Performance Analysis of Decode-and-Forward Relaying with Partial Relay Selection for Multihop Transmission over Rayleigh Fading Channels

Vo Nguyen Quoc Bao and Hyung Yun Kong

Abstract: **Multihop transmission is a promising technique that helps in achieving broader coverage (excellent network connectivity) and preventing the impairment of wireless channels. This paper proposes a cluster-based multihop wireless network that makes use of the advantages of multihop relaying, i.e., path loss gain, and partial relay selection in each hop, i.e., spatial diversity. In this partial relay selection, the node with the maximum instantaneous channel gain will serve as the sender for the next hop. With the proposed protocol, the transmit power and spectral efficiency can be improved over those in the case of direct transmission and conventional multihop transmission. Moreover, at a high signal-to-noise ratio (SNR), the performance of the system with at least two nodes in each cluster is dependent only on the last hop and not on any of the intermediate hops. For a practically feasible decode-and-forward relay strategy, a compact expression for the probability density function of the end-to-end SNR at the destination is derived. This expression is then used to derive closed-form expressions for the outage probability, average symbol error rate, and average bit error rate for M-ary square quadrature amplitude modulation as well as to determine the spectral efficiency of the system. In addition, the probability of SNR gain over direct transmission is investigated for different environments. The mathematical analysis is verified by various simulation results for demonstrating the accuracy of the theoretical approach.**

Index Terms: **Bit error rate (BER), decode-and-forward (DF) relaying, multihop transmission, outage probability, probability of signal-to-noise ratio (SNR) gain, Rayleigh fading, relay selection, spectral efficiency, symbol error rate (SER).**

I. INTRODUCTION

The growing demand for high data rates in current and future wireless networks has resulted in the need for multihop communication. Multihop transmission helps in achieving broader and more efficient coverage in traditional and modern communication networks such as mobile ad-hoc wireless networks and wireless sensor networks. The basic idea of multihop transmission is to allow for communication by relaying information from the source to the destination via intermediate nodes.

Recently, the effectiveness of transmitting data packets over two hops before reaching the destination in cooperative wireless communication systems has been demonstrated. This new form of diversity, which is called cooperative diversity, has attracted considerable attention. In this case, the diversity gain is achieved in a distributed manner via a virtual antenna array [1]–[4]. The use of a cooperative diversity protocol in cluster-based multihop wireless networks has been proposed [5]–[14] as a means of exploiting the advantages of cooperative diversity and multihop transmission and improving the multihop system performance. More specifically, in [5], a multihop diversity protocol archiving full diversity has been proposed and analyzed in terms of outage probability. In this protocol, each node in the multihop route effectively combines all the information obtained from the previous nodes; therefore, relay selection at each hop is not necessary. However, this protocol requires signal connectivity between non-adjacent terminals. Two approaches for developing cooperative mobile ad hoc wireless networks (MANETs) are illustrated in [6], which shows that incorporation of cooperation into the physical layer yields a more reliable physical layer link. More recently, in [7], Le *et al.* proposed an analytical model to quantify the end-to-end performance of a general automatic repeat request (ARQ) cooperative diversity scheme in a cluster-based multihop wireless network. This model can be extended to different transmission schemes where the advantages of both time diversity and spatial diversity have been exploited. In [8]–[14], many routing strategies for multihop cooperative networks, in which a cooperative diversity protocol is incorporated into the routing scheme, have been proposed. It has been confirmed through numerical analysis that higher-order cooperative diversity can be achieved by using these strategies.

However, the major drawbacks of all the above mentioned protocols is the need for perfect time synchronization and a centralized processing approach [15], [16]. Dual-hop relaying with partial relay selection based on amplify-and-forward (AF) has been proposed [17]–[21] for resource-constrained wireless systems (especially ad-hoc or wireless sensor networks) in which only partial channel information is available at the transmitters. However, these dual-hop relaying may not be feasible for practical applications of ad-hoc or wireless sensor networks, where communication between the source and the destination usually take place via a multihop link. Furthermore, dual-hop relaying with partial relaying selection does not offer any diversity gain except for a 3 dB coding gain relative to direct communication [17]. This observation inspired us to develop a cluster-based multihop network with partial relay selection, which combines the advantages of multihop relaying and relay selection in each hop. The proposed protocol is useful for practical ad-hoc systems, where relay selection is based on neighborhood channel

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V. N. Q. Bao is with the School of Telecommunications, Posts and Telecommunications Institute of Technology (PTIT), Ho Chi Minh City, Vietnam, email: baovnq@ptithcm.edu.vn.

H. Y. Kong is the corresponding author and with the Department of Electrical Engineering, University of Ulsan, Korea, email: hkong@mail.ulsan.ac.kr.

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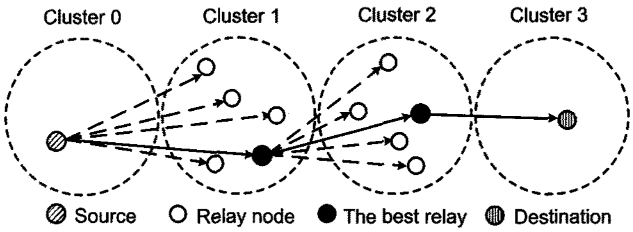

Fig. 1. An example of the proposed network with 3 hops.

knowledge (1 hop). The partial information in the proposed protocol allows for relay selection in the kth hop to follow the best link, i.e., the link with the highest signal-to-noise ratio (SNR). A compact expression for the probability density function (PDF) of the end-to-end SNR is derived and used to obtain a single integral expression for the symbol error rate (SER) of M-ary square quadrature amplitude modulation (M-QAM). The outage probability and bit error rate (BER) of the system are also evaluated in closed forms by using the methods discussed in [22]. Interestingly, the numerical results show that the proposed scheme can be used to increase network coverage without degrading the system performance; in other words, the end-to-end performance of the system at a high SNR depends only on the worst links among K hops.

The rest of this paper is organized as follows. Section II introduces the model under study and describes the proposed protocol. Section III shows the formulas used for evaluation of the outage probability, average SER, and average BER of the system. Section IV presents a comparison of the simulation results and the theoretical results. Finally, Section V includes concluding remarks.

II. SYSTEM MODEL

We consider a wireless relay network where the transmission from the source to the destination is assisted by several relay nodes in between. These nodes are divided into small groups called clusters as illustrated in Fig. 1. It is assumed that the nodes in the network are self-configured and self-organized into disjoint clusters. In particular, we assume a network topology with one level hierarchy without cluster head as discussed in [23, pp. 288-292]. Examples of such networks include wireless sensor networks (WSNs) [15], wireless mesh networks and mobile ad hoc networks [23].

