

Concurrent MAC with Short Signaling for Multi-hop Wireless Mesh Networks

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Abstract – The IEEE 802.11 Distributed Coordination Function (DCF) Medium Access Control (MAC) protocol continues to suffer from throughput degradation when directly applied in multi-hop Wireless Mesh Network (WMN). The Request-to-Send/Clear-to-Send (RTS/CTS) signaling partially solved hidden node problems however the exposed node problems remain unaddressed. The IEEE 802.11 MAC does not allow the exposed nodes to initiate its transmission for the entire duration of ongoing transmission over multi-hop network leads to throughput degradation. Moreover, the amount of needed signaling packets takes place at every hop reduces the overall multi-hop throughput significantly. This project proposes a set of enhancement to the existing IEEE 802.11 DCF MAC by enabling concurrent transmission by the exposed nodes and reduces the amount of signaling packets (CMAC-SS) required at every hop until the data packet reaches its destination. Analytical models are developed and simulated over quasi-static Rayleigh fading channel. The multi-hop network performances are evaluated in terms of throughput and delay. The CMAC-SS protocol outperforms the existing IEEE DCF MAC with more than 14% increase in overall throughput of multi-hop WMN.

Keywords - Concurrent Transmission; Exposed Node Problems; Short Signaling; MAC Protocol; Multi-hop WMNs

I. INTRODUCTION

Wireless Mesh Networks (WMNs) have a huge potential for uses such as providing campus-wide network coverage and bringing broadband Internet connectivity to remote and rural areas. Medium Access Control (MAC) protocols employed in multi-hop WMNs to resolve contentions for accessing the shared medium encountered many issues especially exposed node problems and large overhead due to its unique characteristics and multi-hop communications [1, 2]. In view of the fact that the existing MAC protocols and its derivatives hard to achieve optimal overall throughput as the number of hops increases in WMNs, the enhancements of the existing IEEE 802.11 Distributed Coordination Function (DCF) MAC protocol [3] have been proposed.

Concurrent transmission has been proposed as a transmission strategy to combat exposed node problems in order to improve the overall throughput of multi-hop WMNs. Among the earliest work on enabling concurrent transmission in WMNs is the proposal of Cooperative Medium Access Scheme [4] which contributes to significant improvement in the overall throughput of WMN. The work in [4] is further improved by [5] with the introduction of Multiple Access Collision Avoidance-Parallel or MACA-P protocol. The protocol introduces a control gap between the RTS/CTS exchange and the subsequent DATA/ACK exchange of communicating nodes pair of the first hop. The control gap knowledge is then exploited by the exposed node of the communicating nodes pair of the first hop to complete their own RTS/CTS exchange and to align their data transfer with the DATA and ACK packets of the first hop communicating nodes. However MACA-P is only performing well for specific scenario where large size of payload is considered. In addition the protocol causes wasted idle time due to scheduling of infeasible concurrent transmission at intermediate nodes especially when low traffic is considered in multi-hop communication.

Another interesting work in [6] has proposed an enhancement to the existing IEEE 802.11 MAC by enabling the nodes to identify themselves as an exposed node and opportunistically schedule concurrent transmission whenever possible. However the protocol enables the concurrent transmission for the exposed node which is caused by Network Allocation Vector (NAV) of RTS only.

Since the source relaying its data packets over multiple hops until reaches its destination, the large number of overhead due to signaling at each intermediate hop will degrade the throughput significantly. Medium Access with Reduced Handshake (MARCH) protocol has been proposed to reduce the overhead of multi-hop network [7]. The RTS/CTS handshake only performed by the first hop communicating nodes pair while the subsequent hops communicating nodes pairs utilize a new signaling packet named as CTS-only. Since fewer signaling packets are exchanged over multiple hops, the overall throughput can be increased significantly. Moreover the

probability of packet collision among the signaling packets has been reduced. However the protocol performs poorly when high traffic is considered in multi-hop network and exposed node problem is occurred at the first hop.

