SNR-based relay selection in cooperative wireless ad hoc networks

Muhammad Khalil Afzal

Department of Computer Science,
Comsats Institute of Information Technology,
Wah 47040, Pakistan
Email: khalilafzal@ciitwah.edu.pk

Seung Yeob Nam

Department of Information and Communication Engineering,
Yeungnam University,
Gyeungsan, Gyeungbuk 38541, Korea
Email: synam@ynu.ac.kr

Byung-Seo Kim*

Department of Computer and Information Communication Engineering,
Hongik University,
Sejong 30016, Korea
Email: jsnbs@hongik.ac.kr
*Corresponding author

Sung Won Kim

Department of Information and Communication Engineering,
Yeungnam University,
Gyeungsan, Gyeungbuk 38541, Korea
Email: swon@yu.ac.kr

Abstract: Cooperative communications aim to gain spatial diversity from stations cooperating during data transmission without requiring multiple transceiver antennas on the same station. However, performance from cooperative communications highly depends on the relay-selection method. This paper proposes and evaluates a distributed relay-selection method based on the signal-to-noise ratio of the communication links of candidate relay nodes. A node is selected as a relay node based on the signal-to-noise ratio of its communication link. Moreover, data might be delivered through a relay node that can support high transmission rate rather than through a direct link with a low transmission rate. This paper provides a detailed analysis of the collision probability in the proposed method as compared to a conventional random backoff method. Results demonstrate that the proposed relay-selection method reduces collision probability, and hence, enhances system throughput.

Keywords: cooperative communications; relay selection; collision.

Reference to this paper should be made as follows: Afzal, M.K., Nam, S.Y., Kim, B-S. and Kim, S.W. (2018) 'SNR-based relay selection in cooperative wireless ad hoc networks', *Int. J. Ad Hoc and Ubiquitous Computing*, Vol. 28, No. 1, pp.45–54.

Biographical notes: Muhammad Khalil Afzal received his BS and MS in Computer Science from COMSATS Institute of Info. Tech., Wah Campus, Pakistan in 2004 and 2007, respectively and his PhD from Department of Information and Communication Engineering, Yeungnam University, Korea, in December 2014. He has served as Lecturer from January 2008 to November 2009 in Bahauddin Zakariya University Multan Pakistan, and from December 2009 to June 2011 in King Khalid University Abha, Saudi Arabia. Currently, he is working as an Assistant Professor in Department of Computer Science at COMSATS, Wah Cantt Pakistan. His research interest includes wireless sensor networks, ad hoc networks, reliability in multicasting, and cooperative networks.

Seung Yeob Nam received his BS, MS, and PhD in Electrical Engineering from the Korea Advanced Institute of Science and Technology (KAIST), Daejon, Korea, in 1997, 1999, and 2004, respectively. From 2004 to 2006, he was a Postdoctoral Research Fellow at CyLab at Carnegie Mellon University. In March 2007, he joined the Department of Information and Communication Engineering, Yeungnam University, Gyeongsan, Korea, where he is currently an Associate Professor. His research interests include network security, network monitoring, network architecture, wireless networks, etc.

Byung-Seo Kim received his BS in Electrical Engineering from In-Ha University, Korea in 1998 and his MS and PhD degrees under supervision of Dr. Yuguang Fang in Electrical and Computer Engineering from the University of Florida in 2001 and 2004, respectively. Between 1997 and 1999, he worked for Motorola Korea Ltd., Korea as CIM Engineer in ATR&D. From January 2005 to August 2007, he worked for Motorola Inc., Schaumburg Illinois, as a Senior Software Engineer in Networks and Enterprises. He is currently an Associate Professor at the Department of Computer and Information Communication Engineering in Hongik University, Korea.

Sung Won Kim received his BS and MS from the Department of Control and Instrumentation Engineering, Seoul National University, Korea, in 1990 and 1992, respectively, and his PhD from the School of Electrical Engineering and Computer Sciences, Seoul National University, Korea, in August 2002. In March 2005, he joined the Department of Information and Communication Engineering, Yeungnam University, Gyeongsangbuk-do, Korea, where he is currently a Professor. His research interests include resource management, wireless networks, mobile networks, performance evaluation, and embedded systems.

1 Introduction

Many protocols require a distributed solution for selecting a node from a set of candidate nodes to achieve a specific task (Brandner et al., 2013). Examples of such scenarios include selection of a cluster head in multi-hop ad hoc networks (Basagni, 1999), selection of a relay node in cooperative wireless communications (Laneman et al., 2004), and gathering nodes for data processing in wireless sensor networks (Chou et al., 2003). Cooperative communications have the advantage of offering throughput enhancement and reliability in wireless networks by using several single-antenna nodes to form a virtual antenna array (Li et al., 2014). However, the performance of the media access control (MAC) protocol in cooperative wireless communications highly depends on the relay-selection mechanism (Sharma et al., 2011).

