PERFORMANCE EVALUATION OF MODIFIED IEEE 802.11 MAC FOR MULTI-CHANNEL MULTI-HOP AD HOC NETWORKS

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In this paper, the IEEE 802.11 multiple access control (MAC) protocol was modified for use in multi-channel, multi-hop ad hoc networks through the use of a new channel-status indicator. In particular, in the modified protocol, the RTS/CTS dialogue is exchanged on the common access control channel and data packets are transmitted on a selected traffic channel. We have evaluated the improvement due to the multi-channel use and we report in this paper on the results of the per-node throughput and the end-to-end delay for different network sizes. Using these results, we were able to propose a number of per-node throughput scaling laws. Our simulation results show that the per-node throughput with multiple channels for the fully connected, the line, and the grid ad hoc network topologies increases by 90% to 253%, by 47%, and by 139% to 163%, respectively, for networks with 16 to 64 nodes, as compared with that of a single channel.

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Keywords: Ad Hoc Networks, 802.11, Multiple Channel, Multiple Access Control Protocol

1. Introduction

Mobile Ad Hoc Network (MANET) is an emerging technology that allows establishing instant communication infrastructures for civilian and military applications [3,5]. MANET is a network architecture that can be rapidly deployed, without relying on the pre-existing fixed network infrastructure. The nodes in a MANET can dynamically join and leave the network, frequently, often without warning, and possibly without disruption to other nodes' communication. The nodes in the network can be highly mobile, thus the network topology may be rapidly changing. The main difference between the MANET and the wireless cellular technologies (such as the 2G/3G systems) is in the fact that all the nodes in an ad hoc network serve as routers.

Target applications [5] of mobile ad hoc networks range from collaborative, distributed mobile computing (sensors, conferences, conventions) to disaster recovery (such as fire, flood, earthquake, search and rescue), law enforcement (crowd control, border patrols) and tactical communications (digital battlefields). An ad hoc network is a self-organizing network and communications are mostly implemented with multihop wireless links. Mobility of network members, limited resource (e.g. bandwidth and energy supply), and potential large number of mobile nodes make multiple access control, routing, and management of ad hoc networks extremely challenging.

The IEEE 802.11 WLAN protocol has been used by many researchers as a model for Medium Access Control (MAC) layer protocol for ad hoc networks and many papers (e.g., [9]) have investigated the performance of the 2Mbps IEEE 802.11 MAC for such networks. However, these works used the protocol with a single channel only. This paper extends the single channel IEEE 802.11 MAC for use with multiple channels. Through the use of the OPNET™ simulator, the performance of the modified IEEE 802.11 MAC with multiple channel over multi-hop ad hoc networks has been extensively evaluated. Simulation results show that the multi-channel networks can achieve significant performance improvement, as compared with the single-channel case.

The rest of this paper is organized as follows. The modification of the IEEE 802.11 MAC to accommodate multiple channels is presented in Section II. The model of multihop ad hoc network is given in Section III. The throughput and the scaling laws of multi-channel, multihop ad hoc networks are presented in Section IV. The conclusions are discussed in Section V.

2. The Modification of IEEE 802.11 MAC for Multiple Channels

2.1. *Multi-channel Operation*

In the commercial 2.4GHz or 5GHz ISM and U-NII frequency bands, multiple channels are implemented; see Fig. 1 for the 2.4GHz channel allocation. Typically, these channels are used by different applications. However, if we use multiple channels for a single application in a smart way, we can significantly improve the overall capacity of the network without affecting the other users of these spectral bands.

For example, if we use the multiple channels in the network with a fully connected topology, the maximum per-node throughput will be 1.0 Mbps for channel data rate of 2Mbps with half-duplex operation (without consideration of the transmission overheard), where each pair of nodes would communicate on a different channel and under the assumption that the number of channels is sufficiently large.

In the optimal case, a network will reach its maximum capacity when any pair of nodes communicates on a different channel without being affected by the transmission of any other node. That is, if any pair of nodes can capture a separate channel, the throughput of the network is maximized. Of course, such a scenario would require too many channels and is, thus, impractical. However, if the channels are chosen in such a way that spatial reuse is possible, still the improvement can be significant. This is what we propose in this work.

