A TDMA-BASED MAC PROTOCOL SUPPORTING COOPERATIVE COMMUNICATIONS IN WIRELESS MESH NETWORKS

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Abstract

This paper proposes a TDMA-based medium access control protocol which enables cooperative communications in multi-hop wireless mesh networks. According to the proposed scheme, each router at the two-hop neighbourhood of each other is allocated to a specific time slot for accommodating either direct or cooperative transmissions in a coordinated manner, controlled by mini-slots which are part of the time slot. Benefiting from the elaborate mini-slot design, channel resources are fairly and efficiently allocated to each router so that no handshake is needed prior to each packet transmission. By providing access priority to cooperative transmission through an optimal relay which is determined by combined instantaneous relay channel conditions, higher system throughput can be achieved. To analyze the performance of the proposed cooperative protocol a Markov chain is introduced to model the behavior of the protocol. Simulation results demonstrate that the proposed MAC scheme can improve not only the one-hop transmission throughput but also the end-to-end throughput significantly. Moreover, the throughput performance of the proposed scheme is robust as packet size varies.

Keywords

Cooperative communication, MAC mechanism, TDMA, relay selection, throughput performance

1. INTRODUCTION

Wireless Mesh Networks (WMNs), characterized of high spectrum utilization, dynamic self-organization and low deployment cost, are regarded as a key technology in next-generation wireless communication systems [1]-[3]. A typical topology of WMNs consists of wireline gateways, wireless routers, and mobile stations, organized in three-tier architecture. A mesh router in such a network will forward packets on behalf of other routers that are not within the direct transmission range of their destinations, in a multi-hop manner.

However, multi-hop wireless mesh networks still have some problems that are not trivial. The first one is the end-to-end throughput degradation due to multi-hop transmissions. In multi-hop WMNs, neighbors have to compete for channel access, leading to less opportunity for each node to transmit packets. In addition, the hidden terminal and exposed terminal problems that occur between the links within multiple flows from source node to destination node could also severely degrade system throughput in a heavily loaded network. Moreover, it is possible that any of the links in the multi-hop transmissions suffer from transmission errors, due to either packet collisions or channel fading.

There are lots of proposals in the literature to deal with the above problems. From protocol layer point of view, many solutions are investigated at the PHY layer. For instance, Adaptive Modulation Coding (AMC) can be applied to improve channel efficiency [4], and BPSK could provide robust transmissions at a cost of low data rate. Another alternative is Automatic Repeat reQuest (ARQ) scheme which could boost packet delivery ratio at the link layer. However, traditional ARQ schemes which are developed for wireless channels with random errors will be less efficient in the wireless networks where packet errors emerge as bursts other than randomly

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[5]. For instance, in a high temporal correlative channel, the retransmission from source node may suffer from the same error as in the original transmission [6].

Furthermore, all these solutions are passively dealing with the problem occurring in one specific link without considering other benefit one may obtain from other links. By means of providing diversity gain through diverse relay links, cooperative communication has appeared as a promising way to improve network performance [7]-[11]. However, cooperative communications will confront with the same difficulty that it also requires to extend transmission from a single sender-receiver hop to a sender-relay-receiver two-hop scenario. In this case, medium access technique plays an important role in determining channel utilization, especially end-to-end throughput. Due to the extra transmission phase of packet forwarding, the overhead and transmission delay may compromise the cooperation gain if the Medium Access Control (MAC) mechanism is not properly designed.

Contention-based schemes such as Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) are dominantly explored in the literature for distributed WMNs. However, when a traditional CSMA-based MAC protocol is used, it is known that the performance will deteriorate in a multi-hop network due to its intrinsic MAC design principle. This is because that the contending nodes in the range of its two-hop neighbors can affect channel access opportunity, resulting in serious unfairness and packet collision. Although RTS/CTS can alleviate the hidden terminal problem, it comes at the cost of high overhead. In order to avoid the aforementioned packet collision and hidden terminal problem, Time-Division Multiple Access (TDMA) can be adopted since it schedules transmission time instances of neighboring nodes to occur at different time slots. In this way, packet transmission of each link can be controlled without collision. As a result, the end-to-end throughput will be significantly improved. However, applying TDMA into multi-hop wireless mesh networks could lead to problems such as synchronization, and efficient time slot allocation. While synchronization can be provided by a Global Positioning System (GPS) based solution, how to efficiently schedule each transmission at different time slots, especially for cooperative transmissions, still remains as a challenging task.

In this paper, we propose a novel TDMA-based cooperative protocol in multi-hop wireless mesh networks. By receiving the same copies of the original packet derived from cooperative link with diversity gain, system throughput could be improved with the help of cooperative communication. In [12], cooperation is executed in idle slot which means that cooperation is available, only if there exists free slot. Inspired by the idea of [13], the proposed MAC protocol makes use of control mini-slot to dynamically and efficiently allocate channel resource not only for direct transmission but also for cooperative transmission. In addition, access priority is always given to cooperative transmission through an optimal relay node. The optimal relay is determined by fulfilling a timer based-relay selection algorithm which is executed across nodes in a distributed manner. Moreover, a two state Markov chain is introduced to analyze the performance of the proposed protocol. Simulation results demonstrate that the proposed MAC scheme could improve system throughput significantly.

The rest of the paper is organized as follows. Related work is summarized in Sec. 2, and then the system model is described in Sec. 3. After the proposed cooperative MAC protocol is introduced in details in Sec. 4, Sec. 5 presents the relay selection scheme. The performance analysis is carried out in Sec. 6. Following that, the system performance is evaluated and compared with other three popular schemes in Sec. 7. Finally the paper is concluded in Sec. 8.

2. RELATED WORK

2.1. TDMA MAC Protocols in (Multi-hop) Wireless Networks

In [13], the authors proposed a TDMA based contention-free MAC protocol for a single-channel wireless mesh backbone to provide Quality of Service (QoS) support for multimedia applications. Without the need for RTS/CTS handshake prior to each packet transmission, the overhead is greatly reduced. In [14], the authors proposed a dynamic subcarrier utilization method using Orthogonal Frequency-Division Multiplexing (OFDM) to balance data rate among each link in TDMA multi-hop wireless networks. In order to transmit data flow without self-interference among flows, two time frames and two frequency bands are introduced. Additionally, seamlessly adapting the MAC protocol between TDMA and CSMA according to the level of the contention in the network was investigated in Z-MAC [15]. A probabilistic TDMA scheme is employed in Z-MAC in which time is slotted to adjust access probability for users under high contention while it behaves like CSMA under low traffic load. However, Z-MAC is designed for one-hop wireless network and does not deal with many difficulties that multi-hop networks face. Funneling-MAC [16] is also a hybrid approach where nodes close to the sink employ TDMA since this area is exposed to high traffic load while nodes far away from the sink use CSMA in order to decrease latency. As a consequence, nodes at the edge of both areas must apply both MAC schemes, which is a complicated task. Furthermore, without taking cooperative communications into consideration, these MAC protocols might not efficiently combat channel fading which may happen in each link in a multi-hop wireless network.