To group nodes in clusters, distributed clustering algorithms using iterative schemes can be employed. Nodes decide to join or to create a new cluster depending on whether they can reach the existing ones or not based only on node proximity as discussed in [24]–[31]. More specifically, in this study, we deal with a network in which relays are grouped into clusters where the chosen criterion is based on their geographical proximity (or equivalently average SNRs). Without the notion of a cluster head, each node within a cluster is treated equally. Cluster size is usually controlled by the radio transmit power. To facilitate the clustering algorithms, we further assume that a transmission power is fixed and uniform across the overall network. The physical properties of the clusters, i.e., number of clusters, cardinality of the clusters, etc., vary between clustering protocols employed where the optimal cluster size is usually dictated by the tradeoff between spatial re-use of the channel and delay minimization. Moreover, routing in the network is assumed to be carried out by layer-3 hierarchical protocols. In this paper, we only focus on the physical layer transmission of the proposed protocol with the assumption that routing and clustering are fully supported by the upper layers. In addition, the details of routing protocols are beyond the scope of this paper.

Let a multihop communication consisting of K hops connect the source (in cluster 0) with the destination (in cluster K) via clusters $1, \cdots, K-1$. It is assumed that the source has no direct link with the destination and the information propagates through K hops before arriving at its destination (D). For convenience, we assume that in hop k, there are N_k relays clustered relatively close together (location-based clustering) forming cluster k and it is selected by a long-term routing process for establishing a communication between the source and the destination.

Let us define a $1 \times K$ vector $N = [N_1\ N_2 \cdots N_K]$ to represent the number of relays involved in each cluster. It is noticed that with the last hop, the number of nodes in the cluster is only one for any given networks, i.e., $N_K = 1$.

The node in the kth hop with the highest SNR will become the next sender of the next hop. To that effect, we state that a number of algorithms have been proposed in the literature for performing this task [32]. With this mechanism, all candidate nodes of the next hop do not need to exchange or feedback either global or local state information. The node with the shortest timer transmits first and thus becomes the transmitter of the next hop, while the other nodes discard the packets after receiving this node's transmission.

It is assumed that all channels between the nodes experience slow, flat, Rayleigh fading, i.e., they are constant during a frame but change independently to the next. Moreover, we consider full decoding of the information at the intermediate nodes, which is also called re-generative or decode-and-forward (DF) relaying in various contexts. Due to Rayleigh fading, the channel powers of all channels in the kth hop, denoted by $\alpha_{k,i} = |h_{k,i}|^2$ where $i = 1, \cdots, N_k$, are independent and exponential random variables. We also denote $\lambda_{k,i}$ as the expected value of $\alpha_{k,i}$. Since the clustering algorithms based on node geographical proximity [28]–[31] are employed, this system model ensures that all links in one hop have the same average channel power, i.e., $\lambda_{k,i} = \lambda_k$ for all i, $k = 1, \cdots, K$. To take into account the effect of path-loss, we exploit the relationship between the variance of the channel fading coefficient and the inter-node distance, i.e., $\lambda_k = C_0 d_k^{-\eta}$ where d_k is the distance from the transmit node in cluster $k-1$ to all nodes in cluster k, η is the path loss exponent of the wireless channels and C_0 captures the effects due to antenna gain, shadowing, etc. [15], [33]. The average transmit powers for the source and the relays in K hops are denoted by ρ_k, $k = 1, 2, \cdots, K$, respectively. Each relay node is equipped with single antenna and operates in half-duplex mode. Due to the haft-duplex constraint, each relay node must transmit on separate channels. Hence, for medium access, a time-division channel allocation scheme with K time slots is occupied in order to realize orthogonal channelization. Thus no inter-relay interference is considered in the signal model. It is assumed that the channel state information (CSI) is only known at the receiving nodes.

III. PERFORMANCE ANALYSIS

A. End-to-End SNR

Consider the kth hop with N_k receiving nodes and $y_{k,i}$ as the received signal at node i, then we have

$$y_{k,i} = h_{k,i}s + n_{k,i}, \ \forall i \in [1, N_k] \tag{1}$$

where $h_{k,i}$ is a zero-mean complex Gaussian random variable with a Rayleigh-distributed amplitude and a uniformly distributed phase angle, s is the complex baseband transmitted signal and $n_{k,i}$ is a zero-mean complex Gaussian random variable representing the additive white Gaussian noise (AWGN) with variance N_0 which is the one-sided power spectral.

The node with maximum gain will serve as the sender for the next hop, i.e., hop $k+1$. Thus, (1) becomes

$$\tilde{y}_k = \tilde{h}_k s + \tilde{n}_k \tag{2}$$

where $\tilde{h}_k$ is the corresponding channel response with maximum $|h_{k,i}|^2$. Since $\gamma_{k,i} = \rho_k \alpha_{k,i}$ is an independent and identically distributed (i.i.d.) exponential random variable ($\bar{\gamma}_{k,i} = \bar{\gamma}_k$ for all i), the PDF of $\beta_k = |\tilde{h}_k|^2 = \max\limits_{i=1,\cdots,N_k} \gamma_{k,i}$ can be defined [34, p. 246, (7-14)] as follows

$$\begin{aligned} f_{\beta_k}(\gamma) &= \frac{N_k}{\bar{\gamma}_k} e^{-\frac{\gamma}{\bar{\gamma}_k}} \left(1 - e^{-\frac{\gamma}{\bar{\gamma}_k}}\right)^{N_k - 1} \\ &= \sum_{i_k=1}^{N_k} (-1)^{i_k - 1} \binom{N_k}{i_k} \frac{i_k}{\bar{\gamma}_k} e^{-\frac{i_k \gamma}{\bar{\gamma}_k}}. \end{aligned} \tag{3}$$