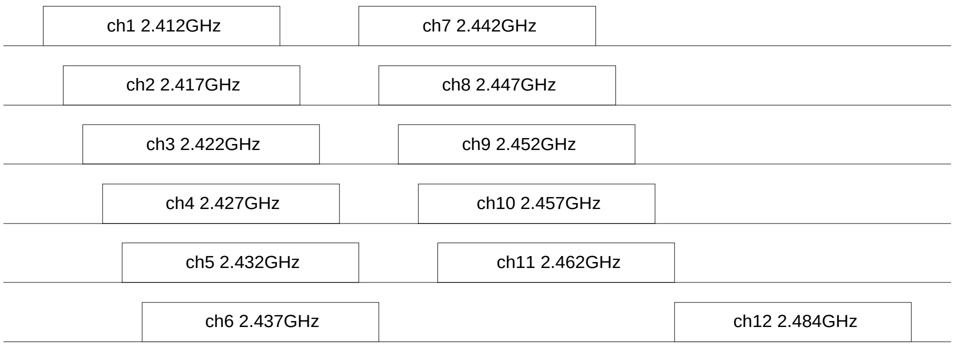


Fig.1: Channel allocation in 2.4GHz ISM band

A number of protocols, such as AACA [8], have been proposed for communication in multi-channel environment with a fixed total bandwidth, which could be, in principle, used for implementation of a multi-channel ad hoc network. However, we opted to evaluate the multi-channel performance of an already existing standard, the IEEE 802.11 protocol, due to its highly accepted commercial status. We use the multiple channels in the IEEE 802.11 standard to create spatial reuse and, consequently, to increase the overall system capacity. The channels are dynamically assigned to the nodes, based on the topological and traffic information.

Two basic methods for channel assignment are possible: the *Measurement-Based Method* and the *Status-Based Method.* In the Measured-Based Method, a node is equipped with the capability to measure either the signal strength, the signal to noise ratio, or the signal to interference ratio. A node periodically scans each channel to find the channels with acceptable interference conditions. Note that additional hardware to scan the channels is necessary. As if only one receiver is available, it might be difficult to share the receiver between the data transmission and channel scanning operations. In the Status-Based Method, each node acquires the channels' busy/idle status through monitoring to the exchanges of the MAC-layer control packets. Based on the channel status, an available channel is then selected for use.

The Status-Based Method is selected as the channel assignment scheme in this paper. To make our scheme compatible with the current IEEE 802.11 standard, we rely on a single common access control channel. Nodes listen on the common access control channel, except when they transmit data on traffic channels.

Since the frame of the IEEE 802.11 standard does not contain any information about the channel status, we propose two possible extensions. In the first method, the channel information is embedded in the RTS (Request–To-Send) and the CTS (Clear-To-Send) frames; in the RTS frame, a (short) list of potential channels is sent out to the receiver. The receiver selects one channel and confirms its choice in the reply CTS frame. The second method is to use a special control packet, the *Self- Organizing Packet (SOP)*, to broadcast the channel status information by every node. The SOP is broadcasted only on the common access control channel.

Each node keeps a table of the currently used channels, with the time until when the current use expected to expire (T_{CH}), as shown in Table 1.

Table 1: Channel status table.

Channel Number	Expiration Time	Sending Node	Receiving Node
CH1	T_{CH1}	S1	R1
CH2	T_{CH2}	S2	R2
…	…	…	…
CHn	T_{CHn}	Sn	Rn

For a particular channel and after the expiration time of its current transmission, the channel is declared idle and ready for use. Such channel can be chosen the next time that the a node is required to send a data packet. The information about sending and receiving nodes can be used to identify whether a recipient in busy or not.

2.2. *IEEE 802.11 MAC Modification*

As explained above, we use the RTS/CTS dialogue, exchanged on the common access control channel, to make reservations of the traffic channel for data packet transmissions. Data packets and the corresponding acknowledgements (ACKs) are transmitted on the traffic channel. The basic procedure for the modified IEEE 802.11 MAC operation with multiple channels is shown in Fig. 2.

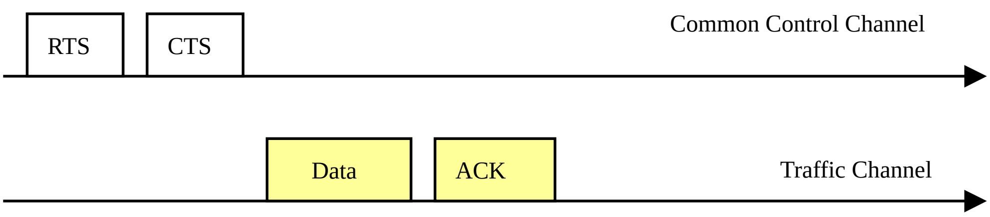


Fig. 2: The operation of the modified IEEE 802.11 MAC with multiple channels

The procedure for channel allocation is as follows. Once the sender receives from the receiver the confirmation (embedded in CTS) of the choice of the traffic channel, it will immediately tune its current channel to that traffic channel. After the data transmission is completed and the corresponding ACK is received, the sender will reset its current channel to the common access control channel. If no ACK is received, the sender will retransmit the packet until the ACK is received or until the data retransmission limit is reached, in which case it will discard the data frame and immediately resets its current channel to the common access control channel.