In this paper, we are focusing on how to reduce both the exposed node and large signaling overhead problems in multi-hop networks with high traffic scenario. The major contribution of this paper is the introduction of Concurrent MAC with Short Signaling (CMAC-SS) protocol which alleviates the exposed node problem in multi-hop WMNs, by enabling the concurrent transmission at the first hop and reduces the number of signaling packets needed at intermediate hops until the data packet reaches its destination.

The rest of this paper is organized as follows. Section II presents the problem definition which leads to the network model of the proposed system in Section III. Then section IV describes the CMAC-SS protocol operations and section V presents the performance model. Section VI explains the performance results and conclusion are given in Section VII.

II. PROBLEM DEFINITION

As the IEEE 802.11 DCF CSMA/CA mechanism was developed with one-hop data communication in mind, it was a later finding that MAC protocols utilizing this mechanism perform poorly in multi-hop networks. Such multi-hop networks however currently exhibit very poor performance in term of overall through-put. It is important to realize that the important factors that contribute to this poor performance are the MAC's inability to efficiently support multi-hop communication.

Several studies [8–10] have shown that, the IEEE802.11 MAC is primarily responsible for sharp drop in through-put when transmitted over multiple hops. One of the reasons behind this through-put degradation is because the current IEEE802.11 MAC which is initiates four way hand shaking control packets prior transmitting its data results unnecessary reduction in channel utilization. For example, refer Figure 1, let's assume node A and B have a data packet to be transmitted to their respective receiver node C and D at the same time. According to the current standard, after a proper carrier sensing let's assume node A have an access to the channel first. When node A initiates its RTS control packet, it will silence its neighboring nodes (i.e. Node B in Case 1) for an entire duration of the transmission. This is same goes when the destination node replies with the CTS control packet where it will silence its neighboring nodes (i.e. Node D in Case2) for an entire transmission. So Node B's transmission to Node D will be delayed until the entire packet exchange from Node A to node C completes. This is so called as exposed node problem, which is still remaining unsolved when using existing protocol.

Now let's consider back Figure 1, since Node A's transmission range does not include Node D (and vice versa),

and Node B's transmission does not includes Node C (and vice versa) the both transmission Node A to Node C and Node B to Node D should be able to perform simultaneously without any collision. However as explained before, the current standard which is invoking virtual carrier sensing disallows this type of transmission and lead to unnecessary reduction in channel utilization. So this paper, we proposed an enhancement to the IEEE802.11 MAC for obtaining higher concurrency in WMNs.

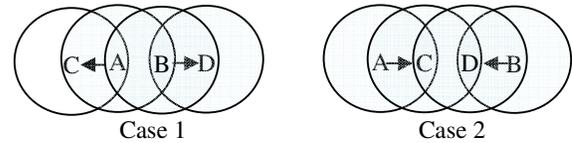


Figure 1. Unnecessary Reduction in Channel Utilization

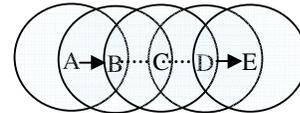


Figure 2. Multi-hop Transmission via intermediate nodes

Other than that, another reason behind throughput degradation in multi-hop communication is number of control packet required when transmitting a data packet from one node to destination via multiple intermediate nodes. As shown in Figure 2, let's consider Node A have data packet to be transmitted to Node E. Since Node E does not include Node A's transmission range, Node A have to transfer its data packet via intermediate to reach the destination. In this case, the data packet must go through 3 intermediate Node B, Node C and Node D to reach the destination. When the existing MAC protocol employ this type of multi-hop communication, the four way handshake must perform at every each intermediate nodes thus increasing the delay and reduce throughput. So, some enhancement is presented in this paper to reduce the number of control packet in multi-hop WMN. In our approach the concurrency is only performs at first hop when the node initiates the transmission to forward the data packet. Whereas the subsequent forwarded hops will initiates its transmission by reducing the signaling packet.

III. NETWORK MODEL

The network we considered consists of n mesh routers, mesh clients and gateways. Gateways to the Internet are chosen from a set of n mesh routers. The other mesh routers are referred to as intermediate mesh routers. The network topology is shown in Figure 3.

