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Cooperative communications with relay selection for wireless networks: design issues and applications†

Xuedong Liang[1] Min Chen[2]* Ilangko Balasingham[3,4] Victor C.M. Leung[1]

Summary

Relay selection schemes for cooperative communications to achieve full cooperative diversity gains while maintaining spectral and energy efficiency have been extensively studied in recent research. These schemes select only the best relay from multiple relaying candidates to cooperate with a communication link. In this paper, we review recently proposed cooperative communication protocols which integrate with relay selection mechanisms. The key design issues for relay selection mechanisms, e.g., relaying candidate selection, optimal relay assignment, and cooperative transmission, are identified. We further discuss the challenges of optimal relay assignment in multi-hop wireless sensor networks, and present the potential applications of cooperative communications with relay selection in such networks. Future research directions are outlined, e.g., the issues of service differentiation and system fairness in cooperative communication systems, and the joint use of game theory and machine learning techniques in relaying candidate selection and optimal relay assignment mechanisms for efficient allocation of network resources. Copyright © 2007 John Wiley & Sons, Ltd.

KEY WORDS: Cooperative communications; optimal relay assignment; quality of service; wireless sensor networks.

1. Introduction

In recent years, cooperative communications [1, 2] have been proposed to exploit the spatial and time diversity gains in wireless networks by utilizing the broadcast nature of the wireless medium. Users in cooperative communication systems work cooperatively by relaying data packets for each other, and thus forming multiple transmission paths or virtual multiple-input-multiple-output systems to the destination without the need of multiple antennas at each user [3].

A significant amount of work has been done in designing cooperative protocols which define the relaying candidate selection [4], coding [5], cooperative transmission [6], and power allocation schemes. However, there lacks a comprehensive survey on the recent proposed cooperative protocols, especially for relay selection mechanisms that only choose optimal relays among multiple relaying candidates to cooperate with communication links. In this survey, we aim at providing background knowledge, potential applications, and key design

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*Correspondence to: Min Chen at minchen@ieee.org

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issues of cooperative communications, particularly for cooperative protocols that integrate with relay selection schemes.

In the literature, most of the research on cooperative communications [7, 8, 9, 10, 11] models the wireless channel as a narrow band Raleigh block fading channel with additive white Gaussian noise (AWGN) [12]. For any two nodes, e.g., i and j, the channel coefficient h_{ij} which captures the effects of path-loss, shadowing, and fading, is modeled as a zero-mean circular symmetric complex Gaussian random variable with the expectation of $E(|h_{ij}|^2) = 1$. For the links between a pair of nodes, the channel coefficients are assumed to be reciprocal, i.e., $h_{ij} = h_{ji}$. The channel coefficients are constant for a given transmitted block, or a codeword, but are independent and identically distributed (i.i.d.) for different blocks [7]. For different links, the channel fading coefficients are statistically i.i.d., which is a reasonable assumption as the nodes are usually spatially deployed [13].

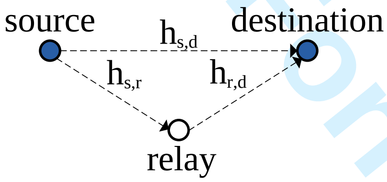

Fig. 1. A three node cooperative communication model

The concept of cooperative communications is illustrated in Fig. 1. The simple cooperative communication system consists of three nodes, the source, relay and destination, which are all within each other's communication range. The cooperative communication protocol usually operates in two phases. In the first phase, i.e., the direct transmission phase, the source transmits a message to the destination. The signal received at the destination that transmitted by the source is expressed as in (1),

$$Y_{d_1} = h_{s,d}X_s + \eta_{s,d}, \tag{1}$$

where X_s is the information symbol transmitted by the source, $h_{s,d}$ is the channel coefficient between the source and the destination, and $\eta_{s,d}$ is the additive noise, which captures the effects of input noise at the receiver and other interferences in the network and is modeled as a zero-mean, circular symmetric, complex Gaussian distribution with variance N_0 [7].

The relay may overhear the message due to the broadcast nature of the wireless medium. The signal received at the relay is expressed as in (2),

$$Y_r = h_{s,r}X_s + \eta_{s,r}, \tag{2}$$

where $h_{s,r}$ is the channel coefficient between the source and the relay, and $\eta_{s,r}$ is the additive noise.

In the second phase, i.e., the relaying transmission phase, the relay can simply amplify and forward the received signal to the destination, or decode the signal first, then encode and forward the message to the destination. The signal received at the destination that retransmitted by the relay is expressed as in (3),

$$Y_{d_2} = h_{r,d}R + \eta_{r,d} = h_{r,d}f(Y_r) + \eta_{r,d}, \tag{3}$$

where R is the symbol transmitted by the relay, and $R = f(Y_r)$ is a function of the received signal Y_r, $h_{r,d}$ is the channel coefficient between the relay and the destination, and $\eta_{r,d}$ is the additive noise.

Thus, two paths, i.e, source-destination and source-relay-destination, are formed from the source to the destination. The destination receives two copies of the original signal, i.e., Y_{d_1} and Y_{d_2}, which are transmitted over the two independent paths and experience different channel fading and shadowing. The destination may combine the signals, e.g., applying maximum-ratio-combining [14] for optimal packet decoding, or simply choose the signal with a higher signal-to-noise-ratio (SNR) and then decode it. Therefore, cooperative diversity gains can be achieved, i.e., a packet transmission failure occurs only when both of the two independent paths experience deep channel fading or shadowing simultaneously.

A variety of cooperative transmission schemes have been proposed to achieve cooperative diversity gains and channel efficiency, which are described as follows.