Bletsas et al. (2006) proposed opportunistic relay (OR) scheme. Each potential relay can overhear the request-to-send (RTS) and clear-to-send (CTS) frames between transmitter and receiver. All potential relays can deduce the channel quality from the strength of the RTS/CTS frames and start a timer based on instantaneous channel measurement. The timer of the relay with the best end-to-end channel conditions will expire first, and that relay node transmits a short duration flag packet, signalling its presence to all other relay nodes. However, $2L$ channel estimations are required to find the best relay node among L candidate relay nodes. Furthermore, all available relay nodes must remain in listening mode during the transmission of RTS and CTS frames, which increases power consumption in the relay nodes (Hwang and Ko, 2007). Zhu and Cao (2006) presented an enhanced protocol named relay-enabled distributed coordination function (rDCF) protocol. They showed that rDCF can improve system performance. Under rDCF, all nodes maintain a ‘willing list’ based on channel quality between nodes. The length of the willing list is limited to 10 entries to reduce overhead. However, nodes frequently broadcast their willing list to their neighbour nodes, which may be unnecessary if a direct link between the source and the destination nodes can support a higher data transmission rate. Chen et al. (2006) had source nodes include their residual power level in the RTS frames, allowing all overhearing nodes to estimate channel state information (CSI) and make an optimal power allocation. The relay-selection decision depends upon relay transmission power and CSI, as well as the residual power of the source and relay nodes. The objective of the protocol is to maximise the overall transmit power using optimal power allocation. However, the proposed protocol leads to collision complexity when the number of nodes increases (Abdulhadi et al., 2012). Nosratinia and Hunter (2007) proposed a multiple relay-selection scheme based on a priority list of candidate relay nodes. The authors considered random selection, received signal-to-noise ratio (SNR) selection, and fixed priority-list selection for creation of the priority list. In the received SNR selection, each node measures its reception and attempts to assist the nodes that have the highest SNR. That is, for each transmission block, a user prioritises the other users in descending order of received SNR. The scheme proposed by Krikidis et al. (2008) is known as a partial relay selection (PRS) scheme, where only neighbouring channel state information is available to the nodes. In this scheme, a cluster of relays is selected based on average SNR and CSI. In another method, Zhou et al. (2008) suggested that sources send an RTS frame that includes their maximum transmission power. The overhearing nodes compete for selection on the basis of signal strength combined with the overheard power information. Adam et al. (2008) studied relay selection with explicit consideration of the energy required to receive the data. They proposed a relay-selection scheme that exhibits benefits with respect to energy efficiency. Each potential relay assesses the CSI and decides whether to participate in the relay-selection process or not. Under a scheme by Shan et al. (2008), overhearing nodes send out a 'busy tone' according to their measured SNR. The relay with the best channel condition sends a longer busy tone. However, this mechanism requires additional transceivers. This approach is similar to the basic mechanism of Zhou et al. (2008). The difference is that Shan et al. (2008) only considered the channel estimation and not the energy.

Kim and Kim (2007) presented a comparison of opportunistic amplify-and-forward (AF) relay schemes with partial or full CSI under a tight power constraint. Partial CSI and full CSI-based relay schemes achieve very similar performance for a small number of nodes. However, as the number of relay nodes increased, the performance of the full CSI relay scheme continuously improved. Costa et al. (2009) presented a relay-selection scheme based only on the instantaneous information about the channel pertaining to the first hop (Krikidis et al., 2008). Furthermore, the authors investigated the end-to-end performance of a cooperative link with fixed gain relays. Fixed gain relays provide reduced implementation complexity, compared to CSI-based gain relay (Costa et al., 2009). However, in all these works (Krikidis et al., 2008; Kim and Kim, 2007; Costa et al., 2009), the PRS method experiences performance loss compared to the scheme with full CSI. Chalise et al. (2012) proposed a centralised relay selection scheme with information about only the first-hop channel. This scheme is attractive because it does not require global CSI at the central node, and hence, reduces the feedback requirements to acquire CSI. Abouelseoud and Nosratinia (2013) proposed heterogeneous relay networks where relays with different protocols co-exist. A heterogeneous network may contain both decode-and-forward (DF) relays and AF relays. However, the authors assumed that the CSI is available to all relays. Brandner et al. (2013) proposed a contention-based distributed node-selection mechanism. The aim of the proposed random access mechanism is to maximise success probability and reduce signalling overhead in terms of reply messages sent by candidate nodes. Moreover, the authors proposed their own access strategies (i.e., uniform access and slow start access).

Cao et al. (2014) proposed a cooperative MAC with an optimal relay-selection algorithm. In particular, they considered the relationship between the cooperative performance gain and MAC overhead caused by retransmissions in error-prone wireless networks. In the relay-selection algorithm, each node maintains a table called a Coop-table, which keeps useful cooperation information. When any selected relay node fails to provide cooperation, the corresponding failure count is incremented by one. When the failure count reaches a predefined threshold, the information about this node is removed from the Coop-table. Their proposed protocol outperforms the existing cooperative MAC mechanisms that do not take into account retransmission overhead. However, relay selection requires additional overhead to maintain the Coop-table on each node.

The distributed scheduling approach proposed for video streaming over multi-channel, multi-radio and multi-hop wireless networks discussed in Zhou et al. (2010) is used to reduce the video distortion. The convex optimisation approach is used to solve the distortion model which is developed to achieve the quality of service (QoS) in the network. Usually, the channel allocation, rate adoption, and routing metrics are taken into consideration while developing the distributed scheduling approach for enhancing the video fairness and to minimise the video distortion. The QoS is achieved through this optimal scheduling of video over multichannel. The nodes in this multi-hop wireless networks communicate the path discovery messages with other nodes with the help intermediate nodes. This path discovery messages contain the link information, congestion weight, and queue length for every stream between the source and destination node. Furthermore, the congestion in the network is minimised which helps to increases the overall performance of the network. This media-aware distortion-fairness distributed scheduling of the video streaming seems to be very practical and adoptive for resource scarce multimedia sensor networks. However, the proposed scheme is not compared with the practical schemes such as orthogonal frequency-division multiplexing (OFDM), which raises the questions about the practical implementation of this video streaming optimal scheduling over multichannel, multi-radio and multi-hop wireless networks. Zhou et al. (2014), adopted the delayed control information (DCI) in distributed scheduling approach for video streaming in multi-channel and multi-hop wireless networks. This optimisation problem is solved using the stochastic optimisation approach. Usually, for this purpose, the two design classes of DCI are adopted to achieve the enhanced fairness in the network. The class with specific variance and an open class without any parameter specification of DCI are taken into consideration to minimise the delay and distortion in the distributed wireless networks. For each class the relationship between the distributed scheduling and DCI is evaluated to gain the optimal performance bound for any optimal scheduling approach for video streaming. From this evaluation, a DCI-based distributed scheduling approach is chalked out to address the video distortion and fairness in the multi-channel, multi-hop, and multi-radio wireless networks.

