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Distributed Interference-Aware Cooperative Random Access in Multi-Hop Wireless Networks

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ABSTRACT Cooperative communication has emerged as a promising technique to improve transmission reliability and spectral efficiency by utilizing virtual antenna arrays formed by multiple nodes in wireless networks. In this paper, we study distributed interference-aware random access strategies based on cooperative link selection scheduling for multi-hop wireless networks. In order to fully exploit the broadcast feature of wireless channels, improve spatial reuse, and achieve diversity gains, the cooperative random access is formulated as a network utility optimization problem with probabilistic model and interference avoidance. In the multi-hop wireless networks, the nodes near the destination node in the current hop that can decode the data packets from the source node are able to serve as candidate relays to take part in the cooperative transmission in the next hop. Simulation results show that our proposed spectrum access strategy significantly improves the system average throughput and spectrum efficiency compared with the existing solutions.

INDEX TERMS Interference, cooperative communications, random access, multi-hop networks.

I. INTRODUCTION

Distributed multi-hop wireless networks have received tremendous attention recently because they can easily build networks without requiring pre-existing infrastructure. However, in such networks, all transmission links usually compete for the limited wireless medium resource simultaneously, resulting in package collision or interference, which sometimes degrades the network performance. Therefore, to obtain the benefits of multi-hop wireless networks, channel fading, collision, and interference must be addressed.

To deal with the above issues, Holland *et al.* [1] proposed a receiver-based auto rate (RBAR) medium access protocol, which adjusts transmission rate adaptively according to the instantaneous channel state information (CSI) through request-to-send/clear-to-send (RTS/CTS) control frames. In [2], a cooperative medium access control protocol (CoopMAC) has been presented to overcome the throughput bottleneck caused by low data rate links. The table-based relay selection strategy proposed in [3] can increase transmission rate with the help of better quality wireless links, which can improve throughput even when the channel condition of the direct link is poor. The table-based cooperative access schemes were modified in [4] and [5]. The modified schemes depend on the storage overhead table information and adjust transmission power and rate based on the instantaneous channel measurements. However, for this kind of cooperative access, the destination node needs to store an analog version of the transmission data packets, which is sometimes difficult to be implemented. Therefore, another cooperative medium access control protocol (COMAC) was developed in [6]. The COMAC coordinates source and relay nodes to send data packets simultaneously in the cooperative phase and perform maximal ratio combining (MRC) at destination, which is easier to be implemented compared to CoopMAC. For wireless nodes with multiple antennas, a cooperative MIMO MAC protocol has been proposed in [7] to improve energy efficiency. In [8], Zhou *et al.* proposed a link-utility-based cooperative channel access protocol for wireless multi-hop networks. The best node that can successfully obtain data packets in the previous hop constitutes virtual antenna with the current sending node, which makes full use of the broadcast feature of wireless multi-hop networks. This protocol achieves higher spectrum and energy efficiency than the traditional one-hop network while with a reasonable complexity to facilitate the practical implementation.

However, most of the existing works ignore cooperative link interference and contention issues. The cooperative channel access protocol of contention resolution was proposed in [9], where a non-directed contention model is first established to describe the interference relationship among the virtual logical links. And then, the virtual link scheduling problem is formulated to optimize the system under the deterministic interference constraints and contention model. However, local clique searching is sometimes complicated, which may lead to imperfect scheduling due to the difference between the interference and communication ranges [10], [11].

In this paper, we propose a cooperative random access strategy for distributed multi-hop wireless networks. With the help of probabilistic model, we establish the framework on network utility maximization based on cooperative link selection to find out the optimal transmit probabilities of primal logical links and their corresponding cooperative links, respectively. Thus, our strategy is also called cooperative link-selection-based medium access control (CLS-MAC). We use flow scheduling technique to address the interference issue caused by cooperative links. The major contributions of this paper are highlighted as follows: 1) an interference-aware multi-relay virtual link scheduling for the primal logical links with consideration of multiuser diversity is obtained and 2) a probabilistic contention-based cooperative random access protocol is designed.