- *amplify-and-forward (AaF)* [15]: the relay amplifies the received signal from the source and forwards it towards the destination.
- *decode-and-forward (DaF)* [15]: the relay decodes the packet received from the source by either full decoding or symbol-by-symbol decoding, and then encodes and forwards the packet to the destination.
- *selection relaying* [15]: whether a relay cooperates with a communication link or not depends on the measured metric $|h_{s,r}|^2$, which denotes the channel gain between the source and the relay. If $|h_{s,r}|^2$ is lower than a certain threshold, the source simply continues its transmission to the destination, in the form of repetition or more

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powerful codes. If $|h_{s,r}|^2$ is higher than the threshold, the relay forwards the signal received from the source, using either AaF or DaF, to achieve diversity gains. The calculation of the threshold value depends on a number of factors, e.g., the source's transmission power, data rate, channel bandwidth, and the noise level at the receiver. More details on the calculation of the threshold can be found in [15].

- *incremental relaying* [15]: to improve spectral efficiency, whether a relay cooperates with a communication link or not depends on the feedback from the destination. If the feedback indicates that the direct transmission is successful, the relay keeps idle. Otherwise, the relay retransmits the overheard signal from the source towards the destination, either using AaF or DaF.
- *coded cooperation* [16]: the cooperation is integrated with channel coding and works by sending different parts of each user's codeword via two independent fading paths. In coded cooperation, each user's data is encoded into a codeword N that is partitioned into two parts, containing N_1 bits and N_2 bits, respectively. The first part of N_1 bits itself is a valid codeword but weakly coded, and the N_2 bits in the second part are the puncture bits [1]. The coded cooperation operates in two phases. In the first phase, each user transmits its first part of the codeword which contains N_1 bits, and also decodes its partner's first part of the codeword containing N_1 bits as well. In the second phase, a user calculates and transmits the second part of the codeword, i.e., the remaining N_2 bits, for its partner, if it can decode the first part of codeword successfully; otherwise, the user transmits its own second part of the codeword that contains the remaining N_2 bits. The basic idea of coded cooperation is that each user tries to transmit incremental redundancy for its partners.
- *CDMA-based cooperation* [17, 18]: the cooperation mechanism is implemented in a code division multiple access (CDMA) system, in which a user constructs a signal to transmit by combining its own signal and the signal received from its partner. Similarly, the user's partner constructs its signal to transmit in a same fashion. Then, the user and its partner cooperate by sending both of their messages to the receiver and use different spreading code to avoid interferences.

In wireless networks where nodes are densely deployed, as shown in Fig. 2, there are usually multiple relaying candidates available for the source and destination. In a conventional multi-node cooperative communication system, all the available relays actively participate in the communication by retransmitting signals towards the destination and thus form multiple paths between the source and destination.

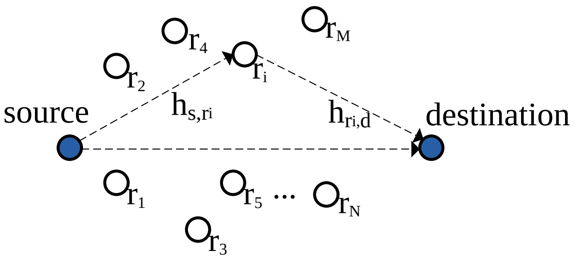

Fig. 2. A multi-node cooperative communication model

The conventional multi-node cooperative communication systems have the potentials of achieving full cooperative diversity gains. For instance, for a pair of source and destination with N relays participating in the cooperative communication, a packet transmission failure occurs only when all the $N+1$ paths (source-destination plus source-relays-destination) experience deep channel fading or shadowing simultaneously. However, the channel efficiency of the multi-node cooperative communication system is much lower than non-cooperative communication systems. The reason is that a total number of $N+1$ time slots is needed for the packet transmission, assuming carrier sense multiple access with collision avoidance (CSMA/CA) or time division multiple access (TDMA) is used as the underlying medium access control (MAC) protocol. Besides, packet transmissions suffer extra delays due to the receiver deferring packet decoding until all of the relays have completed their transmissions. Moreover, the relays' multiple transmissions consume precious network resources, e.g., spectrum, bandwidth, and energy, while increasing the probabilities of channel access contention and packet collision.

To achieve full cooperative diversity gains while still obtaining high channel efficiency and low transmission delay, selective single relay cooperative schemes, in which only one optimal relay is selected from multiple relaying candidates to cooperate with

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the communication link, have been extensively studied in recent research. A number of relay selection mechanisms have been proposed for cooperative communication systems, in which various schemes and criteria are used in optimal relay assignment.

The rest of the paper is organized as follows. The background information on cooperative communications with relay selection, key design issues of relay selection schemes, e.g., relaying candidate selection, optimal relay assignment, and cooperative transmission, are identified in Section 2. Section 3 compares and discusses the main design issues of optimal relay selection schemes. Cooperative communications in multi-hop wireless sensor networks (WSNs) is further discussed in Section 4. In Section 5, we present the potential applications of cooperative communications with relay selection in WSNs. Finally, we conclude the paper and discuss future research directions in Section 6.

2. Cooperative communications with relay selection: background and key design issues

Cooperative communications with single relay selection schemes have been demonstrated to be effective in achieving full cooperative diversity gains and obtaining high channel utilization efficiency. As shown in [8, 10], in DaF cooperative scenarios, using an optimal relay to cooperate with a communication link can achieve the same diversity gains as conventional cooperative protocols that employ all the potential relaying candidates.

Adaptive relay selection schemes for cooperative protocols play important roles in cooperative communication systems, and have significant impacts on diversity gains and network performance. The selected optimal relay should be the best one among all the relaying candidates, which can make the most of contributions in improving the network performance, in terms of packet outage probability and channel utilization efficiency [13, 15, 19]. The challenge of optimal relay selection is finding the best relay in dynamic environments in wireless networks, where the network topology may change and the wireless medium is time-varying, due to the dynamic nature of such networks.

In cooperative communication systems where adaptive relay selection mechanisms are utilized, the cooperative protocols usually operate in three phases, namely, relaying candidate selection, relay assignment, and cooperative transmission. We identify the key design issues for adaptive relay selection mechanisms and discuss them as follows.

2.1. Phase 1: relaying candidate selection

A number of nodes are determined as relaying candidates for the communication link between the source and destination in this phase.

2.1.1. Pre-assigned selection scheme

In pre-assigned selection scheme, the relaying candidates are selected prior to data flow connection.

