

RESEARCH ARTICLE

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

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ABSTRACT

Relay selection schemes for cooperative communications to achieve full cooperative diversity gains while maintaining spectral and energy efficiency have been extensively studied in a recent research. These schemes select only the best relay from multiple relaying candidates to cooperate with a communication link. In the present paper, we reviewed recently proposed cooperative communication protocols that integrate with relay selection mechanisms. The key design issues for relay selection mechanisms, for example, relaying candidate selection, optimal relay assignment, and cooperative transmission, were identified. We further discussed the challenges of optimal relay assignment in multi-hop wireless sensor networks and presented the potential applications of cooperative communications with a relay selection in such networks. Future research directions were outlined, for example, the issues of service differentiation and system fairness in cooperative communication systems and the joint use of game theory and adaptive learning techniques in relaying candidate selection and optimal-relay assignment mechanisms for efficient allocation of network resources. Copyright © 2011 John Wiley & Sons, Ltd.

KEYWORDS

cooperative communications; optimal relay assignment; quality of service; wireless sensor networks

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1. INTRODUCTION

In this section, we first introduce the concept of cooperative communications, then we briefly review the protocols and algorithms that are designed for cooperative communication systems to achieve channel diversity gains.

1.1. Background of cooperative communications

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 to 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 that define the relaying candidate selection [4], coding [5], cooperative transmission [6], and power allocation schemes. However, there lacks a comprehensive survey on the recently 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 issues of cooperative communications, particularly for cooperative protocols that integrate with relay selection schemes.

In the literature, most of the researches on cooperative communications [7–11] model the wireless channel as a narrowband Rayleigh block-fading channel with additive white Gaussian noise [12]. For any two nodes, for example, i and j , the channel coefficient h_{ij} , which captures the

effects of path loss, shadowing, and fading, is modeled as a zero-mean circularly 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, that is, $h_{ij} = h_{ji}$. The channel coefficients are constant for a given transmitted block, or a code word, but are independent and identically distributed for different blocks [7]. For different links, the channel-fading coefficients are statistically independent and identically distributed, which is a reasonable assumption as the nodes are usually spatially deployed [13].

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

$$Y_{d_1} = h_{s,d}X_s + \eta_{s,d} \quad (1)$$

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. $\eta_{s,d}$ captures the effects of an input noise at the receiver and of other interferences in the network and is modeled as a zero-mean circularly symmetric complex Gaussian distribution with variance N_0 [7].

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

$$Y_r = h_{s,r}X_s + \eta_{s,r} \quad (2)$$

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, that is, 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 is retransmitted by the relay is expressed as in Equation (3),

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

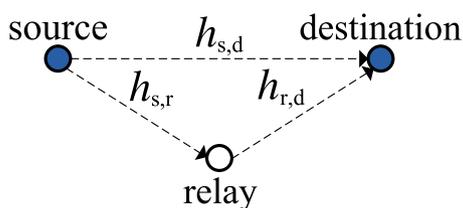


Figure 1. A three-node cooperative communication model.

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, that is, source–destination and source–relay–destination, are formed from the source to the destination. The destination receives two copies of the original signal, that is, 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, for example, applying maximum-ratio-combining [14] for optimal packet decoding, or may simply choose the signal with a higher signal-to-noise ratio (SNR) and then decode it. Therefore, cooperative diversity gains can be achieved, that is, a packet transmission failure occurs only when both of the two independent paths experience deep channel fading or shadowing, simultaneously.

1.2. Cooperative communications: protocols and algorithms

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

- *Amplify-and-forward (AaF)* [15]: The relay amplifies the signal received 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 higher than a certain threshold, the relay retransmits the signal received from the source to the destination, using either AaF or DaF, to achieve diversity gains. If $|h_{s,r}|^2$ is lower than the threshold, the source itself either simply retransmits the packet or uses more powerful error-correcting codes. The calculation of the threshold value depends on a number of factors, for example, 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, using either AaF or DaF.
- *Coded cooperation* [16]: The cooperation is integrated with channel coding and works by sending

different parts of each user's code word via two independent fading paths. In coded cooperation, each user's datum is encoded into a code word with N bits, then the code is partitioned into two parts, containing N_1 bits and N_2 bits, respectively. The first part of N_1 bits is a valid code word itself but is weakly coded, and the second part of N_2 bits are the puncture bits [1]. The coded cooperation operates in two phases. In the first phase, each user transmits his or her own first part of the code word that contains N_1 bits, listens to his or her partner's first part of the code word containing N_1 bits, and attempts to decode it. In the second phase, if a user can decode the first part of the code word of his or her partner successfully, the user then calculates and transmits the second part of the code word, that is, the remaining N_2 bits, for his or her partner; otherwise, the user transmits his or her own second part of the code word that contains the remaining N_2 bits. The basic idea of coded cooperation is that each user attempts to transmit incremental redundancy for his or her partner.

