A Cooperative Multi-Channel MAC Protocol for Wireless Networks

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Abstract—One of the crucial challenges in practical wireless networks is how to provide robust communication over fading channels. Recently, cooperative communications have emerged as a promising approach to achieve spatial diversity and thereby reduce the negative effects of fading on wireless channels. Nevertheless, a few existing works indicate that deploying cooperative relays in large-scale wireless networks can lead to an elevated level of interference which in turn leads to degraded throughput and higher packet losses. It is also well-known that the use of multiple frequency channels can mitigate the wireless interference to a greater extent and thus improve the overall performance of a wireless network. Therefore, it is interesting and important to design and evaluate protocols that can provide the combined potential of both cooperation communication and multiple channels. In this paper, we propose a novel cooperative multi-channel MAC protocol that integrates the capabilities of both multiple channels and cooperative communications at the MAC layer to improve the performance of wireless networks. The performance improvement of our proposed solution is further evaluated by extensive simulations.

I. INTRODUCTION

Spatial diversity, in the form of employing multiple transmitter-receiver (transceiver) radio interfaces e.g., multiple input multiple output (MIMO) [1]-[5], has shown to be very effective in providing robust communication over fading channels. However, equipping a wireless node with multiple radio interfaces may not be practical, particularly handheld wireless devices, and nodes carrying one or two radio interfaces significantly limit the effectiveness of MIMO techniques [1]-[5]. Recent studies address this limitation through the use of a new paradigm known as cooperative communications— also known as virtual MIMO systems—that draws from the idea of using the broadcast nature of the wireless channel to achieve spatial diversity. Under cooperative communications, nodes equipped with a single transceiver (cooperative relay or helper) captures a neighboring source's transmission and relay it to the designated destination. The destination combines multiple streams of the same information from both source and relay nodes to recover the original information with high probability. Therefore, by cooperatively relaying the information to the destination, nodes equipped with one or two radio interfaces achieve the same advantages as those found in MIMO systems.

Due to the advances in cooperative communication, many efforts have been spent in understanding and improving the benefits of deploying cooperative relays in wireless networks, including network capacity analysis, optimal power allocation, resource allocation and relay assignment [5]. In addition to capacity analysis and allocation schemes, several cooperative MAC protocols have been recently proposed for multi-hop wireless networks, e.g., [8]-[9] and the references therein. Nevertheless, while most of the works pertaining to cooperative communication address the benefits of this novel paradigm, naturally a question arise: Is cooperative communication al-ways beneficial for wireless networks? A few studies [4], [7] address the limitation of cooperative communication and demonstrate that deploying cooperative relays in large-scale wireless networks in fact incurs several challenges. For instance, Zhu et. al [4] shows both analytically and experimentally that deploying cooperative relays in large-scale wireless networks can lead to an elevated level of interference which in turn results in degraded throughput and higher packet losses. On the other hand, in the last few years studies [6], [11] also indicate that adopting multiple channels in wireless networks can mitigate the negative effects of interference and thus substantially enhance the performance of wireless networks.

Motivated by such an idea, it is interesting and important to investigate whether we can achieve further benefits by designing and evaluating protocols that integrate the capabilities of both cooperative communications and multiple channels into wireless networks, particularly in multi-hop settings. In [7], we established the capacity of such a model termed as CoopMC (Cooperative Multi-Channel) under random networks and our analysis has revealed that interference is a serious limiting factor in large-scale cooperative wireless networks and hence, by utilizing multiple channels in such networks one can improve the capacity to a greater extent. To realize these capacity benefits in practice, this work presents the design of a MAC protocol for cooperative multi-channel (CoopMC) wireless network[1]. The key idea of CoopMC MAC is to enable the nodes (source, destination and its corresponding helper) to dynamically negotiate channels so that multiple cooperative communications can occur concurrently in the same region. The increased number of simultaneous transmissions together with the channel reliability achieved through cooperative transmissions in turn lead to a network with higher throughput and reliability, as our simulations confirm.

The rest of the paper is organized as follows. In the next section, we present the detailed design of our CoopMC MAC Protocol. Section III presents some simulation results to demonstrate the performance of CoopMC protocol[2]. Finally, we summarize our work in section IV.

