Performance Evaluation of Modified IEEE 802.11 MAC for Multi-Channel Multi-Hop Ad Hoc Network[*]

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Abstract

In this paper, the IEEE 802.11 multiple access control protocol was modified for use in multi-channel, multi-hop ad hoc network, through the use of a new channel-status indicator. In particular, we have evaluated the improvement due to the multi-channel use. We report in this paper on the results of the throughput per node and the end-to-end delay for the modified IEEE 802.11 protocol for different network sizes. Using these results, we were able to propose a number of throughput scaling laws. Our simulation results show that the throughputs per node with multiple channels for the line and the grid ad hoc network topologies will increase by 47.89%, and by 139-163%, respectively, for networks with 16 to 64 nodes, as compared with that of single channel.

1. Introduction

Mobile Ad Hoc Networks (MANETs) are an emerging technology that allows establishing instant communication infrastructures for civilian and military applications [1,2]. MANET is a network architecture that can be rapidly deployed without relying on pre-existing fixed network infrastructure. 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.

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., [3]) have investigated the performance of the 2Mbps IEEE 802.11 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. By using the OPNET™ simulator, the performance of the modified IEEE 802.11 MAC for multi-channel, 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 paper is organized as follows. The modification method of IEEE 802.11 for multiple channels is presented in Section II. The model of multi-hop ad hoc network is given in Section III. The throughputs and their scaling laws of multi-channel multi-hop ad hoc networks are given in Section IV. The conclusion is given in Section V.

2. Modification of IEEE 802.11 for Multiple Channels

2.1. Multi-Channel Operation

In commercial 2.4GHz or 5GHz ISM and U-NII frequency bands, there is enough bandwidth to create many channels. Typically, these multiple channels are used by different applications. However, if we use these channels in a smart way, we can significantly improve the overall capacity of the network, without affecting the

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other users of these spectral bands.

In the optimal case, a network will reach its maximum capacity when any pair of nodes can communicate on a different channel, without being affected by the transmission of any other node. That is, if any pair of nodes can capture a non-collision channel, the throughput of the network will be 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.

A number of protocols, such as AACA in [8], have been proposed for communication in multi-channel environment with a fixed total bandwidth, which could be, in principle, used for implementation of multi-channel ad hoc network. However, we opted to evaluate the multi-channel performance on 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 the additional required 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 listening to the MAC-layer control packets. Based on the channel status, an available channel is selected for use.

The Status-Based Method is used for channel assignment 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 reside on the common access control channel, except when they transmit data on another 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 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
…	…	…	…
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 when 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 RTS/CTS, exchanged on the common access control channel, to make the traffic channel reservations for data packets transmissions. Data packet and its acknowledgement (ACK) are transmitted on the traffic channel. The basic procedure for the modified IEEE 802.11 MAC with multiple channels is shown in Fig. 1.

Once the sender receives the confirmation of the choice of the traffic channel from the receiver, it will immediately change the working channel to that traffic channel. After the data transmission and reception of an ACK, it will reset the working channel to the common control channel. If no ACK is received, the sender will retransmit the packet on the common control channel until the data retransmission limit is reached, in which case it will discard the data frame and immediately resets the working channel to the common control channel.

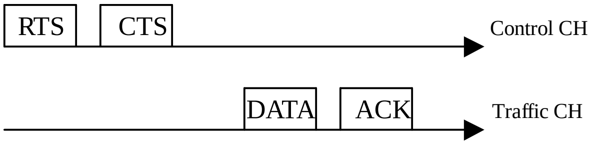


Fig. 1: IEEE 802.11 MAC for Multiple Channel

The receiver will change the working channel to the assigned traffic channel after it had sent the CTS frame. After the data frame is received, the receiver will reset the working channel to the common traffic channel after it had sent the ACK frame. If no data is received in a specified interval (*CTS duration + data packet duration + ACK duration + 3*SIFS (Short Inter Frame Space) + 3*propagation delay*), the receiver will reset immediately the working channel to the common channel.

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 the IEEE 802.11 protocol, NAV_{RTS} = *CTS duration + data frame duration + ACK duration + 3*SIFS + 3*propagation time* after 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 + propagation time*. NAV for CTS can be reduced to zero.