With fixed DF relaying, the relay can forward incorrectly decoded signals to the next hop. Hence, according to [35] and [36], the overall system outage is dominated by the weakest hop. Consequently, the multihop channel can be modeled as an equivalent single hop whose output SNR can be tightly approximated as follows

$$\gamma_{eq} = \min_{k=1,\cdots,K} \beta_k. \tag{4}$$

Under the assumption that the hops are subject to independent fading, order statistics gives the cumulative distribution function (CDF) of γ_{eq} as

$$\begin{aligned} F_{\gamma_{eq}}(\gamma) &= 1 - \Pr\left[\beta_1 > \gamma, \cdots, \beta_K > \gamma\right] \\ &= 1 - \prod_{k=1}^{K} \left[1 - F_{\beta_k}(\gamma)\right] \end{aligned} \tag{5}$$

where $F_{\beta_k}(\gamma) = \Pr(\beta_k \leq \gamma)$ is the corresponding CDF of β_k obtained by integrating (3) between 0 and γ and applying (3.1.7) of [37], we have

$$\begin{aligned} F_{\beta_k}(\gamma) &= \int_0^\gamma f_{\beta_k}(\gamma)\, d\gamma = \sum_{i_k=1}^{N_k} (-1)^{i_k-1} \binom{N_k}{i_k} \left(1 - e^{-\frac{i_k \gamma}{\bar{\gamma}_k}}\right) \\ &= \sum_{i_k=1}^{N_k} (-1)^{i_k-1} \binom{N_k}{i_k} - \sum_{i_k=1}^{N_k} (-1)^{i_k-1} \binom{N_k}{i_k} e^{-\frac{i_k \gamma}{\bar{\gamma}_k}} \\ &= 1 - \sum_{i_k=1}^{N_k} (-1)^{i_k-1} \binom{N_k}{i_k} e^{-\frac{i_k \gamma}{\bar{\gamma}_k}}. \end{aligned} \tag{6}$$

Hence, the joint PDF of γ_{eq} for K hops is given by differentiating (5)

$$f_{\gamma_{eq}}(\gamma) = \sum_{k=1}^{K} f_{\beta_k}(\gamma) \prod_{\substack{j=1 \\ j \neq k}}^{K} \left[1 - F_{\beta_j}(\gamma)\right]. \tag{7}$$

Substituting (3) and (6) into (7) and after some tedious manipulations, the PDF of γ_{eq} can be determined as follows Appendix A

$$\begin{aligned} f_{\gamma_{eq}}(\gamma) &= \sum_{k=1}^{K} \left[\sum_{i_k=1}^{N_k} (-1)^{i_k-1} \binom{N_j}{i_j} \frac{i_k}{\bar{\gamma}_k} e^{-\frac{i_k \gamma}{\bar{\gamma}_k}} \right] \\ &\quad \cdot \prod_{\substack{j=1 \\ j \neq k}}^{K} \left[\sum_{i_j=1}^{N_j} (-1)^{i_j-1} \binom{N_j}{i_j} e^{-\frac{i_j \gamma}{\bar{\gamma}_j}} \right] \\ &= \sum_{k=1}^{K} \prod_{\substack{j=1 \\ j \neq k}}^{K} \left[\sum_{i_k=1}^{N_k} (-1)^{i_k-1} \binom{N_j}{i_j} \frac{i_k}{\bar{\gamma}_k} e^{-\frac{i_k \gamma}{\bar{\gamma}_k}} \right] \\ &\quad \cdot \left[\sum_{i_j=1}^{N_j} (-1)^{i_j-1} \binom{N_j}{i_j} e^{-\frac{i_j \gamma}{\bar{\gamma}_j}} \right] \\ &= \sum_{i_1=1}^{N_1} \cdots \sum_{i_K=1}^{N_K} \kappa \chi e^{-\gamma \chi} \end{aligned} \tag{8}$$

where $\kappa = (-1)^{-K + \sum_{u=1}^{K} i_u} \prod_{v=1}^{K} \binom{N_v}{i_v}$ and $\chi = \sum_{k=1}^{K} \frac{i_k}{\bar{\gamma}_k}$.

Note that for the last hop (the Kth hop), i.e., $N_K = 1$ for any given networks, (8) is reduced to

$$f_{\gamma_{eq}}(\gamma) = \sum_{i_1=1}^{N_1} \cdots \sum_{i_{K-1}=1}^{N_{K-1}} \kappa \chi e^{-\gamma \chi} \tag{9}$$

where $\kappa = (-1)^{-K+1+\sum_{u=1}^{K-1} i_u} \prod_{v=1}^{K-1} \binom{N_v}{i_v}$ and $\chi = \frac{1}{\bar{\gamma}_K} + \sum_{k=1}^{K-1} \frac{i_k}{\bar{\gamma}_k}$.

From (4), we can see that the end-to-end SNR at the destination can be expressed under $\min\limits_{k=1,\cdots,K} \{ \max\limits_{i=1,\cdots,N_k} \gamma_{k,i} \}$ form, which is essential to establish the fact that the worst link among K hops will constitute the bottle-neck in the network and that the link of the last hop plays a more important role than do the links between the other hops. In addition, (9) is in a mathematically tractable form and hence can be conveniently used to derive the exact closed-form expressions for the average SER and average BER of the system.

B. Outage Probability

The outage probability P_o is defined as the probability that the output SNR γ_{eq} of the equivalent single hop falls below a certain predetermined threshold SNR, γ_{th}. Hence, the outage probability of the system can be obtained by integrating the PDF of γ_{eq} as P_o.

$$\begin{aligned} P_o &= \Pr(\gamma_{eq} < \gamma_{th}) = \int_0^{\gamma_{th}} f_{\gamma_{eq}}(\gamma)\ d\gamma \\ &= \sum_{i_1=1}^{N_1} \cdots \sum_{i_{K-1}=1}^{N_{K-1}} \kappa\left(1 - e^{-\gamma_{th}\chi}\right). \end{aligned} \quad (10)$$

To confirm, consider the conventional dual-hop transmission where $N = [N_1\ N_2] = [1\ 1]$. Then, from (10), we have

$$\begin{aligned} P_o &= \sum_{i_1=1}^{N_1} \sum_{i_2=1}^{N_2} (-1)^{i_1+i_2-2} \binom{N_1}{i_1}\binom{N_2}{i_2} \left[1 - e^{-\gamma_{th}\left(\frac{i_1}{\bar{\gamma}_1}+\frac{i_2}{\bar{\gamma}_2}\right)}\right] \\ &= 1 - e^{-\gamma_{th}\left(\frac{1}{\bar{\gamma}_1}+\frac{1}{\bar{\gamma}_2}\right)} \end{aligned}$$

which is in agreement with the previous known results [35] or [38, (28)], as expected.