This paper proposes a distributed relay-selection method that reduces collision, and thus improves system throughput. The basic concept of the method is to select a node with better link reliability among neighbour nodes as the relay node. Nodes with a high SNR in a link between source and destination are well-suited for selection as a relay node, so they are preferred in the random channel access mechanism. The reliability of the link is the probability of correct reception of data at receiver. This reliability is actually a function of transmission rate, transmit power, and the distance between the sender and the receiver (Khandani et al., 2008). Furthermore, the transmission rate depends on received SNR of relay nodes. Therefore, a node with better link reliability is selected as relay node. The main contribution of the paper can be summarised as follows:

- This paper proposes a distributed relay selection method based on the SNR of the link, in which candidate relay nodes choose their backoff time slot based on the SNR of the link. Therefore, the nodes with higher value of SNR are selected as the relay nodes to transmit the data to the destination and hence improves system throughput.

- In addition to this novel relay node selection method, this paper provides a comprehensive analysis of collision probability by considering the widely adopted IEEE 802.11 wireless standard's contention mechanism (IEEE Standard, 2008). The purpose of such analysis is to obtain an analytical expression of the impact of collision on the relay selection process. The benefit of such analysis is how the relay selection process can affect an overall system throughput.
- This paper also considers a more realistic scenario, where relay nodes can also operate as a source or destination node. Furthermore, in contrast to other schemes (Kim and Kim, 2007; Costa et al., 2009), the proposed protocol considers the SNR of both source-relay and relay-destination links.

The rest of the paper is organised as follows. Section 2 first provides the system model and then explains the proposed SNR-based relay-selection scheme. Section 3 demonstrates the numerical analysis. Section 4 discusses the results, and finally, Section 5 concludes the paper.

2 System model and proposed relay-selection scheme

The system model is based on IEEE 802.11, as shown in Figure 1. IEEE 802.11 supports multiple transmission rates depending on the SNR (Bianchi, 2000; Li et al., 2014). The system model consists of source, destination, and other nodes that do not have their own traffic and that serve as relays. Source/destination nodes are randomly chosen. Assume that source, destination, and potential relay nodes are always within communications range of each other. However, the direct link between source and destination supports a low transmission rate. A direct link is a link between source and destination without any relay nodes. Depending on the channel conditions, relay nodes may help the sender to transmit the data at a higher data rate than the direct link. The channels between each transmission pair are assumed to be independent of each other. Nodes are uniformly distributed over the network area. Uniform distribution is probably the most reasonable model to describe the network model when no prior information about the node's locations is available (Etezadi et al., 2012). It is assumed that neighbour nodes are always willing to cooperate (Dianati et al., 2006). Our proposed scheme selects the shortest path to the destination with the highest SNR. For this purpose, the two steps procedure is usually followed. In the first step, the source node transmits a relay request message (indicating its need to find a relay node) to potential relay nodes. In the second step, each relay node compares its received SNR to the threshold value. In this case, the potential relays whose SNR is larger than the threshold value, are called candidate relays. These candidate relays then transmit the relay response message to the destination. There can be multiple candidate relay nodes with various values of SNR. Among these available multiple relay nodes, the source node selects the one with the highest SNR. The end-to-end performance of cooperative diversity is highly depends on the choice of a threshold value for candidate relay nodes. Threshold is the received SNR for candidate relay nodes. Threshold-based approach reduces the number of competing relays. Furthermore, threshold-based relay selection helps to reduce the error propagation (Onat et al., 2007). If the received SNR of the candidate relay nodes is low, the data is likely to have error. It is possible for multiple nodes to receive the relay request message. In this case, nodes that try to send a relay response message may experience collisions. In addition, there is no guarantee that the node having the best link reliability with the source and the destination nodes will send its relay response message earlier than others having less reliability. In order to set a reliable communication path, it is necessary for the node having the best channel quality with the source and destination to be selected as a relay. Therefore, to give priority to the node that has the better link reliability, neighbour nodes receiving the relay request message randomly choose backoff time slots between 1 and 2^n and send relay response messages after waiting for the chosen time slots. The n is obtained as a function of the SNR of the link as follows:

$$n = N - \left\lfloor \frac{\gamma - \mathrm{SNR}_{\min}}{\mathrm{STEP}_{\mathrm{SNR}}} \right\rfloor, \quad \text{if } \gamma \geq \mathrm{SNR}_{\min}, \tag{1}$$

where N is the maximum number for n, $\mathrm{STEP}_{\mathrm{SNR}}$ is $(\mathrm{SNR}_{\max} - \mathrm{SNR}_{\min})/N$, and $\mathrm{SNR}_{\min}$ and $\mathrm{SNR}_{\max}$ are the minimum and maximum SNRs, respectively, required to determine the system bit error rate (BER) (Bergano et al., 1993). γ is defined as $\alpha\mathrm{SNR}_S + (1 - \alpha)\mathrm{SNR}_D$, where α is a system design parameter, and its value is considered to be 0.5. SNR_S and SNR_D are SNRs of the link between the candidate relay node and source node, and between the candidate relay node and destination node, respectively. If $\gamma < \mathrm{SNR}_{\min}$, then the node cannot participate in relay selection. The first node that sends the relay response message is selected as the relay, whereas by overhearing the relay response message, other nodes stop sending relay response messages. When the source and the destination nodes receive the relay response message, they know which node is selected as a relay. If a relay response message is not received within the timeout period, the source node begins direct transmission.

3 Numerical analysis

3.1 *Collision probability*

This section compares the performance of IEEE 802.11 and the proposed method. As discussed in the previous section, multiple nodes can transmit relay response messages at the same time, which can cause collisions, and there is no guarantee that the node having the best channel condition with the source and destination node will be the first node to send its relay response message. To minimise collision probability, backoff times depend on the SNR values of the potential links. It is assumed that all nodes in the same track (or cylindrical region), as shown in Figure 2, have the same SNR values. There are m nodes in the coverage area of the source node. In 802.11 MAC, for each packet transmission, a backoff timer is used and is randomly selected in the range of [0, $W-1$], where W is called the contention window starting with the minimum value $CW_{\min}$, which will be doubled at each failure of transmission/retransmission until it reaches the maximum value, $CW_{\max}$. The relation between $CW_{\max}$ and $CW_{\min}$ is $CW_{\max} = 2^B CW_{\min}$, where B is the maximum backoff stage.