II. DESIGN OF COOPMC MAC PROTOCOL

In this section, we present the design of our proposed CoopMC MAC protocol. As discussed before, though several existing literatures address the benefits of cooperative communication, it is not yet clear whether deploying relays can always provide higher benefits in different scenarios. For instance, in Figure 1, we depict the interference region of

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[1]Though the work in [10] considers cooperative communication in multi-channel environment, their MAC protocol design do not consider the problem of channel assignment in cooperative networks.

[2]In this paper, we interchangeably use CoopMC and CoopMC MAC for the proposed MAC protocol.

both direct and cooperative communications. In [3]-[4],[7], the authors indicate that when relay is placed close to the direct link, the perceived amount of interference is same as that of the direct transmission whereas when the relay is far apart from the direct link, i.e., $\geq 1/\sqrt{2}$, it incurs an increased level of interference. An increased level of interference in turn implies reduction in number of concurrent transmissions and correspondingly, the throughput. So, how can we intelligently exploit the benefits of cooperative transmissions in large-scale networks without impacting the spatial reuse? Our idea is that to dynamically assign each cooperative transmission in a different channel such that multiple cooperative transmissions can take place simultaneously at the same region. Specifically in CoopMC MAC protocol, the nodes are allocated channels in such a way that the relay node captures a neighboring sources transmission on one channel and use another channel to relay it to the designated destination (see Figure 3). Thus, to achieve dynamic channel allocation for each cooperative transmission, the proposed protocol operates at the MAC layer and works in two phases, the CONTROL and the DATA Phase.

- CONTROL Phase: All nodes that have packets to send to the destination via the potential relays (or helper) negotiate channels in this phase.
- DATA Phase: This Phase begins only after the CONTROL Phase has ended. In this Phase, nodes switch to their respective channels for sending data to the destination. To reduce the overhead involved in negotiating channels in CONTROL Phase, we allow the nodes to send multiple number of data packets, denoted as α, in this Phase.

In the sequel, we denote the source, destination and its corresponding relay node as N_s, N_d and N_r^s respectively. Before delving into details of the protocol, we take the following assumptions.
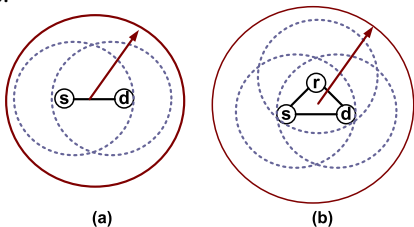

Fig. 1. Interference region of (a) direct and (b) cooperative communication, where s, r, d denote the source, relay and destination.

A. Assumptions

- There are C channels in the network and each node (source, destination and relay) is equipped with two half-duplex interface. We also assume that channel switching can be immediately implemented without delay, which is less than $1\mu s$.
- Due to half-duplex nature, an interface can either transmit or receive data on any one channel at a given time. A cooperative link consists of a direct path $N_s - N_d$, and a relay path $N_s - N_r^s - N_d$. In [7], we assume that both the relay path and direct path use the same channel for transmission and hence, a transmission from source to destination via a relay path is completed in two time slots. As opposed to our previous model, this paper considers that $N_r^s - N_d$ path use a different channel from paths $N_s - N_r^s$ and $N_s - N_d$ and thus, a transmission from

source to destination via a relay path is completed in one time slot.
- We assume that each source node is aware of the potential helper nodes and hence the subject of "best" relay selection is beyond the scope of this paper, and thus will not be discussed hereafter.
- As in IEEE 802.11 power saving mechanism (PSM), this paper also considers that each node periodically send beacons to synchronize time in a distributed manner. In [11], authors discuss several solutions to synchronize time in multi-hop distributed wireless networks and the interested readers can refer the following works [11],[13] and the references therein. In this paper, as in [11], we assume that synchronization is obtained through beacons.

B. Data Structures in CoopMC design

In CoopMC model, each node maintains a list of one-hop neighbor information of its neighbors in a data structure referred to as neighbor-table (NTable). This is a simple process since in a multi-hop distributed network, each node periodically sends a broadcast message, for e.g., HELLO message in AODV Routing Protocol, to all one-hop neighboring nodes. In CoopMC, we need each node to append its list of one-hop neighbors to this message while transmitting to its neighboring nodes. So, when a source node N_s has buffered packets destined for N_d, it combines its one-hop neighbor information with the one send by the destination node to find a potential best relay or helper node to assist the communication between N_s and N_d. There are several works that address the problem of selecting the best relay—for e.g., relay with good Channel State Information (CSI) or minimum interfering neighbors [3]-[5],[8],[9]—between a given $N_s - N_d$ pair and thus the problem of relay selection is not discussed here for brevity. Besides NTable, each node also maintains a data structure of channels termed as channel-table (CTable) that indicates the most favorable channels to use for the node in DATA Phase. Each channel in the CTable is associated with a counter that indicates the number of neighbors that have planned to utilize the channel during the current DATA Phase and thus, the channel that is used by the least number of nodes in the vicinity of sender, receiver and relay node will be selected for data exchange in the DATA Phase.