C. Symbol Error Rate

In this paper, we consider only the SER for M-QAM ($M = 4^m, m = 1, 2, \cdots$) owing to space constraints. However, the closed-form expression of SER for other modulation schemes (e.g., M-phase shift keying (PSK), M-pulse amplitude modulation (PAM) and M-ary rectangular QAM) can be obtained in the same manner [39], [33]. In particular, the SER for M-QAM in the AWGN channel is given in [33, p. 278, (5.279)] as

$$P_s(\varepsilon\,|\gamma) = 2pQ\left(\sqrt{q\gamma}\right) - p^2Q^2\left(\sqrt{q\gamma}\right) \quad (11)$$

where $p = 2(1 - 1/\sqrt{M})$, $q = 3\log_2 M/(M-1)$, $Q(x) = \frac{1}{\pi}\int_0^{\pi/2} \exp[-x^2/(2\sin^2\theta)]\ d\theta$ is the Gaussian Q-function defined in [22, p. 85, (4.2)] and $Q^2(x) = \frac{1}{\pi}\int_0^{\pi/4} \exp[-x^2/(2\sin^2\theta)]\ d\theta$ is also defined in [22, p. 88, (4.9)].

The symbol error rate for M-QAM in slow and flat Rayleigh fading channel can be derived by averaging the error rate for the AWGN channel over the PDF of the SNR in Rayleigh fading.

$$P_s(\varepsilon) = \int_0^{\infty} P_s(\varepsilon\,|\gamma) f_{\gamma_{eq}}(\gamma)\, d\gamma \quad (12)$$

where $P_s(\varepsilon|\gamma)$ is the error rate conditioned on γ. By substituting (9) into (12) and using moment generating function (MGF) approach [22], the closed form expression of SER for the system can be evaluated with the help of [22, p. 151, (5A.11), and (5A.12)] as

$$\begin{aligned} P_s &= \sum_{i_1=1}^{N_1} \cdots \sum_{i_{K-1}=1}^{N_{K-1}} \kappa \left[\begin{array}{c} \frac{2p}{\pi}\int_0^{\pi/2} \frac{\sin^2\theta}{\sin^2\theta + q\chi^{-1}/2}\, d\theta \\ -\frac{p^2}{\pi}\int_0^{\pi/4} \frac{\sin^2\theta}{\sin^2\theta + q\chi^{-1}/2}\, d\theta \end{array}\right] \\ &= \sum_{i_1=1}^{N_1} \cdots \sum_{i_{K-1}=1}^{N_{K-1}} \kappa p \left[\begin{array}{c} 1 - \frac{p}{4} - \sqrt{\frac{q\chi^{-1}}{2+q\chi^{-1}}} \\ \cdot\left(1 - \frac{p}{\pi}\tan^{-1}\sqrt{\frac{2+q\chi^{-1}}{q\chi^{-1}}}\right) \end{array}\right]. \end{aligned} \quad (13)$$

D. Bit Error Rate

The BER of the system over Rayleigh fading channels for M-QAM ($M = 4^m, m = 1, 2, \cdots$) with Gray mapping can be given as [40]

$$P_b = \int_0^{\infty} \sum_{j=1}^{\log_2\sqrt{M}} \sum_{n=0}^{v_j} \phi_n^j \operatorname{erfc}\left(\sqrt{\omega_n\gamma}\right) f_{\gamma_{eq}}(\gamma)\, d\gamma \quad (14)$$

where $v_j = (1 - 2^{-j})\sqrt{M} - 1$, $\omega_k = \frac{(2k+1)^2 3\log_2 M}{(2M-2)}$ and $\phi_k^j = (1)^{\left\lfloor \frac{k2^{j-1}}{\sqrt{M}} \right\rfloor}\left(2^{j-1} - \left\lfloor \frac{k2^{j-1}}{\sqrt{M}} + \frac{1}{2} \right\rfloor\right) \Big/ \left(\sqrt{M}\log_2\sqrt{M}\right)$. Furthermore, we define $\lfloor\cdot\rfloor$ and $\operatorname{erfc}(\cdot)$ as the floor and complementary error function [22, p. 121, (4A.6)], respectively. By substituting (9) into (14) and integrating with respect to γ, we obtain the closed-form expression for BER as follows

$$P_b = \sum_{j=1}^{\log_2\sqrt{M}} \sum_{n=0}^{v_j} \left[\sum_{i_1=1}^{N_1} \cdots \sum_{i_{K-1}=1}^{N_{K-1}} \phi_n^j \kappa \left(1 - \sqrt{\frac{\omega_n\chi^{-1}}{1+\omega_n\chi^{-1}}}\right)\right] \quad (15)$$

At high SNR regime, i.e. $\chi^{-1} \to \infty$ and applying $(1-x)^n \approx 1 - nx$ for small x [37, p. 14, (3.5.8)], (15) can be approximated as follows

$$\begin{aligned} P_b &= \sum_{j=1}^{\log_2\sqrt{M}} \sum_{n=0}^{v_j} \left\{\sum_{i_1=1}^{N_1} \cdots \sum_{i_{K-1}=1}^{N_{K-1}} \phi_n^j \kappa \left[1 - \left(1 + \frac{1}{\omega_n\chi^{-1}}\right)^{-\frac{1}{2}}\right]\right\} \\ &\approx \sum_{j=1}^{\log_2\sqrt{M}} \sum_{n=0}^{v_j} \frac{\phi_n^j}{2\omega_n} \left(\sum_{i_1=1}^{N_1} \cdots \sum_{i_{K-1}=1}^{N_{K-1}} \kappa\chi\right). \end{aligned} \quad (16)$$

By using the result obtained in the Appendix B, (16) can be rewritten as follows

$$P_b = \sum_{j=1}^{\log_2\sqrt{M}} \sum_{n=0}^{v_j} \frac{\phi_n^j}{2\omega_n} \sum_{k=1}^{K} \frac{\delta(N_k)}{\bar{\gamma}_k} \quad (17)$$

where $\delta(N_k)$ is defined as

$$\delta(N_k) = \begin{cases} 1, & \text{for } N_k = 1 \\ 0, & \text{for } N_k > 1. \end{cases} \quad (18)$$

With $\delta(N_k)$ as in (18), we recognize that in (17) for two special cases: i) $N_k = 1$ for all k and ii) $N_k > 1$ for all k in range $1 \le k < K$. It is straightforward to arrive at

$$\frac{1}{\bar{\gamma}_K} \le \sum_{k=1}^{K} \frac{\delta(N_k)}{\bar{\gamma}_k} \le \sum_{k=1}^{K} \frac{1}{\bar{\gamma}_k}. \quad (19)$$

Substituting (19) into (17) gives us a lower and an upper bound for P_b as follows

$$P_b^L \le P_b \le P_b^U \quad (20)$$

where

$$P_b^U = \sum_{j=1}^{\log_2\sqrt{M}} \sum_{n=0}^{v_j} \frac{\phi_n^j}{2\omega_n} \sum_{k=1}^{K} \frac{1}{\bar{\gamma}_k}, \quad (21a)$$

$$P_b^L = \frac{1}{\bar{\gamma}_K} \sum_{j=1}^{\log_2\sqrt{M}} \sum_{n=0}^{v_j} \frac{\phi_n^j}{2\omega_n}. \quad (21b)$$

It can be seen that the performance of the system operating with at least two nodes in each cluster will converge to that of the last hop and will not depend on any intermediate hops, i.e. neither average channel powers nor the number of hops between the source and the destination. In addition, it is clearly seen that our proposed protocol shows better performance as compared to conventional multihop transmission ($N_k = 1$ for all k) as well as direct transmission ($K = 1$ and $N = N_K = 1$).