Figure 1 System model

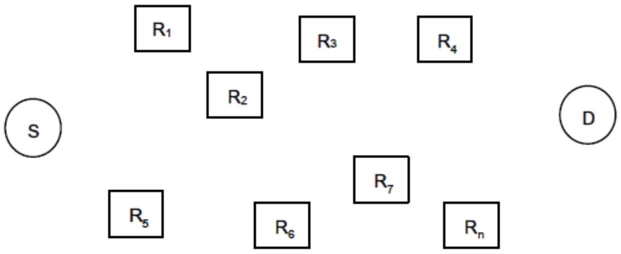
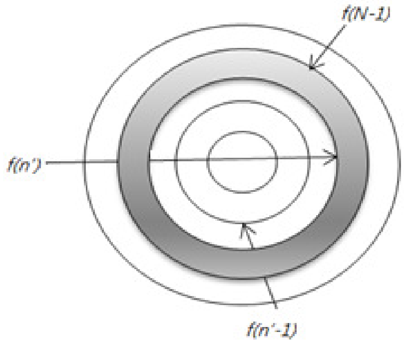


Figure 2 Track vs. SNR in the proposed protocol



Let $p_{c,\text{pro}}$ be the probability that a transmitted relay response message collides on the channel. The collision probability in the proposed protocol can be written as

$$p_{c,\text{pro}} = \sum_{m=1}^{\infty} P(\text{collision}|M=m)P(M=m), \tag{2}$$

where M is a random variable denoting the number of candidate relay nodes within the coverage area of the sender node. There are two possible cases:

- *Case 1*: $m = 1, P(\text{collision}|M=m) = 0$.
  There is no collision if there is only one candidate node within the coverage area of the sender node.
- *Case 2*: $m > 1, 0 \leq n \leq N-1$.

To simplify the analysis, it is assumed that $\text{SNR}_S = \text{SNR}_D$ (Onat et al., 2008). However, the system model allows us to consider the different SNRs for source-relay and relay-destination links. Equation (1) can be written as (Zhou et al., 2008)

$$\begin{aligned} n &= N - \left\lfloor \frac{\gamma - \text{SNR}_{\min}}{\text{STEP}_{\text{SNR}}} \right\rfloor \\ &= N - \left\lfloor \frac{\text{SNR}_D - \text{SNR}_{\min}}{\text{STEP}_{\text{SNR}}} \right\rfloor. \end{aligned} \tag{3}$$

If the value of n is n', then the range of SNR_D can be obtained as follows:

$$N - n' \leq \frac{\text{SNR}_D - \text{SNR}_{\min}}{\text{STEP}_{\text{SNR}}} < N - n' + 1, \tag{4}$$

$$\begin{aligned} &\text{STEP}_{\text{SNR}}(N-n') + \text{SNR}_{\min} \leq \text{SNR}_D \\ &\quad \leq \text{STEP}_{\text{SNR}}(N-n'+1) + \text{SNR}_{\min}. \end{aligned} \tag{5}$$

If it is assumed that SNR_D is inversely proportional to the square of the distance d between sender and receiver, SNR_D can be written as

$$\text{SNR}_D = C - 20\log(d), \tag{6}$$

where C is a constant, and its value depends on the carrier frequency of the signal. Combining equations (5) and (6) yields the following:

$$\begin{aligned} &\text{STEP}_{\text{SNR}}(N-n') + \text{SNR}_{\min} \leq C - 20\log(d) \\ &\qquad < \text{STEP}_{\text{SNR}}(N-n'+1) + \text{SNR}_{\min}, \\ &\frac{\text{STEP}_{\text{SNR}}(N-n') + \text{SNR}_{\min} - C}{-20} \geq \log_{10}(d) \\ &\qquad > \frac{\text{STEP}_{\text{SNR}}(N-n'+1) + \text{SNR}_{\min} - C}{-20}, \\ &10^{\frac{C - [\text{STEP}_{\text{SNR}}(N-n'+1) + \text{SNR}_{\min}]}{20}} < d \\ &\qquad \leq 10^{\frac{C - [\text{STEP}_{\text{SNR}}(N-n') + \text{SNR}_{\min}]}{20}}. \end{aligned} \tag{7}$$

For simplicity, equation (7) can be written as

$$\begin{aligned} &f(n'-1) < d \leq f(n'), \\ &f(n') = 10^{\frac{C - [\text{STEP}_{\text{SNR}}(N-n') + \text{SNR}_{\min}]}{20}}. \end{aligned} \tag{8}$$

If it is assumed that candidate relay nodes are uniformly distributed within the coverage area of the sender node, and all nodes have the same SNR values in the same track/cylinder, as shown in Figure 2, then

$$P(n = n') = \begin{cases} \frac{f(n')^2 - f(n'-1)^2}{f(N-1)^2} & \text{if } n' \geq 1, \\ \frac{f(0)^2}{f(N-1)^2} & \text{if } n' = 0 \end{cases}. \tag{9}$$

Let n_i denote the value of n selected by the ith candidate relay node. Let Z denote the minimum value of n_i, i.e., $Z = \min(n_i)$ where n_i's are mutually independent. To derive an upper bound for collision probability, it is assumed that each node randomly selects a backoff value in the interval of

$[1, 2^n]$. In this case, $P(\text{collision}|M=m)$ can be calculated as follows:

$$P(\text{collision}|M=m) = 1 - P(\text{no collision}|M=m)$$
$$= 1 - \sum_{j=0}^{N-1} P(\text{no collision}, Z=j|M=m), \quad (10)$$
$$P(\text{no collision}, Z=j|M=m)$$
$$= \sum_{i=1}^{m} P(\text{no collision}, L=i, Z=j|M=m), \quad (11)$$

where L denotes the number of candidate relay nodes that have the minimum value of n_i.

