Capacity Evaluation of Multi-Channel Wireless Ad Hoc Networks

Jiandong LI[*], Zygmunt J. Haas[♦]
School of Electrical and Computer Engineering and
Cornell University, Ithaca, NY, 14853 USA
JL384@cornell.edu, haas@ece.cornell.edu,

Min Sheng[+]
Xidian University, China
msheng@mail.xidian.edu.cn

Abstract: *In this paper, we evaluate the capacity of multi-channel, multi-hop ad hoc network. In particular, we show the performance of multi-hop ad hoc network with single channel IEEE 802.11 MAC utilizing different topologies. We also introduce scaling laws of throughputs for large-scale ad hoc networks and propose the theoretical guaranteed throughput bounds for multi-channel grid topology systems. We expect that the results presented in this work will help researchers to choose the proper parameters settings in evaluation of protocols for multi-hop ad hoc networks.*

I. Introduction

Mobile Ad Hoc Networks (MANETs) are an emerging technology that allows establishing an instant communication network for civilian and military applications, without relying on pre-existing fixed network infrastructure [1], [2]. 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 is rapidly changing. The main difference between the ad hoc networking technology and the cellular technology lies in the fact that nodes in an ad hoc network possess traffic routing and relaying ability.

Target applications of mobile ad hoc network range from collaborative, distributed mobile computing (sensors, conferences, conventions) to disaster recovery (such as fire, flood, earthquake), law enforcement (crowd control, search and rescue) and tactical communications (digital battlefields) [1], [2]. An ad hoc network is self-organizing and communications takes place mostly through multi-hop routing. Mobility of the network nodes, limited resource (e.g., bandwidth and energy supply) and potentially large number of mobile nodes make the routing and management of ad hoc networks an extremely challenging problem.

Many papers (e.g., [3]) have investigated the performance of routing protocols based on the 2Mbps IEEE 802.11 WLAN protocols. In such studies, the number of nodes in the network usually ranges from 20 to 100 and the traffic generation per active node ranges from 2 to 4 packets per second. From these studies, one can observe that the throughput of an ad hoc network with large number of nodes is relatively low. Furthermore, many papers (e.g., [4]) have also investigated the TCP performance over mobile ad hoc networks. Such works have shown that the TCP throughput is likewise quite low and TCP performance is affected by the operation of the MAC protocol.

This paper evaluates the capacity of ad hoc networks under different topologies. In particular, the performance of ad hoc networks based on the 2 Mbps and 11 Mbps IEEE 802.11 MAC is extensively examined, initially for a single channel. The scaling laws of throughput for large scale of ad hoc networks are then introduced and the theoretical guaranteed throughput bounds per node for multi-channel, multi-hop ad hoc networks are proposed. The importance of our results lies in their applicability as guidelines for parameter settings in performance evaluation of ad hoc networks.

The paper is organized as follows. The model of multi-hop ad hoc network is given in Section II. The throughput of a multi-hop ad hoc network with single channel is given in Section III. The guaranteed

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[*] Dr. Jiandong LI is a professor at State Key Lab. of ISN, Xidian University, China and is currently a visiting professor at Cornell University, USA. He is supported by the Distinguished Visiting Scholar Program of the Chinese Government and TRAPOYT, 863 Project(2001AA123031) and NSFC Project(69872028).

[♦] Dr. Zygmunt J. Haas is a professor at Cornell University, USA. His work on this project was supported by the AFOSR and the ONR, as part of the Multidisciplinary University Research Initiative (MURI), under the contract numbers F49620-02-1-0217 and N00014-00-1-0564, and by the NSF grant number ANI-0081357.