The second parameter relates to the receiver availability. When A wants to send a frame to node B, A can find out whether B is available (and thus listening to the common 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 after the appropriate time duration has elapsed.

3. The Model of a Multihop Ad Hoc Network

3.1. Node model

The protocols that we used in our evaluation are divided in four layers: physical layer, multiple access control (MAC) layer, network layer and application layer. Each node is equipped with a half-duplex radio transceiver, such as a wireless IEEE 802.11 LAN card available commercially. The transceiver can be tuned to work on different 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^{TM} 8.0.C network simulator. The ad hoc node model is based on the standard OPNET WLAN station model, but we added the routing and the relaying functions in the network layer. The MAC module 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= 10us, T_{RTS} = T_{CTS} = T_{SACK} =128us including two channel information bytes. The data packet is fixed at 1024 bytes. T_{DATA}= 4344us, T_{ACK} = 64us. Propagation time=1us. Time Slot = 20us, DIFS (Distributed IFS)= SIFS + 2 * slot = 30us.

3.2. The Routing Protocol

To concentrate on the evaluation of the network capacity, we used a simple proactive shortest routing algorithm with fixed-overhead in 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 network layer. The SOPs contain the routing messages; each routing message contains the 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 is shown in Table 2. 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.

Table 2 Routing Table

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

We assume that at the application layer, the packet arrival is a Poisson process. Packets' destinations are randomly and independently distributed to the network nodes.

4. Evaluation of Multi-Hop Ad Hoc Network

We evaluate the source-destination capacity and the end-to-end delay of our multi-channel network. To do so, only packets actually delivered to the destinations are counted.

4.1 Single Channel Capacity of Multi-Hop Ad Hoc Network

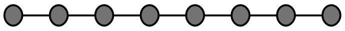
In recent years, the capacity of the ad hoc network with N nodes has been extensively studied. It was shown in [5] that under a Protocol Model of Interference, the per-node throughput of such a network behaves as $O\left(\frac{C'}{\sqrt{N\log N}}\right)$. It was also shown that even under the best possible placement of nodes, such a network could not provide a per-node throughput of more than $O\left(\frac{C''}{\sqrt{N}}\right)$. 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 [6]. The results in [6] indicate that the per-node throughput decays as $O\left(\frac{C}{N^{1.68}}\right)$. In [7], 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 ad hoc network. The first one is the allowed packet loss rate. 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 new packet arrival rate 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.

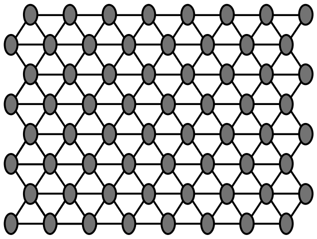
The second factor that one needs to consider when evaluating network throughout is the routing overhead. Large routing overhead would consume much of the network capacity, significantly affecting the throughput available for actual data transmission. Since we want to evaluate the effect of the multi-channel 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 got into the MAC buffer before they are sent on 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 reflect the network capacity. Thus, only packet lost in 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 distinguish between the two loss mechanisms.)

In our evaluation, we used two types of topologies: *line* and *grid*, as shown in Fig. 2.



(a) The *line* topology



(b) The *grid* topology

Fig.2: 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 [9] as:

- $S=0.404 / N^{0.988}$ [Mbps] for the grid topology with RTS/CTS;
- $S=14.845 / N^{3.43}$ [Mbps] for the linear topology with RTS/CTS.

4.2. Capacity of the Multi-Channel Multi-Hop Ad Hoc Networks

To get ride of the effect of the routing overhead on the network capacity, in the following simulations we stopped sending the SOPs after all the nodes in the ad hoc network found the shortest paths to every other node in the network. To simplify the simulation, we also assumed that there are *N* available channels.