- *code division multiple access-based cooperation* [17,18]: the cooperation mechanism is implemented in a code division multiple access system, in which a user constructs a signal to be transmitted by combining his or her own signal and the signal received from his or her partner. Similarly, the user's partner constructs his or her signal to be transmitted in the same fashion. Then, the user and his or her partner cooperate by sending both of their messages to the receiver and by using different spreading code to avoid interferences.

In wireless networks where nodes are densely deployed, as shown in Figure 2, there are usually multiple relaying candidates available for the source and the 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 forming multiple paths between the source and the destination.

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

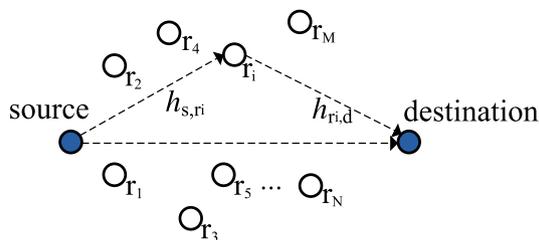


Figure 2. A multi-node cooperative communication model.

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 spectral efficiency of the multi-node cooperative communication system is much lower than that of non-cooperative communication systems. The reason is that the total number of $N + 1$ time slots is needed for the packet transmission, assuming carrier sense multiple access with collision avoidance or time division multiple access is used as the underlying Medium Access Control (MAC) Protocol. Besides, packet transmissions suffer extra delays because of the receiver deferring packet decoding until all of the relays have completed their transmissions. Moreover, the relays' multiple transmissions consume precious network resources, for example, 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 spectral 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 the communication link, have been extensively studied in a 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 and the key design issues of relay selection schemes, for example, 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 in obtaining high spectral efficiency. As shown in [8,10], for the DaF cooperative protocol, 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 on network performance. The selected optimal relay, which can make the most contributions in improving the network performance, in terms of packet outage probability and channel utilization efficiency [13,15,19], should be the best one among all the relaying candidates. The challenge of the optimal relay selection is finding the best relay in wireless networks in dynamic environments, where the network topology may change and the wireless medium is time-varying, because of 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 the 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 [20–22], the relaying candidate selection is implemented by using the mechanism of cooperative multi-hop mesh structure construction, that is, the relaying candidates are assigned in the procedure of multi-hop mesh route discovery and establishment. The pre-assigned selection scheme is the simplest approach for relaying candidate selection, in terms of algorithm design complexity and network operations. However, the pre-assigned relaying candidate selection scheme cannot deal with network dynamics, for example, 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 because of 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 [9–11], the signaling messages in the MAC Layer, that is, the request-to-send (RTS) and the 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 an 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 the 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 an 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, that is, Ad Hoc On-Demand Distance Vector Routing Protocol. In the route discovery procedure, for two adjacent routers (one-hop sender and receiver), a node determines that it is a relaying candidate for the routers if it has heard both the route request signal transmitted by the sender and the route reply 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 the destination. The frequently used criteria for relay assignment are described as follows.

2.2.1. Pre-defined and random relay assignments.

The simplest solution for relay assignment is 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 network overhead. However, such schemes cannot achieve optimal performance in dynamic environments and lacks the capacity of dealing with network dynamics.

2.2.2. Distance-based relay assignment.

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

The distance-based cooperative protocol [21] chooses a node that 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 back-off 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 back-off timer first and wins the competition. The node that wins in the competition procedure will send an M-CTS signal to inform the source that it is ready to send as well as to notify the 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' strength and SNR, due to interferences, 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. Signal-to-noise ratio (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 the destination. Because both of the two paths, that is, source-relay and relay-destination, are important for the end-to-end link performance, each relay should evaluate the link qualities of both paths.