Each mesh router is equipped with single interface except the gateway (another interface to Internet) and has a common transmission range, r . Both the mesh clients and mesh routers use the same Physical Layer (PHY) frequency band by which in this work we consider the use of IEEE 802.11 PHY [11]. The transmission rate is constant and packets are forwarded in

a multi-hop fashion to the gateway. For ease of explanation and without loss of generality, we consider unidirectional traffic, i.e., traffic only going from mesh nodes to the gateway.

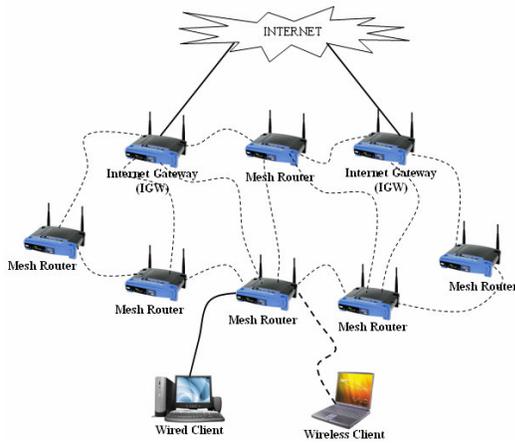


Figure 3. Network topology

We assume that each mesh router has a fixed transmission rate at 54 Mbps and range of 100 meters. Thus two routers can only set up a link between them and communicate when they are within the transmission range. As for the mesh clients, some of them are associated to a certain mesh router forming a cell. Data packets originating from the cells are relayed concurrently by the intermediate mesh routers hop by hop to Internet through the gateways as shown in Figure 4.

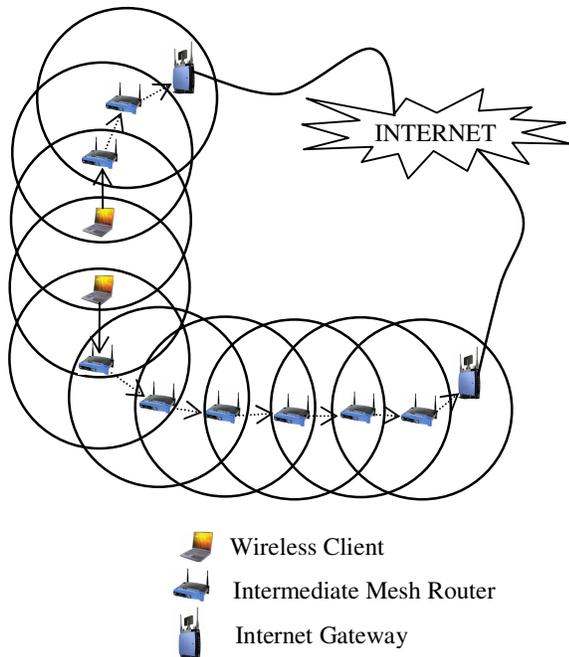


Figure 4. Forward packet to gateway via intermediate router

IV. PROTOCOL DESCRIPTION

The proposed CMAC-SS protocol enable concurrent transmission at the first hop when it has data packet to be transmitted while reduce the amount of control handshake when the nodes relaying data to the gateway in multi-hop fashion.

Assume that node has data packet to be transmitted to a gateway and at the same time another node in the overlapping cell also has data packet to be transmitted to a gateway as shown in Figure 4. The key design of CMAC-SS protocol when compared to existing IEEE 802.11 MAC is the introduction of some overhead to schedule its concurrent transmission with its neighboring mesh nodes thus enable concurrency in the mesh network. This is done through modify the RTS and CTS signaling packets by introducing new duration field in the signaling frame structure. The duration field is designed to hold the DATA and ACK transmission start time. All neighboring nodes which overheard the RTS/CTS signaling packets will look at this duration field to schedule its transmission with the sender of RTS/CTS signaling packet.

When a node has data packet to be transmitted, the node initiates RTS packet which is hold the duration field of its DATA and ACK start time. The receiving intermediate mesh node allows this transmission by sending permission by using CTS packet which is also hold the duration field of its DATA and ACK start time. All of the neighbors of the current source and destination of the first hop are aware about the DATA and ACK start time, thus inviting these nodes to schedule its transmission at this start time. Figure 5 shows the timing diagram when enabling concurrent transmission.