The line topology is shown Fig. 2 (a). This is a typical case where a set of nodes is traveling along a highway or when a set of sensors is used to collect data along a river, for example. The simulation results are shown in Fig. 3. From the figure, we have obtained the following scaling laws of per-node throughput for the single and the multiple channels cases, when the allowable packet loss is between 10% and 15%:

- $S=1215/N^{1.749}$ [kbps] for the single channel
- $S=1568/N^{1.70}$ [kbps] for the multiple channels

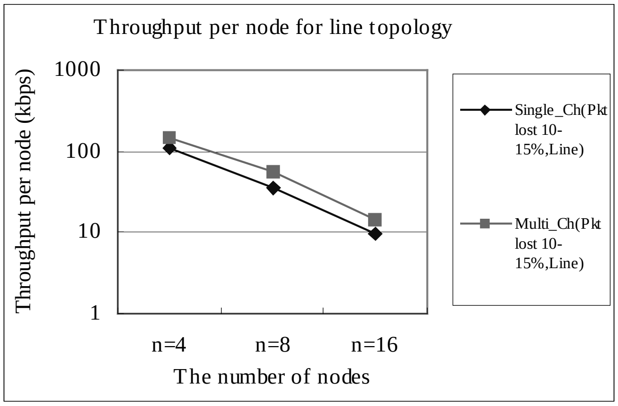


Fig.3: The throughput per node for line ad hoc network

From Fig.3, we find that the per-node throughput with multiple channels increases by 47.8%, compared with that of the single-channel case.

Our second case is the grid topology shown Fig. 2 (b). In this case, every node except the boundary nodes has six neighbors.[1] The simulation results are shown in Fig. 4. From the figure, we obtain the following scaling laws of per-node throughput with multiple channels or single channel for N>8 and when the allowable packet loss is between 10% and 15%:

- $S=285/N^{0.973}$ kbps for the single channel
- $S=883/N^{1.035}$ kbps for the multiple channels

From Fig.4, we find that the throughput per node with multiple channels increases by 139% to 163% for a

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[1] 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.

network with 16 to 64 nodes, as compared with the single-channel case.

End-to-end delay of the line and the grid network topology is shown in Fig.5. For the line network, the delay of the single-channel case is a bit higher than the delay of the multiple-channels 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.

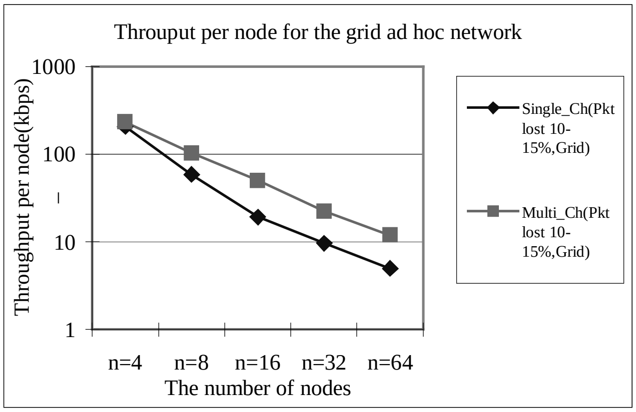

Fig. 4: The throughput per node for the grid topology

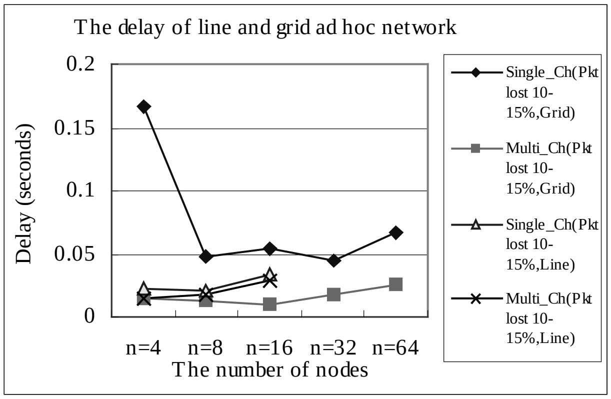

Fig. 5: End-to-end delay of the line and the grid topologies

5. Conclusions

In this work, the IEEE 802.11 MAC protocol was modified to allow communication over multi-channel 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 performances of multi-channel, multi-hop ad hoc networks. Two topologies were considered and simulated: 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 for large scale of networks 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.

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