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

$$\gamma_r = \min(SNR(s, r_i), SNR(r_i, d)) \quad (4)$$

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 that have the two highest of the minimum SNRs of the relay channels, that is, from the source to the relay and from the relay to the destination, as the optimal relays. To keep the list of the SNR information up-to-date, each candidate locally measures the SNRs and sends the information to the source in a fixed time interval, for example, every 1 s in the paper. 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 all the relaying candidates, to cooperate with the communication link between the source and the destination.

In [9], the relaying candidates use the 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 , and 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} and $h_{r_i, d}$ 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 distributively. Under policy I, as defined in Equation (5), the minimum of the two is selected, whereas

under policy II, as defined in Equation (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 link quality represented by H_{r_i} . Therefore, the best relay's timer will expire first and start retransmitting the signal towards the destination.

In [11], the optimal-relay assignment scheme is integrated with the power control mechanism in the physical layer. Individually, the relaying candidates use the RTS and CTS messages to assess the link qualities and compute the required transmission power that can meet the desired link qualities. Different from [9], the source also participates 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 at the relays. The optimal relay is the node that 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 Equation (7), denotes the scaled harmonic mean function and gives an instantaneous indication about the relay's ability to cooperate with the source.

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

where $\mu_H(\cdot)$ is the standard harmonic mean function. q_1 and q_2 are calculated as in Equation (8).

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

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

For M phase-shift keying modulation, A and B can be calculated as in Equations (9) and (10), respectively.

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

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

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

The signaling messages, the RTS and the 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 that has the maximum instantaneous channel gain between the relay and destination, as shown in Equation (11).

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

where r_i^* is the optimal relay and D is the set of relays that 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 weighted channel strengths between the source and the destination, as shown in Equation (12).

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

where K is the set of relaying candidates and 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 that can maximize the mutual information, defined as in Equation (13).

$$r_i^* = \arg \max_{i \in K} W r_i \quad (13)$$

where

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

where Ω_{sr_i} denotes the average channel gain between the source and the relay r_i , γ_{sr_i} is the average SNR for the link between the source and the 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, for example, spectrum, time slots, cooperation and/or contention 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 that the nodes are expected to follow a set of strategies and to choose actions from the strategies to maximize their utilities. In the meantime, the nodes behave selfishly, that is, a node always chooses an action that maximizes its own payoff, without considering the utilities of other nodes. Most papers do not consider cooperative games, as additional signaling messages between the decision-makers are needed to be implemented to achieve common agreements, which makes 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 packets. The authors in [28] proposed a relay selection and power control scheme based on a two-level Stackelberg game, in which the source node and the relay nodes are modeled as a buyer and as 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 the DaF cooperative protocol over the additive white Gaussian noise and the 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 have complete information of the game. That is, a player has the full knowledge of the game, that is, the other players' identities, strategies, payoffs, and utility functions [28]. Furthermore, the game's history, for example, 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 held in realistic scenarios, as nodes in wireless networks usually only have locally observed information and limited knowledge of others' behavior. Therefore, adaptive learning, for example, estimating payoffs that may be obtained by taking certain actions or predicting the other players' strategies, should be involved in the game designs [30].

2.3. Phase 3: Cooperative transmission

The assigned relays can cooperate with the communication link between the source and the destination for any packet transmission by retransmitting the overheard signals. For instance, in cooperative protocol design [25], two selected 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 spectral efficiency, the cooperative communication can be triggered when it is necessary, for example, the packet transmission fails in the direct transmission phase or the direct link between the source and the destination cannot meet the desired quality-of-service (QoS) requirements, as the protocol proposes 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, a cooperative transmission will be invoked, that is, the relay that received the signal in the direct transmission phase forwards the signal to the destination.

In [8], the source computes the ratio of $\frac{\beta_{s,d}}{\beta_{max}}$ and compares it to a cooperation threshold α , which is often defined as 1. If $\frac{\beta_{s,d}}{\beta_{max}} \geq \alpha$, the source uses 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 the destination d , if the link quality that is defined as the modified harmonic mean function of channel gains between source s and relay r_i and destination d is higher than the channel gain between source s and destination d ; otherwise, the source will choose direct transmission only.

3. COMPARISON AND DISCUSSION

In this section, we categorize the recently 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 as the unique criterion for optimal relay assignment and assume that a full or a partial CSI is available at the source, at the destination and at 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 a received SNR-based selection scheme behaves similarly to a random selection scheme, or even slightly worse in some scenarios. Furthermore, a significant communication overhead is incurred in acquiring and in disseminating CSI to all of the cooperative participants, especially for the cooperative protocols, as in [8,9], that an instantaneous CSI is required at all the potential relays for relay selection.