The recipient will change its current channel to the assigned traffic channel after it had sent the CTS frame. After the data frame is received, the recipient will send the ACK frame and retune its current channel to the common access control channel. If no data is received within a specified interval (T_{th}=*CTS duration + data packet duration + ACK duration + 3*SIFS (Short Inter Frame Space) + 3*propagation delay*, as shown in Fig. 3), the recipient will reset immediately its current channel to the common access control channel. A timer for T_{th} is set when the recipient sends the CTS and is terminated when the ACK is sent (at T_a).

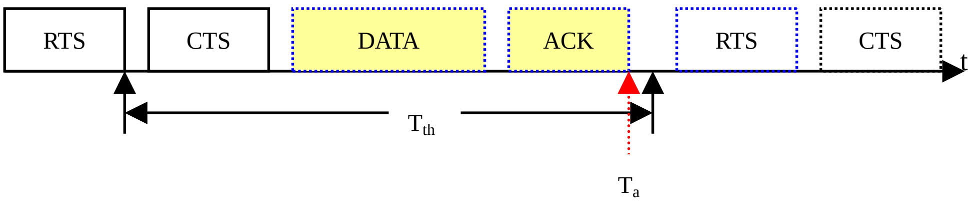


Fig.3: Setting the value of T_{th}

The data retransmission algorithm of the MAC has considerable effect on the throughput. If the first transmission of a data packet fails or if the ACK is not received correctly, the recipient will retune to the common access control channel and any further retransmission on the traffic channel will be lost. To overcome this problem, two procedures can be used. The first procedure is that the sender will resend the RTS on the common access control channel and, after the CTS is received, it will retransmit the data packet on the newly assigned traffic channel. In the second procedure, the retransmission is done on the common access control channel. As the retransmission delay associated with the first procedure is longer, we chose to use the second procedure is this paper, which is shown in the Fig. 4.

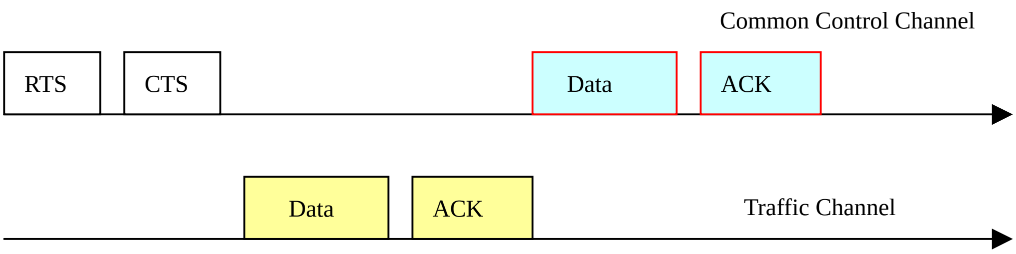


Fig 4: The retransmission procedure used in this paper

In a practical traffic channel, a data packet transmission failure can be caused by channel errors. In addition to channel errors, data packet transmission failure may be caused by the delay of the channel allocation procedure. This could happen when the channel change command is issued while the receiver is receiving. The channel change command only takes effect after the receiver finishes the reception of the current frame, as shown in Fig. 5.

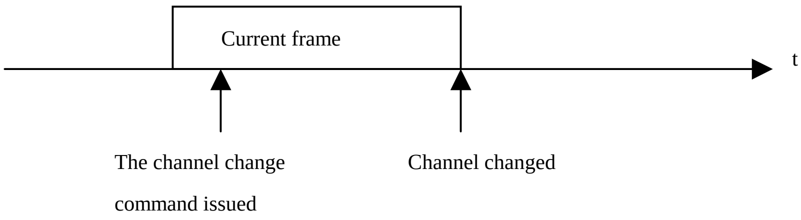


Fig. 5: Channel change delay.

A number of parameters can affect the end-to-end throughput of the network. The first parameter is the NAV (Network Allocation Vector), which is used to reserve the channel for the following data frame transmission. In IEEE 802.11 MAC, NAV_{RTS} = *CTS duration + data frame duration + ACK duration + 3 SIFS + 3 air propagation time* after the RTS is sent. Because the data and ACK frames are on the traffic channel in the multiple channel case, NAV_{RTS} can be reduced to *CTS duration + SIFS + air propagation time*. NAV for CTS can be reduced to zero.