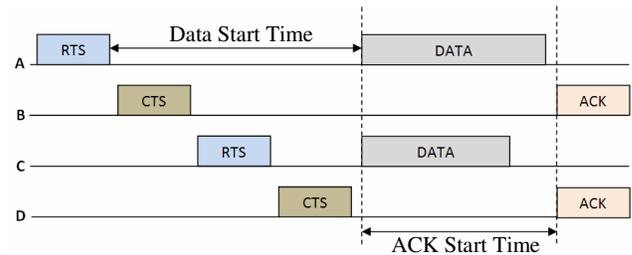


Figure 5. Timing Diagram of Concurrent Transmission

When other exposed nodes in the cell of the first hop communication have data packets to be transmitted, they schedule their data transmission with the source node by sending the RTS packet which is holding the same DATA and ACK start time. Since all the mesh nodes are aware of the DATA and ACK transmission start time, thus the exposed nodes can enable its transmission concurrently without collision with the source and other mesh nodes.

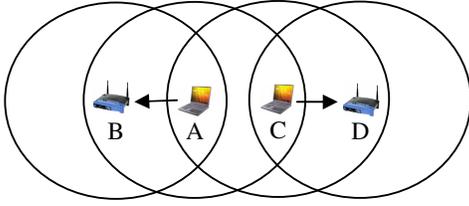


Figure 6. Concurrent Transmission

Let's consider Figure 6, where client A and C are one hop neighbors. During the transmission from client A to router B, it does not permit a feasible concurrent transmission from client C to router D by the client C which is in the range of client A. Our approach can enable such as concurrency as stated before. Let's refer back above figure and assume that client A has data packet to be transmitted to router B. This transmission begins by initiating a RTS/CTS exchange with router B. Since client C overhears RTS control packet from client A, it will update its NAV to indicate that client A has scheduled a transmission to router B. Since client C is aware of the DATA and ACK start time of client A, thus it will schedule its transmission at this start time by initiating a RTS/CTS exchange with router D as discussed before.

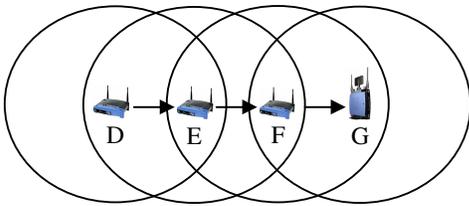


Figure 7. Short Signaling

Let's assume after successfully enabling concurrent transmission at the first hop, the data packet has to relay via some intermediate hops (mesh routers) until it reaches the internet gateway as shown in Figure 7. We instigate some enhancement by reducing the amount of signaling packets that occurs at intermediate nodes. Our proposed protocol exploits the broadcast characteristic of omnidirectional antennas to reduce the number of required handshakes. Since every node which is exploiting omnidirectional broadcast has the capability of overhearing, we can use this capability as a cost advantage to convey the data packet to subsequent nodes.

The signaling overhead is shortened by using a timer mechanism to control the transmission of CTS packets. The timer is activated once the respective node overhears a CTS packet. The duration of the timer is set to be equal to the time taken by a node to transmit its data packet and until it receives an ACK packet. Upon timeout, the sender node invites the receiving node to send the data packet by sending its CTS packet. Thus, the RTS packet that is supposed to be sent by the sender node can be suppressed. This mechanism continues to repeat

at each intermediate hop until reaching the gateways. Figure 8 shows the basic structure of the CMAC-SS protocol.