The rest of the paper is organized as follows. In Section II, we introduce the system model and formulate the optimization problem and its virtual link scheduling rule. In Section III, the proposed distributed interference-aware cooperative random access strategy is described. Then, we present numerical results to demonstrate the performance improvement of the proposed strategy in Section IV. Finally, we conclude the paper in Section V.

II. SYSTEM MODEL AND PROBLEM FORMULATION

In this section, we first introduce the network model and then formulate the problems.

A. NETWORK MODEL

We consider a distributed multi-hop wireless network represented by a directed graph $G(\mathcal{V},\mathcal{E})$, where $\mathcal{V}$ is the set of nodes and $\mathcal{E}$ is the set of primal source-to-destination logical links, as illustrated in Fig. 1. When the source node, S, wants to communicate with its destination node, D, a logical link $S \to A \to B \to D$ can be established by a certain routing protocol. Then, the direct links $S \to A$, $A \to B$, and $B \to D$ belong to set $\mathcal{E}$ and S, A and B become the corresponding casual source nodes. At this point, the communication medium access protocol can be implemented by RBAR [1]. However, when the one-hop channel condition, such as A to B, is not good enough, relay-based cooperative transmission schemes can be used to get better performance, such as both of relay node G and C can help to transmit, which could be denoted as $S \to (A, C) \to B \to D$, or $S \to A \to G \to (A, G) \to B \to D$. In this case, the communication access process can be implemented by COMAC [6].

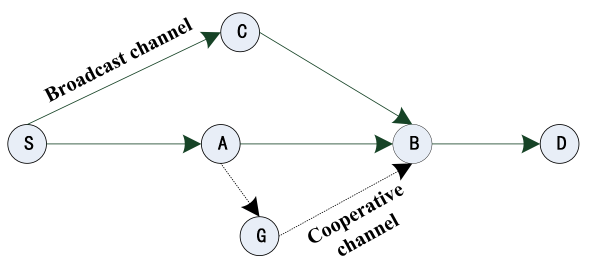

FIGURE 1. Link selection model in multi-hop networks.

Without loss of generality, all nodes in $\mathcal{V}$ are assumed to be equipped with single antenna and the transmission is assumed to operate in a half-duplex mode. The time domain is divided into many equal slots. Considering a specific cooperative link selection process of the primal logical link $A \to B$ as an example. In the first transmission phase, *i.e.*, in time slot t, casual source node A broadcasts its information to all neighbor nodes with a persistence probability $P^A(t)$, which is an important parameter in our contention avoidance strategy. The potential candidate relay nodes are selected from successfully decoding set of the casual source node. In the second transmission phase, *i.e.*, in time slot $(t + 1)$, the highest data rate, $x_{C/G\to B}(t+1)$, that the relay-to-destination link, $C/G \to B$, can support is chosen with a probability $q_{C/G\to B}(t + 1)$ when the candidate relay C or G determines to forward the received data from the corresponding source A to its destination node B and starts cooperative transmission with a probability $P^{C/G}(t + 1)$. We denote $\mathcal{R}(A)$ as the set of candidate relays from casual source node A, $\mathcal{L}_{out}(A)$ and $\mathcal{L}_{in}(A)$ as the sets of outgoing links from node A and incoming links to node A, respectively, $\mathcal{N}^I_{to}(A \to B)$ as the set of nodes whose transmission causes interference to the receiver of link $A \to B$, and $\mathcal{N}^I_{from}(A)$ as the set of links whose transmission gets interfered from the transmission node A [12]. Each relay node may maintain several queues that correspond to different destination nodes, that is to say, each node may be selected as candidate relay by several different sources. The signals from one source sent through different relay-to-destination links represent different transmitted flows [13], [14].