The second parameter relates to the receiver availability. When node A wants to send a frame to node B, A can find out whether B is available (and thus listening to the common access control channel) by checking if B has sent RTS in the preceding time duration of *CTS duration + data frame duration + ACK duration + 3*SIFS + 3*propagation time* or has sent CTS in the preceding time duration of *data frame duration + ACK duration + 2*SIFS + 2*propagation time*. If so, the node A will wait for node B until the appropriate time duration has elapsed.

In addition to the RTS/CTS dialogue and the data frame retransmission, the broadcast frame is also transmitted on the common access control channel.

3. Node Model of Multihop Ad Hoc Network

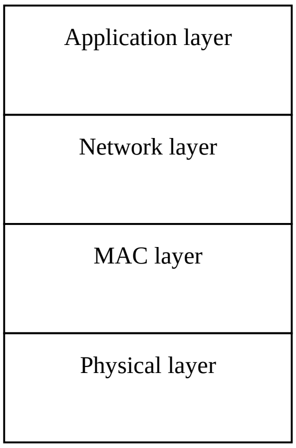
3.1. *Node model*

Protocols used in our evaluation are divided in four layers: the physical layer, the multiple access control (MAC) layer, the network layer, and the application layer, as shown in Fig. 6(a). Each node is equipped with a half-duplex radio transceiver, such as a wireless IEEE 802.11 WLAN card, which is available commercially. However, we assume that the transceiver can be tuned to work on multiplicity of channels. In our evaluation, we assumed that the number of channels is not a limitation on the system capacity.

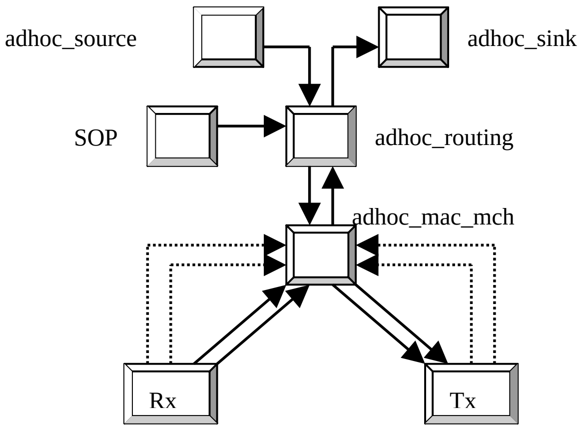
To evaluate the performance of the multi-channel scheme, we used the OPNET™ 8.0.C network simulator. The ad hoc node model as shown in Fig. 6(b) is based on the standard OPNET

WLAN station model, but we added the routing and the relaying functions in the network layer (i.e. the adhoc_routing module). The MAC module (adhoc_mac_mch) has been modified to support the multi-channel function according to the algorithm presented in the last section.

According to the IEEE802.11 standard, RTS and CTS frames are transmitted at 1Mbps. All other frames are transmitted at 2Mbps. The values of the other parameters are as follow: SIFS= 10 μs , T_{RTS} = T_{CTS} =128 μs including two channel information bytes. The data packet is fixed at 1024 bytes. T_{DATA}= 4344 μs , T_{ACK} = 64 μs , and the propagation time=1 μs . Time Slot = 20 μs , DIFS (Distributed IFS)= $SIFS + 2 * slot$ = 30 μs . The minimum contention windows size for selecting backoff slots =31 and the maximum contention windows size for selecting backoff slots =1023. The maximum radio communication distance is 300m, and the MAC layer buffer size is 1024000 bits. Finally, the RTS threshold is set at 256 bytes or to none.



(a) Protocol stack.



(b) Model of an ad hoc node.

Fig. 6: The model of an ad hoc node

To make sure that the common control channel is not the bottleneck of the network, we need to evaluate the throughput of the common access control channel by simulation. The simulation parameters are as follows: a control packet of 228 bits (another 240 bits MAC overhead will be added at MAC layer) is used to replace the RTS/CTS packets, the channel data rate is 2Mbps, and a fully connected topology with 8 nodes is assumed. The simulation results are evaluated for the following parameters: inter-arrival duration per node t=0.0055s and *PLR* (packet lost rate) = 7.5%; i.e., the average data rate of new packets (including all overheads at network and MAC layers) is 708.321kbps and the average successfully delivered data rate = 655.80kbps. Because one control packet transmission time + one ACK transmission time (= 234 μs + 64 μs = 298 μs) is longer then one RTS transmission time + one CTS transmission time (= 160 μs + 128 μs = 288 μs), the simulated control packet traffic is heavier than RTS/CTS traffic exchanged on the common access control channel. Thus the total minimum packet inter-arrival duration offered to the common control channel is t=0.044s to ensure that the successful rate of RTS/CTS > 92.5%.