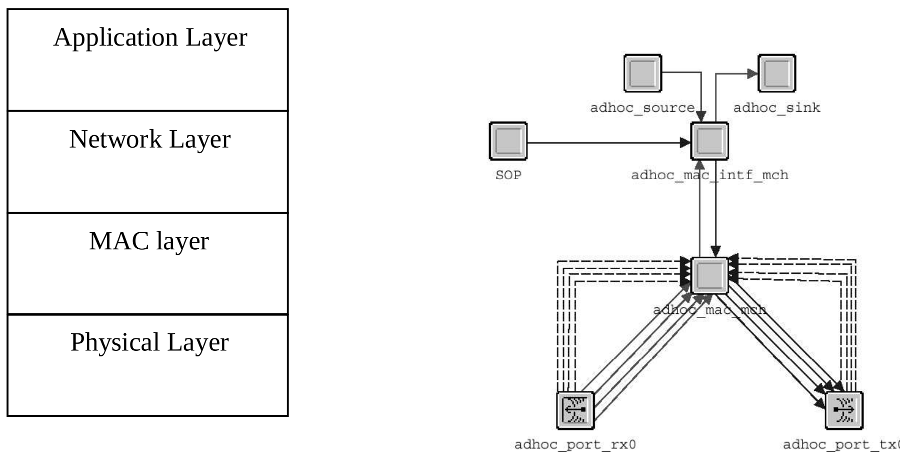
[+] Min Sheng is a Ph. D candidate at Xidian University, China.

throughput and the scaling laws of throughput for large scale of ad hoc networks are presented in Section III. The theoretical performance bounds for ad hoc networks are proposed in Section IV. The conclusions are discussed in Section V.

II. Model of a multihop ad hoc network

For the purpose of our evaluation, we model the protocol stack of an ad hoc node based on four layers: the *physical layer,* the *multiple access control (MAC) layer*, the *network layer*, and the *application layer*, as shown in Fig 1(a).

Each node is equipped with a half-duplex radio transceiver, such as a wireless PCMCIA card, which are available on the commercial market. It is assumed that the transceiver can operate on different channels.



(a) Protocol stack (b) models of an ad hoc node

Fig.1: The model of an ad hoc node

Although there are many available MAC protocols that could be used for ad hoc networks (e.g., *HiperLan, Bluetooth*), the IEEE 802.11 WLAN PC cards are, however, most popular and are easy to install. So, we chose the IEEE 802.11 WLAN MAC as the basis for our evaluation. Note that based on the IEEE 802.11 MAC protocol, the *Request-to-send (RTS)* and the *Clear-to-send (CTS)* messages are used to reduce the effect of the hidden-terminal problem. For comparison purposes, in the following figures, both performances with and without RTS/CTS messages are shown.

We assume a spread-spectrum radio channel operating at the data rate of 2Mbps and 11Mbps and the following parameters: slot duration of 2E-05 sec, short inter-frame gap of 1E-05 sec, and minimum and maximum contention windows size for backoff interval of 31 and 1023, respectively. The radio communication distance is assumed to be 300m, the MAC layer buffer size of 1024 Kbits, and the RTS threshold set at 256 bytes or none. We use the OPNET™ 8.0.C for our simulation, with the ad hoc node model, as shown in Figure 1, being based on the WLAN station model provided by the standard OPNET™ model. We add the routing and the relaying functions to the network layer (i.e., in the MAC interface module[1] (*adhoc_mac_intf_mch*) in Fig 1(b)).

To concentrate our evaluation on the effect of the MAC layer, we use a simple proactive shortest-path routing algorithm with fixed-overhead at the network layer. Thus, it is easy to estimate the effects of the routing algorithm on the overall network performance.

To implement the proactive routing function, we add the *SOP (Self-Organizing Packet)* generation

[1] This module has been modified to support the multi channel function.

module (see Fig. 1). The module generates SOPs periodically, with the period of a given constant plus a random fraction of the constant; i.e., 5 sec + *x* sec, where *x* is randomly chosen between 0 and 1.25 sec. The random part is used for avoiding repeating collisions of the SOPs. The SOPs (see Fig.2) contain the routing information to each destination, as known by the SOP's source node.