In [20, 21, 22], the relaying candidate selection is accomplished by using the mechanism of cooperative multi-hop mesh structure construction. The relaying candidates are assigned in the procedure of multi-hop mesh route discovery and establishment. The pre-assigned scheme is the simplest approach for relaying candidate selection, in term of algorithm design complexity. However, the pre-assigned relaying candidate selection scheme cannot deal with network dynamics, e.g., node mobility, wireless channel variation, and network topology changes, and thus does not fit in dynamic environments. Furthermore, the relaying candidate selection is based on the cooperative mesh structure, which is constructed fully independent from the data flow and thus incurs significant communication overhead.

2.1.2. Adaptive selection scheme

Adaptive relaying candidate selection schemes are more suited for cooperative communications over wireless networks than pre-assigned schemes, due to the dynamic nature of such networks.

To reduce the communication overhead, adaptive relaying candidate selection schemes often utilize the signaling messages defined in the MAC protocol, or integrate with the routing mechanism in the network layer.

In [9, 10, 11], the signaling messages in the MAC layer, i.e., request-to-send (RTS) and clear-to-send (CTS) signals defined in the IEEE 802.11 standard [23], are used in relaying candidate selection. That is, when a node overhears a RTS signal from the source and a CTS signal from the destination, the node determines that it is a common neighboring node for both of the source and destination, and could act as a relaying candidate.

Multiple-RTS (M-RTS) and multiple-CTS (M-CTS) signaling messages, extended from RTS and

CTS, are utilized in [24] to identify the relaying candidates. When a node receives a M-RTS signal from the source, it considers itself to be a relaying candidate, and will start the relay selection competing procedure.

In [25], the selection of relaying candidates are implemented by using Hello messages. By exchanging the Hello messages, a set of nodes which are the common immediate neighboring nodes for both of the source and destination are selected as the relaying candidates.

In [26], the relaying candidate selection scheme is integrated with the route finding mechanism, i.e., ad hoc on-demand distance vector (AODV) routing protocol. In the route discovery procedure, for two adjacent routers (1-hop sender and receiver), a node determines that it is a relaying candidate for the routers, if it has heard both the route request (RREQ) signal transmitted by the sender and the route reply (RREP) replied by the receiver, and has not been selected by the sender as the next hop router.

2.2. Phase 2: relay assignment

When a set of relaying candidates is selected, one of the relaying candidates should be chosen based on some criteria to cooperate with the communication link between the source and destination. The frequently used criteria for relay assignment are described as follows.

2.2.1. Pre-defined and random relay assignments

The simplest solutions for relay assignment are assigning the relays in advance, or choosing the relays randomly in runtime, as proposed in [7, 21]. The pre-defined and random schemes can reduce the design complexity and overhead of the schemes. However, such schemes cannot achieve optimal performance in dynamic environments and lack of the capacity of dealing with network dynamics.

2.2.2. Distance-based relay assignment

An intuitive scheme of optimal relay assignment is using distance, either towards the source or the destination, as the criterion of optimal relay selection.

The distance-based cooperative protocol [21] chooses a node which is the closest one to the destination as the optimal relay. In [24], when a candidate starts the relay selection competing procedure, it first sets a backoff timer with a value proportional to the candidate's distance to the source. Thus, the candidate node, which is the closest one to the source, will expire its backoff timer first and win the competition. The node which wins in the competition procedure will send a M-CTS signal to inform the source that it is ready to send, as well as notifying other candidates to cancel their competing procedures.

However, it is well understood that communications between senders and receivers with similar distances may have significant differences in terms of received signals' SNRs, due to interference, shadowing and multi-path fading effects on the wireless links. Therefore, the use of distance as the criterion of relay assignment cannot reflect the channel state appropriately.

2.2.3. SNR (channel gain)-based relay assignment

The most intuitive solution of optimal relay assignment is to choose the relay that has the highest SNRs, or the maximum wireless channel gains with both the source and destination. Since both of the two paths, i.e., source-relay and relay-destination, are important for the end-to-end performance, each relay should evaluate the link qualities of both paths.

In [25], for a link between the source s and destination d, the source considers the immediate neighboring nodes of both s and d as relaying candidates. The source maintains a list which contains the candidates' MAC addresses and their link qualities to s and d. The source uses a metric γ_r, as shown in (4),

$$\gamma_r = \min\left(SNR(s, r_i),\ SNR(r_i, d)\right), \qquad (4)$$

to sort the candidates, where $SNR(s, r_i)$ and $SNR(r_i, d)$ denote the SNR between the link of s-r_i and r_i-d, respectively. Then,the source selects the two candidates which have the two highest of the minimum SNR of the relay channels, i.e., from s to the relay, and from the relay to d, as the optimal relays. Each candidate measures the SNRs locally and sends the information to the source in a fixed time interval (every one second in the paper), so the source can always have the up-to-date information on the list. The performance evaluation has shown that the selected relays have high link qualities with both s and d based on computer simulations.

In [7], the source chooses N relays, whose received signals' SNRs are the N highest among

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all the relaying candidates, to cooperate with the communication link between the source and destination.

In [9], the relaying candidates use RTS and CTS messages to assess the link qualities of the source-relay and relay-destination. The transmission of the RTS from the source allows for the estimation of the instantaneous wireless channel coefficient h_{s,r_i} between the source and the relay r_i; the transmission of the CTS from the destination allows for the estimation of the instantaneous wireless channel coefficient $h_{r_i,d}$ between the relay r_i and the destination.

The channel coefficients h_{s,r_i}, $h_{r_i,d}$ at each relay, describe the quality of the wireless path between source-relay-destination for the relay. Each relay assesses the link qualities between the source-relay-destination, and uses the following policies to determine the best relaying candidate distributedly. Under policy I, as defined in (5), the minimum of the two is selected, while under policy II, as defined in (6), the harmonic mean of the two is chosen.