C. The Proposed MAC Protocol

The CoopMC protocol is based on the existing Multi-channel MAC protocol (MMAC) [11], with necessary modifications made in both CONTROL and DATA Phase to incorporate the capabilities of cooperative communications. As in IEEE 802.11 PSM [12], in CoopMC protocol, we also divide time into beacon intervals and thus, every node in the network is synchronized by periodic beacon transmissions. This in turn implies that each node will start and end the beacon interval almost at the same time. Each beacon interval is further divided into CONTROL and DATA Phases as shown in Figure 2. Similar to [11], we also allocate fixed time interval for each Phase. In the CONTROL Phase, each node that have packets to send to the destination listens to the default channel for channel negotiation. Note that the default channel is one of the multiple channels available for data transmission and is pre-defined in all nodes so that each node know in advance
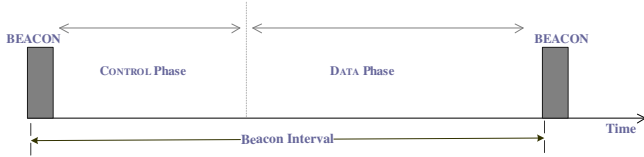
Fig. 2. The time is divided into beacon interval and each beacon intervak is divided into CONTROL and DATA Phase. During the CONTROL Phase, nodes negotiate the channels to use in the next Phase, DATA Phase.
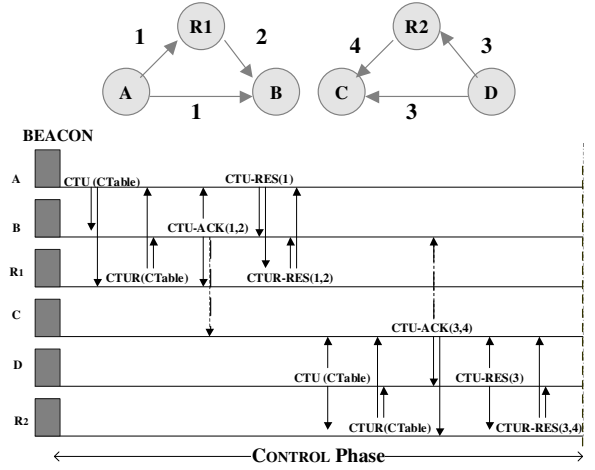

Fig. 3. Example illustrating the process of channel negotiation during the CONTROL Phase. The dashed line shows the end of the CONTROL Phase. The numbers in the topology indicate the channels used for transmission.

the channel to listen during the CONTROL Phase. Specifically, the default channel, as other existing multiple channels, will be used for sending data packets in DATA Phase and thus, no channels will be wasted for transmitting control packets alone as seen in DCA [11]. For the purpose of channel negotiation, we introduce five control packets. The details of the packets employed during the CONTROL Phase is given in Table I.

TABLE I
PACKETS USED IN CONTROL PHASE

Node	Packets
N_s	CTU (Channel-To-Use)
N_r^s	CTU-R (CTU-Relay)
N_d	CTU-ACK (CTU-Acknowledgement)
N_s	CTU-RES (CTU-Reservation)
N_r^s	CTUR-RES (CTUR-Reservation)