B. PROBLEM FORMULATION AND PROBABILISTIC MODEL

In multi-hop wireless networks, each logical link flow suffers from not only location-dependent access collision interference but also local interference [15]. Therefore, flow control is required for local interference so that each casual source node A can choose corresponding cooperative links to transmit $z_{A\to B}(t)$ flows in the time slot t, where $z_{A\to B}(t)$ is an integer less than the number of nodes in $\mathcal{R}(A)$. And then, the location-dependent interference can use backoff random access mechanism to ensure interference between any two flows below a collision threshold, such as in IEEE 802.11 [16]. Let $Q(t)$ denote a certain transmission link scheduling set in the time slot t, and I_X denote an indicator function which is equal to 1 if X is true [13].

Then, we can formulate the cooperative link selection problem with probabilistic model and interference avoidance in cooperative phase, *i.e.*, the time slot $t+1$, as,

$$\max_{Q(t+1)} x^c_{A\to B}(t+1) = \sum_{\substack{l\in\mathcal{L}_{out}(m)\\ m\in\mathcal{R}(A),\forall A}} \rho_l g_l\{x_l(t+1)\} \times I_{l\in Q(t+1)},\ s.t. \sum_{\substack{l\in\mathcal{L}_{out}(m)\\ m\in\mathcal{R}(A),\forall A}} \rho_l = 1 \quad (1)$$

where ρ_l is nonlinear weight factor of link l by MRC or fraction of normalization transmission period. $x^c_l(t+1)$ is the total transmit rate with cooperative MRC at the casual destination node D in the end of time slot $(t+1)$. $l\in Q(t+1)$ means that logical link flow l is permitted to transmit for cooperative communication for casual source node A. As a special case, $A\in\mathcal{R}(A), \forall A$ in this paper. If the link flow l transmits in time slot $(t+1)$, $g_l\{x_l(t+1)\}$ is a non-decreasing function. Otherwise, $g_l\{x_l(t+1)\}=0$.

To calculate the expectation of logical link cooperative transmission rate, we formulate the function $g_l\{x_l(t+1)\}$ in (1) with probability parameters as follows [14],

$$\begin{aligned} g_l\{x_l(t+1)\} &= x_l(t+1)q_l(t+1)P^m(t+1)\\ &\quad\times \prod_{j\in\mathcal{N}^I_{to}(l)} \{1-P^j(t+1)\},\ l\in\mathcal{L}_{out}(m), m\in\mathcal{R}(A), \forall A. \end{aligned} \quad (2)$$

III. PROPOSED TECHNIQUE

In this section, we first present our interference-aware cooperative logical link selection criterion as a distributed solution to multi-hop wireless network throughput maximization problem. Then, we describe the CLS-MAC in detail.

A. COOPERATIVE LINK SELECTION CRITERION BASED ON NETWORK UTILITY MAXIMIZATION

To elaborate, we first derive the expression of the cooperative transmission Shannon capacity limit for (1) with MRC in terms of signal-to-interference ratio (SIR) as,

$$c^c_{A\to B}(t+1) = \frac{(1-\alpha_{A\to B})\log_2(1+\sum_{l\in Q(t+1)}\gamma_l(t+1))}{2} + \frac{\alpha_{A\to B}\log_2(1+\gamma_{A\to B}(t+1))}{2} \quad (3)$$

where γ_l denotes the received SIR through cooperative link l at the output of node B. $\alpha_{A\to B}$ denotes a fraction of the slot for the source's direct message transmission. And the channel capacity limit for each signal link l is expressed as,

$$c_l(t+1) = \frac{1}{2}\log_2(1+\gamma_l(t+1)) \quad (4)$$

where factor 1/2 in the above two formulas denotes half-duplex constraint. Therefore, the average channel capacity on logical link $A\to B$ with the help of cooperative communications is obtained as,

$$C^c_{A\to B}(t+1) = c^c_{A\to B}(t+1)P^A(t) \times \prod_{i\in\mathcal{N}^I_{from}(A)} \{1-P^i(t)\}, \forall A, B\in\mathcal{V}. \quad (5)$$