- *Policy I*:

$$H_{r_i} = \min\left\{ |h_{s,r_i}|^2, |h_{r_i,d}|^2 \right\} \quad (5)$$

- *Policy II*:

$$H_{r_i} = \frac{2}{\frac{1}{|h_{s,r_i}|^2} + \frac{1}{|h_{r_i,d}|^2}} = \frac{2\,|h_{s,r_i}|^2\,|h_{r_i,d}|^2}{|h_{s,r_i}|^2 + |h_{r_i,d}|^2} \quad (6)$$

After receiving the CTS, each relay will start a timer with an initial value of T_i, which is set inversely proportional to the end-to-end channel quality H_{r_i}. Therefore, the best relay's timer will expire first and start retransmitting the signal towards the destination.

The optimal relay assignment scheme [11] is integrated with the power control mechanism in physical layer. The relaying candidates use RTS and CTS messages to assess the link qualities and compute individually the required transmission power that can meet the desired link qualities. Different from [9], the source also participate in the competition procedure, if it believes that it has the potential of being an optimal relay.

The authors in [8] proposed an adaptive relay selection scheme for cooperative communication protocols, based on the channel state information (CSI) at the source and the relays. The optimal relay is the node which has the maximum instantaneous scaled harmonic mean function of its source-relay and relay-destination channel gains.

The relay's metric β_m, as defined in (7), denotes the scaled harmonic mean function and gives an instantaneous indication about the relay's ability to cooperate with the source.

$$\begin{aligned}\beta_m &= \mu_H\left(q_1\,|h_{s,r_i}|^2, q_2\,|h_{r_i,d}|^2\right)\\ &= \frac{2q_1q_2\,|h_{s,r_i}|^2\,|h_{r_i,d}|^2}{q_1\,|h_{r_i,d}|^2 + q_2\,|h_{s,r_i}|^2}\end{aligned} \quad (7)$$

$\mu_H(.)$ is the standard harmonic mean function. q_1 and q_2 can be calculated as in (8).

$$q_1 = \frac{A^2}{r^2}, \qquad q_2 = \frac{B}{r(1-r)} \quad (8)$$

$r = \frac{P_1}{P_1+P_2}$ is the power ratio, where P_1 and P_2 are the transmission power of the source and relay, respectively.

For multiple phase shift Keying modulation, A and B can be calculated as in (9) and (10), respectively.

$$A = \frac{1}{\pi}\int_0^{\frac{(M-1)\pi}{M}} \sin^2\theta d\theta = \frac{(M-1)}{2M} + \frac{\sin(\frac{2\pi}{M})}{4\pi} \quad (9)$$

$$\begin{aligned}B = \frac{1}{\pi}\int_0^{\frac{(M-1)\pi}{M}} \sin^4\theta d\theta &= \frac{3(M-1)}{8M}\\ &+ \frac{\sin(\frac{2\pi}{M})}{4\pi} - \frac{\sin(\frac{4\pi}{M})}{32\pi}\end{aligned} \quad (10)$$

The relay whose metric is equal to $\beta^* = \max\{\beta_1, \beta_2, \ldots, \beta_M\}$, is chosen as the optimal relay.

The signaling messages, RTS and CTS, are also utilized in the single relay selection scheme to assess link quality under aggregate power constraints [10]. For DaF protocol with reactive relay selection, the optimal relay is the candidate which has the maximum instantaneous channel gain between the relay and destination, as shown in (11).

$$r_i^* = \arg\max_{r_i \in D} |h_{r_i,d}|^2 \quad (11)$$

where r_i^* is the optimal relay, D is the set of relays which can decode the received message successfully during the source-destination transmission phase.

For DaF protocol with proactive relay selection, the best relay is chosen prior to the transmissions of source-destination and relays-destination. The best relay is the candidate that can maximize the minimum of the weighted channel strengths between the source and destination, as shown in (12).

$$r_i^* = \arg\max_{r_i \in K} \min\left\{\zeta \left|h_{s,r_i}\right|^2, (1-\zeta)\left|h_{r_i,d}\right|^2\right\} \tag{12}$$

where K is the set of relaying candidates, ζ and $(1-\zeta) \in [0, 1]$ denote the fractions of the total power allocated to the source transmission and overall relay transmission, respectively.

For AaF protocol with proactive relay selection, the optimal relay is the candidate which can maximize the mutual information, defined as follows.

$$r_i^* = \arg\max_{i \in K} Wr_i \tag{13}$$

where

$$Wr_i = \frac{\left|h_{s,r_i}\right|^2 \left|h_{r_i,d}\right|^2}{\frac{\zeta}{1-\zeta}\left(1+\frac{1}{\gamma_{sr_i}}\right)\Omega_{sr_i} + \left|h_{r_i,d}\right|^2} \tag{14}$$

where Ω_{sr_i} denotes the average channel gain between the source and relay r_i, γ_{sr_i} is the average SNR for the link between the source and relay r_i.

2.2.4. *Game theory-based relay assignment*

Game theory provides a set of tools for modeling the interactions of a finite number of decision-makers whose actions often have mutual effects on each other. Thus, game theory is inherently suitable for modeling and analyzing wireless networks, where nodes share limited network resources, e.g., spectrum, time slots, both cooperate and/or contend with each other, and their actions have different outcomes.

There are a number of game theory based schemes in the literature that model the process of optimal relay selection as a non-cooperative game, in which the relaying candidates are modeled as players. Each candidate plays the game against the other candidates in a distributed manner. Whether a candidate cooperates with a communication link or not depends on the payoff it may achieve, which is usually defined as the difference between the benefit and cost of acting as a relay.

In most of the game theory based schemes, the nodes are modeled as rational players, which means the nodes are expected to follow a set of strategies and choose actions from the strategies to maximize their utilities. In the meantime, the nodes behaves selfishly, i.e., a node always chooses action to maximize its own payoff, without considering the utilities of other nodes. Most of the papers do not consider cooperative games, as additional signaling messages between the decision-makers needed to be implemented to achieve common agreements, which make it more difficult to realize in wireless networks.