i When $L = 1$:

$$P(\text{no collision}, L=1, Z=j|M=m)$$
$$= P(n_1 = j, n_i > j (i \neq 1)|M=m)$$
$$+P(n_2 = j, n_i > j(i \neq 2)|M=m) +$$
$$\cdots + P(n_M = j, n_i > j(i \neq M)|M=m) \quad (12)$$
$$= m\left\{\frac{f(j)^2 - f(j-1)^2}{f(N-1)^2}\right\}\left\{1 - \frac{f(j)^2}{f(N-1)^2}\right\}^{m-1}. \quad (13)$$

ii When $L > 1$:

$$P(\text{no collision}, L=k, Z=j|M=m)$$
$$= \sum_{1 \le a_1 < \cdots < a_k \le m} P(n_{a_1} = j, \ldots, n_{a_k} = j, n_i > j$$
$$(i \notin \{a_1, \ldots, a_k\}|M=m)$$
$$\times P(\text{no collision}|n_{a_1} = j, \ldots, n_{a_k} = j, n_i > j$$
$$(i \notin \{a_1, \ldots, a_k\}|M=m), \quad (14)$$

where

$$P(\text{no collision}|n_{a_1} = j, \ldots, n_{a_k} = j, n_i > j$$
$$(i \notin \{a_1, \ldots, a_k\}|M=m)$$
$$= \frac{2^n(2^n-1)\cdots[2^n-(k-1)]}{(2^n)^k}$$
$$= \frac{(2^n-1)!}{(2^n)^{k-1}(2^n-k)!}, \quad (15)$$

and

$$P(n_{a_1} = j, \ldots, n_{a_k} = j, n_i = j$$
$$(i \notin \{a_1, \ldots, a_k\}|M=m)$$
$$= [P(n_{a_1} = j)]^k [P(n_i > j)]^{m-k}$$
$$= \left[\frac{f(j)^2 - f(j-1)^2}{f(N-1)^2}\right]^k \left[1 - \frac{f(j)^2}{f(N-1)^2}\right]^{m-k}. \quad (16)$$

Combining equations (14)–(16) yields

$$P(\text{no collision}, L=k, Z=j|M=m)$$
$$= \sum_{1 \le a_1 < \cdots < a_k \le m} \frac{(2^n-1)!}{(2^n)^{k-1}(2^n-k)!}$$
$$\left[\frac{f(j)^2 - f(j-1)^2}{f(N-1)^2}\right]^k \left[1 - \frac{f(j)^2}{f(N-1)^2}\right]^{m-k}$$
$$= \binom{m}{k} \frac{(2^n-1)!}{(2^n)^{k-1}(2^n-k)!}$$
$$\left[\frac{f(j)^2 - f(j-1)^2}{f(N-1)^2}\right]^k \left[1 - \frac{f(j)^2}{f(N-1)^2}\right]^{m-k}. \quad (17)$$

Combining equations (11), (13) and (16) yields

$$P(\text{no collision}, Z=j|M=m)$$
$$= \sum_{i=1}^{m} \binom{m}{i} \frac{(2^n-1)!}{(2^n)^{i-1}(2^n-i)!}$$
$$\left[\frac{f(j)^2 - f(j-1)^2}{f(N-1)^2}\right]^i \left[1 - \frac{f(j)^2}{f(N-1)^2}\right]^{m-i}. \quad (18)$$

Combining equations (10) and (18) yields

$$P(\text{collision}|M=m)$$
$$= 1 - \sum_{j=0}^{N-1} \sum_{i=1}^{m} \binom{m}{i} \frac{(2^n-1)!}{(2^n)^{i-1}(2^n-i)!}$$
$$\left[\frac{f(j)^2 - f(j-1)^2}{f(N-1)^2}\right]^i \left[1 - \frac{f(j)^2}{f(N-1)^2}\right]^{m-i}. \quad (19)$$

Under the uniform distribution assumption for M, by combining equations (2) and (19), the probability of collision in the proposed protocol can be written as

$$p_{c,\text{pro}} = \frac{1}{M} \sum_{m=2}^{M} \left\{1 - \sum_{j=0}^{N-1} \sum_{i=1}^{m} \binom{m}{i} \frac{(2^n-1)!}{(2^n)^{i-1}(2^n-i)!} \left[\frac{f(j)^2 - f(j-1)^2}{f(N-1)^2}\right]^i \left[1 - \frac{f(j)^2}{f(N-1)^2}\right]^{m-i}\right\}, \quad (20)$$

where $f(-1) = 0$.

In IEEE 802.11 steady state, the collision probability can be written as

$$p_c = 1 - (1-\tau)^{m-1}, \quad (21)$$

where τ is the transmission probability and can be written as follows (Bianchi, 2000):

$$\tau = \frac{2(1-2p_c)}{(1-2p_c)(W+1) + p_c W[1-(2p_c)^B]}. \quad (22)$$

This represents the probability that at least one of the $m-1$ remaining nodes transmits. Equations (21) and (22) represent a nonlinear system in terms of the two unknowns, τ and p_c, which can be solved using numerical techniques.