Packet Size	***Packet Type***	***Rx Node***	***Tx Node***	***Source***	***Destination***

Figure 2: The SOP packet header

Our routing algorithm is the basic distance vector algorithm. Each SOP contains the number of hops to the destination and the next relay node (*Nx node*) on the path to the destination (*Dest i*), as known by the SOP's source. Initially, the SOPs contain no routing information. But after receiving neighbors' SOPs, a node can find who its neighbors are and who can be reached through the neighbors. To speed up the update of the topological information 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 MAC Interface Layer. By checking the received packet headers, nodes can find who their neighbors are, whether the packet destination node is a new node not yet included in the routing table, and whether there is a new shortest route to the destination. The routing table *(RT)* is shown as Table 1.

Table 1 Routing Table

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

When a packet is sent or forwarded, 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 shown Fig. 3.

At the application layer, we model the packet arrival as a Poisson process with exponential inter-arrival times of duration *t*. The packet size is fixed at 1024 bytes. Packets' destinations are randomly and independently chosen from among the network nodes.

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

Figure 3: The SOP packet format

To test the performance of the ad hoc network model, we have selected a number of simple topologies such the *grid*, the *line*, and a *star* with different number of nodes. We define the *total network throughput* as packets successfully delivered across any network link and marked as *WLAN throughput* in the figures in this paper. We define the *source-destination throughput* as packets successfully delivered to their destinations and are marked as *Src_Dest_Packets* in the figures. We define the *channel delay* as the one hop delay, which is marked as *WLAN delay* in the figures. Finally, we define the *source-destination delay* as the end-to-end delay and we mark it as *Src_Dest delay* in the figures. All the above parameters are measured and are collected through simulation.

III. Single Channel Performance of Multihop Ad Hoc Network

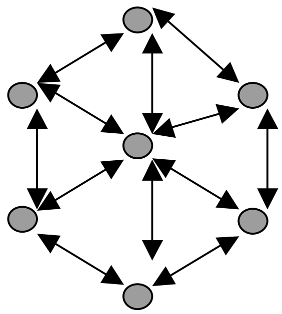


Fig. 4: An example 7-node ad hoc network

The first test network that we consider here is a 7-nodes ad hoc network, shown in Figure 4. Simulation results are shown in Figures 5 and 6 for different channel data rates. To find the maximum throughput, we have carefully chosen the start interarrival interval *t*. Total new packets, the WLAN throughput, and the Source-Destination throughput with or without RTS/CTS are shown in the figures. In multihop ad hoc network, one of the most interesting parameter is the source-destination throughput. From Figures 5 and 6, we learn that the maximum throughput values are: 894 kbps (at 2Mbps channel rate with RTS/CTS), 489 kbps (at 2Mbps channel rate without RTS/CTS), 3214 kbps (at 11Mbps channel rate with RTS/CTS), and 3650 kbps (at 11Mbps channel rate without RTS/CTS). For 2Mbps channel, the packet delivery rate (the source-destination packets / new packets) is 82%~89% when *t*=0.1 and each node can deliver 9.7 new packets per second (79.6kbps). For 11Mbps channel, the packet lost rate is very low when *t* >0.025, and each node can deliver 39.4 new packets per second (322.3kbps) at *t*=0.025. RTS/CTS will improve the throughput at 2 Mbps channel rate, but not at 11Mbps channel rate.