In [27], game theory is used to model a wireless network consisting of selfish nodes, wherein a credit-based micro-economical model involving exchange of virtual currencies is proposed to manage node interactions. Whether a node involves a cooperative link depends on the credit that can be earned and the resource needed for relaying packet. The authors in [28] proposes a relay selection and power control scheme based on a two-level Stackelberg game, in which the source node and relay nodes are modeled as buyer and sellers, respectively. The proposed scheme jointly considers the benefits of both the buyer and the sellers and can achieve the best system performance with minimum power consumption. [29] presents a game-theoretic analysis of DaF cooperative communications over AWGN and Rayleigh fading channels. The analysis shows that a mutually Nash Equilibrium exists if proper power control is utilized and users care about their long-term performance.

The game theory based schemes in the literature often assume that players has complete information of the game, i.e., a player has the full knowledge of the game, i.e., the other players' identities, strategies, payoffs, and utility functions [28]. Furthermore, the game's history, e.g., the actions of each player in previous stages, is also assumed to be known to all players in a multi-stage game [27]. However, this assumption is not always hold in realistic scenarios, as nodes in wireless networks usually only have locally observed information and limited knowledges of others' behavior. Therefore, adaptive learning, e.g., estimating payoffs may obtain by taking certain actions, predicting the other players' strategies, should be involved in the game designs [30].

2.2.5. *Reinforcement learning-based relay assignment*

Reinforcement learning [31, 32] provides a framework in which an agent can learn control policies in dynamic environment based on experiences and rewards. A variety of reinforcement learning algorithms haves been implemented for nodes to learn adaptive policies such as protocols for MAC [33], routing [34, 35, 36] layers, QoS provisioning [37], and cooperative communications [21, 22, 26, 38, 39].

In [26], reinforcement learning is used to learn the optimal policy of relay selection in multi-hop wireless sensor networks. For a pair of sender and receiver along the established route, the sender chooses a relay from all the potential relays to cooperate with a link between the sender and receiver in an arbitrary manner in the beginning of the procedure of optimal relay selection, as the sender does not have knowledge of the channel gains between the sender-relays and relays-destination. After the selected relay's transmission, the sender evaluates the quality of relay selection based on the feedback from the receiver, e.g., the SNR improvement on the link. After a series of trial-and-error interactions with the network, the sender can learn an optimal policy of relay selection, and tend to choose a relay which can make the biggest improvement on the link quality in a long-term run. To avoid being stuck in a sub-optimal solution, the relay selection algorithm uses the ε greedy method [31] to explore the environment with a certain probability. That is, with the probability of 1-ε, the sender chooses a relay that is expected to be able to make the biggest improvement on the link quality. And with the probability of ε, the sender randomly chooses a relay to cooperate with the communication link (ε is set to 0.1 in the algorithm). By doing so, the sender continues exploring the dynamic environment.

2.3. Phase 3: Cooperative transmission

The relays can cooperate with the communication link between the source and destination for any packet transmission by retransmitting the overheard signals. For instance, in CRP [25], two selected optimal relays retransmit each message overheard from the source towards the destination. Therefore, the destination may receive three copies of the signals for any packet transmitted from the source.

To reduce network overhead and increase channel efficiency, the cooperative communication can be triggered when it is necessary, e.g., the packet transmission fails in the direct transmission phase, or the direct link between the source and destination cannot meet the desired QoS requirements, as the protocol proposed in [26].

In [13], a new automatic repeat request (ARQ) mechanism is introduced in the cooperative communication protocol. That is, if the destination can successfully decode the signal transmitted by the source in the direct transmission phase, it sends back an acknowledgment (ACK) and the relay keeps idle. Otherwise, if the destination cannot decode the signal successfully, it sends back a negative acknowledgment (NACK). In the latter case, cooperative transmission will be invoked, i.e., the relay which received the signal in the direct transmission phase forwards the signal to the destination.

In [8], the source computes the ratio $\frac{\beta_{s,d}}{\beta_{max}}$ and compares it to a cooperation threshold α, which is often defined as 1. If the $\frac{\beta_{s,d}}{\beta_{max}} \geq \alpha$, then the source use direct transmission only; otherwise, if $\frac{\beta_{s,d}}{\beta_{max}} < \alpha$, the source will choose an optimal relay to retransmit the signal. The mechanism can be interpreted as that the source s will pick up a relay r_i to cooperate with the communication link between the source s and destination d, if the link quality that defined as the modified harmonic mean function of channel gains between s-r_i-d is higher than the channel gain between s-d. Otherwise, the source will choose direct transmission only.

3. Comparison and discussion

In this section, we categorize recent proposed mechanisms of relay selection and list their features in Table I, then we compare and discuss the main design issues of optimal relay selection for cooperative communication protocols.

3.1. Optimal relay selection criterion

In the literature, most of the relay selection schemes for cooperative communications utilize SNR or channel gain and its variations as the unique criterion for optimal relay assignment, and assume that full or partial CSI is available at the source, destination and all of the potential relays. However, the use of SNR as the unique relay selection criterion is not sufficient in dynamic wireless networks. It has been shown in [7] that received SNR based selection scheme behaves similarly to random selection scheme, or even slightly worse in some scenarios. Furthermore, significant communication overhead is incurred in acquiring and disseminating of CSI to all of the cooperative participants, especially for the cooperative protocols, as in [8, 9], that instantaneous CSI is required at all the potential relays for relay selection.

