ANALYSIS OF MULTIHOP RELAYING NETWORKS

Communication Between Range-Limited and Cooperative Nodes

Bilal Zafar, Soheyl Gherekhloo, and Martin Haardt

The focus of this article is on analyzing the impact of the number of hops and the number of transmit and receive antennas, at the relay nodes, on the performance of multihop networks. The vision of future wireless networks includes a greater role for ubiquitous ad hoc networks based on multihop transmissions between machines and general mobile devices carried around by users. With this in mind, the standards are set to include greater capabilities and specifications regarding ad hoc mesh networks, especially ones that employ multiple antennas for transmissions. Therefore, there is a need for an in-depth analysis of the performance of such networks. In this analysis, we consider equidistant distributed relays between the source and destination. The statistics of the channels of all hops and the noise powers at all terminals are assumed to be the same. The capacity for the amplify-and-forward (AF) and decode-and-forward (DF) relaying schemes over the single-input single-output (SISO) channel is compared. Moreover, we derive a

Digital Object Identifier 10.1109/MVT.2012.2204547
Date of publication: 14 August 2012

closed-form solution of the ergodic capacity in the presence of Rayleigh fading for multihop wireless transmissions when the DF-relaying scheme and SISO links between the relay nodes are employed. The quality of service (QoS) of the single-input multiple-output (SIMO) and multiple-input multiple-output (MIMO) [Alamouti space-time block code (STBC)-based scheme] multihop networks are studied, and their performance is compared analytically with each other.

The communication networks of the future will be highly adaptive and flexible. This is due to the rapid emergence of new paradigms that help the communicating devices in adapting themselves to be able to use any kind of wireless network in their vicinity. Thus, we have seen a huge interest in new communication techniques such as ad hoc and mesh networking, cognitive radios, cooperative networking, and sensor networking. There will be an exponential rise in the number of wireless devices in the near future, and many of these will have limitations on their battery, physical size, and transmission range. Multihop relaying is a promising technique for generating communication between a source and destination node via some relay nodes when the nodes have limited transmission ranges. This technique becomes even more attractive in cases where the direct channel between the source and destination is subject to a deep fade and the power resources at the transmitter become limited. In the multihop relaying technique, every relay retransmits the received signal after performing some processing of its own. Based on the processing at the relays, we have different relaying schemes such as AF relaying, DF relaying, and compress-and-forward relaying.

In [1] and [2], the three-terminal relay channel was introduced. In [3], the capacity of a Gaussian-degraded relay channel was studied. The capacity for different Gaussian single-relay and multirelay channels has been analyzed in [4]–[7] and [8]–[10], respectively. However, studying the performance of the relay channel becomes interesting when considering the fading channel, which is a more realistic scenario.

From outage probability and error rate point of view, [11]–[13] have studied the wireless relaying transmission over fading channels. In [6], the upper and lower bounds of the ergodic capacity with optimal power allocation have been derived for a single-relay channel in Rayleigh fading. In [7], by considering MIMO single-relay channels in Rayleigh fading, the lower and upper bounds of the ergodic capacity have been derived.

This article starts with the analysis of the ergodic capacity of the DF-relaying technique for the SISO link, considering that the channel-state information (CSI) of every hop is available at the corresponding terminal and the total transmit power of every relay cannot exceed a threshold. We achieve a closed-form solution for the DF scheme as a function of the number of hops. Moreover, the performances of AF and DF schemes are compared with each other from an ergodic capacity point of view. The analysis highlights the important fact that decreasing the number hops can increase the ergodic capacity of the multihop transmission in the high signal-to-noise ratio (SNR) regime.

IN MULTIHOP NETWORKS, THE DIRECT TRANSMISSION BETWEEN THE SOURCE (TX) AND DESTINATION (RX) IS SO WEAK THAT SOME RELAYS HAVE TO BE EMPLOYED ON THE PATH BETWEEN THE SOURCE AND DESTINATION TO AID COMMUNICATION.

Increasing the number of antennas at the transmitter and receiver sides can increase the diversity order. This method is used to reduce the number of hops in the network for a given QoS. Extracting the benefits of the spatial diversity to decrease the number of hops is the main goal of this analysis. Different multihop schemes, such as MIMO (Alamouti STBC-based) and SIMO, are compared.

System Model

In multihop networks, the direct transmission between the source (TX) and destination (RX) is so weak that some relays have to be employed on the path between the source and destination to aid communication. Figure 1 illustrates the model of multihop relaying between the TX and RX over M hops using SISO links between the relays.