3.2. Centralized versus distributed mechanisms

In centralized mechanisms of relay selection, a coordinator, usually the source, is responsible to select the relay. 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 that has the highest metric among all the relaying candidates and broadcasts a control signal to all the relays and the destination to indicate its decision on 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, for example, using channel gain as a metric, and then starts a *relay-competition-timer* that 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 broadcast a *flag* message to the other candidates informing that it won 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, for example, cooperating or remaining silent, and then takes 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 [31].

Centralized mechanisms often need exchanging additional signaling messages to perform relay selection, which inevitably introduces overhead to the network. Furthermore, the need for 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 or not with a

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 (one-hop network)	Random	Continuous	Reactive
Received SNR selection [7]	N/A (one-hop network)	SNR	Continuous	Reactive
Fixed priority selection [7]	N/A (one-hop network)	Pre-defined	Continuous	Reactive
Scheme in [8]	N/A (one-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	Required transmission power	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, spectral efficiency	Triggered/ARQ	Reactive
Scheme in [27]	N/A (one-hop network)	Credit (benefits minus cost)	Continuous	Reactive

N/A, not applicable; SNR, signal-to-noise ratio; DaF, decode-and-forward; AaF, amplify-and-forward; EECC, energy-efficient cooperative communication; MISO, multiple input single output; CRP, cooperative routing protocol; QoS-RSCC, quality of service-supported relay selection scheme for cooperative communication; RTS, ready-to-send; CTS, clear-to-send; M-RTS, multiple-RTS; M-CTS, multiple-CTS; ARQ, automatic repeat request.

communication link 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 the same value, both of them will reduce their timers to zero and start retransmitting simultaneously, which will result in a packet collision. And in [27], if the candidates make inaccurate estimations of their opponents' strategies, relay selection failure, for example, collision or no candidate decides to act as the optimal relay, may happen.

3.3. Proactive versus reactive relay assignment

The relay can be assigned prior to a source–destination transmission, which is called proactive relay assignment, or selected after a 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 design 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 instant of a packet transmission between the source and the destination. In proactive assignment mechanisms,

assigning a relay before the start of a 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 versus triggered cooperation

Continuous cooperation schemes can guarantee diversity gains by always choosing relays to participate in the communication. However, because of 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 spectral efficiency.

In triggered cooperation mechanisms, feedback, for example, the 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. In the latter case, a relay, either selected by the source or determined distributively by the relaying candidates, will cooperate with the communication link between the source and the destination.

Triggered cooperation has the advantage of spectral efficiency because the relaying transmission is invoked only when the direct link between the source and the destination experiences deep channel fading, shadowing, or interferences. 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. A trade-off should be considered between network performance and algorithm complexity [32–34].

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, for example, 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, choosing nodes that have already been involved in other data flows, for example, acting as intermediate routers or relays, should be avoided. 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 to estimate. Reinforcement learning [35,36] could be a promising approach to address this issue, as the reinforcement learning-based approaches [37] choose the relays through experience and reward without actually measuring the nodes states, which is similar to the procedure of a human or an 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, for example, network topology changes and 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 such networks. Distance-based schemes cannot guarantee that the selected relays are the optimal ones, as distance is not the only factor that has an effect on a communication link, and the other factors such as interferences, shadowing, and fading also affect the link qualities. Furthermore, distance-based schemes require that the distance information, that is, from the source to the relays or from the relays to the destination, is available at each relay in order to make a decision on relay selection, which is more difficult to realize in dynamic environments. In SNR and channel gain-based relay selection schemes, optimal relays are chosen by measuring the SNRs or signal strengths of the signaling messages that are 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. Game theory and reinforcement learning-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, need 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 [38,39] that the number of interactions, often between 20 and 60, depending on the network scale, topology, and channel variations, is needed for the algorithms to reach a convergence. Compared with the above-mentioned adaptive relay selection schemes, random relay selection schemes have the advantages of lower computational and communication overhead and still can achieve a moderate network performance [7].