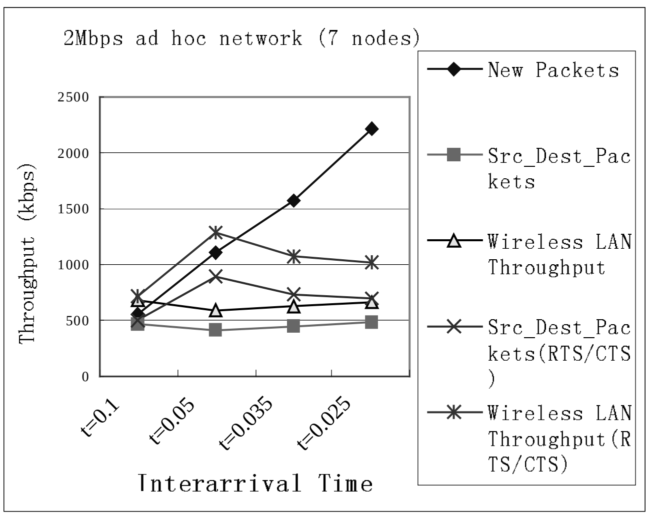


Fig. 5: Throughputs of ad hoc network with 7 nodes at 2Mbps

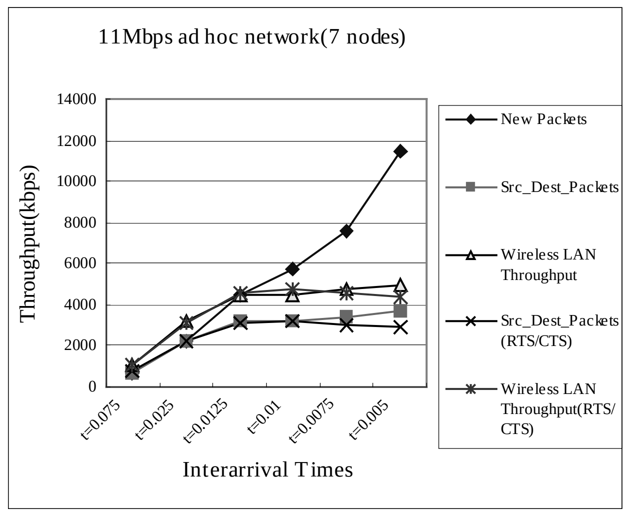


Figure 6: Throughputs of ad hoc network with 7 nodes at 11Mbps

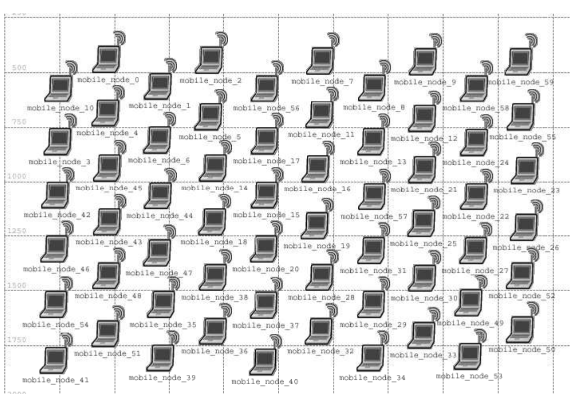
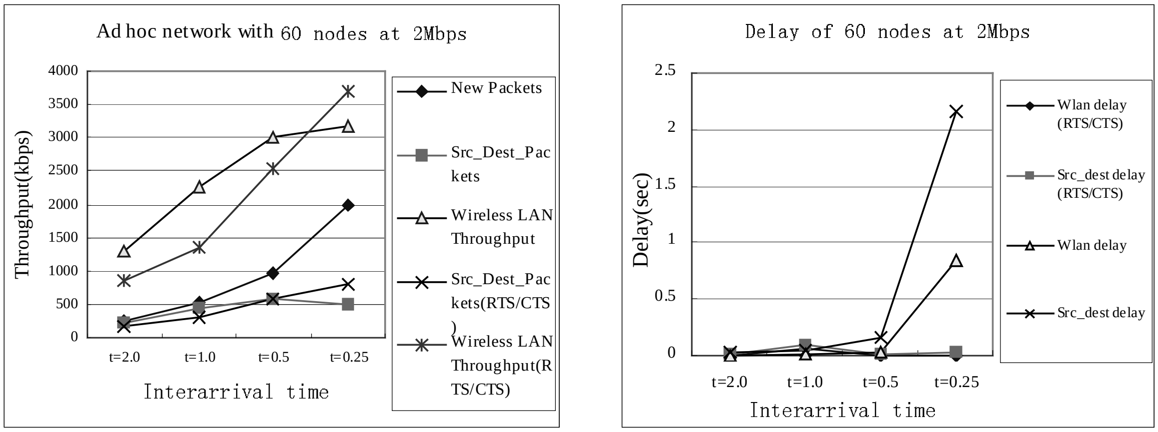


Fig. 7: A 60-nodes ad hoc network

The multihop ad hoc network with 60 nodes is shown in Figure 7. In this topology, each node, except the boundary nodes, has exactly six neighbors.The performances of this network are shown in Figure 8 and Figure 9.