The received signal at the ith relay is given by

$$y_i = \sqrt{P_s} \cdot h_i \cdot x_{i-1} + v_i, \qquad i = 1, 2, \ldots, M, \tag{1}$$

where P_s is the transmit power of the nodes, which is assumed to be the same for all the relays; x_{i-1} denotes the signal transmitted by the $(i-1)$th relay; h_i is the SISO quasi-static frequency flat-block fading channel between the $(i-1)$th and ith relay nodes and is modeled with independent, identically distributed, zero-mean, circularly symmetric, complex Gaussian (ZMCSCG) random variables, with the variance depending on the number of hops. Moreover, v_i is the additive white Gaussian noise (AWGN) for the ith relay, which is also modeled as ZMCSCG. Note that, in this analysis, the transmit power of the relays is assumed to be constant, and by changing the number of hops, the transmit power of the relays does not change. In other words, we consider an individual power constraint. It is assumed that the variance of

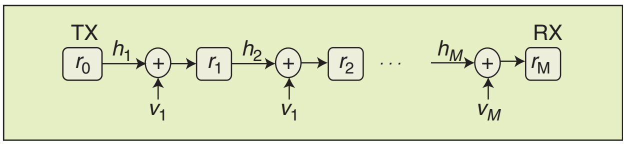

FIGURE 1 The model of AF relaying for multihop scenarios.

the noise (σ_v^2) is the same for all of the relay nodes. Assuming equidistant relay nodes, all located on a straight line between the TX and RX, the channel variance corresponding to all the hops is the same. Because the statistics of the channels are the same for all hops, we can drop the subscript i, which refers to the hop number, and write

$$\mathbb{E}_h\{|h_i|^2\}_{i=1}^{M} = \mathbb{E}_h\{|h|^2\} = \xi_M = \xi_1 \cdot M^{\alpha}, \quad (2)$$

where $\mathbb{E}\{\cdot\}$ stands for the statistical expectation, ξ_1 is the channel variance corresponding to the direct channel between the source and destination, ξ_M denotes the channel variance of the channels by using M relay nodes, α is the path loss exponent, and $|\cdot|$ denotes the magnitude of a complex number. As (2) implies, increasing the number of hops increases the channel variance by decreasing the distance between the relay nodes. By considering a reference distance to describe the path loss of the channel, we can define the maximum number of hops. In other words, by using the maximum number of hops, the length of every hop is the same as the reference distance, and the channel variance of each hop is one. If the maximum number of hops that can be used in the transmission is denoted by $\hat{M}$, then using (2), we can write

$$\frac{\xi_M}{\xi_{\hat{M}}} = \frac{M^{\alpha} \cdot \xi_1}{\hat{M}^{\alpha} \cdot \xi_1} = \left(\frac{M}{\hat{M}}\right)^{\alpha}.$$

We know that by using the maximum number of hops, the path gain will be one ($\xi_{\hat{M}} = 1$). In other words, we employ so many relay nodes that the channels do not deteriorate the signal power. Therefore, we can write

$$\xi_M = \left(\frac{M}{\hat{M}}\right)^{\alpha} \triangleq V. \quad (3)$$

Considering the fact that the channels are all modeled as ZMCSCG, it can be concluded that the distribution of the magnitude of the channel is χ^2 with two degrees of freedom. If q denotes $|h|^2$, the probability density function (PDF) and cumulative distribution function (CDF) of $q \sim \chi_2^2$ for $q \in [0, \infty)$ can be written as

$$f_Q(q) = \frac{1}{V} \cdot \exp\left(-\frac{q}{V}\right),$$
$$F_Q(q) = 1 - \exp\left(-\frac{q}{V}\right). \quad (4)$$

The instantaneous CSI of h_i is known at the next relay node, r_i. With the aid of the known CSI at the relay, the channel phase is compensated at the relay nodes. Depending on the relaying scheme, the relay nodes do some processing on the received signal before forwarding the signal to the next relay node.

Analysis of the Ergodic Capacity for the Relaying Scheme

Because the channel capacity is an indication of two important factors, the error probability and rate of the transmission, we consider the ergodic capacity as a parameter for studying the performance of a multihop network.

Comparing AF- and DF-Relaying Schemes

First, we compare the most popular relaying schemes, AF and DF, for the SISO links between the relay nodes from the capacity point of view. We know that the capacity for the DF scheme is given by

$$C_{\text{DF}} = \frac{1}{M}\min\{c_1, c_2, \ldots, c_M\}$$
$$= \frac{1}{M}\log_2(1 + \min\{\gamma_1, \gamma_2, \ldots, \gamma_M\}),$$

where γ_i denotes the received SNR for the ith hop and c_i is the channel capacity of the ith hop. The ergodic capacity for the AF scheme is given by

$$C_{\text{AF}} = \frac{1}{M}\log(1 + \gamma_{\text{total}}),$$

where γ_{total} stands for the received SNR at the destination. It is shown for the AF scheme that the relays amplify the received noisy signal. Therefore, the SNR is not changed after amplifying. On the other hand, the amplified signal is attenuated over the channel toward the next relay, and the antenna at the relay adds some noise to the received attenuated signal. Therefore, the received SNR decreases by forwarding over the hops. Let the kth hop be the weakest hop between the source and destination for the DF scheme. Considering the aforementioned facts about the AF scheme, one can easily show that $\gamma_{\text{total}} \leq \gamma_k$ and

$$C_{\text{DF}} = \frac{1}{M}\log_2(1 + \min\{\gamma k\}),$$
$$C_{\text{DF}} \geq C_{AF}. \quad (5)$$

This comparison is also shown through a simulation for a different number of hops and varying the transmit power of nodes. The result of the simulation is illustrated in Figure 2.