3.2. *The Routing Protocol*

To concentrate on the evaluation of the network capacity, we used a simple proactive shortest path routing algorithm with fixed-overhead on the network layer (the distance vector algorithm), so that it is easy to estimate its effects on the network performance. To implement the routing function, we added a *Self-Organizing Packet* (SOP) module in the network layer (Fig. 6(b)). The SOPs contain the routing messages; each routing message contains the number of hops to the network destinations and the next relay node to the destination. After receiving a neighbor's SOP, a node finds out the identity of the neighbor and who can be reached through the neighbor. The routing table (RT) is shown in Table 2, where *Nx* node is the next relay node and *Dest i* is the destination *i*. The SOP module generates the SOPs periodically, with the period equal to a given constant plus a random number (in our simulation, it is equal to 5+*x* [sec], where *x* is random between 0 and 1.25 sec). The random part is used for avoiding repeated collisions of SOPs. The SOP packet format is shown in Fig. 7.

Table 2: Routing table.

Destination Node ID	Next Relaying Node ID	Hops To Destination
1	R_1	H_1
……		
N	R_N	H_N

SOP Header	Dest 1	Nx Node	Hops	……	Dest N	Nx Node	Hops

Fig. 7: SOP format.

To speed up the topology information collection and to make the best use of radio broadcasting channels, the WLAN MAC module (*adhoc_mac_mch*) has been modified to report every correctly received packet header to the *adhoc_routing* module. By checking the received packet header, a node can find out who is the neighbor that sent the packet and if the packet destination node is a new node not already included in the routing table. The node can also determine whether there is a new shortest route to a destination.

When sending or forwarding a packet, each node (Tx node), whether the source or a node relaying a packet, will consult the RT to determine the next relaying node (Nx node)) to the destination. The node then includes in packet header the next relying node as the current receiver

(Rx Node). The data packet header is as shown Fig. 8.

Packet Size	Packet Type	Rx Node	Tx Node	Source	Destination

Fig. 8: The packet header

We assume that at the application layer, the packet arrival is a Poisson process. Packets' destinations are randomly and independently distributed in the network nodes. This scenario corresponds to the situation when the ad hoc network is an independent network and network nodes communicate with each other freely.

To test the performance of the ad hoc network model, we have selected a number of typical topologies such the *grid*, the *line*, and the *fully connected*, with different number of nodes. We define the *source-destination throughput per node (S kbps)* as the total packet data rate in the network that is successfully delivered to the destinations divided by the number of nodes in the network. We define the *source-destination delay* as the end-to-end delay. All the above parameters are measured and are collected through simulation.

4. Throughput Evaluation of the Multihop Ad Hoc Network

4.1. *Overview of Single Channel Capacity of Multihop Ad Hoc Networks*

In recent years, the capacity of an ad hoc network with N nodes has been extensively studied. It was shown in [2] that under the Protocol Model of Interference, the per-node throughput of such a network behaves as $O\left(\frac{1}{\sqrt{N \log N}}\right)$, where N is the number of nodes in the network. It was also shown that even under the best possible placement of nodes, such a network could not provide a per-node throughput of more than $O\left(\frac{1}{\sqrt{N}}\right)$. To evaluate how current technology approaches these theoretically optimal results, the empirical scaling law of an ad hoc network with 8 nodes, each with a standard 2Mbits/s IEEE 802.11 compliant Lucent WaveLan card, was reported in [1]. The results in [1] indicate that the per-node throughput decays as $O\left(\frac{1}{N^{1.68}}\right)$. In [6], it was reported that the per-node throughput scaling law of the ad hoc network with large number nodes (from 200 to 600) is $\frac{0.047}{\sqrt{N}}$ Mbps with packet loss rate of 20% for the 2 Mbps Lucent WaveLan card model.

There are three factors that affect the throughput of an ad hoc network. The first one is the allowed packet loss rate. In general, the maximum throughput of a network using the IEEE

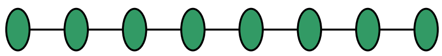
802-like random multiple access protocols depends on the offered traffic to the network; if we continue to increase the input arrival rate of new packets, after a certain thresholds the throughput increase will be marginal at best. However, the packet loss rate will increase exponentially. Thus, when comparing results, one needs to fix the packet loss rate to make sure that the comparison is meaningful.

The second factor that one needs to consider when evaluating network throughout is the routing overhead. Large routing overhead would consume much of the network capacity, significantly affecting the throughput available for actual data transmission. Since we want to evaluate the effect of the multi-channel use at the MAC layer, we need to make sure that either the routing (network) layer overhead is small, or use other method to eliminate its effects on the results. In general, if the routing overhead is less than 10% of the total capacity, its effect can be ignored.