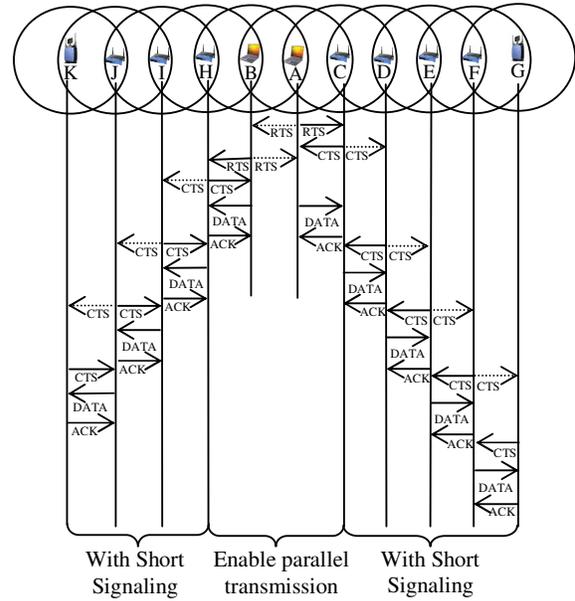


Figure 8. Basic Structure of CMAC-SS Protocol

V. PERFORMANCE MODELS

In this section, analytical models are developed and analyzed for IEEE 802.11 protocol [3], MACA-P protocol [5], MARCH protocol [7] and the proposed CMAC-SS protocol. The models are evaluated in terms of throughput and delay of the system. The delay is defined as the time consumed while the data packets travel from the source nodes (mesh clients) to destination nodes (gateways). Also, the delay term includes inter-frame space (IFS), back-off time, and transmission time of all signaling frames.

We simply divide the MAC Service Data Unit (MSDU or $Payload_{SIZE}$) with the total delay per payload ($Delay$) to get the maximum throughput of the system. Therefore, the throughput provided at the MAC layer can be given as:

$$MAC_{Throughput} = \frac{Payload_{SIZE}}{Delay} \quad (1)$$

The delay per payload is given as:

$$Delay_{per\ Payload} = T_{DIFS} + Backoff\ Interval + T_{RTS} + T_{SIFS} + T_{CTS} + T_{SIFS} + T_{DATA} + T_{SIFS} + T_{ACK} \quad (2)$$

The times taken for the signaling such as RTS, CTS, and ACK are given as:

$$T_{RTS} = T_{Preamble} + T_{Signal} + T_{SYM} \times \left[\frac{L_{Service} + L_{Tail} + 8 \times L_{RTS}}{N_{DBPS}} \right] + T_{EX} \quad (3)$$

$$T_{ACK} = T_{Preamble} + T_{Signal} + T_{SYM} \times \left[\frac{L_{Service} + L_{Tail} + 8 \times L_{ACK}}{N_{DBPS}} \right] + T_{EX} \quad (4)$$

$$T_{CTS} = T_{Preamble} + T_{Signal} + T_{SYM} \times \left[\frac{L_{Service} + L_{Tail} + 8 \times L_{CTS}}{N_{DBPS}} \right] + T_{EX} \quad (5)$$

The time taken to transmit DATA packet is given as:

$$T_{DATA} = T_{Preamble} + T_{Signal} + T_{SYM} \times \left[\frac{L_{Service} + L_{Tail} + 8 \times (L_{MAC} + Payload)}{N_{DBPS}} \right] + T_{EX} \quad (6)$$

Thus the total delay per payload can be simplified as a function of payload size (χ) in bytes:

$$Delay \text{ per Payload } (\chi) = [(a\chi + b) + c] \mu s \quad (7)$$

where $a\chi + b$ is the delay component for DATA packet and c is delay component for summation of signaling period, IFS and back-off period.

Therefore, we can get $MAC_{Throughput}$ as a function of payload size (χ) by simply divide the number of payload (in bits) by the total delay which is given as follow:

$$MAC_{Throughput}(\chi) = \frac{8 \times \chi}{[(a\chi + b) + c]} \times Mbps \quad (8)$$

By using Equation (8), we can perform the performance analysis for the following related models. Table 1 gives all the related system parameters.