DF Relaying

In the DF transmission, the relay nodes fully decode the received signal and reencode it before transmission. Using the result in [3], the overall system capacity cannot be larger than the capacity of each hop. Therefore, the ergodic capacity of the DF relay network with M hops is written as

$$C_{\text{DF}} = \frac{1}{M} \cdot \mathbb{E}\{\min\{c_1, c_2, \ldots, c_M\}\}, \quad (6)$$

where c_i is the channel capacity of the ith hop. The instantaneous capacity of the ith hop is expressed as

$$c_i = \log_2\left(1 + \frac{P_s}{\sigma_v^2}|h_i|^2\right). \quad (7)$$

Considering equidistant relays and the same distribution for all channels h_i $(i = 1, 2, \ldots, M)$, the distribution of the instantaneous channel capacity of all hops is the same. For simplicity in writing the equations, we use c' as the instantaneous channel capacity of hops. Using (4), we can rewrite the PDF of $c' = \log_2(1 + \rho \cdot q)$ as

$$f_{C'}(c') = \exp\left(-\frac{2^{c'} - 1}{\rho \cdot V}\right)\frac{2^{c'} \cdot \ln(2)}{\rho \cdot V}, \quad (8)$$

where q denotes $|h_i|^2$ and $\rho = P_s/\sigma_v^2$. In the next step, we have to find the distribution of $C_{\mathrm{DF}} = \frac{1}{M}\min\{c_1, c_2, \ldots, c_M\}$. It is obvious that $M \cdot C_{\mathrm{DF}} = c_i$ if $c_i \le c_k$, where $k = \{1, 2, \ldots, i-1, i+1, \ldots, M\}$. This expression can be written as

$$P(M \cdot C_{\mathrm{DF}} = c_i) = P(c_i) \cdot \prod_{\substack{k=1 \\ i \neq k}}^{M} P(c_i \ge c_k),$$

and the PDF of $c'' = M \cdot C_{\mathrm{DF}}$ can be expressed as

$$\begin{aligned} f_{C''}(c'') &= \sum_{i=1}^{M} f(c''|c_i) \cdot f(c_i), \\ &= \frac{2^{c''} \cdot \ln(2) \cdot M}{\rho \cdot V}\exp\left(-M\frac{2^{c''} - 1}{\rho \cdot V}\right). \end{aligned} \quad (9)$$

Using the PDF of c'', the average of C_{DF} is obtained as

$$\begin{aligned} \mathbb{E}\{C_{\mathrm{DF}}\} &= \frac{1}{M}\int_0^{\infty} c'' \cdot f_{C''}(c'')dc'', \\ &= \frac{\mathrm{Ei}\left(\frac{-M}{\rho \cdot V}\right) \cdot \exp\left(\frac{M}{\rho \cdot V}\right)}{M \cdot \ln(2)}, \end{aligned} \quad (10)$$

where $\mathrm{Ei}(x)$ denotes an exponential integral. It is more interesting to understand, analytically, how the ergodic capacity changes with respect to the number of hops. It is true that the number of hops can be only natural numbers, but for simplicity, we assume that M is a real positive number. Therefore, remembering that $V = \left(M/\hat{M}\right)$, we calculate the derivative of $\mathbb{E}\{C_{\mathrm{DF}}\}$ with respect to M as

$$\frac{\partial \mathbb{E}\{C_{\mathrm{DF}}\}}{\partial M} = \frac{\exp\left(\frac{\hat{M}^{\alpha}}{\rho \cdot M^{(\alpha-1)}}\right) \cdot \mathrm{Ei}\left(-\frac{\hat{M}^{\alpha}}{\rho \cdot M^{(\alpha-1)}}\right) \cdot \left[\frac{\hat{M}^{\alpha}}{\rho \cdot M^{(\alpha-1)}} \cdot (\alpha - 1) + 1\right] + (\alpha - 1)}{(M^2 \cdot \ln(2))}. \quad (11)$$