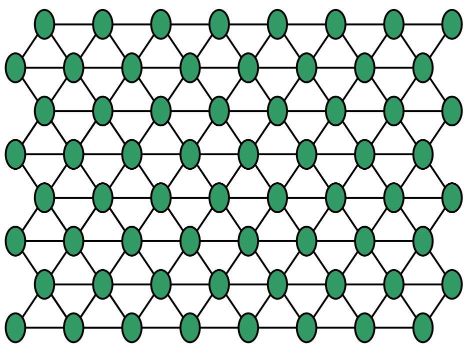
The third factor is the MAC layer buffer capacity. Packets are processed by the MAC buffer before they are sent onto the channel. If the MAC buffer is full, the MAC layer discards the newly arriving packets. If this kind of packet loss is counted in total packet lost, the final result will not accurately reflect the network capacity. Thus, only packet lost in the channel due to the operation of the MAC protocol should be counted. (Note that the situation is a bit more complicated, as in a multi-hop ad hoc network, the input packets to the MAC layer include the newly generated packets and the relayed packets. Both types of packets can be discarded when the MAC buffer is full and proper accounting is required to differentiate between the two loss mechanisms.)

It is very difficult to distinguish the packets whether they are lost in the channel or in MAC buffer. So, we need to observe the packet lost (indicated by *PLR* in simulation) both in the channel and in MAC buffer.

In our evaluation, we used three types of topologies: the *fully connected*, the *line,* and the *grid,* as shown in Fig. 9.



(a) Line topology.



(b) Grid topology.

Fig.9: Ad hoc network topologies.

When the routing protocol with the SOP module is used and the total packet lost rate is under 10%, the throughput results (*S*) for the single-channel case for the line and the grid topologies with the number of node N > 8 were reported in [7] as:

$S = 0.404 / N^{0.988}$ Mbps - for grid topology with RTS/CTS;

$S = 14.845 / N^{3.43}$ Mbps - for linear topology with RTS/CTS.

4.2. *The Throughput for Multi-channel, Multi-hop Ad Hoc Networks*

To eliminate the effect of routing overhead on the network throughput, in the following simulation we will stop sending the SOP in routing protocol after all the nodes in the ad hoc network found a shortest path to every other node in the network. To simplify the simulation, we assumed that there are N available channels and, thus, the channel assignment does not affect the network throughput evaluation.

The first case that we study is the full-connected network with N nodes. The per-node throughput results of the network with single channel and multiple channels are shown in Fig. 10. The *SCH* and *MCH* in the figures refer to the signal channel and multiple channel cases, respectively. The scaling laws of the per-node throughput based on the results in Fig. 10 are:

$S=1136/N^{1.05}$ kbps - for the single channel with packet lost rate=10% to 15%;

$S=583/N^{0.734}$ kbps - for the multiple channels with packet lost rate = 5% to 10%;

$S=651/N^{0.613}$ kbps - for the multiple channels with packet lost rate = 10% to 15%.