Another important issue that 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, and network throughput and lifetime, by exploiting the spatial diversity of the wireless medium. However, the use of cooperative communications also associates with a certain cost, for example, power consumption, because of nodes conducting extra tasks of signal processing and packet receiving and retransmitting. Furthermore, using cooperative communications, particularly for cooperative protocols integrated with relay selection schemes, also increase network operations, as optimal relays need to be either assigned by a coordinator or determined in a distributed manner on a packet-by-packet basis. Therefore, both the benefits and the cost should be considered when designing cooperative communication systems.

4. COOPERATIVE COMMUNICATIONS IN MULTI-HOP WIRELESS SENSOR NETWORKS

Wireless sensor networks have received much research attention and have been applied in many areas in recent years because of the features of low cost, low power consumption, and deployment flexibility. Compared with traditional wireless networks, for example, wireless local area networks, WSNs are often resource-constrained and have some unique features. For instance, WSNs usually operate in a distributed manner without centralized control, and the packet transmissions between nodes are often of multi-hop manner, that is, the communication between a source and its destination usually involves a number of nodes, which act as intermediate routers by establishing a multi-hop route for the source and the destination. In this section, we discuss some important issues of applying cooperative communications in WSNs.

In multi-hop WSNs, as shown in Figure 3, nodes may play multiple roles, for example, source, destination, relays, and intermediate routers. For instance, nodes that are selected as optimal relays for a data flow may also be chosen as intermediate routers or as 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.

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

Furthermore, there are often multiple data flows that coexist in the network, which may have impacts on the performance of the source–destination data flow, because the network resources, for example, spectrum, bandwidth, and energy, are shared by all nodes in the network. Thus, it is necessary to jointly consider cooperative communications with network optimization [40,41].

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 scheme may find various potential applications, especially in resource-constrained WSNs.

5.1. Reliable and energy-efficient data dissemination

For some wireless systems, the network used for communication must ensure that data packets can be delivered to the data processing center reliably and efficiently.

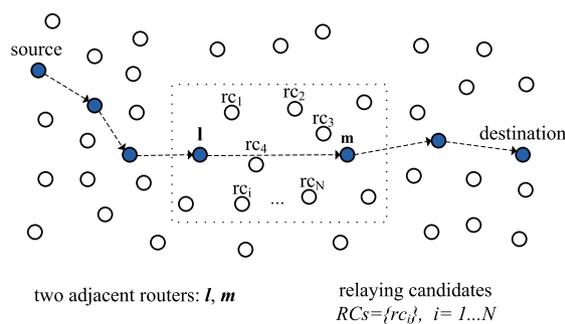


Figure 3. Cooperative communications in multi-hop wireless sensor networks.

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 by adding redundancies. However, a significant computational and communication overhead is incurred in the multi-path routes establishment and data transmitting. Besides, the energy consumption of a multi-path routing is much higher than that of a *uni-path* routing, because of 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, that is, choosing nodes to help in the packet delivering in case deep channel fading, shadowing, or interferences occur in the multi-hop route from the source to its destination [20,21].

5.2. Quality-of-service provisioning in wireless sensor networks

Because of low-cost node platforms, self-organizing manner, and ease of deployment, WSNs have numerous potential applications, for example, medical care, battlefield surveillance, wildlife monitoring, and disaster response. In these mission-critical applications, a set of QoS requirements, for example, delay, packet delivery ratio, network lifetime, throughput, and communication bandwidth, on network performances must be satisfied [42]. However, providing guaranteed QoS is almost impossible in dynamic WSNs [43,44], because of the dynamic network topology, time-varying wireless medium, and severe constraints on power supply, computation power, and communication bandwidth [45–50].

Thus, it is more practical to provide soft QoS [51] than guaranteeing hard QoS in multi-hop WSNs [43,44]. 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 the 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 Figure 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, for example, using ARQ mechanism, from l to m might not be effective in this case, because 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 [52]. Therefore, there might exist a node, for example, node rc_i , which is a neighboring node for both l and m , that may overhear the packet transmission between l and m because of 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 if 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 relay for the communication between the intermediate routers l and m . When QoS violations happen, the cooperative relays may help in the packet delivering by retransmitting the signals and thus reassuring the QoS attributes. Therefore, the 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 this 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, the cooperative protocols integrated with adaptive relay selection can be more effective in improving the network performance by exploiting diversity gains, while still achieving spectral efficiency. However, the use of cooperative communications with relay selection incurs computational and communication overhead, as well as increases the design and analysis complexity of cooperative communication systems. Depending on user applications and QoS demands, a trade-off should be made to achieve an 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 nodes are *passive* in the sense that they are chosen passively by the source node(s) as optimal relays, without the consideration of their task priorities and the willingness of being relays. In order to provide differentiated network services, to achieve system fairness, and to prolong the network lifetime, the trade-off between task priority and system fairness should be further investigated. Moreover, the use of reinforcement learning [53] and game theory [27,54] can be promising in the design