E. Probability of SNR Gain

The definition of the probability of SNR gain for dual-hop relaying reported in [41] motivates the study of the probability of SNR gain of a multihop system as compared to that of a single-hop system in this subsection. Such a SNR gain offers us an explicit view of the advantage achieved by multihop system with partial relay selection. Mathematically speaking, the probability of SNR gain achieved by the proposed protocol over direct transmission or over a conventional multihop system is defined as follows [41]

$$\begin{aligned}\Omega &\triangleq \Pr\left\{\frac{\gamma_{eq}}{\gamma_0} > \mu\right\} \\ &= 1 - \int_0^\infty \Pr\{\gamma_{eq} \le \mu\gamma_0 | \gamma_0 = \gamma\} f_{\gamma_0}(\gamma)\, d\gamma \\ &= 1 - \int_0^\infty F_{\gamma_{eq}}(\mu\gamma) f_{\gamma_0}(\gamma)\, d\gamma \end{aligned} \tag{22}$$

where μ is the pre-determined SNR gain that we wish to obtain and γ_0 denotes the instantaneous received SNR at the destination in a single-hop system and $F_{\gamma_{eq}}(\gamma)$ is the corresponding CDF of γ_{eq} obtained by integration of (9) between 0 and γ as

$$F_{\gamma_{eq}}(\gamma) = \int_0^\gamma f_{\gamma_\Sigma}(\gamma)\, d\gamma = \sum_{i_1=1}^{N_1} \cdots \sum_{i_{K-1}=1}^{N_{K-1}} \kappa \left(1 - e^{-\gamma\chi}\right). \tag{23}$$

By substituting (23) into (22), we can obtain the probability of SNR gain for the system as

$$\begin{aligned}\Omega &= 1 - \int_0^\infty \left[\sum_{i_1=1}^{N_1} \cdots \sum_{i_{K-1}=1}^{N_{K-1}} \kappa\left(1 - e^{-\mu\gamma\chi}\right)\right] \frac{1}{\bar{\gamma}_0} e^{-\gamma/\bar{\gamma}_0}\, d\gamma \\ &= \sum_{i_1=1}^{N_1} \cdots \sum_{i_{K-1}=1}^{N_{K-1}} \frac{\kappa}{1 + \bar{\gamma}_0 \mu \chi} \end{aligned} \tag{24}$$

where $\bar{\gamma}_0 = E(\gamma_0)$.

As a special case, i.e., conventional DF multihop $N_k = 1$ for all k, the probability of SNR gain can be reduced as follows

$$\Omega = \frac{1}{1 + \bar{\gamma}_0 \mu \sum_{k=1}^K \bar{\gamma}_k^{-1}}. \tag{25}$$

F. Spectral Efficiency

Spectral efficiency is one of the important information metrics of the system. Here, the achievable spectral efficiency of the system can be obtained by the average of the instantaneous spectral efficiency over the fading distribution as follows

$$\begin{aligned} C &\triangleq E_{\gamma_{eq}}\left[\frac{1}{K}\log_2(1 + \gamma_{eq})\right] \\ &= \frac{1}{K \ln 2} \sum_{i_1=1}^{N_1} \cdots \sum_{i_{K-1}=1}^{N_{K-1}} \kappa e^{\chi} \Gamma(0, \chi) \end{aligned} \tag{26}$$

where $\Gamma(a, x) = \int_x^\infty t^{a-1} e^{-t} dt$ is an incomplete Gamma function [37, p. 260, (6.5.3)].

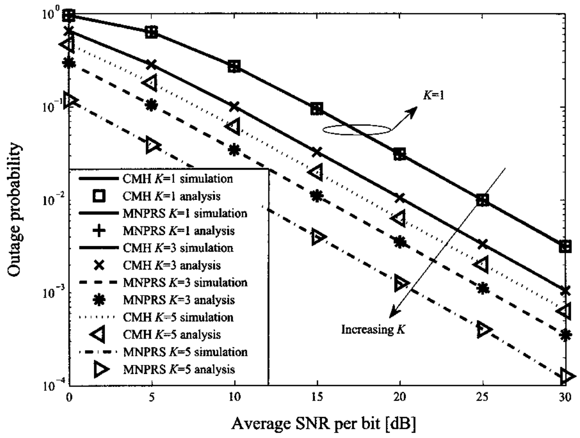

Fig. 2. Outage probability for MNPRS ($N_k = 5$ for all k) and for CMH ($N_k = 1$ for all k), $\gamma_{th} = 5$ dB.

IV. NUMERICAL RESULTS AND DISCUSSION

In this section, we provide some simulation results of the system performance and verify these results with our derived formulas. For ease of exposition, we consider a linear network consisting of multiple clusters, each of which has an arbitrary number of nodes. For a fair comparison with direct transmission, the overall distance of all hops has to be one, i.e. $\sum_{k=1}^K d_k = 1$. Without loss of generality, we assume $C_0 = 1$ throughout this section and $\eta = 3$ for all results in Figs. 2–6, 8, and 9. It is noted that no latency in DF processing at each relay node is assumed. However, in practice, the latency should be taken into account as it positively limits the actual number of hops used for the multihop relaying system.

In Figs. 2–4, we study the outage probability, the average SER and the average BER of the system as functions of average SNR when each cluster is equidistant from each other ($d_k = 1/K$ for all k, $k = 1, \cdots, K$) and equal power allocation is exploited ($\rho_k = \rho/K$ for all k, $k = 1, \cdots, K$) where ρ is the total transmit power of the system and is also the transmit power of the source in case of direct transmission. In addition, we compare the performance of the proposed protocol (denoted as multihop network with partial relay selection (MNPRS)) with that of the conventional multihop network (CMN) $N_k = 1$ for all k. For all the values of SNRs, the performance of our proposed system is better than that of the others. It is obvious that the performance of the proposed system with the improvement of the

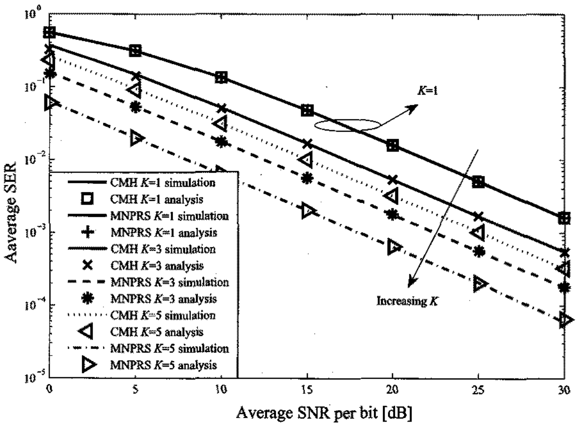

Fig. 3. Average SER (16-QAM) for MNPRS ($N_k = 5$ for all k) and for CMN ($N_k = 1$ for all k).