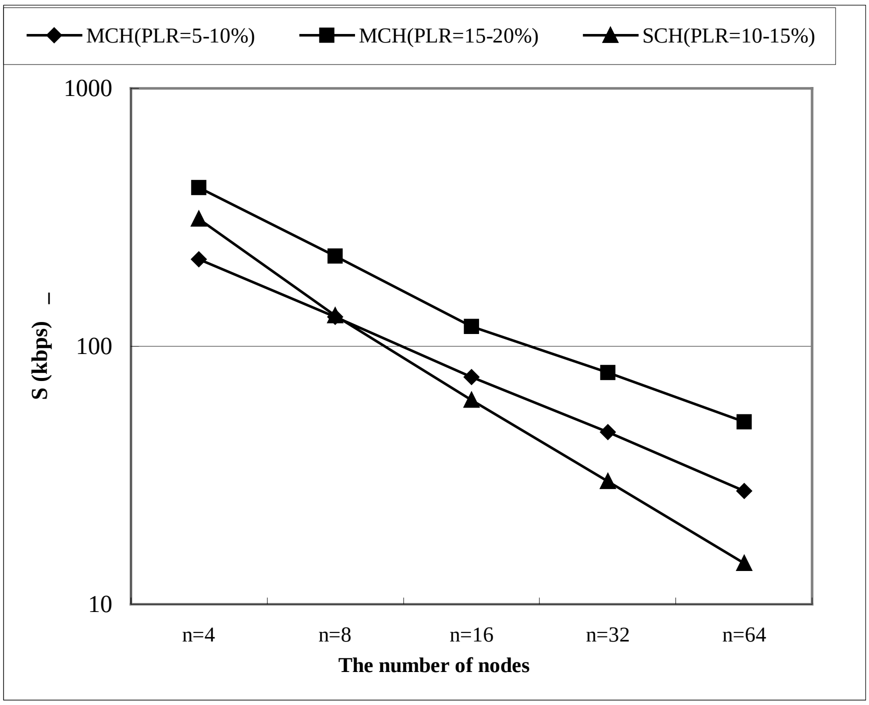


Fig. 10: The per-node throughput results for the fully-connected topology

From Fig.10, we can find that the per-node throughput for the multiple channel case will increase from 90% to 253% for n=64, as compared with that for the single channel case.

Our second case is the line topology, as shown Fig. 9 (a). This is a representative case of a situation when a set of nodes is traveling along a highway or when a set of sensors is used to collect data along a riverside, for example. The simulation results are shown in Fig. 11. From the figure, we have obtained the following scaling laws of the per-node throughput for the single- and the multiple-channels cases, when the allowable packet loss rate is between 10% and 15%:

$S=1215/N^{1.749}$ kbps - for the single channel with packet lost rate=10% to 15%;

$S=1568/N^{1.70}$ kbps - for the multiple channels with packet lost rate = 10% to 15%.

From Fig.11, we observe that the throughput per node with multiple channels increases by 47.8%, as compared with that of single channel.

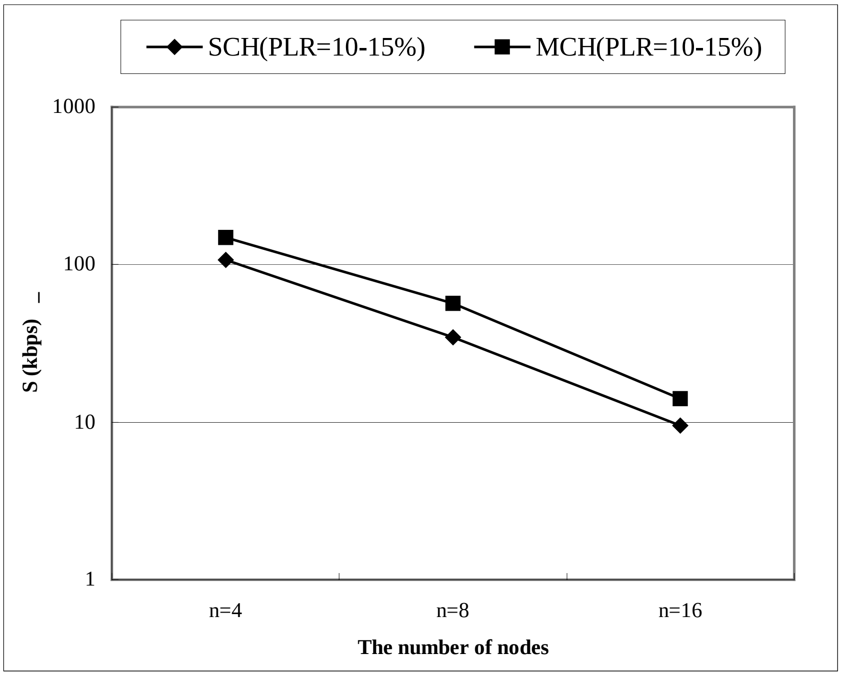


Fig.11: The per-node throughput for the linear topology

The third case is the grid network topology, as shown Fig. 9 (b). In this case, every node except the boundary nodes has six neighbors[a]. The simulation results are shown in Fig. 12. From the figure, we obtain the following scaling laws of the per-node throughput with multiple and single channel for N>8 and when the allowable packet loss rate is between 10% and 15%:

$S=285/N^{0.973}$ kbps - for the single channel with packet lost rate=10% to 15%;

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[a] Some studies consider the case of six neighbors to be the optimum topology for multi-hop networks, as far as capacity vs. connectivity trade-off is concerned.

S=883/N$^{1.035}$ kbps - for the multiple channels with packet lost rate = 10% to 15%.

From Fig.12, we can find that the per-node throughput with multiple channels increases from 139% to 163% for N=16 to 64, as compared with single channel case.