If the logical link $A\to B$ transmits in the time slot t, it can obtain a positive network utility $U_{A\to B}(x_l(t+1), P^A(t), P^m(t+1), q_l(t+1))$ which is an non-decreasing function of the data rate and the link transmission probability. Otherwise, it equals to zero. To maximize the expectation of system performance and degree of satisfaction of its terminal users A and B, we formulate the network utility maximization framework of interference-aware cooperative random access, i.e., objective function, as the sum of all primal logical link flow's expectation throughput is given by,

$$\begin{aligned} &\max_{l\in Q(t+1)} \sum_{\substack{(A\to B)\in\mathcal{E}, l\in\mathcal{L}_{out}(m)\\ m\in\mathcal{R}(A),\forall\mathcal{E}}} E\{U_{A\to B}\{x_l(t+1), P^A(t), P^m(t+1), q_l(t+1)\}\},\\ &s.t. \sum_{\substack{l\in\mathcal{L}_{out}(m)\\ m\in\mathcal{R}(A)}} q_l(t+1)\leqslant 1, \forall A, \forall(A\to B)\in\mathcal{E},\\ &x_l(t+1)\le c_l(t+1),\\ &x^c_{A\to B}(t+1)\le C^c_{A\to B}(t+1). \end{aligned} \quad (6)$$

where

$$\begin{aligned} U_{A\to B} &= \sum_{(A\to B)\in\mathcal{E}} P^A(t) \prod_{i\in\mathcal{N}^I_{from}(A)} (1-P^i(t))\\ &\quad\times \sum_{\substack{l\in\mathcal{L}_{out}(m)\\ m\in\mathcal{R}(A)}} \rho_l x_l(t+1)P^m(t+1)q_l(t+1)\\ &\quad\times \prod_{j\in\mathcal{N}^I_{to}(l)} (1-P^j(t+1)), \end{aligned} \quad (7)$$

The optimal values $P^A(t)^\star$, and $P^m(t+1)^\star$, and $q_l(t+1)^\star$ for the above problem can be obtained with the tools in [14]. Therefore, each transmitter A updates its local interference graph to get $\mathcal{L}_{out}(A)$, $\mathcal{L}_{in}(A)$, $\mathcal{N}^I_{from}(A)$ and $\mathcal{N}^I_{to}(A)$, $l\in\mathcal{L}_{out}(m), m\in\mathcal{R}(A), \forall A$.

Since random access schemes in multi-hop wireless networks usually include contention avoidance and contention resolution, the exponential-backoff (EB) access used for contention solution depends on not only its own transmission chance but also transmission situation of other links due to collisions. Therefore, we can decide to access the channel and transmit data with corresponding transmission probability as obtained above. Then, the current window (CW) sizes of primal logical source and the corresponding cooperative link l based on the optimal probabilities of the primal logical links and their corresponding cooperative links are given by,

$$CW_{A\to B}(t) = 1/P^{(A)}(t), \quad (8)$$

$$CW_l(t+1) = 1/q_l(t+1), \quad (9)$$

In this process, the backoff values (bt) are selected as the following updating criteria,

$$bt_{A \to B}(t) = uniform(1, CW_{A \to B}(t)), \quad (10)$$
$$bt_l(t + 1) = uniform(1, CW_l(t + 1)). \quad (11)$$

At the end of each time slot, each transmitter A including its corresponding cooperative relays initializes the transmission probabilities in a distributed manner. And then, they can be implemented in the backoff process.

B. CLS-MAC

In this subsection, we propose a random channel access strategy based on cooperative link selection to approach the optimal scheduling for multi-hop wireless networks in a distributed manner, *i.e.*, CLS-MAC. Each node near the casual destination that has received a complete data packet in the previous hop will have a chance to constitute virtual antennas with the transmitting node in the current hop. The best relay (*i.e.*, cooperative link) is selected based on the preceding rule and implemented by a backoff process. In such a backoff process, we modify the excellent backoff scheme [8], [17] into the binary exponential backoff mechanism through three contention process: inter-group contention, intra-group contention, and re-contention [8]. The instantaneous CSI of the casual transmitter-receiver channel is carried by CTS, which can be overheard by the transmitter and all candidate relays. The nodes based on the received CSI will send packets to the destination node through cooperative communication. In CLS-MAC, all candidate relay nodes listen to the control frame (RTS/CTS), and then calculate the corresponding probabilities independently according to the received CSI carried with control frame.