3.2 Throughput analysis

As seen in Bianchi (2000), throughput is defined as the fraction of time the channel is used to successfully transmit payload bits. Throughput can be obtained by analysing the possible events that may occur on the shared medium in a randomly chosen time slot . Define p_{idle}, p_c, and p_s to be idle slot, collision, and successful transmission probabilities, respectively. Define σ, T_c, and T_s as the durations of an idle slot, a collision slot, and a successful transmission time slot, respectively. Define p_{tr} as the probability that there is at least one transmission in a slot, since m stations contend on the shared channel, and each transmits with probability τ:

$$p_{tr} = 1 - (1 - \tau)^m. \tag{23}$$

The successful probability p_s is given by the probability that exactly one station transmits on the channel, and can be written as

$$p_s = \frac{m\tau(1-\tau)^{m-1}}{p_{tr}} = \frac{m\tau(1-\tau)^{m-1}}{1-(1-\tau)^m}. \tag{24}$$

Throughput S can be written as

$$S = \frac{p_s p_{tr} E[p]}{(1-p_{tr})\sigma + p_{tr} p_s T_s + p_{tr}(1-p_s)T_c}, \tag{25}$$

where $E[p]$ is the average packet payload size. The denominator in equation (25) is the average duration of a slot, which may be an idle time slot, a success transmission, or a collision. The duration of the idle time slot is specific to the physical layer. The duration for the RTS/CTS mechanism can be written as

$$\begin{aligned} T_{s,\text{legacy}} &= T_{\text{RTS}} + 3T_{\text{SIFS}} + 4\delta \\ &\quad + T_{\text{CTS}} + T_{\text{DATA},b} + T_{\text{ACK}} + T_{\text{DIFS}}, \qquad (26) \\ T_{s,\text{pro}} &= T_{\text{RTS}} + 3T_{\text{SIFS}} + 4\delta + T_{\text{CTS}} \\ &\quad + T_{\text{DATA},R1} + T_{\text{DATA},R2} \\ &\quad + T_{\text{ACK}} + T_{\text{DIFS}}, \qquad (27) \end{aligned}$$

where $T_{\text{DATA},b}$ is the duration of a data packet with a basic rate, and the basic rate is the minimum rate supported by a direct link under the non-cooperative protocol. $T_{\text{DATA},R1}$ and $T_{\text{DATA},R2}$ are the transmission rates of the first hop and the second hop, respectively. T_{DIFS} and T_{SIFS} are the DCF interframe space (DIFS) and short interframe space (SIFS) intervals, respectively. T_{RTS} and T_{CTS} are the duration of RTS and CTS frames, respectively. According to the SNR of the links in the proposed method, T_c is the duration of a collision slot and is given as

$$T_c = T_{\text{RTS}} + \delta + T_{\text{DIFS}}. \tag{28}$$

4 Numerical results

To evaluate the performance of the proposed scheme, this paper compares throughput performance of the proposed relay-selection method with relay-enabled DCF-based MAC (for simplicity, hereinafter we refer to relay-enabled DCF-based MAC as relay-enabled MAC). In addition, this paper compares the proposed protocol with a non-cooperative protocol. The system parameters are shown in Table 1 and are based on the orthogonal frequency division multiplexing (OFDM) physical layer used in the IEEE 802.11a standard. Table 2 shows the supported rates depending on SNR (Ergen and Varaiya, 2005).

Table 1 Parameter values and description

Parameter	*Value*	*Description*
$aCW_{\min}$	15	Min contention window
$aCW_{\max}$	1023	Max contention window
tSIFSTime	16 μs	SIFS duration
tDIFSTime	34 μs	DIFS = SIFS + 2 × slot time
tSlotTime	9 μs	Slot duration
MAC header	24 bytes	MAC header length
tPLCPPreamble	16 μs	PLCP preamble duration
tACK	44 μs	Acknowledgement duration
tRTS	52 μ s	RTS duration
tCTS	44 μs	CTS duration
$E[P]$	8192 bits	Packet payload size

Table 2 SNR vs. data rate of IEEE 802.11a

SNR	*Data rate* (Mbps)
25	6
27	9
30	12
32	18
35	24
40	36
42	48
45	54

Figure 3 shows an example of finding the collision probability and transmission probability for a conventional IEEE 802.11-based system. Intersection points between the results of equations (21) and (22) are the values of collision probability and transmission probability, where the number of nodes is set at 10.

Given a certain number of candidate relay nodes, there are two main factors that can determine maximum channel throughput. The first is the average idle time on the channel, and the second is the probability that a transmission on the channel results in a collision. Figure 4 shows the collision probability. As the number of nodes increases, collision probability increases monotonically in all cases. However, collision probability is lower under the proposed protocol, as compared to the non-cooperative protocol. When the number of tracks increases, collision probability decreases because this reduces the number of nodes in one track.

Figure 3 Transmission probability and failure probability (see online version for colours)

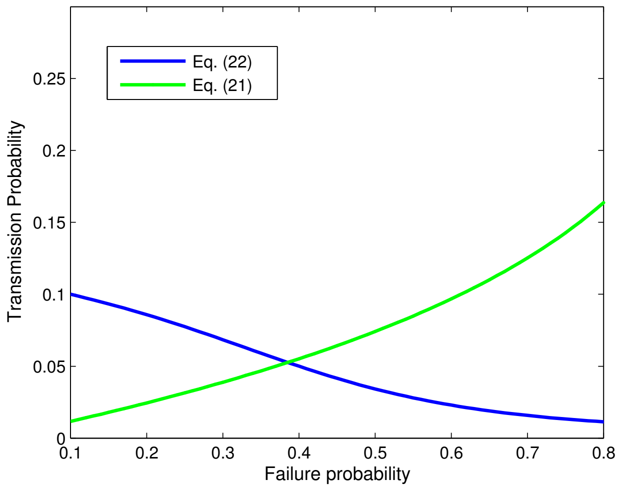


Figure 4 Collision probability as a function of the number of nodes (see online version for colours)

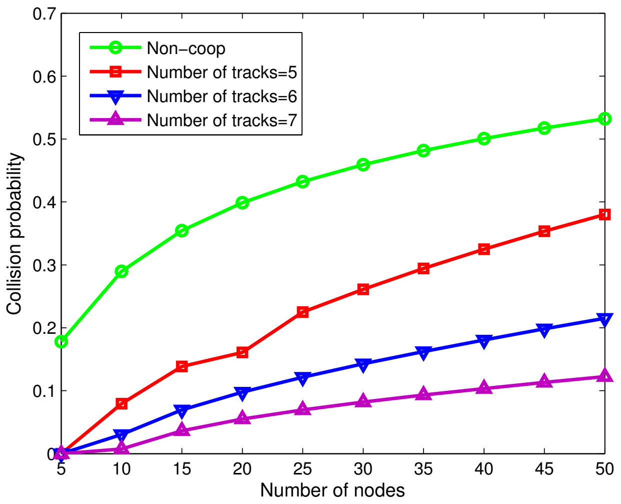


Figure 5 presents throughput performance vs. the number of nodes, with different values for the contention window under relay-enabled MAC and the non-cooperative protocol. The value of the contention window in the proposed method is chosen according to the channel condition. As shown in Figure 5, the proposed protocol outperforms relay-enabled DCF and the non-cooperative protocol, because the proposed protocol shows fewer collisions during the relay-selection process. Furthermore, the selected relay has better link reliability than the direct path and provides a higher data rate than the direct path. When the number of nodes increases, throughput decreases because collision probability increases, and nodes experience a longer backoff duration, which results in a reduction in throughput.