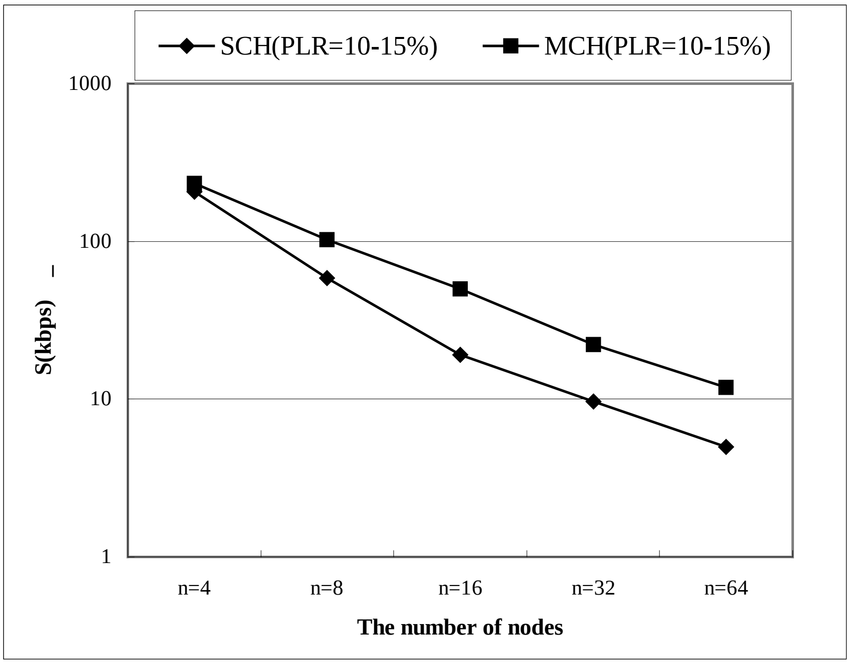

Fig. 12: The per-node throughput for the grid topology

End-to-end delays of the line and grid networks are shown in Fig.13. For the line network, the delay of the single-channel case is a bit higher than the delay of the multiple-channel case. For the grid network, the delay of the multiple-channels case is significantly reduced, as compared with the delay of the single-channel case.

5. Conclusions

In this work, the IEEE 802.11 MAC protocol was modified to allow communication over multiple channels in a multi-hop ad hoc network. We have presented an algorithm for channel selection and channel tuning rules. Based on the modified MAC protocol, we have evaluated the performance of the multi-channel, multi-hop ad hoc networks. Three typical topologies were considered and simulated: the full connected, the line and the grid topologies. We have presented the per-node throughput and the end-to-end delays with the modified IEEE 802.11 MAC for different network sizes. The scaling laws of the per-node throughput were presented. The simulation results have shown that the per-node throughput increases by 50% to 160%, when the multiple channels are used in the multi-hop ad hoc network.

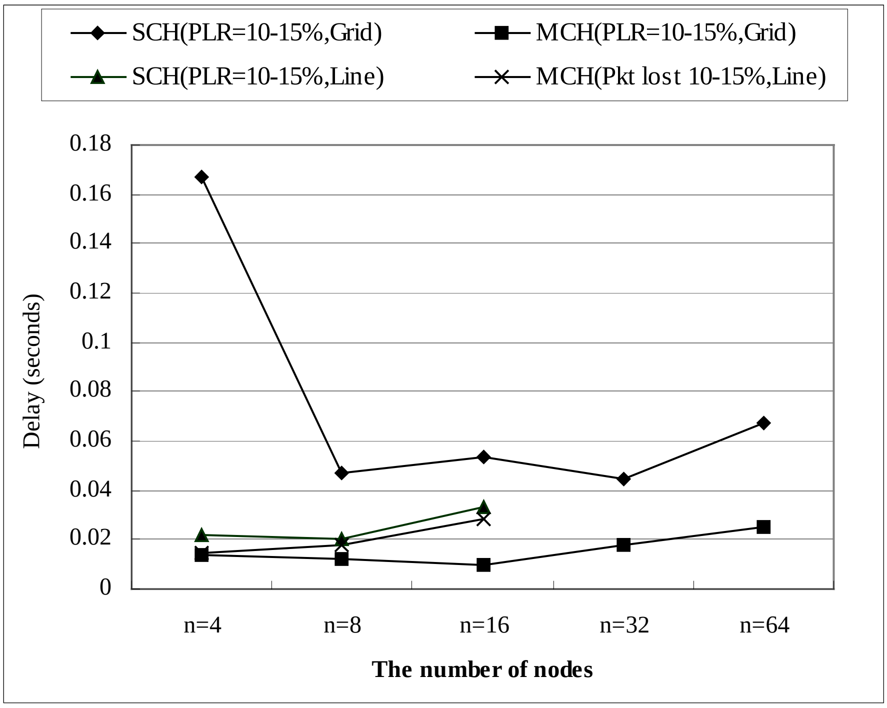

Fig. 13: The end-to-end delays of the line and the grid topologies

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