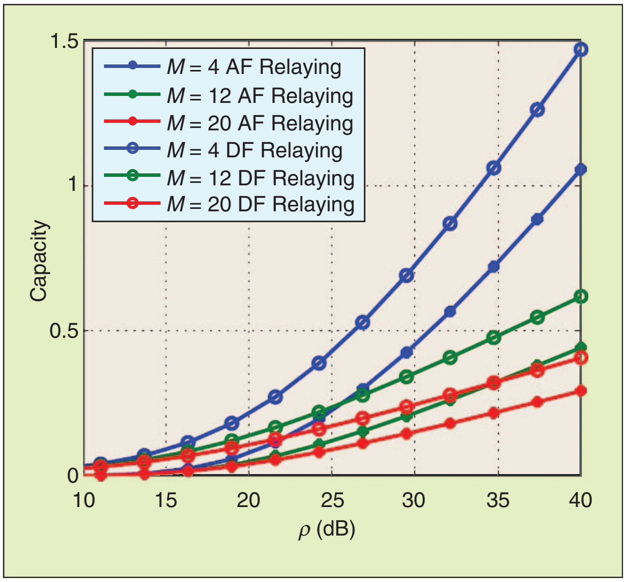

FIGURE 2 Comparing AF and DF schemes from ergodic capacity point of view for different number of hops.

By comparing (11) with zero and studying its sign, we figure out that (11) is negative in the high-SNR regime and is independent of the choice of α. However, in the low-SNR regime, the choice of α plays a decisive role in determining the sign of (11). This phenomenon is shown in Figure 3, where $x = (\hat{M}/M) \cdot \rho^{(-1/\alpha-1)}$.

Figure 3 shows that, in the very low-SNR regime, changing the number of hops cannot result in an improvement in the performance of the transmission, while in the intermediate-SNR regime, increasing the number of hops can increase the performance when the environment imposes a higher value of the path-loss exponent. Figure 4 also confirms this conclusion. In

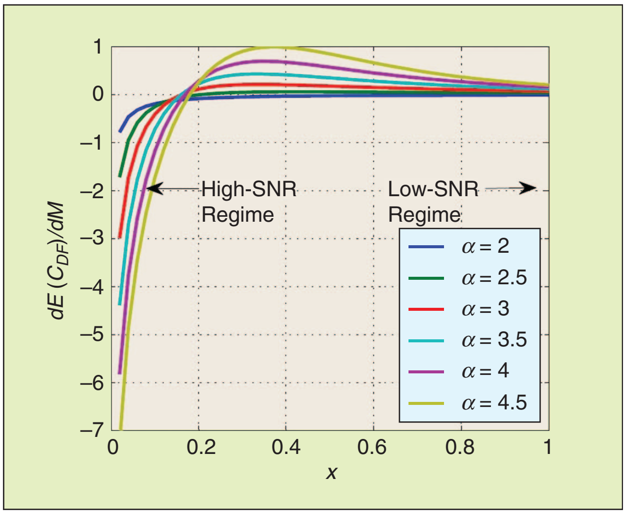

FIGURE 3 The differentiation of $\mathbb{E}\{C_{\mathrm{DF}}\}$ with respect to M, where $x = (\hat{M}/M) \cdot \rho^{(-1/\alpha-1)}$ and $\hat{M} = 10$.

In a non-line-of-sight or relatively lossy environment, the reliability of the transmission in the low-SNR regime is improved by using more hops

Figure 4, the analytical result of $\mathbb{E}\{C_{DF}\}$ versus ρ is illustrated for a different number of hops and different values of α by using (10).

The analysis of the ergodic capacity for the DF scheme shows that improving the performance of the transmission by changing the number of hops depends on different factors, such as the SNR regime, the path loss exponent, and the distance between the transmitter and destination. In a non-line-of-sight or relatively lossy environment, the reliability of the transmission in the low-SNR regime is improved by using more hops, while in the high-SNR regime, it is always more reliable to decrease the number of hops without the need for taking any environmental conditions into consideration.