When a source node N_s has buffered packets destined for destination node N_d, N_s first listens to the default channel. If the channel is idle for a DIFS time period and N_s has completed the required backoff process, a CTU packet will be sent to notify N_d and N_r^s. The MAC address of the selected helper node, destination and the CTable at N_s will be included in the CTU packet. If the channel is busy, node N_s should wait until the channel is idle plus a DIFS time period, and then send the CTU packet. During this period N_s also monitors the channel selected by the nodes for data transmission in DATA Phase in its vicinity. This information is in turn used to update the counter of each channel in its CTable. Upon receiving the CTU packet from N_s, the helper node will sent out a CTU-R packet in a SIFS time after the CTU is received. The CTU-R packet also includes the CTable at N_r^s. This packet will be heard both by N_s and N_d. If the helper node cannot assist the transmission between $N_s - N_d$, it just stays idle. A helper node cannot cooperate with N_s because either the surrounding medium around helper is busy due to other transmissions or the helper node has already agreed to serve another transmission in the DATA Phase. The destination node N_d will be expecting the CTU-R packet after receiving the CTU packet. If the CTU-R packet is received, N_d selects two channels based on the CTables at N_s, N_d and the relay node, N_r^s and send out CTU-ACK packet. Specifically, in CoopMC model N_d selects same channel for paths $N_s - N_r^s$ and $N_s - N_d$ and a different channel for path $N_r - N_d$ and includes this information in the CTU-ACK packet for N_s and N_r^s. If the CTU-R packet is not heard after the SIFS time period, N_d will also send the CTU-ACK packet with the channel information for path $N_s - N_d$ alone.

When N_s receives the CTU-ACK packet and if it selects the channel specified in the CTU-ACK packet, it sends out a CTU-RES packet, in a SIFS time period, with the selected channel

information in the packet. The CTU-RES packet in turn notifies the nodes in the vicinity of N_s regarding the channel N_s is going to use in the DATA Phase. All those neighboring nodes in the vicinity of N_s can use this information to update their CTable. Also, note that if N_s (or N_r^s) cannot select the channel specified in CTU-ACK, it implies that it cannot send packets to N_d during the current DATA Phase and has to wait until the next Phase. Since this can be a waste of bandwidth resources, as in [11], we also need N_s (N_r^s) to select the channels specified by N_d in CTU-ACK. Similarly, N_r^s also replies with the CTUR-RES packet, if it agrees to the channels specified by N_d in the CTU-ACK packet. Again, the CTUR-RES packet notifies the nodes in the vicinity of N_r^s regarding the channel N_r^s is going to use in the DATA phase. If the CTUR-RES packet is not heard in a SIFS time period, the nodes N_s and N_d switch to direct transmission mode in the DATA Phase. The process of channel negotiation is illustrated with an example in Figure 3. In this example, we have two simultaneous transmissions A-B and D-C using relays R1 and R2 respectively. As part of the negotiation process, we can see that node B selects channels 1 for paths A-B and A-R1 and channel 2 for path R1-B in CTU-ACK, which is based on the CTables at A, B and R1. This CTU-ACK packet in turn will be overheard by node C and hence the CTable at C will be updated by incrementing the counter values for channels 1 and 2 respectively. As a result, C selects channel 3 for paths D-C and R2-D and channel 4 for path R2-C during its turn in the negotiation process.

After the CONTROL Phase, nodes N_s, N_r^s, N_d switch to their selected channels and start communicating by exchanging RTS/HTS/CTS packets[3]. The reason we use RTS/HTS/CTS in DATA Phase is because when all the channels in the neighborhood of N_d is selected, node N_d will still select two channels for data transmission during the DATA Phase and CoopMC protocol requires nodes N_s and N_r^s to select the channels specified by N_d in CTU-ACK. Thus, as in original

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[3]RTS and CTS have the similar meaning of the packets used in IEEE 802.11 whereas HTS is the helper-to-send packet that is sent by relay node if it can assist the transmission between N_s and N_d by switching to the appropriate channels.

Cooperative MAC protocol [8]-[9], nodes exchange control packets (RTS/HTS/CTS) before sending the data packets during the DATA Phase. Similar to the traditional Cooperative MAC protocol, a RTS packet will be sent out to N_d and N_r^s from the source N_s. If node N_r^s can communicate to N_s and N_d using the channels specified in CTU-ACK, it will transmit a HTS packet to both N_s and N_d in a SIFS time after RTS is received. For instance, in Figure 3, relay node R1 may send the HTS to nodes A and B using channels 1 and 2 respectively, if it agrees to assist the transmission.. Eventually, when HTS packet is received by N_d, the CTS packet is sent to the source and relay node after a SIFS time. One may note that if a HTS packet is not heard by N_s or N_d after SIFS time period, CoopMC requires nodes N_s and N_d to switch to direct transmission mode. However this time, node N_d will send the CTS to source alone. After this handshaking process, the data transmission begins. Here, to reduce the overhead involved in negotiating channels in CONTROL Phase, we need the source nodes to send multiple number of data packets, denoted as α, in DATA Phase. Specifically, the source node will send α data packets to relay and destination node on one channel and the relay node at the same time use its second channel to transmit the packets to the destination node. After the transmission of α data packets, the destination will acknowledge these data packets by sending a Cumulative ACK (CACK) packet to the source node after a SIFS period. For instance, in Figure 3, B may
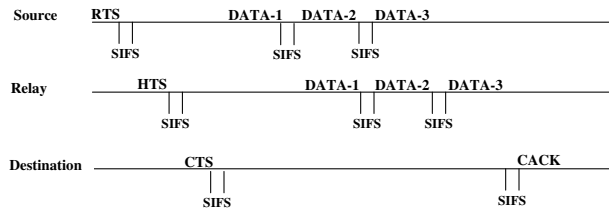