2.2. Cooperative MAC Protocols

COMAC [17] is a cooperative medium access control protocol designed based on the widely adopted IEEE 802.11 MAC protocol. By considering different physical layer data rates, variable transmission range and network size, it enables cooperation in a realistic scenario and leverages cooperative communications by making use of the overhead packet from neighboring nodes of a source node. CoopMAC [18] is also an 802.11-based cooperative MAC protocol that increases the aggregate throughput in a way that high data rate nodes assist low data rate nodes to forward their data packet. In CD-MAC [19], each node preselects a relay for cooperation and enables it to transmit simultaneously by using distributed space time coding to obtain optimal network performance. However, the intrinsic nature of CSMA that requires nodes to access the medium only if it is sensed as idle can severely limit the effectiveness of not only the direct transmission but also the cooperative transmission [20].

Since CSMA-based multiple access control schemes are not efficiently suitable to obtain potential gains from cooperation, one trend for cooperative MAC design is shifting to schedule-based MAC schemes. In [12], the authors proposed a multiple access approach based on an idea in which the relay node utilizes the empty time slot available in a TMDA frame to launch cooperation. However, this approach will encounter the difficulty that few or even no slots are available if the network is heavily loaded. In [21], the authors proposed a protocol for scheduled TDMA scenarios based on network coded retransmission. However, they did not mention how to allocate cooperative transmission in the scheduled time slot. C-TDMA [22] attempts to handle this problem in a way that by using its own time slot neighbour nodes help the source node to retransmit the unsuccessful packets. However, due to the sacrifice of its own time slot the neighbor node may confront a situation that no slot to use for its own packet transmission. Therefore, this method will bring unfair transmission into the network which may affect aggregate throughput from a multi-hop point of view.

To summarize, TDMA-based MAC protocols are becoming popular in wireless mesh networks thanks to their high efficiency and feasibility in static topologies. However, how to introduce cooperative communications into a TDMA MAC protocol in an efficient way still remains as an open question.

3. SYSTEM MODEL

In this study, we consider a wireless mesh network where the mesh backbone is shown in Fig. 1 as an example. In this example, a traffic flow generated at source router S is transmitted to destination router D via intermediate router I in a two-hop transmission manner. A number of mesh routers with dashed line are deployed around routers S, I and D. We assume each router is able to overhear its one-hop neighbors' transmission. The overheard packet is temporally stored at the router till the next overhead transmission comes. In case any of transmission fails in one of the two links, i.e., the S-I link or the I-D link, other routers within the coverage area could help forward the packet. Each router may join several cooperation groups depending on its position, capability and willingness to cooperate [5].

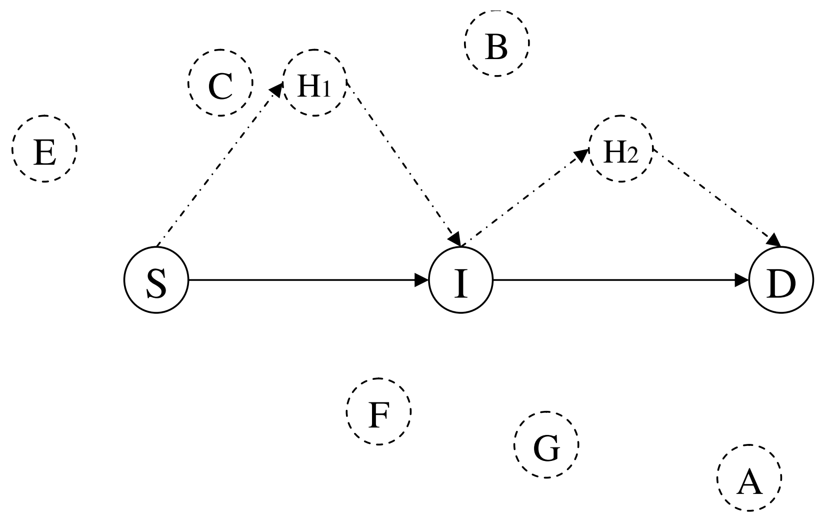

Figure 1. An example of wireless mesh backbone.

4. THE PROPOSED COOPERATIVE MAC SCHEME

4.1. Time Slot Structure

The system time is broken down into time slots of constant duration, which are allocated to each router in a distributed manner. In order to avoid packet collision and increase resource utilization, the one-hop and two-hop neighbors of a router are allocated to different time slots. It implies that the same slot could be allocated to routers which do not interfere with each other. As shown in Fig. 2, in the proposed cooperative MAC scheme one time slot consists of three portions, as control part, data part and acknowledgement part respectively. The control part is used to exchange resource request among one-hop and two-hop neighbors and allocate resources based on specific strategies. In addition to a small portion of the slot time, the control part is further partitioned into several small parts, called mini-slots, indexed sequentially with numbers 1, 2, 3, ..., m, 0, where m is the total number of routers in a two-hop neighborhood. The data part is dedicated for data packet transmission and dynamically distributed among routers according to the packet transmission allocation assigned by the control part. The Call For Cooperation (CFC) segment is used to send out the cooperation request, if necessary, and it is executed only if the direct transmission fails. We assume that the transmission of CFC packet is error-free.

In the wireless mesh backbone, mini-slots are assigned to each router with a mini-slot index in a cluster to allocate channel resource. In this study a cluster indicates the routers within the two-hop neighborhood of a router. Additionally, we use one bit as the status value of each mini-slot to indicate whether the channel is occupied or not, as shown in Fig. 2, where "0" means that the channel is idle while "1" indicates that the channel is occupied. The mini-slot index indicates the channel is occupied by which router[1], and mini-slot 0 is reserved for cooperative communication. Within one slot, at most one mini-slot is allowed to have its status as "1". All mini-slots are emptied with "0" if CFC is received in the previous slot.

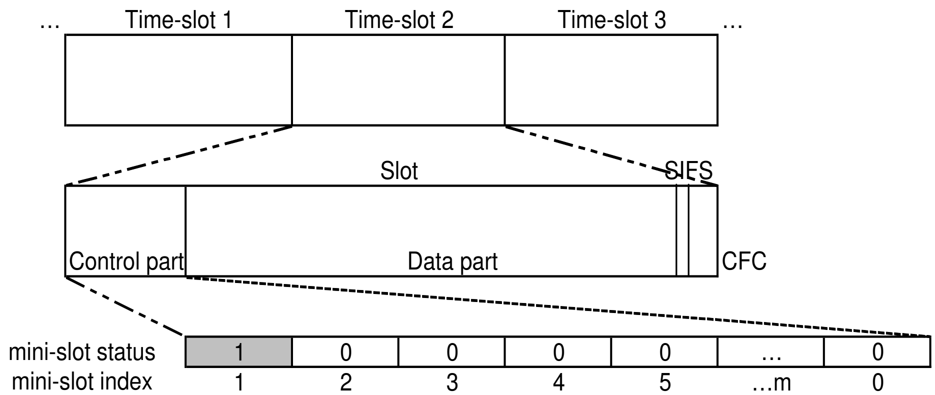

Figure 2. Time-slot and mini-slot structures.

4.2. Mini-slot Allocation

The mini-slot allocation has the following requirement: 1) Any two routers which are within the two-hop neighborhood of each other will not be assigned the same mini-slot; 2) The number of mini-slots should be minimum as a constraint for requirement 1) [13]. These two requirements can be implemented by graph coloring. From the graph theory a graph $G=(V,E)$ is defined with a set of vertices V and a set of edges of E connecting the vertices in a way that loops and multiple edges between vertices are forbidden. A vertex coloring for the graph G is a map $s: V(G)\rightarrow F$, where F is a set of colors. The coloring is permissible only if $s(Vi)\neq s(V_j)$ for all Vi and V_j that are two-hop away from each other. For the optimal coloring, the size of the color set should be minimum.