For better understanding of CLS-MAC, we describe the second hop in Fig.1 in detail, where node A wants to send data packets to node B. After sensing [18] the channel to be idle, A broadcasts a RTS control frame to reserve the channel, which carries the length of data packets in bits and includes the channel occupancy time, D_{RTS}. Besides, node A should set up a timer and wait for the arrival of the CTS frame. If no CTS frame from node B is received before the timer expires, node A will give up the transmission and retransmit a RTS. Every node that has overheard RTS will calculate the instantaneous transmission probability between itself and node A based on the signal strength sensed at receiver. As long as node B receives the RTS successfully, it will reply a CTS frame after a period of short interframe space (SIFS) to announce that the medium is reserved for transmission.

Any node that has received both RTS and CTS is regarded as a candidate for possible cooperative transmission. The candidates are filtered again according to whether a candidate detects data packets transmitted in the previous hop correctly or not. After receiving the CTS frame, the causal transmitter and candidate relays will calculate their own transmission probabilities independently and contend to participate in the transmission. Each node can get the CSI by local information exchange and maximize its own utility according to the CSI by jointly adjusting the transmission rate and the probability, which could be implemented by the backoff window procedure. Appling the backoff scheme, the best node with maximum transmission probability will have minimal backoff window, then the corresponding transmission links are determined. Once data packets are correctly transmitted, the receiver broadcasts an ACK frame to cancel unnecessary channel reservation.

By doing the above process, the CLS-MAC will give the better cooperative relay link more access chances. Eventually, there will be more messages passing with diversity gains and it can obtain optimal system throughput with less co-channel interference compared to the existing medium access techniques.

IV. NUMERICAL RESULTS

In this section, we evaluate the performance of CLS-MAC by considering random network topology in an area and compare our strategy with two existing algorithms: RBAR [1] and COMAC [6]. Terminal nodes are uniformly distributed in a rectangle area of 400 m × 300 m. Four different modulation modes, BPSK, QPSK, 16-QAM, and 64-QAM are available at physical layer and the transmit power, P_X, of control/data frames is 30mW [14]. In addition, the reception decoding threshold is set to 20 dB and eight available physical data rates, ranging from 6 Mbps to 54 Mbps [16], are used. By default, the length of data packets, number of nodes, and geographical distance interval are set to 8192, 50, and 80 m, respectively. In the following simulation, we will study how each parameter individually affects the system performance while others are fixed.

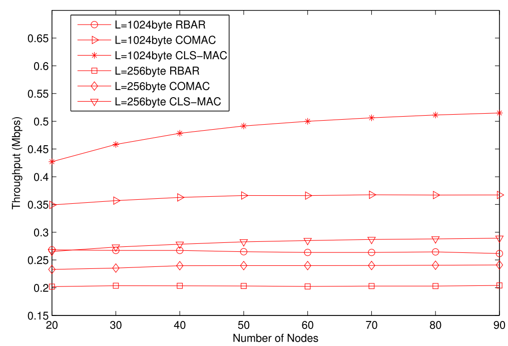

FIGURE 2. Comparison of throughput of RBAR, COMAC and CLS-MAC versus node density and packet size in chain topology.

Fig. 2 demonstrates the average throughputs of CLS-MAC, RBAR and COMAC with varying node density and packet size L. From Fig. 2, we can see that the system average throughput of RBAR is almost fixed with the increase of the node density while it can be improved significantly by CLS-MAC and COMAC due to the relay cooperation diversity gains. In addition, Fig. 2 also shows that our proposed CLS-MAC significantly outperforms COMAC in different network density environments. The reason lies in COMAC assumes the scheduling ratio limit for each virtual cooperative link determined by the average data rate. In fact, the logical links have collision when channel conditions vary. Furthermore, the combinations corresponding to many virtual links will cause unacceptable delay although it is conquered a little by restricting the maximal number of relays for each source node. However, our persistence probability model can not only reduce the message passing overhead but also map the time fraction of transmit link into probability. Furthermore, the selection probability of cooperative opportunistic relays and diversity gains also increase with the number of terminal nodes, as the number of 3-diclique [19] increasing can improve the cooperative chance. Finally, we also find out that all the system average throughputs of CLS-MAC, RBAR and COMAC increase with the data packet size as shown in Fig. 2. The reason lies in the percentage of transmit time occupied by the control frames is reduced as the packet size grows.