TABLE 1. IEEE802.11G PARAMETERS

Parameters	Value
$T_{PREAMBLE}$	16 μs
T_{SIGNAL}	4 μs
$L_{SERVICE}$	16 bits
T_{SLOT}	9 μs
T_{SIFS}	10 μs
T_{DIFS}	28 μs
T_{SYS}	4 μs
T_{EX}	6 μs
L_{TAIL}	6 bits
L_{ACK}	14 bytes
L_{CTS}	14 bytes*
L_{RTS}	20 bytes*
L_{MAC}	34 bytes
CW	15- 1023

* The length of RTS and CTS packets, L_{RTS} and L_{CTS} respectively different for every each model. MACA-P defines $L_{RTS} = 24$ bytes, $L_{CTS} = 18$ bytes and MARCH defines $L_{RTS} = L_{CTS} = 28$ bytes. We define $L_{RTS} = L_{CTS} = 32$ bytes. The length of these control frames vary for each model due to the different approaches and modification that have been made for

the protocols. The standard lengths for IEEE 802.11 MAC are as defined in the Table 1.

A. Performance Evaluation of IEEE 802.11 MAC

According to the existing IEEE 802.11 MAC mechanism, every node will perform four way handshakes for transferring its data packet to destination. The neighboring nodes who hear the control frames will update its NAV and must remain silent until the entire transmission is complete. If these nodes have data packets to be transmitted during this period, this implies that the node delayed its transmission for the duration which specified in its NAV. This delay must take into consideration when calculating its throughput. The neighboring nodes which hear the RTS control frame must remain silent for the duration as given below:

$$T_{NAV(RTS)} = T_{SIFS} + T_{CTS} + T_{SIFS} + T_{DATA} + T_{SIFS} + T_{ACK} \quad (9)$$

The neighboring nodes which hear the CTS control frame must remain silent for the duration as given below:

$$T_{NAV(CTS)} = T_{SIFS} + T_{DATA} + T_{SIFS} + T_{ACK} \quad (10)$$

The overall throughput of the system which is using this access mechanism can be finding by using the following equation:

$$MAC_{Throughput}(\chi) = \frac{8 \times \chi}{n \times [(a\chi + b) + c] + k \times T_{NAV}} Mbps \quad (11)$$

where k is the number of exposed mesh nodes. This is due the characteristic of virtual carrier sensing.

B. Performance Evaluation of MACA-P

The overall throughput for MACA-P can be found by using the following equation:

$$MAC_{Throughput}(\chi) = \frac{8 \times \chi}{t \times [(a\chi + b) + c] + t \times [T_{DATASTR}] + t \times [T_{ACKSTR}]} Mbps \quad (12)$$

where $T_{DATASTR}$ and T_{ACKSTR} are the additional delays which are introduce in this protocol for enable possible scheduling thus performing concurrent transmission and can be given as:

$$T_{DATASTR} = T_{DIFS} + Backoff \text{ Interval} + T_{RTS} + T_{SIFS} + T_{CTS} + T_{SIFS} + T_{RTS \text{ Prime}} + T_{SIFS} \quad (13)$$

$$T_{ACKSTR} = T_{DATAMASTER} - T_{DATASECONDARY} \quad (14)$$

where t is the number of hops.

C. Performance Evaluation of MARCH

The delay at the first hop is different compared to the delay experiences for subsequent hops to the gateways due to reduction mechanism of control overhead at intermediate nodes

till the data packet reaches gateways. Therefore the delay introduced at subsequent intermediate nodes can be given as:

$$\tau_{NODESSQN} = T_{SIFS} + T_{CTS} + T_{SIFS} + T_{DATAe} + T_{SIFS} + T_{ACK} \quad (15)$$

The overall throughput of the system can be found by:

$$MAC_{Throughput}(\chi) = \frac{8 \times \chi}{n \times [\tau_{NODESSQN}] + l \times [T_{NAV}] + q \times [(a\chi + b) + c]} Mbps \quad (16)$$

where q is nodes which initiates its transmission by using four way handshake access mechanism.