The mini-slot allocation can be mapped to graph coloring. If we want to optimally assign mini-slots to a set of routers $\{V_i\}$, an interference graph $G=(V,E)$ can be considered. The vertex set V is mapped to the set of routers $\{V_i\}$. The set of edges E consists of the vertices $\{V_k, V_l\}$, corresponding to the routers V_k and V_l that will interfere with each other within a two-hop neighborhood, should be assigned with different mini-slots. Eventually, the set of colors, F, corresponds to the collection of mini-slots for the routers. The mini-slot allocation task is resolved by coloring of G with the color set F. More details of the algorithm can be found in [23].

Considering that the routers in a wireless mesh network have no mobility and form a static topology, the mini-slot allocation algorithm is able to be performed by each router at the initialization phase of the network. Therefore, all the mini-slot allocations are pre-defined and known to all the routers.

4.3. Mini-slot Allocation

In our scheme, cooperation is employed only if it is needed. Since cooperative relaying needs channel reservation for source, destination, and relay, it is often combined with medium access protocols. The proposed MAC scheme efficiently allocates all required channel resources by answering the following questions:

[1] The mini-slot status is set by a busy tone signal. It is sent out by the router with a low data rate in order to cover two-hop neighbors.

- How does a router reserve the channel and which router will reserve the channel first?
- When a router is allocated to a time slot, how to prevent other routers from using this slot?
- How to carry out cooperative transmission when the direct transmission fails?
- Which router would be selected to forward the packet if there are multiple relay nodes available?
- How does routers' transmission order rotate in the mini-slots after each transmission?

To better explain the proposed MAC scheme, a simple example is introduced to illustrate the operation procedure. As shown in Fig. 3-(a), a two-hop network composed of routers S, I, and D is considered, and for simplicity there exists another router between each pair, which could be the potential relay. i.e., H_1, H_2. Assume that there is a flow transmitted from S to D, and relay H_1 helps to forward the packets in the first hop if the direct transmission from S to I fails. After that, each router will follow the same principle to forward the packets to the final destination.

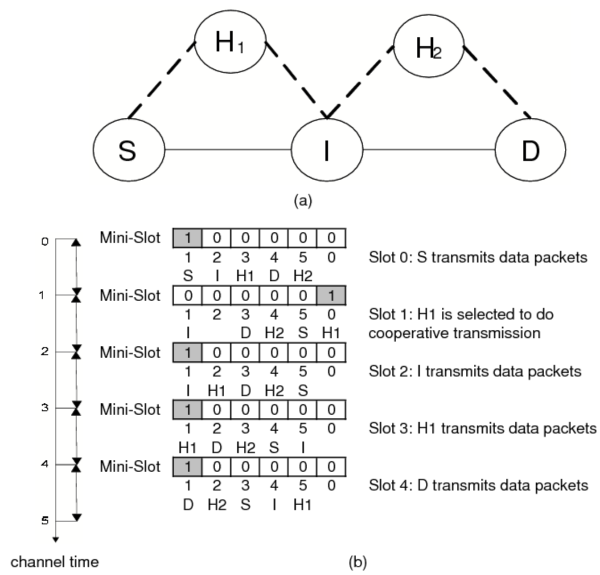

Figure 3. An example to illustrate the operation procedure of the proposed MAC scheme.

A basic rule for the MAC scheme is that *a router can transmit in a time slot when all the mini-slots prior to its own mini-slot are idle*. For instance, when a router (e.g. router *S* assigned with mini-slot i) starts a communication attempt, it firstly monitors all the mini-slot status from 1 to i-1. If "1" is detected at any mini-slot, the router will defer its transmission at the current slot. Otherwise, it means that all other routers within two hops from S which have been assigned mini-slots 1 to i-1 have no packet to transmit. Router S will then set its status value as "1" to reserve the channel and correspondingly transmit the packet at the data part of the same slot.

In the initialization phase, all the status of mini-slots is set to "0". Then the router with the smallest index of the mini-slot will reserve the channel first. The mini-slot allocation is shown in Fig. 3-(b), where router S is assigned to mini-slot 1, router I is assigned to mini-slot 2, and so on. After the initialization of the mini-slot allocation, router S will set the mini-slot value as "1" at mini-slot 1 because it has the smallest index and therefore will get priority to reserve the channel. As a consequence, routers I, D, H_1 and H_2 will detect "1" at mini-slot 1, indicating that the channel is occupied at mini-slot 1. Then they will defer their transmissions at slot 0. Consequently, router S sends its packets at the data part of the same slot without collision.

When router I receives the data packet, it will check if the packet can be decoded correctly or not. If the router fails to decode the packet, CFC will be sent out immediately at the CFC part of the current slot. The direct transmission is regarded as successful if no CFC packet is sensed. The CFC packet not only indicates that the received data packet is corrupted but also informs relays to initiate cooperative communication. Meanwhile, the mini-slot scheduled in the next time slot will be frozen (i.e., the mini-slot status is reset as "0") by the CFC packet because it is sent as a broadcast message. The transmission priority is given to the relay node rather than the node in the original schedule.

Next, we discuss how to do cooperation by the optimal relay node without interfering with other existing transmissions. Mini-slots reserve the medium for all the transmissions including both direct transmission and cooperative transmission, where mini-slot 0 is reserved for cooperation. As shown in Fig. 3-(b) in the example, since the neighbors have already received and stored the overheard packets at slot 0, they will attempt to forward the packets to the intended router at slot 1 after sensing the CFC packet. The optimal relay will acquire the channel by means of a timer-based optimal relay selection algorithm which is implemented in a distributed manner at each node. The details of the optimal relay selection algorithm will be presented in the following section.

Since the router with small mini-slot index will always have priority to transmit packets, the router with largest index may starve. In order to allocate channel resource to each router in a fair manner, the transmission order of each router will rotate after each transmission. More specifically, the second mini-slot in the current slot will become the first one in the next slot, and the first mini-slot in the current slot will become the last one in the next slot, and so on. For instance, originally, router S gets the opportunity to transmit at slot 0 according to the rotation. After that, router I would seize slot 1 to transmit packet. However, since priority has been given to cooperative transmission, slot 1 will be allocated by relay H_1. The original mini-slot schedule is frozen by sensing the CFC packet, i.e., only mini-slot 0 is active and the associated router could transmit while other routers should give up their transmissions. The schedule will be activated after the cooperative transmission finishes. As shown in Fig. 3-(b), at slot 2, router I catches the smallest mini-slot index, mini-slot 1, and it will transmit its packet at this slot. In case there is no packet to transmit at a router, e.g., H_1 in slot 3, it will keep silent and leave the transmission chance to the next router. Thus, the data parts of all the time slots are fully utilized as long as at least one router has packet to transmit. As a consequence, fair access and efficient channel occupation among all routers can be achieved.

5. RELAY SELECTION SCHEME

5.1. Optimal Relay Selection

In the section above we mentioned that the optimal relay is determined by a timer-based relay selection algorithm. In case there exist more than one relay nodes around each transmitter-receiver pair (i.e., the S-I link and the I-D link), the packets sent out from these relay nodes may corrupt each other if they transmit in the same time interval. In order to avoid packet collision, we select only one optimal relay in our cooperation scheme.