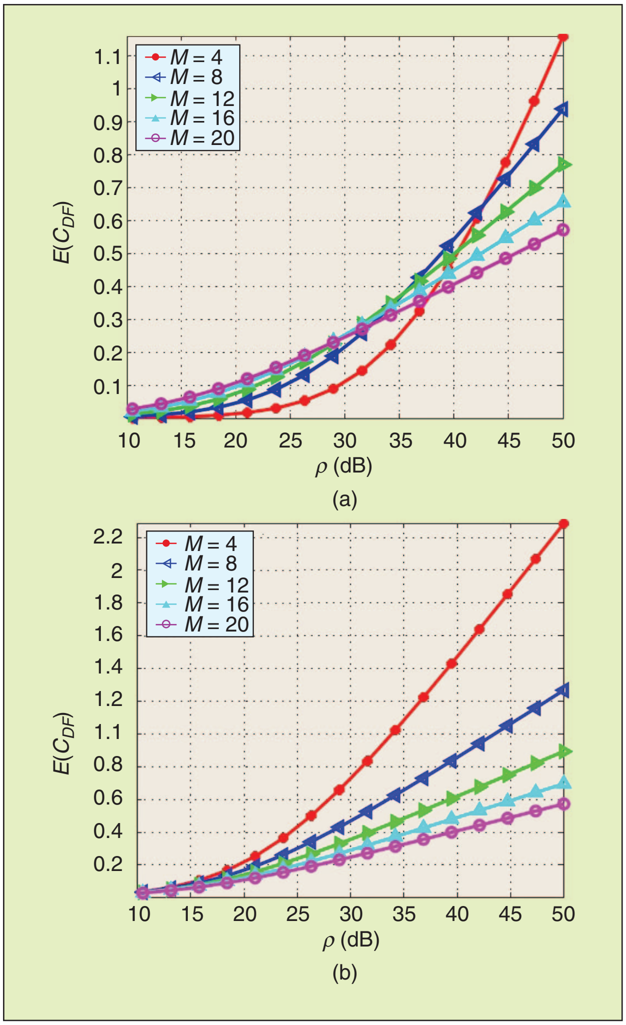

Figure 4 Analytical result of $\mathbb{E}\{C_{DF}\}$ versus $\rho = P_s/\sigma_v^2$ for different number of hops and different path loss exponent (α). (a) $\alpha = 4$ and (b) $\alpha = 2$.

Number of Receive Antennas and Number of Hops

We have shown that reducing the number of hops improves the performance of the transmission, especially in the high-SNR regime. However, reducing the number of hops also causes an increased bit error rate and thereby a drop in QoS at the destination. One attractive method for reducing the number of hops and ensuring the QoS is to employ additional antennas at the TX and/or RX side and/or relays. By using more antennas, we can extract the benefits of the MIMO channels and increase the range of transmission.

The goal is to study the performance of the transmission over an optimum multihop route that is found based on MIMO, SIMO, and SISO links. We assume that the number of transmit and receive antennas are the same for all hops. Moreover, the selection methods of the transmit antennas are not considered in this article. For simplicity, we do not consider more than two antennas at the TX side, and we study only the Alamouti STBCs-based scheme for the MIMO multihop network.

Optimum Multihop Network

Assuming that we can put the relay nodes wherever required between the transmitter and destination and the number of antennas at the relay nodes are not limited, we can generate a multihop network for varying number of transmit and receive antennas. This multihop network is optimum in terms of the number of hops because we use the least number of hops for a given threshold of the QoS.

Assuming that the average of the loss of the channels of all hops and the noise at the relays are identical, the symbol error rate (SER) is the same for all hops. The SER at the destination is written as

$$\mathrm{SER}_{\mathrm{total}} \leq 1 - (1 - \mathrm{SER})^M, \tag{12}$$

where M and SER denote the number of required hops and the SER of one hop, respectively. Let $\mathrm{SER}_{\mathrm{th}}$ denote the maximum allowable SER at the destination. In other words, $\mathrm{SER}_{\mathrm{th}}$ is the given threshold for QoS. Now the goal is to find the minimum number of required hops under this SER constraint.

In general, for maximum-likelihood estimation, the probability of the SER in the AWGN channel can be approximated as

$$\mathrm{SER} \approx \bar{N}_e \cdot Q\left(\sqrt{\frac{\eta \cdot \tilde{d}_{\min}^2}{2}}\right), \tag{13}$$

where Q represents the Q-function, which is the tail probability of the standard normal distribution, and $\bar{N}_e$, η, and $\tilde{d}_{\min}$ denote the number of nearest neighbors, the average of the SNR at receiver after receive combining, and the minimum distance of separation of the underlying scalar constellation.

Using the Chernoff bound $Q(x) \leq 1/2 \cdot \exp(-x^2/2)$, and considering the fact that the energy is shared equivalently between the transmit antennas, (13) can be bounded for high-SNR regime, which yields

$$\text{SER} \leq \frac{\bar{N}_e}{2} \cdot \left(\rho \cdot \left(\frac{M}{\hat{M}} \right)^{\alpha} \cdot \frac{\tilde{d}^2_{\min}}{4 \cdot N_t} \right)^{-D}, \qquad (14)$$

where N_t and D denote the number of transmit antennas and diversity, respectively, and $\rho = E_s/N_0$, where E_s and $N_0/2$ represent the transmit energy per symbol and noise power spectral density, respectively.

SISO Multihop Network

Substituting $D = 1$ in (14) and its result in (12), the SER at the destination for SISO multihop network over M hops in the high-SNR regime is given by

$$\text{SER}_{\text{SISO}} \leq 1 - \left(1 - \frac{\bar{N}_e}{2} \cdot \left(\left(\frac{M}{\hat{M}} \right)^{\alpha} \cdot \frac{\rho \cdot \tilde{d}^2_{\min}}{4} \right)^{-1} \right)^{M}. \qquad (15)$$

SIMO Multihop Network

Using maximal ratio combining at the receiver, the received SNR is maximized and the diversity gain (D) is the number of received antennas (N_r). Using this result and (12) and (14), the SER at the destination for SIMO multihop network over M hops in the high-SNR regime is obtained as

$$\text{SER}_{\text{SIMO}} \leq 1 - \left(1 - \frac{\bar{N}_e}{2} \left[\left(\frac{M}{\hat{M}} \right)^{\alpha} \cdot \frac{\rho \cdot \tilde{d}^2_{\min}}{4} \right]^{-N_r} \right)^{M}. \qquad (16)$$