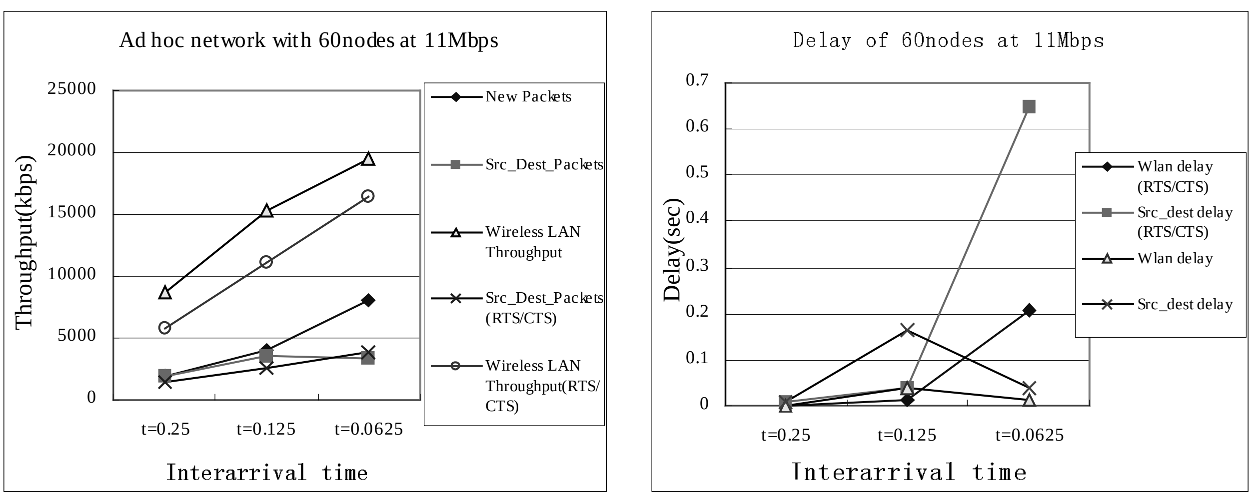
From Figures 8 and 9, we conclude that the maximum throughput values are: 793 kbps (at 2Mbps channel rate with RTS/CTS), 574 kbps (at 2Mbps channel rate without RTS/CTS), 3865 kbps (at 11Mbps channel with RTS/CTS), and 3551 kbps (at 11Mbps channel rate without RTS/CTS). For the 2Mbps channel, the packet delivery rate (the source-destination packets / new packets) is 88.5% without RTS/CTS and when *t* =1.0; i.e. 7.5kbps (0.92 new packets per second) can be delivered by each node. For 11Mbps channel, the packet lost rate is 11.2% without RTS/CTS and when *t* =0.125; i.e. 59.2kbps (7.2 new packets per second) per node can be delivered. RTS/CTS can improve or decay the throughput, depending on the channel traffic and the channel data rate. This reason lies in the affect of the exposed terminal problem, present in this topology.



(a) Throughput (b) Delay

Fig. 8 Performance of the Ad Hoc Network with 60 nodes at 2Mbps

The delays of the ad hoc network with 60 nodes are low when *t* >0.5 at the channel data rate of 2Mbps and when *t* >0.125 at the channel data rate 11Mbps, no matter whether RTS/CTS is used or not. However, with further increase in the offered data traffic (i.e., decrease in *t*), the delay will increase very rapidly, indicating system saturation. The point at which this happened depends on the channel data rate and on whether RTS/CTS is used or not.