For cooperative transmission, each relay is connected with two channels, i.e., the channel from the source node to the relay node and the channel from the relay node to the destination node. In general, the cooperative benefits from relay nodes depend on both channels. If one of the channels corrupts, the relay cannot successfully forward the packet. Therefore, we apply the following criterion to select the relay: among all these relay nodes, the optimal one is selected according to the relay whose worse channel has the best link quality.

$$SNR_{opt} \Leftrightarrow \max\{SNR_i\}, i \in [1,n] \Leftrightarrow \max\{\min\{SNR_{si}, SNR_{id}\}\}, i \in [1,n] \tag{1}$$

where n is the number of relays available for the transmitter-receiver pair; SNR_{si} and SNR_{id} are the link conditions in terms of received Signal to Noise Ratio (SNR) from source to relay and from relay to destination respectively. The relay i with maximal SNR_i is the optimal one. This scheme is able to balance the signal strength of these two links. The diversity gain of this scheme is analyzed in [24] based on the outage probability.

5.2. Distributed Relay Selection Process

Whether or not the optimal relay could provide maximum benefits depends not only on the relay selection algorithm but also how it is implemented in the medium access control scheme. In the TDMA-based MAC scheme, there is neither handshake between each node to collaborate with nor a centralized node to decide which relay transmits first. We consider a timer-based relay selection process because of its distributed feature and no feedback during the process. Each relay sets its own timer T_i such that the timer of the node with largest SNR_i expires first.

$$T_i = \frac{SNR_{threshold}}{SNR_i} mT_{ms}, \tag{2}$$

where $SNR_{threshold}$ is the SNR threshold to guarantee that the channel is in a good condition. Only relays with $SNR_i \geq SNR_{threshold}$ are qualified as the candidate for optimal relay. T_{ms} is the time duration of one mini-slot. It means that the timer of the eligible relay should expire within the time interval of all m number of mini-slots. Note that mini-slot 0 is not included in this interval. In other words, the optimal relay should be selected before the data transmission part of the same slot, as shown in the relay selection process in Fig. 4, where T_{ctrl} is time duration of the total number of mini-slots with $T_{ctrl} = (m+1) \cdot T_{ms}$.

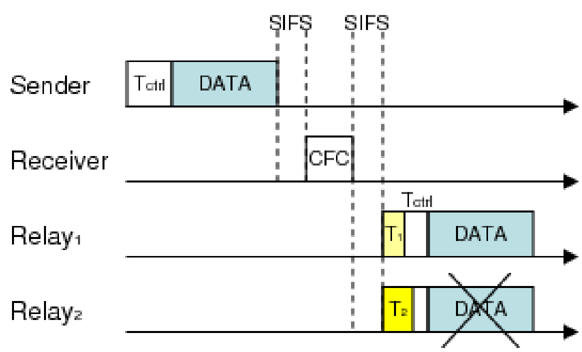

Figure 4. Relay selection process.

In [24], if there is no enough time for the second optimal relay to freeze its transmission when its timer also decreases to 0, it is possible that the packet sent out from the optimal relay would collide with the packet sent out subsequently by the second optimal relay. Additionally, potential collision caused by the packet from a relay which is hidden from the optimal relay may also occur. In our scheme, by means of the busy tone signal incorporated in the mini-slot design, those potential collisions could be avoided. More specifically, after the timer expires, the optimal relay will send out a busy tone signal to reserve the status of mini-slot 0 as "1" instead of sending the data packet immediately. Then the rest of relays will freeze their timers after they sense the status of mini-slot 0 as "1". Consequently, after all the mini-slots elapse, the optimal relay could transmit its packet with collision free. If none of the relay nodes expires within the time interval $m \cdot T_{ms}$, i.e., no qualified relay node is available in the network, the mini-slot 0 will keep status as "0". Then the source node will try to retransmit the packet. On the other hand, if the packet transmitted by the optimal relay is not successfully decoded at the destination, another CFC packet will then be sent out to initiate another round of cooperative transmission till the packet is correctly received.

The benefits of the proposed scheme is not only that the collision could be efficiently avoided but the relay selection time which is generally not negligible could also be finished within the inherent time of the system, i.e., control mini-slot time. Relay selection time in this study is defined as the interval from the time the relay nodes receive the CFC packet to the instant it starts to send the data packet.

The operations of the cooperative MAC protocol at the source, relay and destination nodes are illustrated in Fig. 5-7, respectively. Note that all these three flow charts need to be implemented in any mesh router and the router may execute one of these procedures according to its role in each transmission, as the source, the relay, or the destination node.

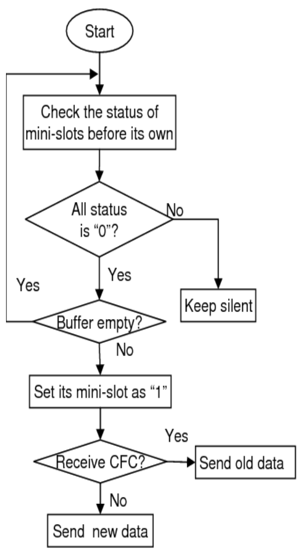

Figure 5. Flow chart at source node.

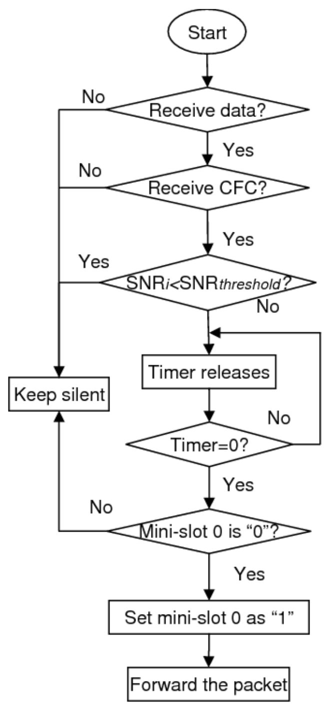

Figure 6. Flow chart at relay node.

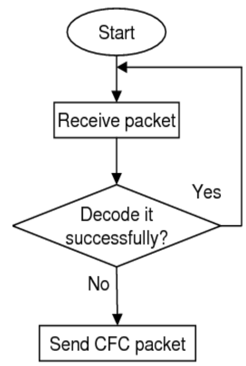

Figure 7. Flow chart at destination node

6. Performance Analysis

Since three channels have impact on the system performance, we model each channel as a two state discrete time Markov process. As system throughput is contributed by both direct transmission and cooperative transmission, we derive transmission efficiency of the proposed protocol based on another Markov model.

6.1. Channel Model

The transmitted signal is sampled once in each packet transmission, and it is assumed that the channel does not significantly change in this period. In fact, the channel characteristics used to compute the performance of the protocol at higher layer should reflect the physical layer characteristics to make these results meaningful. In this study, a two-state discrete time Markov process is considered to illustrate the sampled process of packet transmission over wireless channels, as shown in Fig. 8. If the received signal is above certain threshold Δ during the transmission time, the channel is regarded as in an "on" state. Otherwise, it is categorized as in an "off" state. The packet is assumed to be decoded correctly by the receiving router in the "on" state, but not in the "off" state.

In [5], [25], it has been observed that for a Rayleigh fading channel, the transition probability of the two state Markov chain can be expressed as

$$y = \frac{Q(\theta, \rho\theta) - Q(\rho\theta, \theta)}{e^{\Delta} - 1}, \qquad x = \frac{1 - e^{-\Delta}}{e^{-\Delta}} y, \tag{3}$$

where $Q(\cdot,\cdot)$ is the Marcum Q function, $\theta = \sqrt{\frac{2\Delta}{1-\rho^2}}$, $\rho = J_0(2\pi f_m T_f)$, and $J_0(\cdot)$ is the zero order Bessel function of the first kind. In addition, the packet error rate in the direct link is defined by the ratio between the sum of dropped packets and the total number of packets transmitted. According to the channel properties, the probability that a packet is in error during the direct transmission, is given by

$$\varepsilon = \frac{x}{x+y}. \tag{4}$$

Intuitively, we could obtain the probability of the packet transmission being successful as 1-ε, which is defined as throughput efficiency.