Fig. 4. Example illustrating the process of channel negotiation during the DATA Phase for $\alpha = 3$.

receive the data packets from A and R1 using channel 1 and 2 respectively, but a CACK is sent to A using channel 1 alone. The data exchange process is illustrated in Figure 4 for $\alpha = 3$. In this figure, we observe that only $(\alpha + 1)T_{data}$ time slots are required to complete the data transmission under CoopMC model. Nonetheless in existing cooperative protocols [7], [9], where the relay use two time slots to complete the transmission between source and destination, we need $2\alpha T_{data}$ time slots to complete the data transfer.

III. PERFORMANCE EVALUATION

We evaluate CoopMC model and compare with two models, single-channel cooperative transmission and direct transmission, using the ns-2 simulator with CMU wireless extensions. The simulation area consists of a grid of 40 wireless nodes located in 1000 meter by 1000 meter. The bit rate of channel is 2Mbps and the transmission range of each node is set approximately 250m. We use $\alpha = 3$ and this value is shown to be the best for throughput in our experiments. We randomly select the source and destination pairs and each source initiates an user datagram protocol (UDP)/constant bit rate (CBR) traffic flow to its intended destination. Besides source and destination

nodes, we also assume that sufficient number of relay nodes are present in the network. Each simulation was performed for a duration of 50 seconds and each data point in the result graphs is an average of five runs. Unless otherwise specified, we assume packet size is 1000 bytes. Further, the beacon interval is set to 150ms and CONTROL Phase duration as 32ms. Note that we have longer duration for CONTROL Phase as opposed to MMAC[11] in which the CONTROL Phase duration is 20ms long. This is due to the additional packets employed in CoopMC model to incorporate cooperative communication in a multi-channel network. In the plots, the curves labeled as "CoopSC" and "Direct" refer to the models that employ cooperative communications and direct transmissions respectively in a single-channel network.

In this paper, we study the performance of CoopMC model for the following scenarios. First, we study the throughput of the models by varying the network load. We use the packet arrival rate of CBR flows to generate different network load. After that, we examine the packet loss rate of these models in the presence of channel errors for varying network load. In these two preceding cases, we study the performance of CoopMC model with six channels. Finally, we also investigate the impact of number of channels on the throughput of CoopMC model.

In Figure 5, we study and compare the throughput of CoopMC model with the two models, CoopSC and Direct. Our results show that when the network load is low—the network is not saturated—all models perform similarly. However as the load increases, CoopMC performs significantly better than the other two models because in the proposed framework the simultaneous transmissions in the same region are allocated to different channels and as a result, the amount of time spent by each node waiting to access the channel for data transmission is reduced. On the other hand, as the load increases the throughput of both CoopSC and Direct model in fact degrades with the network load when compared to the CoopMC model. Interestingly, the performance of CoopSC is worse as opposed to the Direct model. This throughput degradation is due to, as explained in Section II, the enlarged interference region in the presence of cooperative relays which in fact increases the time spent by each node waiting to access the medium for data transmission. In other words, an increased level of interference greatly reduces the number of simultaneous transmissions in CoopSC model and correspondingly, the throughput.
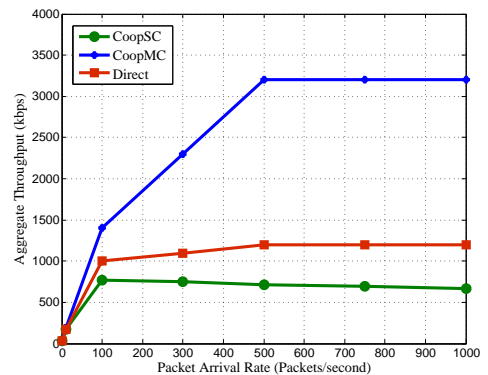

Fig. 5. Aggregate Throughput vs. Packet Arrival Rate.