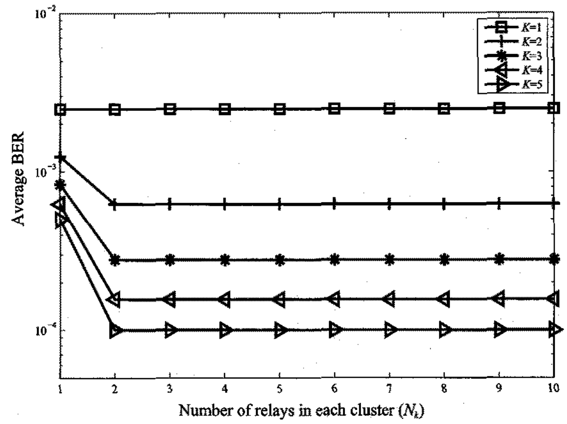

Fig. 5. Average BER (4-QAM) vs. number of relays in each cluster (N_k), SNR = 20 dB.

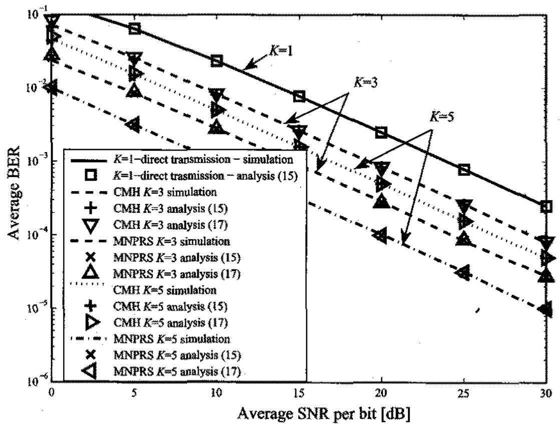

Fig. 4. Average BER (16-QAM) for MNPRS ($N_k = 5$ for all k) and for CMN ($N_k = 1$ for all k).

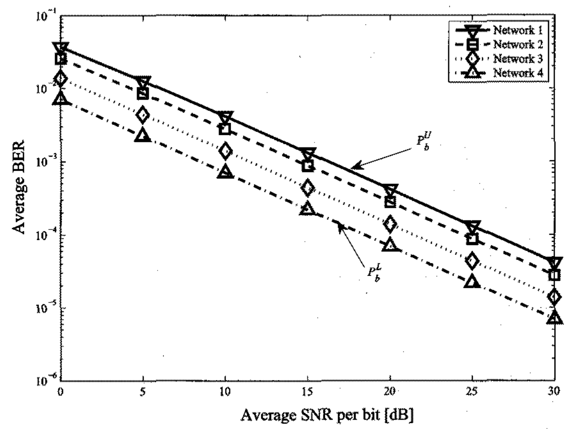

Fig. 6. Average BER for different network topologies (4-QAM).

Table 1. Network topologies for Fig. 6.

Network	Network topologies
1	N =[1 1 1 1 1 1]
2	N =[1 1 5 1 2 1]
3	N =[2 1 4 5 2 1]
4	N =[2 5 3 4 8 1]

outage probability, the average SER or the average BER is proportional to the number of hops (K) under the assumption of no-delay at the relays. For example, at the target outage probability of 10^{-2} (Fig. 2), our proposed protocol (MNPRS) with three hops ($K = 3$) outperforms CMN with transmit power gain of about 5 dB. All results obtained from the analysis as well as the simulations are in excellent agreement. In Fig. 4, we also compare two expressions for average BER of square M-QAM, i.e., (15) and (17). It can be seen that the results obtained from the approximation expression match those obtained at a high SNR. However, there is a small difference between the results obtained for two cases at a low-SNR ($\leq$ 10dB) because the condition for approximation in (16) is not satisfied.

In Figs. 5 and 6, we study the relationship of average BER with number of relays in each cluster (N_k) and number of hops (K) for MNPRS. Again, the performance enhancements for the end-to-end bit error rate of the system are very significant due to multihop relaying and spatial relay selection. In Fig. 5, we can see that the more the number of hops, the better is the performance achieved. Moreover, with our attenuation channel model, we benefit by increasing the number of hops because the error probability associated with the last hop over the distance $1/K$ will be proportional to K. Consequently, our protocol can provide a good trade-off between system performance and spectral efficiency. Moreover, Fig. 5 also shows that the performance of MNPRS operating with at least two relays in each cluster does depend neither on the number of relays in each cluster nor on the average channel powers of the channels in each cluster except the last hop. Therefore, our proposed protocol can diminish the decoding error retransmission in fixed DF relaying which is the main drawbacks induced by the relays and limits the performance of multihop transmission. In Fig. 6, the average BER of the system with 6 hops is investigated for four kinds of networks whose topologies are given in Table 1. It can be seen that among them, network 1 (CMN) gives the most inferior perfor-

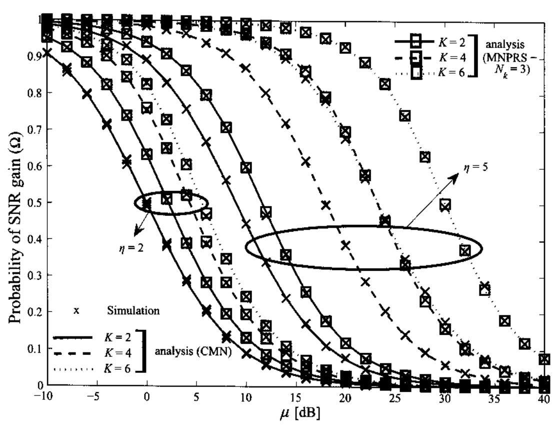

Fig. 7. Probability of SNR gain for two networks CMN and MNPRS.