(a) Throughput (b) Delay

Fig.9: Performance of the ad hoc network with 60 nodes at 11Mbps

IV. The Scaling Law of the Single-Channel Throughput for Multihop Ad Hoc Network

Recently, the capacity of an ad hoc network has been subject of a number of studies. For example, it was shown in [5] that under the assumption of a *Protocol Model*[2], a network could provide the throughput of $\frac{C'}{\sqrt{N \log N}}$ bits/sec per node. It was also shown there that even under the best possible placement of nodes, a network could not provide throughput of more than $\frac{C''}{\sqrt{N}}$ bits/sec per-node. To evaluate how current technology standards approach these theoretically optimal results, the experimental scaling law from the ad hoc network with 8 nodes, each with a standard 2Mbits/s IEEE 802.11-compliant Lucent WaveLan™ card, was reported in [6]. The per node throughput decays as $\frac{C}{N^{1.68}}$ bits/sec [6]. In [7], it was reported that the scaling law for the ad hoc network with large number nodes (200 to 600) is $\frac{0.047}{\sqrt{N}}$. This latter result was obtained using the *NS* simulator with CMU wireless extensions[8], whose parameters are tuned to model the Lucent WaveLan™ card at the 2 Mbps data rate.

From Fig. 8, we observe that the throughput becomes saturated at about 500 kbps; further increase in the new packet arrival rate will result only in a much smaller increase in the throughput. The difference between the new packet data rate and the throughput of the network, which is caused by packet loss, increases exponentially beyond this saturation point. Note that the packet lost is the result of two mechanisms: the channel collisions[3] and the MAC layer buffer overflow[4]. Thus, to address the capacity of an ad hoc network, we define the throughput at some loss rate. More specifically, we define the *guaranteed throughput* as the throughput when the packet loss rate is less than 10%.

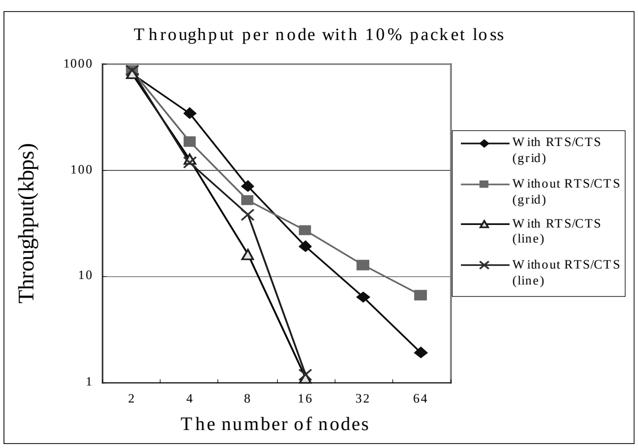


Fig 10: Throughput per node with 10% packet lost

Following extensive simulations in OPNET™ with different topologies of ad hoc networks and with different number of nodes[5], we have obtained the plot of the guaranteed throughput per node as a function of the number of nodes, as shown in Fig. 10.

From Fig. 10, we extrapolate the following scaling laws of the guaranteed throughputs for different type of ad hoc networks with number of nodes greater than 8:

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

***S* = 2.627 / *N*$^{1.744}$ Mbps -** for grid topology without RTS/CTS

***S* = 1181 /*N*$^{4.98}$ Mbps -** for linear topology without RTS/CTS

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[2] Where all nodes have a common transmission range *R* and the packet transmission will be successful if the receiver is within the sender transmission range and the distance of all other simultaneously transmitting nodes to the receiver are large than *R*.

[3] When the number of retransmission of a packet reaches the limit, the packet will be discarded.

[4] When the buffer at MAC layer is full, the newly arrived packets will be discarded.

[5] All nodes were modeled as 2Mbps IEEE 802.11 compatible.

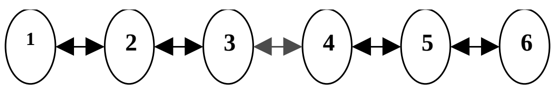
$S = 14.845 / N^{3.43}$ Mbps - for linear topology with RTS/CTS

where S is the throughput per node and N is the number of nodes in the multi-hop ad hoc network.

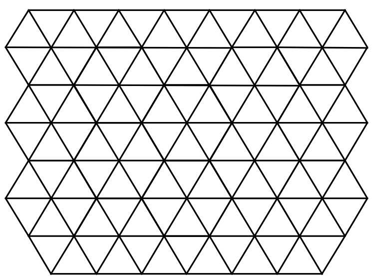
By using those results, we can predict the throughput of a large-scale of ad hoc network. For example, for 100-, 200-, and 300-node network with 2Mbps links, the guaranteed throughput per node without RTS/CTS for the grid topology is estimated to be: 4.27kbps, 2.25kbps, and 1.44kbps, respectively.