Figure 6 shows the impact of SNR on throughput. Since the data rate under the non-cooperative protocol is fixed at 6 Mbps, throughput is constant, regardless of SNR, under the error-free channel. However, under the proposed protocol and relay-enabled MAC, throughput increases as SNR increases. Furthermore, the proposed protocol shows higher throughput than relay-enabled MAC, as shown in Figure 6. Compared to relay-enabled MAC, the performance gains obtained by using the proposed protocol come from the higher data rate supported by the selected relay under the proposed protocol. Moreover, it is observed that at a low SNR, the transmission rates of the direct path and the relay path are similar. However, the relay path required two transmissions to deliver data to the destination, which caused the lower throughput under the proposed protocol and under relay-enabled DCF MAC compared to the direct path.

Figure 5 Throughput as a function of the number of nodes (SNR = 35 dB) (see online version for colours)

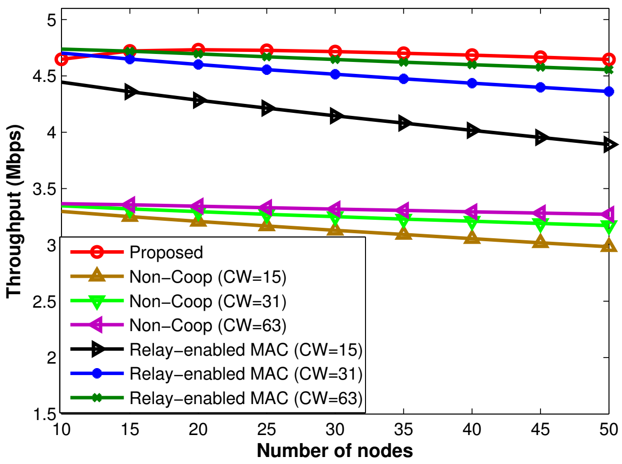
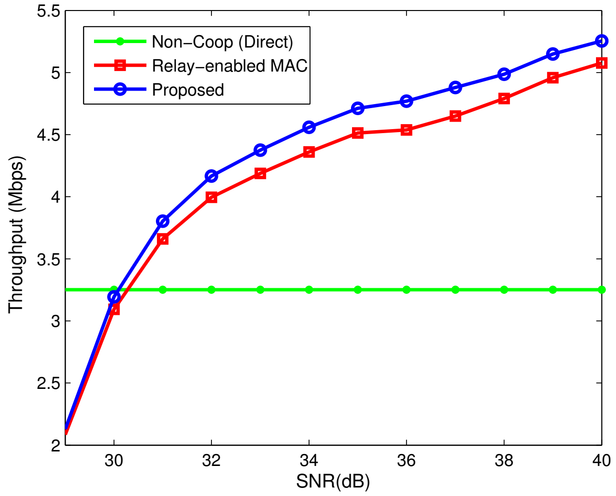


Figure 6 Impact of channel condition on throughput with 15 nodes (see online version for colours)



5 Conclusion

Cooperative communications improve system throughput via the use of spatial diversity in wireless ad hoc networks. However, relay selection plays an important role in maximising system throughput in cooperative wireless communications. Collision probability is a major factor affecting system throughput. The backoff duration increases because of collision. Therefore, this paper proposed an SNR-based relay-selection scheme that minimises collision probability and selects a reliable node as a relay node with the best SNR channel between the source and the destination. This paper provides a detailed analysis of the proposed protocol. The results show that the proposed protocol increases system throughput by selecting the best node to be a relay that can provide a high transmission rate, compared to a direct link.

Acknowledgement

This research was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education (2015R1D1A1A01059186) (2015R1D1A1A01058751).

References

Abouelseoud, M. and Nosratinia, A. (2013) 'Heterogeneous relay selection', *IEEE Transactions on Wireless Communications*, Vol. 12, No. 4, pp.1735–1743.

Abdulhadi, S., Jaseemuddin, M. and Anpalagan, A. (2012) 'A survey of distributed relay selection schemes in cooperative wireless ad hoc networks', *Wireless Personal Communication*, Vol. 63, No. 4, pp.917–935.

Adam, H., Bettstetter, C. and Senouci, S.M. (2008) 'Adaptive relay selection in cooperative wireless networks', *Proceedings of IEEE PIMRC*, Cannes, France, pp.1–5.

Basagni, S. (1999) 'Distributed clustering for ad hoc networks', *Proceedings of the International Symposium on Parallel Architectures, Algorithms, and Networks*, Perth, pp.310–315.

Bergano, N.S., Kerfoot, F.W. and Davidsion, C.R. (1993) 'Margin measurement in optical amplifier system', *IEEE Photonics Technology Letters*, Vol. 5, No. 3, pp.304–306.

Bianchi, G. (2000) 'Performance analysis of the IEEE 802.11 distributed coordination function', *IEEE Journal on Selected Areas in Communications*, Vol. 18, No. 3, pp.535–547.

Bletsas, A., Khisti, A., Reed, D.P. and Lippman, A. (2006) 'A simple cooperative diversity method based on network path selection', *IEEE Journal on Selected Areas in Communications*, Vol. 24, No. 3, pp.659–672.