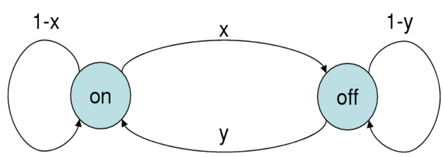

Figure 8. Markov model for transmission process over wireless fading channels.

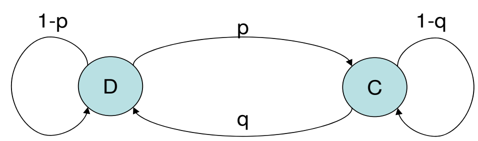

Figure 9. Markov model for time slot.

6.2. Transmission Model

Since in each time slot of the proposed MAC protocol, either direct transmission or cooperative transmission is executed, it is possible to model this process by using another two-state Markov chain as shown in Fig. 9. The parameters of this Markov model are defined as

$$p \Rightarrow P\{M(k) = C \mid M(k-1) = D\}, \; q \Rightarrow P\{M(k) = D \mid M(k-1) = C\}, \tag{5}$$

where *M(k)* denotes the transmission mode of the protocol, either direction transmission (D) or cooperative transmission (C) in time slot *k*. *M(k)* will transit between the two states according to the transmission logic[2] of the protocol described in Table 1, with the corresponding state transition probability matrix **V** (16×16). We assume that there always exist relay nodes in the network to prepare for cooperation. As mentioned in the above section, if a packet transmitted by the source or relay node is not successfully received at the destination node, cooperation will

[2] This logic (or transmission order) in *M(k)* is the cooperative transmission policy designed in our protocol which takes the status of all three channels in two consecutive slots into account.

start. The next transmission mode of the system depends on the states of both the three current channels and the current transmission mode. For example, when the current transmission mode is D, the transmission mode in the next state is only influenced by the direct channel in the current state rather than the relay channels. As shown in the table, from row S_8 to S_{11}, *M(k)* becomes C because the direct channel is "off". Then the direct transmission will fail and cooperative transmission would be initiated in the next state. Similarly, when the current transmission mode is C, the next transmission mode relies on both the current direct channel and the relay channels. If the direct channel or both two relay channels are "on", the transmission could be successful. On the contrary, when the direct channel is "off", that one of the relay channels is "off" would lead to transmission failure. The cases are represented in states S_0, S_1, and S_2.

Table 1. State transition logic for time slot allocation.

{M(k-1), CH_{SD}(k-1), CH_{SH}(k-1), CH_{HD}(k-1)}	**M(k)**
S_0:{C, off, off, off}	C
S_1:{C, off, off, on}	C
S_2:{C, off, on, off}	C
S_3:{C, off, on, on}	D
S_4:{C, on, off, off}	D
S_5:{C, on, off, on}	D
S_6:{C, on, on, off}	D
S_7:{C, on, on, on}	D
S_8:{D, off, off, off}	C
S_9:{D, off, off, on}	C
S_{10}:{D, off, on, off}	C
S_{11}:{D, off, on, on}	C
S_{12}:{D, on, off, off}	D
S_{13}:{D, on, off, on}	D
S_{14}:{D, on, on, off}	D
S_{15}:{D, on, on, on}	D

Knowing the transition probabilities, we can calculate the steady state probability. The vector is expressed as **S**=[S_0,...,S_{15}], where S_i is the steady state probability of each state in Table 1. The vector can be obtained by solving the equations given by

$$S = V \cdot S\,, \tag{6}$$

and the sum of all the probabilities would follow

$$S_0 + \ldots + S_{15} = 1\,. \tag{7}$$

By solving Eqs. (6) and (7), we can get all state probability S_i, for *i*=0,...,15. Then the parameters of the two-state Markov model for the transmission mode can be obtained by

$$p = \frac{S_8 + S_9 + S_{10} + S_{11}}{\sum_{i=8}^{15} S_i}, \qquad q = \frac{S_3 + S_4 + S_5 + S_6}{\sum_{i=0}^{7} S_i}. \tag{8}$$

Therefore, the throughput efficiency of the cooperative scheme can be obtained as

$$\alpha = \frac{q}{p+q}. \tag{9}$$

6.3. System Throughput

In this subsection, we analyze the performance of the proposed cooperative MAC protocol in terms of system throughput. The normalized system throughput, denoted as η, is defined as successfully transmitted payload bits per time unit.

$$\eta = \frac{E[G]}{T_{frame}}, \tag{10}$$

where *E[G]* is the number of payload information bits successfully transmitted in the time interval, and T_{frame} is the expected time interval which is known as the frame duration in the proposed TDMA system. In this study, *E[G]* is contributed by two kinds of transmissions, i.e., the direct transmission and the cooperative transmission, respectively. Therefore, *E[G]* can be expressed as

$$E[G] = uL(1-P_e^D) + uLP_e^D(1-\prod_{j=1}^{w} P_e^{C,j}) \qquad w \geq 1, \tag{11}$$

$$P_e^{C,j} = 1-(1-P_e^{si})(1-P_e^{id}), \tag{12}$$

where L is the packet length; P_e^D is the Packet Error Rate (PER) of the direct link; $P_e^{C,j}$ is the PER of the cooperative transmission at the j attempt, and w is the cooperative transmission attempts; P_e^{si} and P_e^{id} are the PER of the link from source to optimal relay and the link from optimal relay to destination respectively, which could be obtained from the physical layer modulation scheme [26], [27]. Note that for each cooperation round, the optimal relay might be different; u is the number of packets transmitted in the direct link during the frame time. Note that among u number of packets, uP_e^D out of u direct packet transmissions failed. Thus, these packets need to be retransmitted in the cooperative link. However, the total transmission time of these data packets should be smaller or equal to the frame duration. It is clear that u satisfies the following constraint, and we select the largest integer value of u for throughput calculation.

$$T_{frame} \cdot \frac{T_{slot}-T_{ctrl}}{T_{slot}} \geq \begin{cases} \left\lceil u\dfrac{L}{R_D} + uP_e^D T_{C,1} \right\rceil, w = 1 \\ \left\lceil u\dfrac{L}{R_D} + uP_e^D (T_{C,1} + \sum_{j=2}^{w} T_{C,j} P_e^{C,j-1}) \right\rceil, w \geq 2 \end{cases} \tag{13}$$

$$T_{C,j} = \frac{L}{R_{C,j}} + T_{CFC} + SIFS, \tag{14}$$

where $\lceil \cdot \rceil$ is the ceiling function, T_{slot} is the slot time duration; T_{CFC} is the transmission time of CFC, *SIFS* is the duration of *SIFS* silence period, R_D is the effective payload transmission rate for direct transmission, and $R_{C,j}$ is the transmission rate for cooperative transmission at the j attempt.