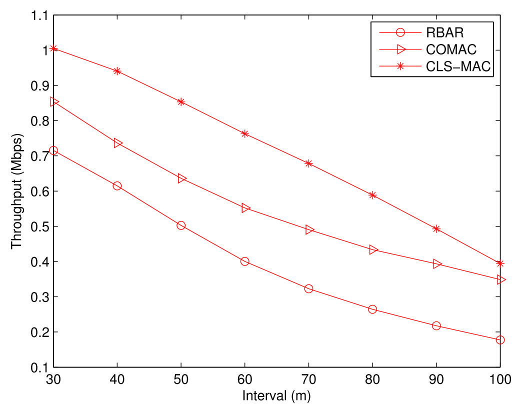

FIGURE 3. Comparison of throughput of RBAR, COMAC, and CLS-MAC versus varied interval.

Fig. 3 compares the system average throughputs of the three schemes versus geographical distance intervals between any two adjacent nodes, which results in different supporting data rates. From Fig. 3, we can see that the throughputs of all schemes degrade as the interval increases because channel fading gets worse with longer distance. By fully utilizing the broadcast feature of wireless channels, CLS-MAC can achieve higher throughput than COMAC and RBAR. Similar to Fig. 2, both CLS-MAC and COMAC outperform RBAR due to cooperative diversity. Since larger interval results in lower probability of interference or collision, the decreasing in CLS-MAC throughput is faster than that of COMAC, but CLS-MAC still outperforms COMAC.

The energy efficiency [20] of these three schemes versus geographical distance intervals is illustrated in Fig. 4. The energy consumption of CLS-MAC is the least and that of RBAR is the most. As the interval increases, the energy consumption of RBAR increases sharply, whereas that of CLS-MAC and COMAC increases slowly. For long-range transmission, the quality of direct link is poor, however, alternative path that is more efficient can be employed by CLS-MAC and COMAC. Since interference and collision would waste lots of transmission power, CLS-MAC outperforms COMAC in energy efficiency.

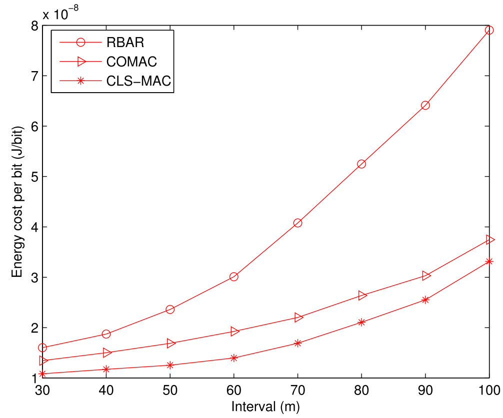

FIGURE 4. Comparison of energy efficiency of RBAR, COMAC, and CLS-MAC versus varied interval.

In brief, the numerical results show that the performance of CLS-MAC significantly outperforms that of COMAC and RBAR in multi-hop wireless networks in terms of throughput and energy efficiency.

V. CONCLUSION

In this paper, we have proposed a distributed interference-aware cooperative random access strategy based on cooperative link selection for multi-hop wireless networks through persistence probabilistic model. By utilizing relays, CLS-MAC fully exploits the broadcast feature of wireless channels. Different from the existing works on the relay-based medium access problem, we solve both interference contention and multiuser diversity by a virtual link flow probabilistic control technique. CLS-MAC can significantly improve throughput and energy efficiency compared to the existing medium access schemes.

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