma_{\min}^{(i)}$ should be chosen. In each cluster, we have a source (S) a candidate relay (R) and a destination (D), indexed by l = 1,…,L. Let γ_{SR} being a received SNR from a source to a relay and γ_{RD} being a received SNR from a relay to a destination, r_k is the optimal selected relay at the k^{th} cluster, where k = 1,…,K-1. The joint selection path with the maximum $\gamma_{\min}^{(i)}$ approach can be provided as below.

> Given L and M, let r_k^* denote the index of relay node selected at k^{th} cluster, where k = 1,…,K-1 and m is a number of hop, where m = 1,…,M.
>
> *Initialization:* $r_0^* = S$
>
> *Recursion:*
>
> For k = 1 : K-1
>
> $$r_k^* = \arg\max_{l=1,\dots,L} \min(\gamma_{SR_{m,l}}, \gamma_{R_{(m+1),l}D_{(m+1),l}});$$
>
> End loop
>
> $$r_K^* = \arg\max_{l=1,\dots,L} \min(\gamma_{SR_{(M-2),l}}, \gamma_{R_{(M-1,l)}D_M})$$
>
> Output the optimal path $\left\{r_k^*\right\}$

The receive signal from a source to a relay and from a relay to a destination when transmitting a symbol X through the optimal path follows (1) and (2), respectively.

B. Max-Min Cooperative Approach I (MCA I)

In this technique, we assume that a destination can receive a signal from a source. In *MA*, after the joint selection path with the maximum $\gamma_{\min}^{(i)}$, the cooperative relay and optimal path were chosen. Then a direct transmission is combined by using cooperative maximum ratio combining [1]. Let γ_{SD} being a receive SNR from a source to a destination, the received signal processing follows (3), (4) and (6), respectively. The detail of this approach is provided below.

Given L and M, let r_k^* denote the index of relay node selected at k^{th} cluster, where k = 1,…,K-1 and m is a number of a hop, where m = 1,…,M. In addition, $r_{d_k}^*$ denotes a source-to-destination path.

Initialization: $r_0^* = S$

Recursion:

For k = 1 : K-1

$$r_k^* = \arg\max_{l=1,\ldots,L} \min(\gamma_{SR_{m,l}}, \gamma_{R_{(m+1),l}D_{(m+1),l}});$$

$r_{d_k}^*$ is chosen by connecting the source and destination nodes.

End loop

$$r_K^* = \arg\max_{l=1,\ldots,L} \min(\gamma_{SR_{(M-2),l}}, \gamma_{R_{(M-1,l)}D_M})$$

Output the optimal path $\left\{r_k^*, r_{d_k}^*\right\}$

C. Max-Min Cooperative Approach II (MCA II)

Firstly, we select the best direct transmission by choosing a maximum $\gamma_{SD}^{(i)}$. Then, we select a cooperative relay who has the same destination to direct link by using the *MA* technique. The received signal processing is the same as the case of *MCA I*, following (3) to (6).

Given L and M, let r_k^* denote the index of relay node selected at k^{th} cluster, where k = 1,…,K-1 and m is number of hop, where m = 2,4,6,…,M. In addition, $r_{d_k}^*$ denotes a source-to-destination path.

Initialization: r_0^* =S

$$r_{d_k}^* = \arg\max_{l=1,\ldots,L} (\gamma_{SD_{m,l}})$$

$r_k = \arg\max_{l=1,\ldots,L} \min\left(\gamma_{SR_{(m-1),l}}, \gamma_{R_{(m,l)}D_{(m,l)}}\right)$, for a relay to destination only in the same destination to the chosen direct link.