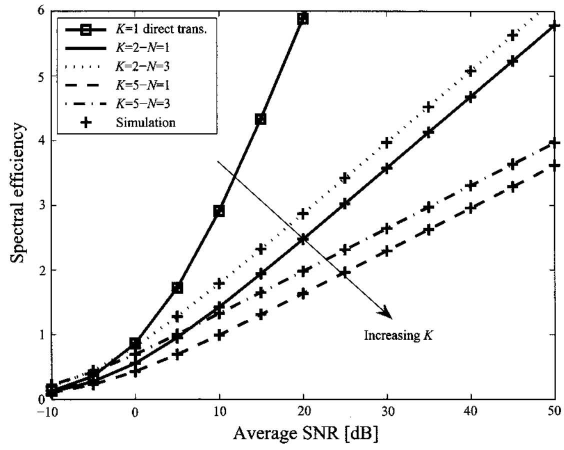

Fig. 8. Spectral efficiency for MNPRS.

mance, network 4 gives the best performance, and the performance qualities of the others lie in between. Network 1 and network 4 are the two extremes of the system performance calculated by (21a) and (21b), respectively. Obviously, they could be treated as upper bounds and lower bounds for the average BER of the system. These bounds are very useful in case we would like to estimate the system performance of the proposed protocol when the number of nodes in each cluster is generally unknown and varying due to the mobility of relays. Observing the slope of the curses in Figs. 2–4, it is evident that our proposed protocol attains diversity only of order one. This can be verified by rewriting (21b) as follows [42]

$$P_b^L = (G_c \bar{\gamma}_K)^{-G_d} \tag{27}$$

where G_c and G_d denote the coding and diversity gain, respectively, given by

$$G_c = \frac{\sqrt{M}\log_2\sqrt{M}}{\sum_{j=1}^{\log_2\sqrt{M}} \sum_{n=0}^{v_j} \frac{\phi_n^j}{2\omega_n}}, \tag{28a}$$

$$G_d = 1. \tag{28b}$$

In Fig. 7, we draw the probability of the SNR gain achievable by MNPRS in different communication environments, η. In comparing the probabilities of SNR gain for different values of η, it can be seen that our proposed protocol outperforms the conventional DF multihop system in all the operating ranges of SNRs. The results also show that the SNR gain significantly increases in poor communication environments, i.e., $\eta > 2$. The spectral efficiency for the MNPRS system is also illustrated in Fig. 8. We can see that the more number of hops the system uses, the lower is the spectral efficiency of the system achieved.

Up to this point, we have not taken into account bandwidth efficiency, which is an important factor for evaluating the performance of the system beside outage probability, the SER or the BER. It is evident that increasing the number of hops reduces the bandwidth efficiency of the system. Obviously, there is a trade-off between the advantages offered by path loss savings

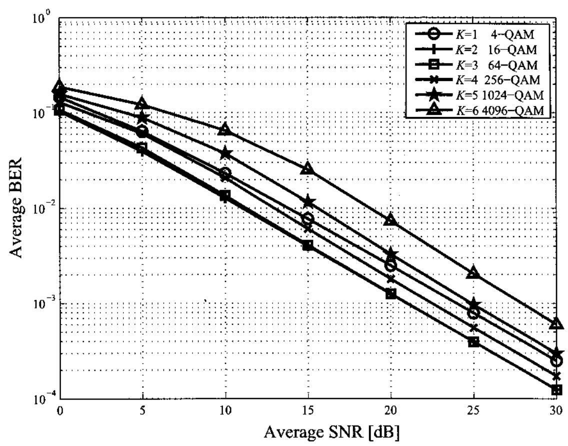

Fig. 9. BER vs. average SNR subject to fixed bandwidth efficiency and total transmit power.

and spatial relay selection and the bandwidth efficiency of the system. Thus, for a fair comparison, the bandwidth efficiency of the system will be fixed (Figs. 9 and 10). In order to achieve this, the system must use a modulation technique whose spectral efficiency is proportional to that of the modulation technique for the direct transmission with respect to number of hops (K) to maintain the same bandwidth efficiency, i.e., 4^K-QAM is used for the K-hop system where $K = 1, 2, \cdots$.

Fig. 9 represents the average BERs versus average SNR per bit in dB when K varies from 1 to 6 with $\eta = 3$. It can be seen that our proposed protocol does not always outperform direct transmission under constraint of fixed total transmit power and bandwidth efficiency. In particular, only the system with two, three and four hops can have advantages over direct transmission. In addition, the average BER of the system with $K = 2$ and $K = 3$ is nearly same in high SNR regime. Thus, we can conclude that under certain environments (η), the system with an appropriate number of hops achieves better performance as compared with that of direct transmission. This gives rise to the following question: What is the optimal number of hops for the proposed protocol under a specific environment, i.e. a predeter-

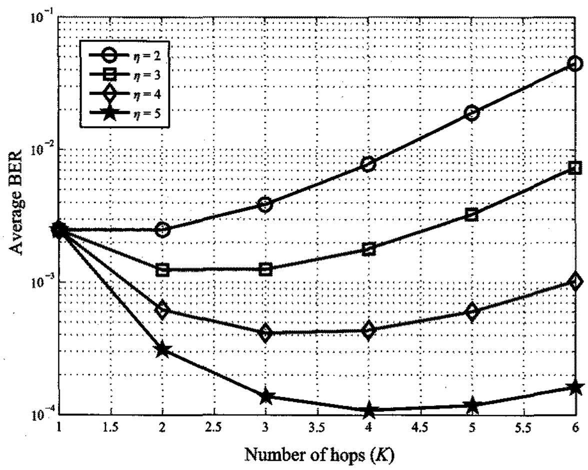

Fig. 10. BER vs. number of hops for different pass loss exponents at 20 dB.

mined value of path-loss exponent? In Fig. 10, the relationship between the average BER and the number of hops for each value of the pass-loss exponent is investigated to find the answer for this question. The optimal number of hops for the system is the value that minimizes the average BER performance. It can be seen that the average BER is minimized at $K = 1,\ 2,\ 3$, and 4 corresponding to $\eta = 2,\ 3,\ 4$, and 5, respectively. The results reveal that the environment significantly affects the performance of the proposed protocol. It is obvious that the system performance reduces because the advantages offered by relay selection and multihop relaying cannot compensate for the bandwidth efficiency loss incurred by utilizing higher number of hops. Moreover, it should be noted that the curves in Fig. 10 have the form of a convex function, which means that the optimal value of K is unique for each η. In summary, the optimal number of hops gives us a useful insight from a practical viewpoint in multihop network design subject to fixed power and bandwidth efficiency.