V. The Throughput of Multichannel Multihop Ad Hoc Networks

In the commercial 2.4GHz and 5GHz ISM frequency band and in the U-NII frequency band, there are a lot of channels available for use. Thus use of multi-channels at the MAC layer is, in principle, possible. However, we need to determine what is the advantage of using multiple channels in this context.



(a) Line Topology



(b) Grid Topology

Fig.11: Ad hoc network topologies

In this work, we assume a single, fixed bandwidth, and frequency-agile transceiver per node. Although each transceiver can operate on a single channel at any time, the transceivers can be tuned to different channels at different times. This frequency agility is the source of improvement of the multi-channel case, as it allows to reduce the transmission collisions and to increase the overall throughput.

If we use the multiple channels in the network with fully connected topology, the maximum throughput per node will be 1.0 Mbps for channel operating at data rate of 2Mbps with half-duplex operation (neglecting the transmission overheard), assuming that each pair of nodes can communicate on a different channel, if the number of channels is large enough.

In multiple-channel networks, all nodes can dynamically share the multitude of channels. Each node will be allowed to use a channel, if no conflict exists with its one-hop and two-hop neighbors. To find the theoretical bound of throughput in the multi-channel, multi-hop communications environments, we assume that the number of channels is large enough, so that no channel conflict occurs. The theoretical bounds of multi-channel throughput (neglecting all overheads) for two selected topologies, *linear* and *grid* topologies are shown in Fig 11. We discussed these results next.

For the line topology, assume that there are $N=2K$ nodes, numbered as $1, 2, \ldots, K, K+1, \ldots, N$. If the traffic pattern is symmetrical, equally distributed, with bi-directional communications among the nodes, then the link between node K and node $K+1$ is the "bottleneck" link. There are total $2K^2$ routes through link $(K, K+1)$. If the maximum link throughput is C, then the guaranteed maximum throughput per node is: $(N-1)C/2K^2$. The maximum link throughput for half-duplex radio with the channel data rate of 2Mbps is C=1.0Mbps. Thus, the guaranteed throughput bound *(GTB)* per node for the line topology under multi-channel *(M_CH)* environment is: $S = (N-1)C/2K^2 = 2(N-1)/N^2$ [Mbps] and as shown in the Fig. 12. For the comparison, the single-channel *(S_CH)* throughput per node with 10% packet loss rate is also shown in Fig. 12.

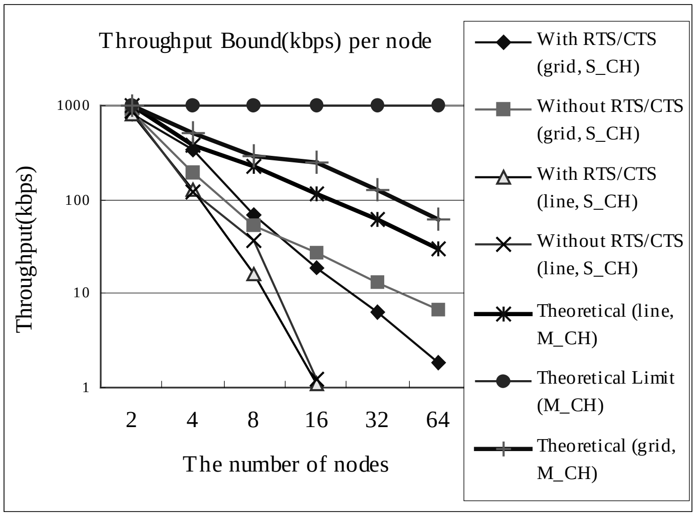


Fig. 12 Throughput bound for multiple channels at 2Mbps

However, when the multi-channels are used, there is a new kind of "collision" – *receiver blocking*, i.e., when node *A* sends a packet to its neighbor *B*, *B* might be listening on a different channel than *A* is transmitting on. This will cause the packet to be discarded and will reduce the throughput. So, the actual throughput by using multi-channels will be lower than the guaranteed theoretical throughput.