MIMO Multihop Network for the Alamouti STBCs-Based Scheme

Since the Alamouti scheme extracts a diversity order of $2.N_r$, the SER at the destination for MIMO (Alamouti STBCs-based) multihop network over M hops in the high-SNR regime can be written as

$$\text{SER}_{\text{Alamouti}} \leq 1 - \left(1 - \frac{\bar{N}_e}{2} \left[\left(\frac{M}{\hat{M}} \right)^{\alpha} \cdot \frac{\rho \cdot \tilde{d}^2_{\min}}{8} \right]^{-2 \cdot N_r} \right)^{M}. \qquad (17)$$

Comparison between MIMO (Alamouti STBCs-Based), SIMO, and SISO Multihop Networks

The purpose of using SIMO and MIMO links in the multihop networks is to increase the diversity and extend the transmission distance, which leads to a decrease in the number of hops. In the analysis in the last section, we have assumed that the devices were equipped with a large number of antennas. However, this assumption cannot be accomplished in a real scenario. Therefore, we will need cooperation among users with a limited number of antennas or just one antenna each. By using this cooperation, we can exploit the benefits of the spatial diversity, and, at the same time, we render the users busier due to their participation in many transmissions and, thus, increase the interference in the network. Also, some synchronization mechanism will become necessary at the transmitter side. Considering these facts, it becomes more important to figure out the conditions in which increasing the number of antennas is worthwhile. In this section, we compare SISO, SIMO, and MIMO (Alamouti STBCs-based) multihop with respect to the number of hops and the rate of transmission.

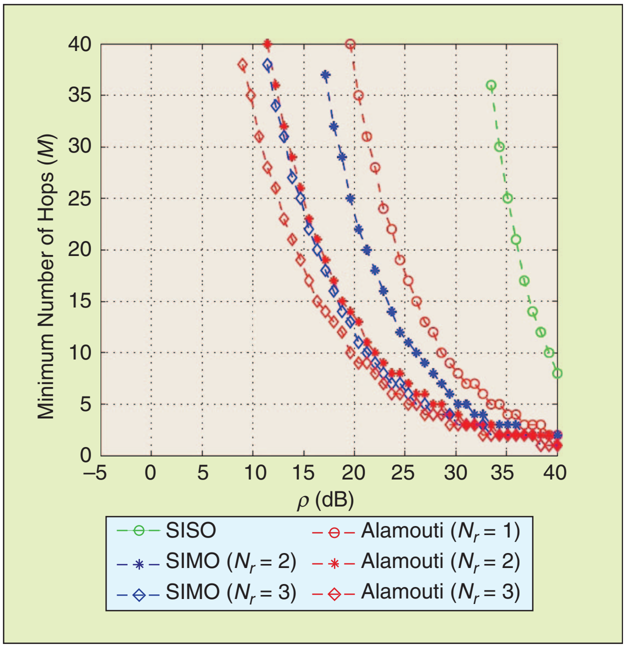

FIGURE 5 Minimum number of hops versus transmit energy per symbol for SISO, MISO, and MIMO (Alamouti STBCs-based) multihop networks for different number of receive antennas, where $\hat{M} = 40$ and $\text{SER}_{\text{th}} = 0.01$.

This simulation has been done in MATLAB for the scenario based on Rayleigh fading channels and additive noise at the antennas. The noise variance is assumed to be the same for all receive antennas, and the variance of the channels depends on the number of relays between the source and destination. In this simulation, we will figure out how much gain we will obtain in a multihop network by increasing the number of antennas. In this simulation, we determine a fixed value of an SER as a threshold of the SER for the entire transmission. By implementing (15)–(17), the minimum number of hops is computed for a given transmit energy per symbol. It is

THE ANALYSIS POINTS TO THE FACT THAT THE SLOPE OF THE INCREASE IN THE GAIN AND THE DECREASE IN THE NUMBER OF HOPS BECOMES SMALLER BY INCREASING THE NUMBER OF RECEIVE ANTENNAS.

obvious that the SER of the entire transmission should not exceed the fixed threshold. The minimum number of hops versus the transmit energy per symbol for SISO, MISO, and MIMO (Alamouti STBCs-based) multihop networks for the different number of receive antennas has been simulated. The result of this simulation is illustrated in Figure 5.