of cooperative communication protocols for WSNs [55]. In particular, the process of optimal relay assignment can be modeled as a mixed-strategy game, where each player plays the game with the other players in a distributed manner. By taking different actions, for example, relaying a packet or remaining silent, and calculating the benefits 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 encouraging cooperation and discouraging selfish behavior, for example, using the pricing mechanism [31] to regulate players' strategies. To solve the problem that the available information in a game is often incomplete and inaccurate, as well as adapting to dynamic environments, learning algorithms, for example, fictitious learning, reinforcement learning, and adaptive regret-based learning [54] should be involved in game designs [27,30].

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REFERENCES

1. Nosratinia A, Hunter TE, Hedayat A. Cooperative communication in wireless networks. *IEEE Communications Magazine* 2004; **42**: 74–80.
2. Hong Y-W, Huang W-J, Chiu F-H, Jay Kuo C-C. Cooperative communications in resource-constrained wireless networks. *IEEE Signal Processing Magazine* 2007; **42**: 47–57.
3. Chen X, Hu H, Wang H, Chen H-H, Guizani M. Double proportional fair user pairing algorithm for uplink virtual MIMO systems. *IEEE Transactions On Wireless Communications* 2008; **7**(7): 2425–2429.
4. Chen X, Hu H, Jin S, Chen H-H. Broadcast reserved opportunity to achieve diversity relaying and its performance evaluation. *EURASIP Journal On Wireless Communications And Networking* 2008; **7**(2): 1–9.
5. Peng M, Zhang J, Wang W-B, Chen H-H. Heterogeneous cooperative relay selection with maximal-ratio combining for multi-radio access networks. *International Journal of Communication Systems* 2010; **23**(6–7): 732–750.
6. Yang L-L, Chen H-H. Error probability of digital communications using relay diversity over Nakagami-m