For the grid topology with large number of nodes (N>8), where each node has six neighbors and randomly distributed traffic, the one-direction maximum link throughput is 2.0/12 Mbps for large-scale networks with perfect channel scheduling (such as TDMA). The total number of routes is $N \cdot (N-1)$. For the symmetric grid topology with the shortest route algorithm, which balances the traffic well, the number of routes through link *(i, j)* will equal to the number of route through link *(j, i)*. Thus the "bottleneck" link is at the center of the network and half of the routes use the "bottleneck" link. However, each node will have six possible route directions. Thus, the maximum number of one-way routes through the "bottleneck link" is: $N \cdot (N-1)/(2 \cdot 2 \cdot 6)$. Consequently, the guaranteed throughput bound per node is:

$$(N-1) \cdot (2.0/12) \Big/ (N \cdot (N-1)/(6 \cdot 2 \cdot 2)) = 4.0 \big/ N \text{ [Mbps]}$$

For summary, the guaranteed throughput bound per node for a grid topology with different *N* is shown in Figure 12. For the cases that the numbers of network nodes are 100, 200, and 300, the limits of the guaranteed throughput values per node are 40 kbps, 20 kbps, and 13.3 kbps, respectively. As compared with the single channel system, the theoretical maximum guaranteed throughput per node with multiple channels is increased 9.23 to 9.36 times.

VI. Conclusions

In this paper, the performance of multi-hop ad hoc networks was evaluated. In particular, the throughput for different network sizes and channel data rates were studied.

The scaling laws of the throughput for large ad hoc networks based on the 802.11 MAC were presented. If the number of nodes in the network ranges from 100 to 300, the guaranteed source-destination throughput per node for randomly distributed traffic model is between 4.27kbps and 1.44kbps, with 2Mbps channel rate.

The theoretical guaranteed throughput bounds for multichannel ad hoc networks were proposed as well. If the number of nodes in the network ranges from 100 to 300, the guaranteed source-destination throughput limits per node with multiple channels for randomly distributed traffic model are between 40.0 to 13.3 kbps, respectively, with 2Mbps channel rate and the grid topology – an increase of 9.23 to 9.36 times relative to the single channel case.

References

[1] X. Hong, M. Gerla, Y. Yi, K. Xu and T. J. Kwon, "Scalable Ad Hoc Routing in Large, Dense Wireless Networks Using Clustering and Landmarks", *IEEE International Conference on Communications (ICC) 2002,*

New York City, NY, April 2002
[2] Z. J. Haas, J. Deng, B. Liang, P. Padadimitratos and S. Sajama, "Wireless Ad Hoc Networks", *Encyclopedia of Telecommunications*, John Proakis, editor, John Wiley, 2002
[3] Charles E. Perkins," Performance Comparison of On-Demand Routing Protocols for Ad Hoc Networks", *IEEE Personal Communications*, Feb. 2001, pp.16-28
[4] Gavin Holland and Nitin Vaidya, "Analysis of TCP Performance over Mobile Ad Hoc Networks", *Wireless Networks*, vol.8, 2002. pp.275-288,
[5] P. Gupta and P. R. Kumar, "The Capacity of Wireless Networks", *IEEE Transactions on Information Theory*, vol. 46, no.2, March 2000, pp.388-404
[6]P. Gupta, R. Gray and P. R. Kumar, "An Experimental Scaling Law for Ad Hoc Networks", www.black.cs1.uiuc.edu/~prkumar
[7]J. Li, C. Blake, D. S. J. De Couto, H. I. Lee and R. Morris, "Capacity of Ad Hoc Wireless Networks", 7th ACM International Conference on Mobile Computing and Networking, Rome, Italy, July 2001. www.pdos.lcs.mit.edu/papers/grid:mobicom01
[8]CMU Monarch Group. CMU Monarch Extensions to *ns*. http://www.monarch.cs.cmu.edu/.