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Table I. Relay selection schemes for cooperative communications

	Relaying candidate selection	**Optimal relay assignment criterion**	**Cooperative transmission scheme**	**Relay selection**
Random selection [7]	N/A (1-hop network)	Random	Continuous	Reactive
Received SNR selection [7]	N/A (1-hop network)	SNR	Continuous	Reactive
Fixed priority selection [7]	N/A (1-hop network)	Pre-defined	Continuous	Reactive
Scheme in [8]	N/A (1-hop network)	Weighted channel gain	Triggered/threshold	Reactive
Opportunistic DaF-1 [10]	RTS and CTS	Channel gain	Continuous	Reactive
Opportunistic DaF-2 [10]	RTS and CTS	Weighted channel gain	Continuous	Proactive
Opportunistic AaF [10]	RTS and CTS	Mutual information	Continuous	Proactive
EECC [11]	RTS and CTS	Channel gain	Continuous	Reactive
MISO [24]	M-RTS and M-CTS	Distance	Continuous	Proactive
CRP [25]	Hello message	SNR	Continuous	Reactive
QoS-RSCC [26]	Route finding mechanism	Outage probability, channel efficiency	Triggered/ARQ	Reactive
Game theoretic scheme [27]	N/A (1-hop network)	Payoff (benefit minus cost)	Continuous	Reactive

3.2. Centralized vs. distributed mechanisms

In centralized mechanisms of relay selection, a coordinator, usually the source, is responsible to select the relay. As the mechanisms in [8], each relaying candidate measures its channel gains of source-relay and relay-destination, calculates their harmonic mean functions, and sends this metric to the source. Then, the source selects a relay which has the highest metric among all the relaying candidates and broadcasts a control signal to all the relays and the destination to indicates its decision of relay assignment. Similar procedures can also be found in [25].

In distributed mechanisms, *relay-competition-timer* is often used to decide which candidate should act as the optimal relay. In the mechanisms proposed in [9, 11, 24], each relaying candidate measures its source-relay and relay-destination link qualities, e.g. using channel gain as a metric, and then starts a *relay-competition-timer* which is set inversely proportional to the metric. The candidate with the highest metric will have its timer reduced to zero first, as its timer is set with the lowest value. Then, the candidate will broadcasts a *flag* message to the other candidates informing that it wins in the *relay-competition* procedure, and will cooperate with the communication link.

Most of the game theory based approaches are also of distributed mechanisms. For instance, as in [27], a relaying candidate estimates its opponent's possible strategy, e.g., cooperating or remaining silent, and then take the best response to its opponent's strategy. That is, the candidate will cooperate with the communication link, if it estimates that the opponent's probability of cooperating is lower than a threshold; otherwise, the candidate will remain silent. The threshold is defined as the cooperating probability of candidates at the Nash Equilibrium, which can be interpreted as a steady network state in the context of wireless networks, as none of the nodes will intend to deviate from the strategy profile to increase its payoff [40].

Centralized mechanisms often need exchanges of additional signaling messages to perform relay selection that inevitably introduces overhead to the network. Furthermore, the need of centralized control limits the scalability of such mechanisms, especially in multi-hop wireless networks. In contrast, information exchange is usually not necessary in distributed mechanisms, and a relaying candidate decides whether to cooperate with a communication link or not in a distributed manner. Distributed mechanisms based algorithms often scale well in large-scale networks, however, it may happen that more than one candidate decide to cooperate with a communication link which will result in a packet collision, or no candidate chooses to act as the optimal relay. For instance, in [11], if two candidates set their *relay-competition-timer* with a same value, both of them will reduce the timer to zero and start retransmitting simultaneously and a packet collision happens. And in [27], if the candidates make inaccurate estimations of their opponents' strategies, relay selection failure, e.g., collision or no candidate decides to act as the optimal relay, may happen.

3.3. Proactive vs. reactive relay assignment

The relay can be assigned prior to source-destination transmission, which is called proactive relay assignment; or selected after source-destination transmission, named as reactive relay assignment [10].

Proactive relay assignment has the advantage of energy efficiency, because only the selected relay needs to be in the receiving mode during the source's transmission, and the unselected relaying candidates can switch to power-down mode for energy saving. Furthermore, proactive relay assignment schemes simplify the algorithm deign and overall network operations, as well as reducing the probability of channel access contention. However, proactive relay selection schemes cannot guarantee optimal performance in dynamic environments. As shown in [8], to achieve full diversity gains, the best relay must be chosen at each time instant of packet transmission between source-destination. In proactive assignment mechanisms, assigning a relay before the start of transmission cannot ensure that the relay is the real best one, as the wireless channel is assumed to be varying over time.

3.4. Continuous cooperation vs. triggered cooperation

Continuous cooperation schemes can guarantee diversity gains by always choosing relays to participate in the communication. However, due to the shared and contention nature of the wireless medium, the use of continuous cooperation increases the probabilities of channel access contention and packet collision, and thus leads to low channel utilization efficiency.

In triggered cooperation mechanisms, feedback, e.g., ACK or NACK messages from the destination is often used to trigger the cooperative communication. That is, an ACK message sent by the destination indicates that the source-destination transmission is successful; and a NACK message will invoke a cooperative transmission, and a relay, either selected by the source or determined distributedly by the relaying candidates, will cooperate with the communication link between the source-destination.

Triggered cooperation has the advantage of spectral efficiency, because the relaying transmission is invoked only when the direct link between source-destination experiences deep channel fading, shadowing, or interference. However, the use of triggered cooperative scheme increases the cooperative algorithm design complexity and computational overhead, as signaling messages are needed to indicate whether the direct transmission between the source and destination is successful or not. Trade-off should be considered between network performance and algorithm complexity [41, 42, 43].

3.5. Impact of relaying candidate's state on cooperative communications

Although the relaying candidates in the wireless networks are assumed to be functionally equivalent (in terms of radio communications and signal processing), their individual states, e.g., incoming traffic, duty cycle, and processing and queuing delays may vary. Relaying candidates' states could have significant impacts on the performance of cooperative communications, and should be taken into account in the optimal relay selection. Intuitively, it should be avoided that choosing nodes which have already involved in other data flows, e.g., acting as intermediate routers or relays. The reason is that assigning too many tasks will pose heavy computational and communication burden on the nodes, which may become bottlenecks of the network, as well as resulting in severe network traffic imbalance.

Only a few papers in the literature consider node's state as a metric of relay selection, as these parameters are difficult to measure or even estimate. Reinforcement learning could be a promising approach to address this issue, as the reinforcement learning based approaches [26, 38] choose the relays through experience and rewards without actual measuring the nodes states, which is similar to the procedure of human or animal learning in a dynamic environment from scratch. That is, in the beginning of the procedure of relay selection, relays are selected randomly. After a series of trial-and-error interactions, the optimal selection can be strengthened and sub-optimal selections are weakened by utilizing the reinforcement learning algorithm.