Brandner, G., Bettstetter, C. and Schilcher, U. (2013) 'Contention-based node selection with applications to relay communications and load balancing', *EURASIP Journal on Wireless Communications and Networking*, Vol. 2013, pp.1–15.

Cao, B., Feng, G., Li, Y. and Wang, C. (2014) 'Cooperative medium access control with optimal relay selection in error-prone wireless networks', *IEEE Transactions on Vehicular Technology*, Vol. 63, No. 1, pp.252–265.

Chalise, B.K., Zhang, Y.D. and Amin, M.G. (2012) 'A novel partial relay selection method for amplify-and-forward relay systems', *Proceedings of IEEE Global Communication Conference (GLOBECOM)*, Anaheim, CA, pp.4695–4700.

Chen, Y., Yu, G., Qiu, P. and Zhang, Z. (2006) 'Power-aware cooperative relay selection strategies in wireless ad-hoc networks', *Proceedings of IEEE PIMRC*, Helsinki, Finland, pp.1–5.

Chou, J., Petrovic, D. and Ramachandran, K. (2003) 'A distributed and adaptive signal processing approach to reducing energy consumption in sensor networks', *Proceedings of the IEEE INFOCOM*, San Francisco, Vol. 2, pp.1054–1062.

Costa, D.B. and Aïssa, S. (2009) 'End-to-end performance of dual-hop semi-blind relaying systems with partial relay selection', *IEEE Transactions on Wireless Communications*, Vol. 8, No. 8, pp.4306–4315.

Dianati, M., Ling, X., Naik, K. and Shen, X. (2006) 'A node-cooperative ARQ schemes for wireless ad hoc networks', *IEEE Transaction on Vehicular Technology*, Vol. 55, No. 3, pp.1032–1044.

Ergen, M. and Varaiya, P. (2005) 'Throughput analysis and admission control for IEEE 802.11a', *Mobile Networks and Applications*, Vol. 10, No. 5, pp.705–716.

Etezadi, F., Zarifi, K., Ghrayeb, A. and Affes, S. (2012) 'Decentralized relay selection schemes in uniformly distributed wireless sensors networks', *IEEE Transactions on Wireless Communications*, Vol. 11, No. 3, pp.938–951.

Hwang, K.S. and Ko, Y.C. (2007) 'An efficient relay selection algorithm for cooperative networks', *Proceedings of IEEE Vehicular Technology Conference*, Baltimore, MD, pp.81–85.

IEEE Standard (2008) *IEEE 802.11 WG*, Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications.

Khandani, A.E., Abounadi, J., Modiano, E. and Zheng, L. (2008) 'Reliability and route diversity in wireless networks', *IEEE Transactions on Wireless Communications*, Vol. 7, No. 15, pp.4772–4776.

Kim, J.B. and Kim, D. (2009) 'Comparison of tightly power-constrained performances for opportunistic amplify-and-forward relaying with partial or full channel information', *IEEE Communications Letters*, Vol. 13, No. 2, pp.100–102.

Krikidis, I., Thompson, J., McLaughlin, S. and Goertz, N. (2008) 'Amplify-and-forward with partial relay selection', *IEEE Communications Letters*, Vol. 12, No. 4, pp.235–237.

Nosratinia, A. and Hunter, T.E. (2007) 'Grouping and partner selection in cooperative wireless networks', *IEEE Journal on Selected Areas in Communications*, Vol. 25, No. 2, pp.369–378.

Laneman, J.N., Tse, D.N. and Wornell, G.W. (2004) 'Cooperative diversity in wireless networks: efficient protocols and outage behavior', *IEEE Transactions on Information Theory*, Vol. 50, No. 12, pp.3062–3080.

Li, P., Guo, S., Zhuang, W. and Ye, B. (2014) 'On efficient resource allocation for cognitive and cooperative communications', *IEEE Journal on Selected Areas in Communications*, Vol. 32, No. 2, pp.264–273.

Onat, F.A., Fan, Y., Yanikomeroglu, H. and Poor, H.V. (2008) 'Threshold based relay selection in cooperative wireless networks', *Proceedings of IEEE Global Telecommunication Conference (GLOBECOM)*, New Orleans, USA, pp.1–5.

Onat, F.A., Adinoyi, A., Fan, Y., Yanikomeroglu, H. and Thompson, J.S. (2007) 'Optimum threshold for SNR-based selective digital relaying schemes in cooperative wireless networks', *Proceedings of IEEE Wireless Communications and Networking Conference*, Kowloon, pp.969–974.

Shan, H., Wang, P., Zhuang, W. and Wang, Z. (2008) 'Cross-layer cooperative triple busy tone multiple access for wireless networks', *Proceedings of IEEE Global Telecommunication Conference (GLOBECOM)*, New Orleans, USA, pp.1–5.

Sharma, S., Shi, Y., Hou, Y.T. and Kompella, S. (2011) 'An optimal algorithm for relay node assignment in cooperative ad hoc networks', *IEEEACM Transactions on Networking*, Vol. 19, No. 3, pp.879–892.

Zhou, Z., Zhou, S., Cui, J.H. and Cui, S. (2008) 'Energy-efficient cooperative communications based on power control and selective relay in wireless sensor networks', *IEEE Journal on Wireless Communications*, Vol. 7, No. 8, pp.3066–3078.

Zhou, L., Wang, X., Tu, W., Muntean, G.M. and Geller, B. (2010) 'Distributed scheduling scheme for video streaming over multi-channel multi-radio multi-hop wireless networks', *IEEE Journal on Selected Areas in Communications*, Vol. 28, No. 3, pp.409–419.

Zhou, L., Yang, Z., Wen, Y. and Rodrigues, J.J. (2014) 'Distributed wireless video scheduling with delayed control information', *IEEE Transactions on Circuits and Systems for Video Technology*, Vol. 24, No. 5, pp.889–901.

Zhu, H. and Cao, G. (2006) 'rDCF: a relay-enabled medium access control protocol for wireless ad hoc networks', *IEEE Transactions on Mobile Computing*, Vol. 5, No. 9, pp.1201–1214.