- fading channels. *IEEE Transactions on Wireless Communications* 2008; **7**(5): 1806–1811.
7. Hunter TE, Nosratinia A. Distributed protocols for user cooperation in multi-user wireless networks. In *The IEEE 47th Annual Global Telecommunications Conference (GLOBECOM'04)*, Dallas, TX, USA, November 2004; 3788–3792.
 8. Ibrahim AS, Sadek AK, Su W, Liu KJR. Cooperative communications with relay-selection: when to cooperate and whom to cooperate with? *IEEE Transactions on Wireless Communications* 2008; **7**(7): 2814–2817.
 9. Bletsas A, Khisti A, Reed DP, Lippman A. A simple cooperative diversity method based on network path selection. *IEEE Journal on Selected Areas in Communications* 2006; **24**: 659–672.
 10. Bletsas A, Shin H, Win MZ. Cooperative communications with outage-optimal opportunistic relaying. *IEEE Transactions on Wireless Communications* 2007; **24**(3): 3450–3460.
 11. Zhou Z, Zhou S, Cui J-H, Cui S. Energy-efficient cooperative communication based on power control and selective single-relay in wireless sensor networks. *IEEE Transactions on Wireless Communications* 2008; **7**(8): 3066–3078.
 12. Simon MK, Alouini M-S. *Digital Communication over Fading Channels: A Unified Approach to Performance Analysis*. John Wiley & Sons, Inc.: New York, NY, 2000.
 13. Sadek A, Wei Y, Liu K. When Does Cooperation Have Better Performance in Sensor Networks? In *IEEE The 3rd Sensor and Ad Hoc Communications and Networks (SECON'06)*, Reston, VA, USA, 2006; 188–197.
 14. Brennan DG. Linear diversity combining techniques. *Proceedings of the IEEE* 2003; **91**(2): 331–356.
 15. Laneman JN, Tse DNC, Wornell GW. Cooperative diversity in wireless networks: efficient protocols and outage behavior. *IEEE Transactions on Information Theory* 2004; **50**: 3062–3080.
 16. Hunter TE, Nosratinia A. Cooperation diversity through coding. In *International Symposium on Information Theory (ISIT'02)*, Laussen, Switzerland, June 2002; 220.
 17. Sendonaris A, Erkip E, Aazhang B. User cooperation diversity-part I: system description. *IEEE Transactions on Communications* 2003; **51**: 1927–1938.
 18. Sendonaris A, Erkip E, Aazhang B. User cooperation diversity-part II: implementation aspects and performance analysis. *IEEE Transactions on Communications* 2003; **51**: 1939–1948.
 19. Xu F, Lau FCM, Zhou QF, Yue D-W. Outage performance of cooperative communication systems using opportunistic relaying and selection combining receiver. *IEEE Signal Processing Letters* 2009; **16**(2): 113–136.
 20. Chen M, Kon T, Mao S, Yuan Y, Leung VCM. Reliable and energy-efficient routing protocol in dense wireless sensor networks. *International Journal on Sensor Networks* 2008; **4**(1/2): 104–117.
 21. Chen M, Liang X, Leung VCM, Balasingham I. Multi-hop mesh cooperative structure based data dissemination for wireless sensor networks. In *The 11th International Conference on Advanced Communication Technology (ICACT'09)*: Phoenix Park, Gangwon-Do, Korea, 2009; 102–106.
 22. Liang X, Chen M, Xiao Y, Balasingham I, Leung VCM. A novel cooperative communication protocol for QoS provisioning in wireless sensor networks. In *The 5th International Conference on Testbeds and Research Infrastructures for the Development of Networks & Communities and Workshops (Trident-Com'09)*, Washington, DC, April 2009; 1–6.
 23. IEEE. IEEE Standard 802.11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specification, *IEEE Standard*, 1997.
 24. Jakllari G, Krishnamurthy SV, Faloutsos M, Krishnamurthy PV, Ercetin O. A cross-layer framework for exploiting virtual MISO links in mobile ad hoc networks. *IEEE Transactions on Mobile Computing* 2007; **6**: 579–594.
 25. Lin Y, Song J-H, Wong VWS. Cooperative protocols design for wireless ad-hoc networks with multi-hop routing. *Mobile Networks and Applications* 2009; **14**(2): 143–153.
 26. Liang X, Balasingham I, Leung VCM. Cooperative Communications with Adaptive Relay Selection for QoS Provisioning in Wireless Sensor Networks. In *the 52nd IEEE Global Communications Conference (GLOBECOM'09)*, Honolulu, HI, Hawaii, USA, 2009; 1–8.
 27. Sergiilia S, Pancaldi F, Vitetta GM. A game theory approach to selection diversity in wireless ad-hoc networks. In *The 8th 2009 IEEE International Conference on Communications (ICC'09)*. Dresden, Germany, 2009; 4184–4189.
 28. Wang B, Han Z, Ray Liu KJ. Distributed relay selection and power control for multiuser cooperative communication networks using Stackelberg game. *IEEE Transactions on Mobile Computing* 2009; **8**(7): 975–990.
 29. Chen Y, Kishore S. A game-theoretic analysis of decode-and-forward user cooperation. *IEEE Transactions on Wireless Communications* 2008; **7**(5–2): 1941–1951.
 30. Wang B, Wu Y, Ray Liu KJ. Game theory for cognitive radio networks: an overview. *Computer Networks* 2010; **54**(14): 2537–2561.