D. Performance Evaluation of CMAC-SS

The proposed CMAC-SS performs the concurrent transmission at first hop. The delay at first hop can be given by:

$$\tau_{TDH1} = 2 * [(a\chi + b) + c] + T_{DATASTR} + T_{ACKSTR} \quad (17)$$

The throughput of CMAC-SS protocol can be found by using the following equation:

$$MAC_{Throughput}(\chi) = \frac{8\chi}{\tau_{TDH1} + g * [\tau_{NODESSQN}]} \times 10^6 \text{ bps} \quad (18)$$

where τ_{TDH1} is the total delay at the first hop when the protocol performs concurrent transmission and $\tau_{NODESSQN}$ is the delay at intermediate nodes per payload. The total delay for intermediate nodes can be calculated by multiplying it with number of intermediate hop, g .

VI. PERFORMANCE RESULTS

Figure 9 depicts the variation of throughput as a function of payload for various MAC protocols. We can observe that the proposed CMAC-SS protocol outperforms IEEE 802.11, MARCH and MACA-P protocols.

The high traffic scenario is considered at the first hop. Since MACA-P was designed with concentric ring topology in mind, it suffers throughput degradation when applied for suggested topology as shown in Figure 4. This is due to the scheduling of infeasible concurrent transmission at intermediate nodes causing a lot of time wasted idling.

Also, we observe in the Figure 9 that the other two protocols, MARCH and IEEE 802.11 MAC have gained higher throughput over MACA-P protocol. Perhaps this observation is due to the smaller total delay per payload.

Moreover the proposed CMAC-SS protocol outperforms the other protocols especially when the larger payload size is considered as shown in Figure 10. Obviously this observation shows that the proposed CMAC-SS reducing the delay caused by the exposed node phenomenon at the first hop and reducing

the delay caused by idling at intermediate mesh nodes significantly.

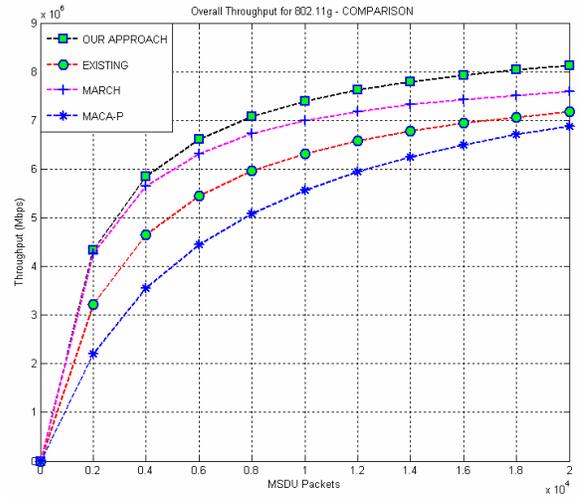


Figure 9. Throughput vs. payload size for various MACs

VII. CONCLUSIONS

We propose a set of enhancement to the existing IEEE 802.11 DCF MAC by enabling concurrent transmission by the exposed nodes and reduce the amount of signaling packets required at every hop until the data packet reaches its destination. The protocol is known as Concurrent MAC with Short Signaling or CMAC-SS. Analytical models are developed and the multi-hop mesh network performances are evaluated in terms of overall throughput and delay. We have shown that CMAC-SS protocol outperforms the existing IEEE DCF MAC with more than 14% increase in overall throughput of multi-hop WMN.

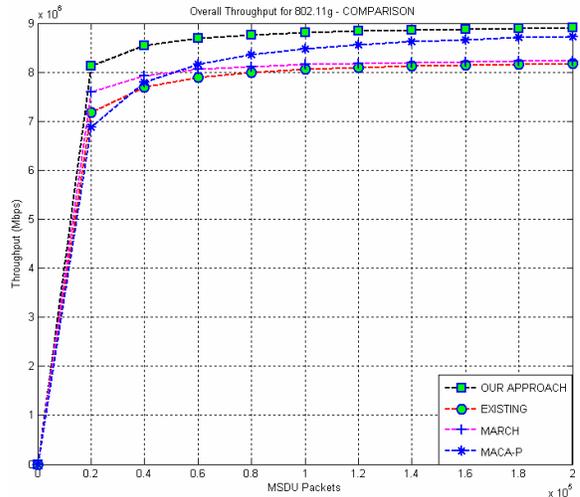


Figure 10. Throughput vs. large payload size

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