V. CONCLUSION

We propose a cluster-based multihop transmission protocol with partial relay selection for overcoming the disadvantages of conventional multihop transmission and fixed DF relaying. The proposed model exploits the advantages of multihop transmission (path loss gain) and partial relay selection (spatial diversity). This form of protocol is especially applicable to multihop packet relaying network with minimal impact to existing serial relaying transmission. In addition, we have derived closed-form expressions of the outage probability, average SER, and average BER for M-QAM and verified the analysis results by carrying out various performance evaluation tests. The simulation results are in excellent agreement with the derived expressions. Upper and lower bounds for the average BER of the system are defined for evaluating the system flexibility. Analysis of this relaying protocol reveals an interesting result: At a high SNR, the performance of a system with at least two nodes in each cluster depends only on the channel power of the last hop and not on the number of hops or the average channel power between intermediate hops.

APPENDICES

I. AN EXAMPLE OF THE PDF FOR THE CASE OF TWO HOPS

With $N = [N_1\ N_2] = [2\ 2]$, from (9), we have

$$
\begin{aligned}
f_{\gamma_{eq}}(\gamma) &= \sum_{k=1}^{2} f_{\beta_k}(\gamma) \prod_{\substack{j=1\\ j\neq k}}^{2} \left[1 - F_{\beta_j}(\gamma)\right] \\
&= \left[\binom{2}{1}\frac{1}{\bar\gamma_1}e^{-\frac{\gamma}{\bar\gamma_1}} - \binom{2}{2}\frac{2}{\bar\gamma_1}e^{-\frac{2\gamma}{\bar\gamma_1}}\right]\left[\binom{2}{1}e^{-\frac{\gamma}{\bar\gamma_2}} - \binom{2}{2}e^{-\frac{2\gamma}{\bar\gamma_2}}\right] \\
&\quad + \left[\binom{2}{1}\frac{1}{\bar\gamma_2}e^{-\frac{\gamma}{\bar\gamma_2}} - \binom{2}{2}\frac{2}{\bar\gamma_2}e^{-\frac{2\gamma}{\bar\gamma_2}}\right]\left[\binom{2}{1}e^{-\frac{\gamma}{\bar\gamma_1}} - \binom{2}{2}e^{-\frac{2\gamma}{\bar\gamma_1}}\right] \\
&= \binom{2}{1}\binom{2}{1}\left(\frac{1}{\bar\gamma_1}+\frac{1}{\bar\gamma_2}\right)e^{-\gamma\left(\frac{1}{\bar\gamma_1}+\frac{1}{\bar\gamma_2}\right)} - \binom{2}{1}\binom{2}{2}\left(\frac{1}{\bar\gamma_1}+\frac{2}{\bar\gamma_2}\right)e^{-\gamma\left(\frac{1}{\bar\gamma_1}+\frac{2}{\bar\gamma_2}\right)} \\
&\quad - \binom{2}{2}\binom{2}{1}\left(\frac{2}{\bar\gamma_1}+\frac{1}{\bar\gamma_2}\right)e^{-\gamma\left(\frac{2}{\bar\gamma_1}+\frac{1}{\bar\gamma_2}\right)} + \binom{2}{2}\binom{2}{2}\left(\frac{2}{\bar\gamma_1}+\frac{2}{\bar\gamma_2}\right)e^{-\gamma\left(\frac{2}{\bar\gamma_1}+\frac{2}{\bar\gamma_2}\right)} \\
&= \sum_{i_1=1}^{2}\sum_{i_2=1}^{2} (-1)^{i_1+i_2-2}\binom{2}{i_1}\binom{2}{i_2}\left(\frac{i_1}{\bar\gamma_1}+\frac{i_2}{\bar\gamma_2}\right)e^{-\gamma\left(\frac{i_1}{\bar\gamma_1}+\frac{i_2}{\bar\gamma_2}\right)} \\
&= \sum_{i_1=1}^{2}\sum_{i_2=1}^{2} \kappa\chi e^{-\gamma\chi}
\end{aligned}
$$

where $\kappa = (-1)^{i_1+i_2-2}\binom{2}{i_1}\binom{2}{i_2}$ and $\chi = \frac{i_1}{\bar\gamma_1} + \frac{i_2}{\bar\gamma_2}$.

II. THE PROOF FOR THE (16)

From the binomial theorem [37], we know that

$$(1-x)^N = \sum_{i=0}^{N}\binom{N}{i}(-1)^i x^i. \qquad \text{(B.1)}$$

Differentiating both sides of (B.1) with respect to x, we obtain

$$N(1-x)^{N-1} = \sum_{i=1}^{N}\binom{N}{i}(-1)^{i-1} i x^{i-1}. \qquad \text{(B.2)}$$

Evaluating (B.2) at $x = 1$ yields

$$\sum_{i=1}^{N}(-1)^{i-1} i = \begin{cases} 1, & N=1 \\ 0, & N>1 \end{cases} \qquad \text{(B.3)}$$

where $0^0 = 1$.

Substituting (B.3) into (16) for each pair of (N_k, i_k), we can get the desired result in (17).

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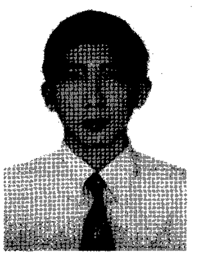

Vo Nguyen Quoc Bao received the B.E. and the M.S. degrees in Electronics and Telecommunications Engineering from Ho Chi Minh City University of Technology, Vietnam, in 2002 and 2005, respectively. And he received Ph.D. degree from University of Ulsan, Korea in Feb 2010. Currently he is an assistant professor at School of Telecommunications, Posts and Telecommunications Institute of Technology (PTIT), Ho Chi Minh City, Vietnam. His major research interests are modulation and coding techniques, MIMO system, combining technique, and cooperative communications. He is a Member of KICS, IEICE, and IEEE.

Hyung Yun Kong received the M.E. and Ph.D. degrees in Electrical Engineering from Polytechnic University, Brooklyn, New York, USA, in 1991 and 1996, respectively. And he received the B.E. degree in Electrical Engineering from New York Institute of Technology, New York in 1989. Since 1996, he was with LG electronics Co., Ltd. in Multimedia Research Lab. Developing PCS Mobile Phone Systems and LG Chair Man's Office Planning Future Satellite Communication Systems from 1997. Currently he is a Professor in Electrical Engineering at University of Ulsan, Ulsan, Korea. He performs several government projects supported by information technology research center (ITRC), Korean science and engineering foundation (KOSEF), etc. His research area includes high data rate modulation, channel coding, detection and estimation, cooperative communications, and sensor network. He is Member of IEEK, KICS, KIPS, IEICE, and IEEE.