7. PERFORMANCE EVALUATION

To evaluate the performance of our proposed cooperative MAC protocol, we have developed a network simulating program by using Matlab. We define a communication area (500 *m* × 500 *m*) and three nodes are set along the center of the area in a two-hop route with an equal distance *d* between each node as illustrated in Fig. 3-(a). In every transmission, potential relay nodes are randomly generated to connect each source and destination pair. The channels among each node are modeled as i.i.d. Rayleigh fading channel. In general, with the same transmit power, the better the channel condition, the higher the received power. The received power P_{rx} when the pass loss coefficient between the two communication nodes is three and the reference distance d_o=1 meter is shown in the following equation.

$$P_{rx} = P_{tx} + 20\log_{10}(\frac{\lambda}{4\pi d_o}) + 30\log_{10}\frac{d_o}{d}, \qquad (15)$$

where P_{tx} is the transmit power. In this paper, we consider four modulation schemes as BPSK, QPSK, 16QAM and 64QAM according to the 802.11a specification. The modulation is adaptively changed according to the received SNR at the receiver, and the corresponding data rates are 6, 12, 36 and 54 *Mbps* respectively. The threshold of modulation is calculated for given BER as 10^{-5}. The threshold is given by Table 2. The noise level is assumed to be -95 *dBm*. The other configuration parameters of the proposed protocol are summarized in Table 3.

Table 2. Threshold for adaptive modulation.

Modulation	**Threshold SNR**
BPSK	6.8 *dB*
BPSK-QPSK	9.8 *dB*
QPSK-16QAM	16.5 *dB*
16QAM-64QAM	22.4 *dB*

Table 3. Configuration parameters.

Parameter	**Value**
Mini-slot duration	9 μs
Slot duration	1.6 *ms*
Frame duration	16 *ms*
SIFS	16 μs
DIFS	34 μs
CFC	14 *bytes*

Two scenarios are considered in the simulation. Firstly, we focus the scenario on one-hop transmission. Then, the benefit of flexible extension to a multi-hop transmission by the proposed protocol is illustrated by obtaining the end-to-end throughput gain in a two-hop transmission manner. For presenting our simulations we refer to our mini-slot based cooperative TDMA scheme as MS-C-TDMA in all these figures. In comparison, we illustrate the performance of the CSMA/CA, original TDMA and CoopMAC [18] schemes, together with ours.

7.1. **Throughput Efficiency**

To observe the impact of the channel condition on the transmission performance, throughput efficiency with different signal thresholds of the direct channel is investigated in Fig. 10 by plotting Eqs. (4) and (9), respectively. It reveals that by decreasing the threshold of signal strength, which means the receiver has much more powerful signal processing capabilities, the probability of losing a packet decreases, leading to higher throughput efficiency. As the threshold of the signal to decode packets correctly increases, the relative channel condition decreases and more packets suffer from errors. In this case, cooperative transmissions are required to help deliver packets to the final destination. In other words, throughput derived from cooperative transmission could compensate the total throughput efficiency for all curves. It is observed that the participation of cooperation could greatly improve the communication performance in all range of signal thresholds. Particularly, if the signal threshold of the relay channels to decode packet successfully is always low (-4 *dB* in the figure), which means the relay channel is always good, the obtained throughput efficiency could be maximized. The benefit is much more evident when the signal threshold of direct channel is high.

While channel condition has great impact on transmission performance, system throughput also depends on the overhead of MAC layer and layers above. Therefore, we further evaluate the performance of the proposed cooperative MAC protocol in the next subsection.

7.2. **System Throughput**

In Fig. 11, we compare the throughput performance of these four schemes against link error rate of the direct channel. It is observed that as long as the direct link suffers from errors, MS-C-TDMA could provide higher throughput than that of CSMA, TDMA and CoopMAC schemes. The higher the error rate, the better the throughput improvement. This is because that the proposed scheme could provide priority access to cooperative transmission, ensuring channel access to the router which has better channel condition. In case there is slow fading in the direct transmission channel, the channel might remain in deep fading for long time with channel correlation (several data packets transmission time), hence retransmission from source router may not help in this case. As excepted, cooperative transmission from the optimal relay could most potentially help eliminate this problem.

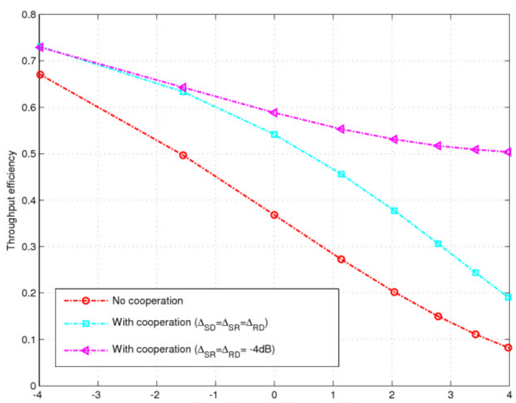

Figure 10: Throughput efficiency vs. different signal threshold.

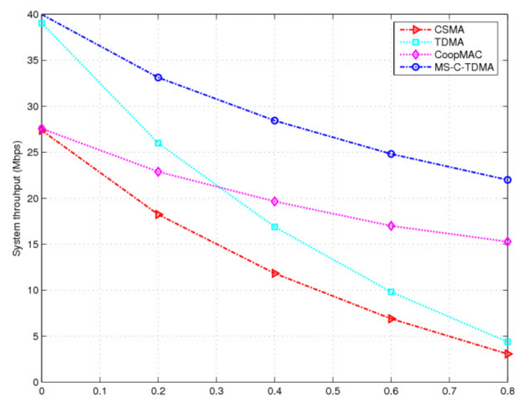

Figure 11: System throughput vs. direct channel error rate.

Meanwhile, compared with CoopMAC, the throughput improvement of MS-C-TDMA is not only from the cooperative transmission but also due to that it is able to efficiently schedule the nodes to utilize the channel resource. Moreover, it can avoid packet collision, which is a main reason for system performance degradation of contention-based MAC schemes, such as the IEEE 802.11. Since the overhead caused by control mini-slots is much smaller than that caused by the backoff and RTS/CTS control messages, significant control overhead reduction in the proposed scheme is achieved.

Additionally, in a traditional TDMA system, channel reservation for all transmissions may lead to a situation of over-reservation. If a router does not have a packet to transmit during the time slot, this slot remains idle, i.e., the slot becomes wasted. However, in our proposed scheme the mini-slot design could efficiently schedule each transmission to guarantee the channel is fully utilized at the cost of only a small portion of the total slot time. If the current router with mini-slot status as "1" has no packet to transmit, the router corresponding to the next mini-slot will quickly initiate a new transmission. Therefore, the control mini-slot based scheme could improve channel utilization, and this benefit can be translated into throughput improvement.

7.3. **Transmit Power**

Fig. 12 shows the system throughput performance of the four schemes with the transmit power from -10 *dB* to 15 *dB*. As shown in the figure, the MS-C-TDMA scheme consistently outperforms the other two conventional schemes, and the gap becomes more significant when the transmit power is low (from -10 *dBm* to 5 *dBm*). This is due to the fact that lower transmit power will lead to less reliable transmission and cooperative diversity is fully exploited by cooperative transmission in this case. In this range the selected relay could provide better channel quality compared with the direct link. For instance, with the transmit power of -5 *dBm* MS-C-TDMA could obtain throughput of 26 *Mbps*, while the CSMA and TDMA schemes get merely 12 *Mbps* and 17.6 *Mbps* respectively.