Output the optimal path $\left\{r_{d_k}^*, r_k^*\right\}$

IV. SIMULATION RESULTS

In this section, based on a simulation, the performance evaluation of the proposed *MCA I* and *MCA II* for multihop relay communications will be examined. The modulation with binary phase shift keying (BPSK) constellation is employed. In addition, Jake's model [28] is employed with a normalized doppler shift of 100,000 Hz. for simulating Rayleigh fading channels. We are setup the simulation in four cases. We also setup and investigate the simulation results in four scenarios, including a case of increasing number of candidate relays with one destination, a case of increasing number of destination relay, a case of increasing number of cluster, and a case of good/bad direct transmission channel quality.

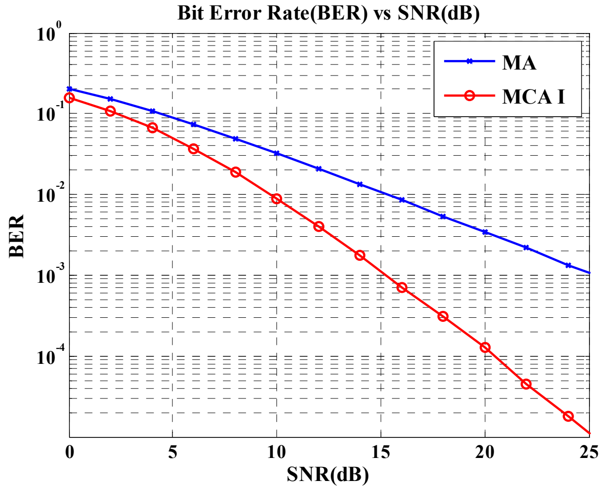

Figure 5. The curves of BER versus SNR for MA and MCA I for a case of only one candidate relay and one destination in a cluster

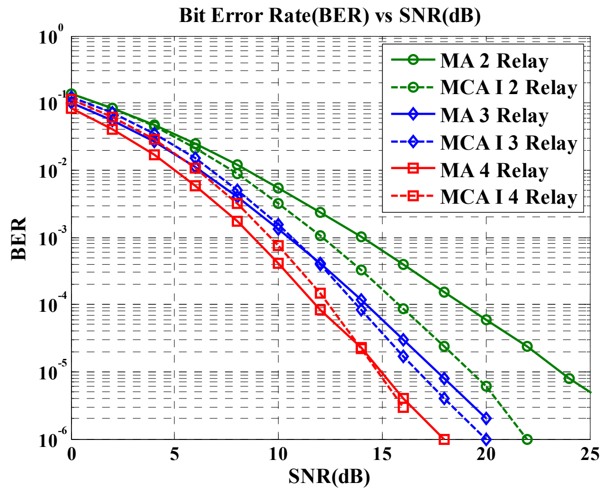

Figure 6. The curves of BER versus SNR for MA, MCA for a case of increasing candidate relays in a cluster

Firstly in fig.5, it is a case of only one relay and one destination in a cluster. *MCA I* achieves lower BER than *MA* even we reduce the transmit power by 50% (for a fair comparison with MA) and achieve more diversity gain. The diversity gain comes from two received signals sent from a source and a relay. In this scenario, we do not show the performance of *MCA II* because it yields the same result.

Secondly in fig.6, it is a case of increasing more candidate relays in a cluster. Obviously, for both techniques (*MA* and *MCA II*), the diversity gain is increased according to a number of relay. When we consider BER, *MCA I* achieves lower BER than MA in case of only one or two candidate relays in a cluster. However, when increasing a number of candidate relays more than two, *MCA I* achieves lower *BER* than *MA* at high SNR. In addition, *MCA II* yields the same result as *MCA I* because we have only one destination in the first cluster.

Thirdly in fig.7, it is a case of four candidate relays and four destinations in two clusters.