3.6. Applicabilities of relay selection schemes in wireless networks

To apply relay selection schemes in dynamic wireless networks, the schemes should have the capability of dealing with network dynamics, e.g., network topology changes, varying wireless link qualities.

Usually, pre-defined relay selection schemes in dynamic networks do not work well, as the fixed assignment of relays cannot adapt to dynamic networks. Distance based schemes cannot guarantee that the selected relays are the optimal ones, as distance is not the only factor that has effect on a communication link, and other factors, such as interference, shadowing, and fading also affect the link qualities. Furthermore, distance based schemes require that the distance information, i.e., from the source to relays, or from relays to the destination is available at each relay to make decision of relay selection, which is more difficult to implement in dynamic environments. In SNR (channel gain) based relay selection schemes, optimal relays are chosen by measuring the SNRs of the signaling messages that transmitted prior to the transmission of data packets. To adapt to the varying wireless channel, the measurements are often conducted on a packet-by-packet basis, which inevitably introduces a high communication overhead. Reinforcement learning and game theory based schemes might be the most adaptive schemes, as prior knowledge of network model and link qualities are not necessary, and the policy of relay selection are cooperatively learned via a series of trial-and-error interactions by the relaying candidates. However, the convergence speeds of the relay assignment algorithms might limit the applicabilities of such schemes. The reason is that relaying candidates, regarded as agents, needs a certain number of interactions to learn the optimal policy and then jointly adjust their behavior to achieve a system level optimal performance. It is shown in [27, 38, 44] that the number of interactions, often between 20 and 50, depending on the network scale, topology, and channel variations, is needed for the algorithms to reach convergence. Compared with the above mentioned adaptive relay selection schemes, random relay selection schemes have the advantages of lower computation and communication overhead, and still can achieve a moderate network performance [7].

Another important factor needs to be considered is the cost of utilizing cooperative communications. As we know, cooperative communications is effective in improving the network performance in terms of transmission reliability, robustness, adaptivity, network throughput and lifetime, by exploiting the spatial diversity of the wireless medium. However, the use of cooperative communications also associates with certain costs because of nodes conducting extra tasks of signal processing, packet receiving and retransmitting. Furthermore, using cooperative communications, particularly for cooperative communication protocols integrated with relay selection schemes, also increases network operations, as optimal relays need to assigned either by a coordinator or in a distributed manner on a packet-by-packet basis. Therefore, both the benefits and cost should be considered when designing cooperative communication systems.

4. Cooperative communications in multi-hop WSNs

In multi-hop WSNs, as shown in Fig. 3, the communication between a source and its destination usually involves a number of nodes, which act as intermediate routers and establish a multi-hop route for packet transmission.

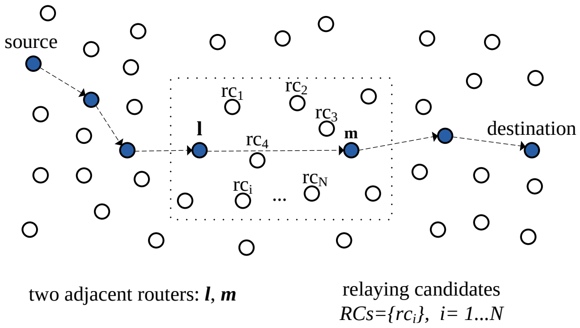

Fig. 3. Cooperative communications in multi-hop WSNs

Due to the lack of centralized control in multi-hop WSNs, the cooperative communication protocol should work in a distributed manner, i.e., for each hop of the route, the cooperative partner assignment and cooperative transmission scheme should be determined locally without the need of global network state information.

In multi-hop WSNs, nodes may play multiple roles, e.g., source, destination, relays and intermediate routers. For instance, nodes which are selected as optimal relays for a data flow, may also be chosen as intermediate routers, or relaying candidates for other data flows. Therefore, nodes may have varying incoming traffic, computational burden, and processing and queuing delays. This feature increases the design and analysis complexity of cooperative communication protocols.

Furthermore, there are often multiple data flows coexist in the network, which may have impacts on the performance of the source-destination data flow, because the network resources, e.g., spectrum, bandwidth and energy, are shared by all nodes in the network. Thus, it is necessary to jointly consider cooperative communications with network optimization [45, 46].

5. Applications of cooperative communications with relay selection

The main benefit of applying cooperative communications in wireless networks is to achieve diversity gains, without the need of maintaining multiple antennas at each user. Moreover, spectral efficiency is still guaranteed by employing adaptive relay selection techniques. Therefore, cooperative communications with relay selection may find various potential applications, especially in resource-constrained WSNs.

5.1. Reliable and energy-efficient data dissemination

In mission-critical WSN applications, e.g., battlefield surveillance, medical care and disaster response, the network used for communication must ensure that data packets can be delivered to the data processing center reliably and efficiently.

Multi-path routing has been proposed for reliable data dissemination, in which important data packets are delivered to the destination through multiple paths to achieve fault-tolerance. However, significant computational and communication overhead is incurred in the multi-path routes establishment and data transmitting. Besides, the energy consumption of multi-path routing is much higher than *uni-path* routing, due to the redundant packet transmissions in multiple paths. Cooperative communications with relay selection can be an effective approach for reliable and energy-efficient data dissemination in WSNs, by exploiting the spatial diversity gains, i.e., choosing nodes to help in the packet delivering in case deep channel fading, shadowing or interference occurs in the multi-hop route from the source to its destination [20, 21].

5.2. QoS provisioning in WSNs

Due to low-cost node platforms, self-organizing manner and ease of deployment, WSNs have numerous potential applications, e.g., medical care, battlefield surveillance, wildlife monitoring, and disaster response. In these mission-critical applications, a set of quality of service (QoS) requirements, e.g., delay, packet delivery ratio, network lifetime, throughput and communication bandwidth, on network performances must be satisfied [47]. However, providing guaranteed QoS is almost impossible in dynamic WSNs [48, 49], due to the dynamic network topology, time-varying wireless medium, and severe constraints on power supply, computation power, and communication bandwidth [50, 51, 52, 53, 54, 55].