In addition, MS-C-TDMA enhances the throughput more significantly than that of CoopMAC. That is because the elaborate design of the proposed MAC protocol could greatly reduce the MAC layer overhead. Each node could transmit the packet in its own time slot without packet corruption. Besides, with the contribution of cooperative transmission by the optimal relay node, system throughput could always be enhanced significantly when the direct link suffers from channel fading. Moreover, the relay selection time could be regarded as negligible as protocol overhead.

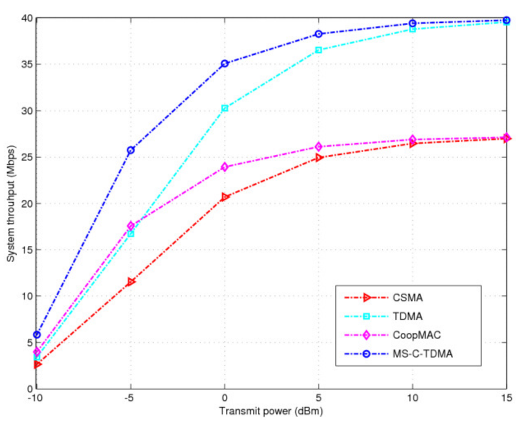

Figure 12: System throughput vs. different transmit power.

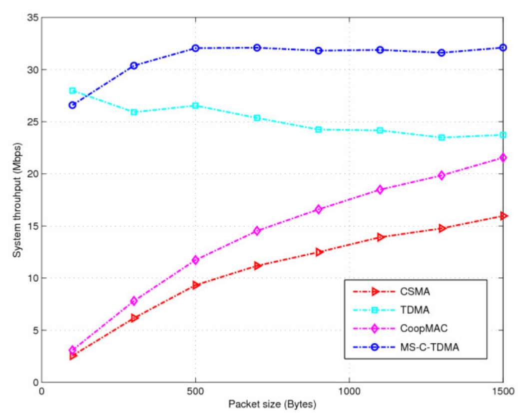

Figure 13: Throughput vs. packet length.

7.4. **The effect of payload Length**

As known, payload length has major impact on the efficiency of a MAC protocol. To illustrate the advantage of the proposed scheme we exhibit the impact of packet length on system throughput. It is observed in Fig. 13 that compared with other schemes, the proposed scheme performs more stable as the packet length varies.

It is clear that the throughput of CSMA scheme increases as the packet length grows. The reason behind this is that as the packet length increases the portion of data packet in the total transmission increases correspondingly, resulting in higher transmission efficiency. CoopMAC also agrees with the similar observation. In the TDMA-based scheme, a fixed number of data packets are transmitted for given packet length and transmission rate during the frame time duration. When the data rate is fixed in one frame, the larger the packet length, the smaller the number of packets. However, without heavy control overhead, like RTS/CTS, TDMA could obtain almost stable throughput when the payload length varies. Note that as the packet length becomes larger, the probability that packet transmission suffers from fading also increases, resulting in more transmission failures. That is why the curve of TDMA throughput decreases slightly when the payload length becomes larger. However, the proposed MS-C-TDMA scheme could efficiently alleviate this problem because of cooperative transmission. Therefore, MS-C-TDMA could achieve more stable throughput.

7.5. **Throughput Gain versus Per-hop Distance**

In this subsection, we evaluate the system performance of the protocol where the per-hop distance *d* between the source node and the destination node varies from 30 *m* to 130 *m*. Fig. 14 shows the throughput gain of the proposed MS-C-TDMA protocol over the original CSMA scheme. It is observed that as the per-hop distance increases, the throughput gain of cooperative schemes increases while conventional TDMA scheme keeps almost stable throughput gain. More specially, MS-C-TDMA outperforms CoopMAC in all ranges of distance. The increment of the throughput gain by MS-C-TDMA is larger than that of CoopMAC.

The reason is due to the fact that as the transmission distance is increased the throughput of the non-cooperative schemes is decreased correspondingly, while the performance of cooperative schemes is only degraded slightly. More specifically, with a short distance, the CSMA scheme could maintain stable delivery ratio. Therefore, cooperative transmission may not help a lot in this case. However, as *d* increases, the link is not robust that the frame error rate rises correspondingly. Then the benefit of cooperative transmission becomes convincing. Compared with one-hop transmission with low data rate, two-hop transmissions with high data rate by the cooperative transmission provide significant throughput gains. Note that nodes have to compete to access the channel at each hop when the contention-based scheme is applied. Therefore, with collision free in the two-hop cooperative transmission by MS-C-TDMA, the achieved increment of throughput gain is higher than that of CoopMAC. For instance, when the distance is equal to 50 *m*, the original scheme could obtain throughput of 17.4 *Mbps*. And CoopMAC could achieve 21.3 *Mbps* while MS-C-TDMA is able to attain 34.3 *Mbps*. Therefore, the throughput gain by MS-C-TDMA is 1.97, which is larger than 1.22, obtained by CoopMAC.

7.6. **End-to-End Throughput Gain versus Network Density**

Another advantage of the proposed scheme comes that it could feasibly extend the transmission from one-hop to multi-hop scenarios. In this subsection, we evaluate the performance of the proposed MS-C-TDMA in a two-hop transmission manner. Fig. 15 illustrates the end-to-end throughput gain against CSMA scheme as network density rises.

Since the proposed scheme combats against packet collision and poor efficiency of the spatial reuse, the obtained end-to-end throughput gain by our proposed scheme is larger than 1. In addition, the curves depict that significant improvement is achieved by MS-C-TDMA as network density increase from 0.1 to 0.45. This feature is attributed to the fact that as the number of nodes increases in the communication area, the probability of successful cooperative transmission increases. However, further increasing networking density does not help for achieving higher throughput gain. In fact, a flat throughput gain curve is observed when network density is around 0.5. This can be explained as in a high dense network, large number of two hop neighbors corresponding to the same number of mini-slots will bring non-ignorable overhead. In that case, our solution may not be able to give such significant improvement.

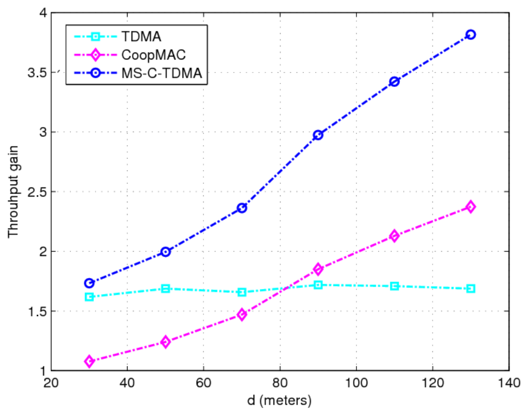

Figure 14: Throughput gain vs. per-hop distance.

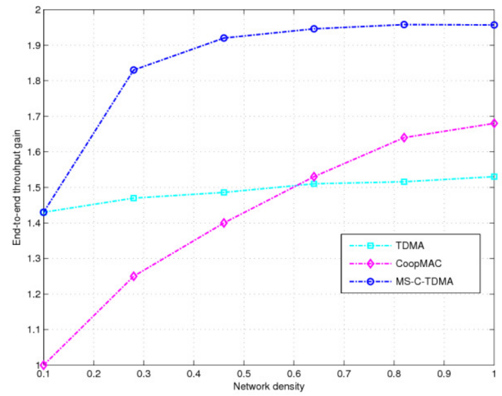

Figure 15: End-to-end throughput gain vs. network density.