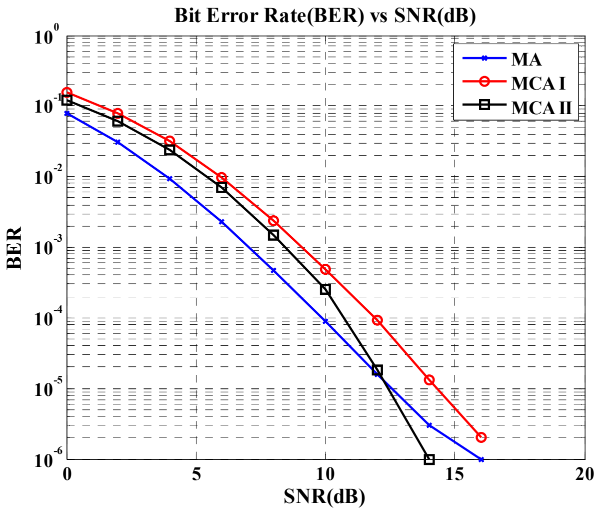

Figure 7. The curves of BER versus SNR for MA, MCA I and MCA II for a case of four candidate relays and four destination in two clusters

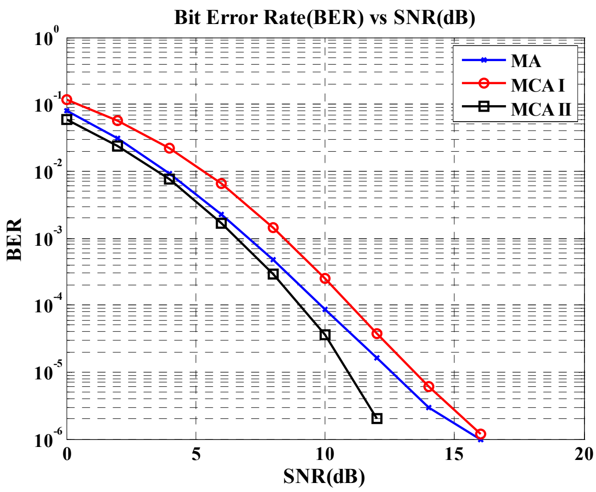

Figure 8. The curves of BER versus SNR for MA, MCA I and MCA II for a case of four candidate relays and four destinations in two clusters with good channel quality in a direct link

V. Complexity Comparison

The complexity of the proposed relay and path selection algorithms stem from a large number of possible paths before calculating a maximum of a minimum SNR. For example, in a cluster $k = 2$, a hop $m = 4$, and a candidate relay $l = 4$, we can calculate a possible path for *MA* by summing a number of path at hop 1 (l), hop 2 (l^2) , hop 3 (l^2) and hop 4 (l^2). Hence, we get $4+4^2+4^2+4^2 = 52$ possible paths. Then, we use a *MA* technique to find the optimal path. For *MCA I*, it is the same as *MA* because we select the relay path before selecting a direct link with the same destination. For *MCA II*, we consider a possible path for a direct transmission first from the following combination.

$$C_{n,r} = \binom{n}{r} = \frac{n!}{r!(n-r)!} \tag{7}$$

where n is number of the destination to choose from, and we choose r from them.

Firstly, we choose the best direct link form four destinations ($C_{4,1}$), then choosing a cooperative optimal path from four candidate relays ($C_{4,1}$) using *MA* technique. Hence, we have 4x4 = 16 possible paths in a cluster one. For the second cluster, after we know the destination of the first cluster, it will become a source for the second cluster. We choose a direct link and a cooperative optimal path in the same way as the first cluster. Then, we have 4x4 =16 possible paths for the second cluster. Hence, the total possible path of the first cluster and the second cluster are 32 paths. Thus, the complexity of *MCA II* is less than *MA* and *MCA I.*

VI. Conclusion

In this paper, we have investigated the performance of cooperative multihop communications in comparison with non-cooperative communications. The simulation results show that when the number of candidate relays increased, the diversity gain of all techniques are increased. The non-cooperative trends to achieve a lower BER at low SNR. On the other hand, at high SNR, cooperative communication protocols trend to achieve lower BER. Especially, when the channel quality of the direct link is good, the proposed *MCA II* will be the good solution for this environment. Furthermore, *MCA II* yields less complexity for the path calculation than other techniques.

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