We can see that the obtained gain by adding just one receive antenna to the SISO case and, thus, creating a SIMO link is much higher than the gain by adding one receive antenna to SIMO ($N_r = 2$). Figure 5 shows that adding receive antennas is more effective at lower orders of SIMO. In other words, the amount of gain decreases when a receive antenna is added if the order of the receive array was already high. The effectiveness of increasing the number of transmit antenna can also be seen clearly, by comparing SIMO and Alamouti STBCs-based curves with the same number of receive antennas, in this figure. The comparison between SIMO and Alamouti STBCs-based MIMO is performed from the total number of antennas point of view. Under the condition that the total number of antennas is the same for both Alamouti STBCs-based MIMO network and SIMO multihop network, we can see that the gain by SIMO will always be better than Alamouti STBCs-based MIMO. Thus, for cooperative

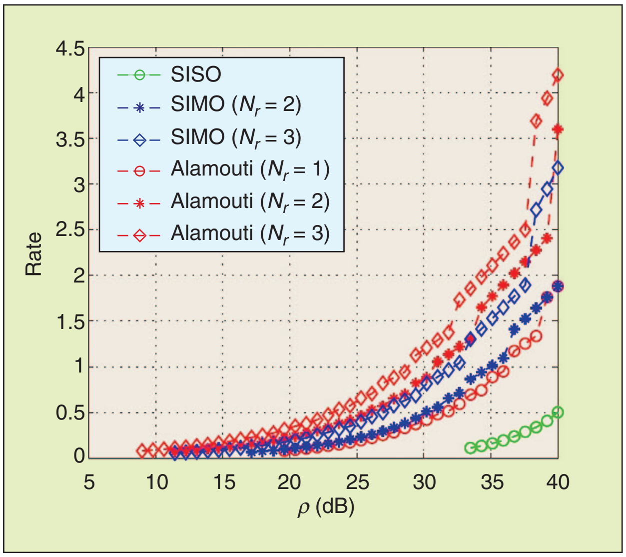

FIGURE 6 Rate of the transmission based on the computed minimum number of hops in Figure 5.

MIMO, when the antennas belong to different devices, if the position of a device is somewhere in the middle of the transmitter and receiver, it gives us more gain if this device is used as an antenna element of the receiver side.

Another important comparison is the one concerning the rate of transmission. Our system is based on DF relaying, so the mutual information for the multihop case is given by

$$I_{DF} = \frac{1}{M} \cdot \min\{I_1, I_2, \ldots, I_M\}, \qquad (18)$$

where I_i is the open-loop capacity of the ith hop (no channel knowledge is available at the transmit relay) and given by

$$I_i = \log\left[\det\left(I_{N_r} + \frac{\rho}{N_t} \cdot \left(\frac{M}{\hat{M}}\right)^{\alpha} \cdot \breve{H} \cdot \breve{H}^{H}\right)\right], \qquad (19)$$

where the elements of $\breve{H} \in \mathbb{C}^{N_r \times N_t}$ are modeled as independent identically distributed ZMCSCG random variables with unit variance, and N_t stands for number of transmit antennas. The result of this simulation is shown in Figure 6.

Conclusions and Future Work

The results presented in this article are of importance to network designers as we move toward the standardization of cooperative multihop networks. The analytical results can help decide the thresholds at which nodes can switch between different modes of transmission, such as the relaying scheme, diversity order, and the appropriate number of hops to ensure QoS.

In the first part of this article, the ergodic capacity of the multihop network for DF relaying has been studied. We assumed an optimum multihop network in which the variances of the channels of all hops are the same and the antennas at the relays are identical. The analysis of the ergodic capacity of the DF scheme points to the fact that, in the high-SNR regime, decreasing the number of hops increases the performance of the transmission. In the low-SNR regime, the environmental factors, such as path loss exponent and the distance between the source and destination, have to be considered before making any comment about increasing or decreasing number of hops for improving the performance of the network. Moreover, comparing AF and DF relaying has shown that DF relaying always provides more ergodic capacity than the AF scheme by using the same number of hops.

In the second part, increasing the number of antennas at the relays with an arbitrary antenna selection has been studied for a multihop network. The analysis points to the fact that the slope of the increase in the gain and the decrease in the number of hops becomes smaller by increasing the number of receive antennas. Although the obtained gain by a MIMO (Alamouti STBCs-based) multihop network is higher than SIMO multihop network by using the same number of receive antennas, the obtained gain of SIMO multihop network is better than MIMO (Alamouti STBCs-based) multihop network by using the same number of total antennas. In other words, in a network with single antenna devices, increasing the receive diversity should be given precedence over increasing the transmit diversity.

For future work, it would be interesting to evaluate these relaying schemes in the presence of interference from external users and from those within the network. In the analysis presented in this article, we have only considered the case when only a single multihop communication link is active at a time. It is also important to implement a trial version of these types of cooperative networks on some hardware platform and evaluate the performance in real-world scenarios. So far, not many such implementations have been presented, and most of them are not comprehensive enough to give an idea about the feasibility of these schemes in real-world scenarios. The next step would then be an extensive deployment of such a network with a large enough number of nodes for researchers and network planners to see the effects the scheme has on network-level statistics, such as the network load, delay statistics, overhead, and QoS.