Thus, it is more practical to provide soft QoS [56] than guaranteeing hard QoS in multi-hop WSNs [48, 49]. In soft QoS provisioning, when a QoS-support route is established, and the data flow is in transmission, there may exist a transient amount of time that the QoS requirements cannot be met. The level of soft QoS provisioning can be quantified by the fraction of total disruption time over the total connection time. The ratio should not be higher than a threshold, which is determined by user applications.

For a QoS-support route, QoS violations may occur because the intermediate routers cannot fulfill the QoS attributes, that they have been assigned or promised in the QoS route discovery and establishment procedure, which might be caused by network topology change, concurrent transmission interferences, thermal noise, shadowing and multi-path fading. For instance, as shown in Fig. 3, for the two adjacent routers l and m, which are the immediate routers along the established route, the link between l and m may experience channel fading and thus cannot meet the assigned QoS attributes. Retransmitting the packet, e.g., using ARQ mechanism, from l to m might not be effective in this case, since the link between l and m may remain in deep fading or shadowing for a long period in a slowly varying channel [13].

The channel fading and shadowing for different links are assumed to be statistically independent in WSNs, because the nodes in WSNs are usually spatially well separated [57]. Therefore, there might exist a node, e.g., node rc_i, which is a neighboring node for both l and m, overhear the packet transmission between l and m, due to the broadcast nature of the wireless medium. Node rc_i may help in the packet delivering between l and m by retransmitting the packet to m, even it has not been assigned any routing task in the route discovery and establishment procedure. This is known as spatial diversity gain and has been demonstrated to be effective in improving network performance. In the context of cooperative communications, the neighboring node rc_i acts as a cooperative partner for the communication between the intermediate routers l and m. When QoS violations happen, the cooperative partners may help in the packet delivering by retransmitting the signals and thus reassuring the QoS attributes. Therefore, the transient amount of time of QoS violation can be minimized and the satisfied level of soft QoS provisioning is increased, by applying cooperative communications with adaptive relay selection in WSNs.

6. Conclusions and future research directions

In the paper, we have reviewed the relay selection schemes for cooperative communication protocols, identified the key design issues for the adaptive relay selection schemes, and discussed the potential applications of cooperative communications with relay selection in WSNs. Compared with conventional cooperative communication protocols, cooperative protocols integrated with adaptive relay selection can be more effective in improving the network performance by exploiting diversity gains, while still achieving channel efficiency. However, the use of cooperative communications with relay selection incurs computational and communication overhead, as well as increasing the design and analysis complexity of cooperative communication systems. Depending on user applications and QoS demands, trade-off should be made in designing cooperative communication systems to achieve optimal network performance.

In future research, service differentiation and system fairness could be interesting topics in the development of cooperative protocols. The distribution of relaying tasks are important in resource-constrained WSNs, where multiple data flows coexist. In most of the current research, it has been assumed that sensor nodes are *passive* in the sense that they are chosen passively by the source node(s) as optimal relays, without consideration of their task priorities and willingnesses of being relays. In order to provide differentiated network services, achieve system fairness, and prolong the network lifetime, the trade-off between task priority and system fairness should be further investigated. Moreover, the use of game theory can be promising in the design of cooperative communication protocols for WSNs [58]. In particular, the process of optimal relay assignment can be modeled as a mixed-strategy game, where each player plays the game with other players in a distributed manner. By taking different actions, e.g., relaying a packet or remaining silent, and calculating the benefit and cost achieved, each player can evaluate the actions' qualities and then adjusts its probabilities of taking different actions in a dynamic environment. Optimal network performance can be achieved by by encouraging cooperation and discouraging selfish behavior, e.g., using the Pricing mechanism [40] to regulate selfish players strategies. To solve the problem that the available information in a game is often incomplete and inaccurate, as well as adapting to the dynamic environments, learning algorithms, e.g., fictitious learning, reinforcement learning should be involved in game designs. [27, 30].

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Authors' Biographies

Xuedong Liang is a Postdoctoral Research Fellow at the Department of Electrical and Computer Engineering, University of British Columbia, Vancouver, Canada. He received his Ph.D degree in the Department of Informatics, University of Oslo in 2009. His research interests are in the areas of wireless communication protocols, formal modeling and validation of wireless networks, QoS provisioning in wireless sensor networks.

Min Chen received the Ph.D degree in Electrical Engineering from South China University of Technology in 2004, when he was 23 years old. He has been a Research Associate in the Dept. of Computer Science at University of British Columbia (UBC) for half year, and worked as a Post-Doctoral Fellow in Department of Electrical and Computer Engineering at UBC for three years, where his faculty advisor is Prof. Victor C.M. Leung. Before joining UBC, he was a Post-Doctoral Fellow at SNU for one and half years. He received the Best Paper Runner-up Award from QShine 2008. He was interviewed by Chinese Canadian Times where he appeared on the celebrity column in 2007. He is the author of OPNET Network Simulation (Tsinghua University Press, 2004). He has more than 60 technical publications.

Ilangko Balasingham received the Siv.Ing (MSc) and Dr.Ing. (PhD) degrees both in signal processing from Norwegian University of Science and Technology (NTNU), Trondheim, Norway in 1993 and 1998, respectively. He has been with the Interventional Center, Rikshospitalet University Hospital, Oslo, Norway as a Research Scientist and Head of the Biomedical Sensor Network Research Group. He was also appointed as an Adjunct Professor of Signal Processing in Medical Technology at NTNU in 2006. His research interests are in areas of biomedical sensors, wireless sensor network and its applications in medical care.

Victor C.M. Leung received the B.A.Sc. (Hons.) degree and the Ph.D. degree in from the University of British Columbia (UBC) in 1977 and 1981, respectively, both in electrical engineering. Dr. Leung