8. CONCLUSIONS

In this paper, we have presented a novel TDMA based multiple access scheme to facilitate cooperation in wireless mesh networks. With the help of mini-slots, channel resources are efficiently allocated to mesh routers in a distributed manner and higher priority has been given to cooperative transmission which is performed through an optimal relay. The optimal relay node is selected based on the combined instantaneous relay channel conditions. The effectiveness and the efficiency of this novel MAC scheme have been demonstrated with respect to system throughput, throughput gain in one-hop and two-hop scenarios respectively by considering several factors such as signal threshold, channel error rate, transmission power, hop distances, and network density. The obtained numerical results demonstrate that the proposed scheme is able to improve system performance significantly. This study could provide helpful insight to the development and deployment of cooperative communications for future broadband wireless mesh networks.

REFERENCES

[1] M. Hassan, S. K. Das, P. Mohapatra, and C. E. Perkins, "Wireless mesh networks", *IEEE Communications Magazine*, Vol. 8, No. 7, pp. 62-63, Nov. 2007.

[2] I. F. Akyildiz and X. Wang, "A survey on wireless mesh networks", *IEEE Communications Magazine*, Vol. 43, No. 9, pp. S23-S30, Sep. 2005.

[3] R. Bruno, M. Conti, and E. Gregori, "Mesh networks: commodity multihop ad hoc networks", *IEEE Communications Magazine*, Vol. 43, No. 3, pp. S23-S30, May 2005.

[4] P. Cheng, Z. Zhang, G. Yu, H.-H. Chen, and P. Qiu, "Cross-layer bandwidth and power allocation for a two-hop link in wireless mesh network", *Wireless Communications and Mobile Computing*, Vol. 9, No. 2, pp 155-167, Feb. 2009.

[5] M. Dianati, X. Ling, S. Naik, and X. Shen, "Performance analysis of the node cooperative ARQ scheme for wireless ad-hoc networks", *Proc. of IEEE GLOBECOM*, St. Louis, MO, USA, Nov. 2005.

[6] A. Sadek, W. Yu, and K. Liu, "When does cooperation have better performance in sensor networks?", *Proc. of IEEE SECON*, Reston, VA, USA, Sep. 2006.

[7] J. N. Laneman, D. N. C. Tse, and G. W. Wornell, "Cooperative diversity in wireless networks: efficient protocols and outage behavior", *IEEE Trans. on Information Theory*, Vol. 50, No. 12, pp. 3062-3080, Dec. 2004.

[8] A. Sendonaris, E. Erkip, and B. Aazhang, "User cooperation diversity-Part I: system description", *IEEE Trans. on Communications*, Vol. 51, No. 11, pp. 1927-1938, Nov. 2003.

[9] A. Sendonaris, E. Erkip, and B. Aazhang, “User cooperation diversity-Part II: implementation aspects and performance analysis”, *IEEE Trans. on Communications*, Vol. 51, No. 11, pp. 1939-1948, Nov. 2003.

[10] S. Valentin, H. S. Lichte, H. Karl, G. Vivier, S. Simoens, J. Vidal, and A. Agustin, “Cooperative wireless networking beyond store-and-forward perspectives in PHY and MAC design”, *Wireless Personal Communications*, Vol. 48, No. 1, pp. 49-68, Jan. 2009.

[11] A. Nosratinia, T. E. Hunter, and A. Hedayat, “Cooperative communication in wireless networks”, *IEEE Communications Magazine*, Vol. 42, No. 10, pp. 74-80, Oct. 2004.

[12] A. K. Sadek, K. Liu, and A. Ephremides, “Collaborative multiple-access protocols for wireless networks”, *Proc. of IEEE ICC*, Istanbul, Turkey, Jun. 2006.

[13] P. Wang, and W. Zhuang, “A collision-free MAC scheme for multimedia wireless mesh backbone”, *IEEE Trans. on Wireless Communications*, Vol. 8, No. 7, pp. 3577-3589, Jul. 2009.

[14] T. Fujii, “Dynamic subcarrier controleed TDMA/OFDM multi-hop wireless network for improving end to end throughput”, *Proc. of IEEE WCNC*, Budapest, Hungary, Apr. 2009.

[15] A. Warrier, J. Min, and Injong Rhee, “Z-MAC: a hybrid MAC for wireless sensor networks”, *IEEE/ACM Trans. on Networking*, Vol. 16, No. 3, pp. 511-524, Jun. 2008.

[16] G.-S. Ahn, S. G. Hong, E. Miluzzo, A. T. Campbell, and F. Cuomo, “Funneling-MAC: A localized, sink-oriented MAC for boosting fidelity in sensor networks”, *Proc. of 4th ACM Conf. on Embedded Networked Sensor Systems (SenSys)*, Boulder, Colorado, USA, Oct. 2006.

[17] M. Gokturk, and O. Gurbuz, “Cooperation in wireless sensor networks: design and performance analysis of a MAC protocol”, *Proc. of IEEE ICC*, Beijing, China, May 2008.

[18] P. Liu, Z. Tao, S. Narayanan, T. Korakis, and S. Panwar, “CoopMAC: A cooperative MAC for wireless LANs”, *IEEE JSAC*, Vol. 25, No. 2, pp. 340-354, Feb. 2007.

[19] S. Moh, C. Yu, S. Park, and H. Kim, “CD-MAC: Cooperative diversity MAC for robust communication in wireless ad hoc networks”, *Proc. of IEEE ICC*, Glasgow, UK, Jun. 2007.

[20] M. Levorato, A. Munari, and M. Zorzi, “On the effectiveness of cooperation in carrier sense-based ad hoc networks”, *Proc. of IEEE SECON*, Rome, Italy, Jun. 2009.

[21] A. Munari, F. Rossetto, and M. Zorzi, “Hybrid coooperative-network coding medium access control for high-rate wireless personal area networks”, *Proc. of IEEE ICC*, Cape Town, South Africa, May 2010.

[22] Z. Yang, Y.-D. Yao, X. Li, and D. Zhang, “A TDMA-based MAC protocol with cooperative diversity”, *IEEE Communications Letters*, Vol. 14, No. 6, pp. 542-544, Jun. 2010.

[23] J. Riihijarvi, M. Petrova, P. Mahonen, and J. Barbosa, “Performance evaluation of automatic channel assignment mechanism for IEEE 802.11 based on graph coloring”, *Proc. of IEEE PIMRC*, Helsinki, Finland, Sep. 2006.

[24] A. Bletsas, A. Khisti, D. P. Reed, and A. Lippman, “A simple cooperative Diversity method based on network path selection”, *IEEE JSAC*, Vol. 24, No. 3, pp. 695-672, Mar. 2006.

[25] M. Zorzi, R. R. Rao, and L. B. Milstein, “ARQ error control for fading mobile radio channels”, *IEEE Trans. On Veh. Technol.*, Vol. 46, No. 2, pp. 445-455, May 1997.

[26] H. Jiao and F. Y. Li, “Cooperative MAC design in multi-hop wireless networks-Part II: when source and destination are the two-hops away from each other”, *Wireless Personal Communications*, ISSN 0929-6212 (Print) 1572-834X (Online), DOI 10.1007/s11277-010-0073-x, Jul. 2010.

[27] H. Jiao and F. Y. Li, “A mini-slot-based cooperative MAC protocol for wireless mesh networks”, *Proc. of IEEE International Workshop on Heterogeneous, Multi-Hop, Wireless and Mobile Network (HeterWMN 2010) in conjunction with IEEE GLOBECOM*, Miami, FL, USA, Dec. 2010.