31. Felegyhazi M, Hubaux JP. Game Theory in Wireless Networks: A Tutorial. *Technical Report: LCA-REPORT-2006-002*, École Polytechnique Fédérale de Lausanne, 2006.
32. Cheng P, Zhang Z, Yu G, Chen H-H, Qiu P. Cross-layer bandwidth and power allocation for a two-hop link in wireless mesh network. *Wireless Communications and Mobile Computing* 2009; **9**(2): 155–167.
33. Hu H, Luo J, Chen H-H. Radio resource management for cooperative wireless communication systems with organized beam-hopping techniques. *IEEE Wireless Communications* 2008; **15**(2): 100–109.
34. Li L, Hu H, Chen X, Chen H-H. Adaptive cooperative coding with power allocation in wireless relay networks. *IEEE Transactions on Wireless Communications* 2009; **8**(9): 4604–4615.
35. Sutton RS, Barto AG. *Reinforcement Learning: An Introduction*. MIT Press: Cambridge, MA, 1998.
36. Kaelbling LP, Littman ML, Moore AP. Reinforcement learning: a survey. *Journal of Artificial Intelligence Research* 1996; **4**: 237–285.
37. Liang X, Chen M, Leung VCM, Balasingham I. Soft QoS provisioning for wireless sensor networks: a cooperative communications approach. In *The 5th International ICST Conference on Communications and Networking in China (ChinaCom'10)*, Beijing, China, 2010; 1–8.
38. Chen L. A distributed access point selection algorithm based on no-regret learning for wireless access networks. In *The 71st IEEE Vehicular Technology Conference (VTC2010-Spring)*, Taipei, Taiwan, May 2010; 1–5.
39. Liang X, Chen M, Leung VCM. Relay assignment for cooperative communications over distributed wireless networks: a game-theoretic approach. *Technical Report: DCG12*, 2010.
40. Wang W, Peng D, Wang H, Sharif H, Chen H-H. Cross-layer multirate interaction with distributed source coding in wireless sensor networks. *IEEE Transactions On Wireless Communications* 2009; **8**(2): 787–795.
41. Wang H, Peng D, Wang W, Sharif H, Chen H-H. Cross-layer routing optimization in multirate wireless sensor networks for distributed source coding based applications. *IEEE Transactions On Wireless Communications* 2008; **7**(10): 3999–4009.
42. Li J, Andrew LLH, Foh CH, Zukerman M, Chen H-H. Connectivity, coverage and placement in wireless sensor networks. *Sensors* 2009; **9**: 7664–7693.
43. Qian Zhang, Ya-Qin Zhang. Cross-layer design for QoS support in multihop wireless networks. *Proceedings of the IEEE* 2008; **19**(10): 64–76.
44. Mohapatra P, Li J, Gui C. QoS in mobile ad hoc networks. *IEEE Wireless Communications* 2003; **10**(3): 44–52.
45. Djukanovic G, Sunjevaric M, Gospic N, Chen H-H. Dynamic guard margin CAC algorithm with ensured QoS and low CDP in heterogeneous wireless networks. *Computer Communications* 2010; **33**(14): 1645–1650.
46. Yang K, Galis A, Chen H-H. QoS-aware service selection algorithms for pervasive service composition in mobile wireless environments. *Mobile Networks and Applications* 2010; **15**(4): 488–501.
47. Zhang C, Wang X, Guan X, Chen H-H. Quality-of-service in cognitive radio networks with collaborative sensing. In *The 52nd IEEE Global Communications Conference (GLOBECOM'09)*, Honolulu, HI, USA, 2009; 1–5.
48. Hu H, Zhang Y, Chen H-H. An effective QoS differentiation scheme for wireless mesh networks. *IEEE Network* 2008; **22**(1): 66–73.
49. Zhang X, Tang J, Chen H-H. Space-time diversity-enhanced QoS provisioning for real-time service over MC-DS-CDMA based wireless networks. *Wireless Communications and Mobile Computing* 2008; **8**(6): 733–744.
50. Wang W, Peng D, Wang H, Sharif H, Chen H-H. Energy-constrained quality optimization for secure image transmission in wireless sensor networks. *Hindawi Advances in Multimedia Journal* 2008; **7**(1): 1680–1687.
51. Veres A, Campbell AT, Barry M, Sun L-H. Supporting service differentiation in wireless packet networks using distributed control. *IEEE Journal on Selected Areas in Communications* 2001; **19**: 2081–2093.
52. Sadek AK, Su W, Liu KJR. Multinode cooperative communications in wireless networks. *IEEE Transactions on Signal Processing* 2007; **55**: 341–355.
53. Naddafzadeh-Shirazi G, Kong PY, Tham CK. Distributed reinforcement learning frameworks for cooperative retransmission in wireless networks. *IEEE Transactions on Vehicular Technology* 2010; **59**(8): 1–10.
54. Maskery M, Krishnamurthy V, Zhao Q. Decentralized dynamic spectrum access for cognitive radios: cooperative design of a non-cooperative game. *IEEE Transactions on Communications* 2009; **57**(2): 459–469.
55. Zhang Z, Shi J, Chen H-H, Guizani M, Qiu P. A cooperation strategy based on Nash bargaining solution in cooperative relay networks. *IEEE Transactions On Vehicular Technology* 2008; **57**(4): 2570–2577.

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