Author Information

Bilal Zafar (bilal.zafar@tu-ilmenau.de) completed his B.E. degree in electrical engineering from the National University of Technology (NUST), Pakistan, in 2007, and his M.S. degree in wireless systems from KTH, Sweden, in 2009. He is currently pursuing his Ph.D. degree at the International Graduate School on Mobile Communications (GS-Mobicom) and the Communications Research Laboratory (CRL) at the Ilmenau University of Technology, Germany. His research interests include decentralized and ad hoc networks, cooperative MIMO schemes, routing, network coding, and wireless communications.

Soheyl Gherekhloo (soheyl.gherekhloo@tu-ilmenau.de) received his B.E. degree from the Ilmenau University of Technology, Germany, in 2010, and his master's degree in information and communication technology from the Ilmenau University of Technology in 2012. He is currently working as a research assistant in CRL.

Martin Haardt (martin.haardt@tu-ilmenau.de) studied electrical engineering at Ruhr-University Bochum, Germany, and at Purdue University. He received his Diplom-Ingenieur (M.S.) degree from Ruhr-University, Bochum, in 1991 and his Doktor-Ingenieur (Ph.D.) degree from the Munich University of Technology in 1996. In 1997, he joined Siemens Mobile Networks in Munich, Germany, where he was responsible for strategic research for third-generation mobile radio systems. From 1998 to 2001, he was the director for international projects and university cooperation in the mobile infrastructure business of Siemens in Munich, where his work focused on mobile communications beyond the third generation. Since 2001, he has been a full professor in the Department of Electrical Engineering and Information Technology and the head of the CRL at the Ilmenau University of Technology, Germany. He has received the 2009 Best Paper Award from the IEEE Signal Processing Society, the Vodafone (formerly Mannesmann Mobilfunk) Innovations Award for outstanding research in mobile communications, the ITG Best Paper Award from the Association of Electrical Engineering, Electronics, and Information Technology (VDE), and the Rohde and Schwarz Outstanding Dissertation Award. His research interests include wireless communications, array signal processing, high-resolution parameter estimation, as well as numerical linear and multilinear algebra.

References

[1] E. C. van der Meulen, "Transmission of information in a t-terminal discrete memoryless channel," Ph.D. dissertation, Dept. Statistics, Univ. California, Berkeley, CA, 1968.

[2] E. C. van der Meulen, "Three-terminal communication channels," *Adv. Appl. Prob.*, no. 3, pp. 120–154, 1971.

[3] T. M. Cover and A. A. E. Gamal, "Capacity theorems for relay channels," *IEEE Trans. Inform. Theory*, vol. 25, no. 5, pp. 572–584, Sept. 1979.

[4] A. E. Gamal and S. Zahedi, "Capacity of a class of relay channels with orthogonal components," *IEEE Trans. Inform. Theory*, vol. 51, no. 5, pp. 1815–1817, May 2005.

[5] A. E. Gamal, M. Mohseni, and S. Zahedi, "Bounds on capacity and minimum energy-per-bit for AWGN relay channels," *IEEE Trans. Inform. Theory*, vol. 52, no. 4, pp. 1545–1561, Apr. 2006.

[6] A. Host-Madsen and J. Zhang, "Capacity bounds and power allocation for wireless relay channels," *IEEE Trans. Inform. Theory*, vol. 51, no. 6, pp. 2020–2040, June 2005.

[7] B. Wang, J. Zhang, and A. Hst-Madsen, "On the capacity of MIMO relay channels," *IEEE Trans. Inform. Theory*, vol. 51, no. 1, pp. 29–43, Jan. 2005.

[8] L. L. Xie and P. R. Kumar, "A network information theory for wireless communication: Scaling laws and optimal operation," *IEEE Trans. Inform. Theory*, vol. 50, no. 5, pp. 748–767, 2004.

[9] A. Reznik, S. R. Kulkarni, and S. Verdu, "Degraded Gaussian multirelay channel: Capacity and optimal power allocation," *IEEE Trans. Inform. Theory*, vol. 50, no. 12, pp. 3037–3046, Dec. 2004.

[10] G. Kramer, M. Gasper, and P. Gupta, "Cooperative strategies and capacity theorems for relay networks," *IEEE Trans. Inform. Theory*, vol. 51, no. 9, pp. 3037–3063, Sept. 2005.

[11] M. O. Hasna and M. S. Alouini, "End-to-end performance of transmission systems with relays over Rayleigh fading channels," *IEEE Trans. Wireless Commun.*, vol. 2, no. 6, pp. 1126–1131, Nov. 2003.

[12] G. K. Karagiannidis, T. Tsiftsis, and R. K. Mallik, "Bounds for multihop relayed communications in Nakagami-m fading," *IEEE Trans. Commun.*, vol. 54, no. 1, pp. 18–22, Jan. 2006.

[13] G. Farhadi and N. C. Beaulieu, "On the performance of amplify and forward cooperative links with fixed gain relays," *IEEE Trans. Wireless Commun.*, vol. 7, no. 5, pp. 1851–1856, May 2008.

VT