In Figure 6, we study the performance of the models in the

presence of normal wireless losses. We make the following observations: (a) In the absence of wireless losses together with the low network load i.e., 10 packets/second, we observe that all the models have zero packet loss rate; However, as the network load increases from 10 to 100 packets/second, the packet loss rate of CoopSC model is in fact increased by $\approx 40\%$. Again, this occurs due to the increased interference region and thereby the channel contention time in CoopSC model as opposed to other two models. In particular, as the channel contention increases, the number of packets waiting to get transmitted also increases. Thus, when the number of data packets in the queue exceeds the limit, node starts dropping the data packets. (b) As the wireless loss increases, Direct model incurs more packet losses. However, in both CoopMC and CoopSC model we observe that the loss rate almost remains a constant with the normal loss rates. This is because in cooperative transmissions, the destination combines the transmission from both source and relay nodes to obtain the final packet and though the direct link faces wireless losses, the packet is successfully reached at the destination via the relay. (c) Since CoopMC model employs multiple channels, it performs significantly better than other two models. However, the negligible packet loss rate of CoopMC model for higher network load is due to its overhead for channel negotiation i.e., 32ms of every beacon interval is used for channel negotiation. Finally in figure 7, we study the throughput of CoopMC model

Fig. 7.   Impact of Channels on Throughput

IV. CONCLUSION

Interference plays a key role in limiting the performance of the wireless networks. We mainly indicate that when cooperative relays are deployed in a wireless network, it incurs an increased level of interference and thereby lower throughput. Our simulation results also confirm this drawback of cooperative communication. However, cooperative communications have emerged recently as a key factor for improving the performance of fading channels. Thus, to realize the benefits of cooperative communication in wireless network, we propose a cooperative multi-channel (CoopMC) MAC protocol that allocates each cooperative transmission dynamically in a different channel. Our simulation results manifest that employing multiple frequency channels can mitigate the interference in cooperative wireless network and thus improve the performance to a greater extent. In future, we plan to investigate a scheme that dynamically sets the duration of CONTROL Phase and the parameter α.
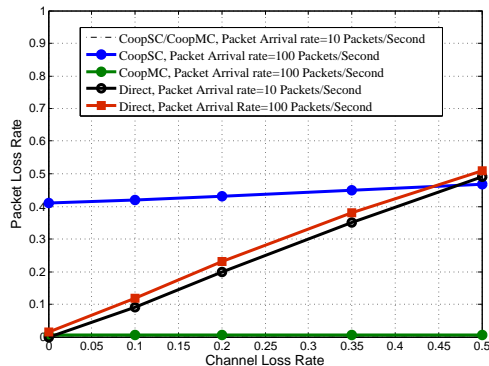

Fig. 6.   Sensitivity of models to wireless errors

for varying number of channels for packet arrival rates 10 and 100 packets/second. When only one channel is available in the network, CoopMC model has lower throughput in comparison to the CoopSC model. This comes about the fixed duration alloted for the CONTROL Phase. That is even though a single channel is present in the network, nodes still have to switch to the default channel for 32ms which in turn leads to wastage of bandwidth resources. This also implies that CONTROL Phase length in fact depends on the number of channels and the number of flows present in the network. Due to space constraints, the results graphs depicting the impact of channels on the duration of CONTROL Phase are omitted here for brevity. Hence, to obtain optimal throughput in all situations, one has to dynamically set the CONTROL Phase duration which is left as our future work. However, as the number of channels increases, CoopMC performs better than the single-channel cooperative model and the throughput reaches a constant at six channels.
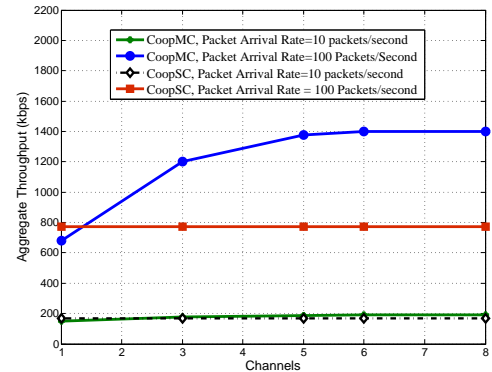
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