Capacity Evaluation of Multi-Channel Multi-Hop Ad Hoc Networks

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Abstract: The performance of multi-channel multi-hop ad hoc network is evaluated in the paper. The performances of multi-hop ad hoc network with single channel IEEE 802.11 MAC for different topologies are given. The scaling laws of throughputs for large scale of ad hoc networks are presented. The theoretical guaranteed throughput bound for multi-channel systems for grid topology are proposed. The results will help to choose the proper parameters for multi-hop ad hoc network evaluations.

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 posses 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 extremely challenging.

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 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 IEEE 802.11 MAC is extensively examined, initially for a single channel. The scaling laws of throughput for large scale of ad hoc networks then presented 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 multihop 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 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 Multihop Ad Hoc Network

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

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

Although there are many available MAC protocols that could be used for ad hoc networks (e.g., HiperLan, Bluetooth), however, the IEEE 802.11 WLAN PC cards are most popular and are easy to install. So, we chose the IEEE 802.11 WLAN MAC as the basis for our evaluation.

We assume a spread-spectrum radio channel operating at data rate of 2Mbps 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 1024000 bits,

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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) of Figure 1).

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

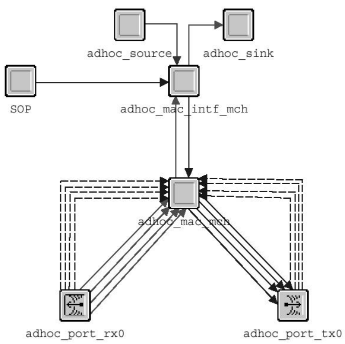

Fig. 1: The ad hoc node model

To implement the proactive routing function, we add the SOP (Self-Organizing Packet) generation module (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 repeat collisions of the SOPs. The SOPs (Fig.2) contain the routing information to each destination, as known by the SOP's source.

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

Fig. 2: The SOP format

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) 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 topology 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 already included in the routing table, and whether there is a new shortest route to the destination. The routing table (RT) is shown in Table 1.

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

When the 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 as shown Fig. 3.

Table 1: The Routing Table format

Destination Node ID	Next Relaying Node ID	Hops To Destination
1	R_1	H_1
2	R_2	H_2
…	…	…
N	R_N	H_N

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 among the network nodes.

Packet Size	Packet Type	Rx Node	Tx Node	Source	Destination

Fig. 3: The data packet header format

To test the performance of the ad hoc network model, we have selected a number of typical topologies such the *grid*, the *line*, and a *star* with different number of nodes. We define the *source-destination throughput* as packets successfully delivered to their destinations and are marked as *Src Dest Packets* in the figures in this paper. We define the *source-destination delay* as the end to end delay and is marked as *Src Dest delay* in the figures. All the above parameters are measured and are collected through simulation.

III. Single Channel Performance of A Multi-hop 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 a Protocol Model of Interference, such a network could provide per node throughput of $\frac{C'}{\sqrt{N \log N}}$ bits/sec. It was also shown there that even under the best possible placement of nodes, such a network could not provide per-node throughput of more than $\frac{C''}{\sqrt{N}}$ bits/sec. 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, whose parameters are tuned to model the Lucent WaveLan card at a 2 Mbps data rate.

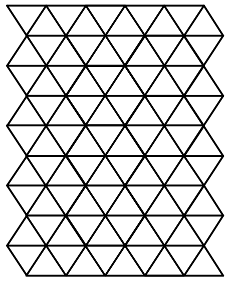

Fig.4: The gird topology; nodes are located at the cross points

As an example, take a grid ad hoc network with 60 nodes, where nodes are locate on the cross points of the grid, as shown in Fig. 4. In this topology, each node, with the exception of the boundary nodes, has six neighbors. The network throughput as a

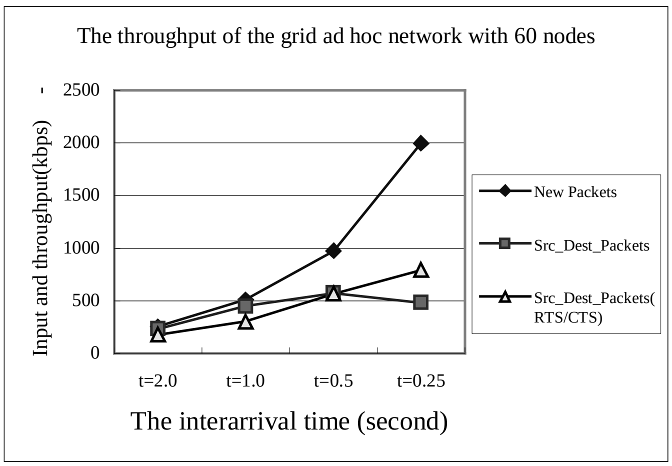

Fig.5: The throughput of the grid ad hoc network

function of the network loading (expressed through the parameter *t*) corresponding to this topology is shown in Fig. 5.

From Fig. 5, we see that the throughput becomes saturated at about 500 kbps; further increase in the new packet arrival rate will result in much smaller increase in the throughput. The difference (or packet loss rate) between the new packet data rate and the throughput of the network increases exponentially beyond this saturation point. Note that the packet lost is a result of two mechanisms: the channel collision (when the number of retransmission of a packet reaches the limit, the packet will be discarded) and the MAC layer buffer overflow (when the buffer at MAC layer is full, the newly arrived packets will be discarded). 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 where the packet loss rate is less than 10%.

After extensive simulations in OPNET with different topologies of ad hoc networks and with different number of nodes (all nodes are 2Mbps IEEE 802.11 compatible), we have obtained the plot of the guaranteed throughput of per node as a function of the number of nodes, as shown in Fig. 6. Note that in IEEE 802.11, the Request-to-send (RTS) and Clear-to-send (CTS) are used to reduce the effect of the hidden-terminal problem. For comparison purposes, in the figure, both performances with and without RTS/CTS are shown.

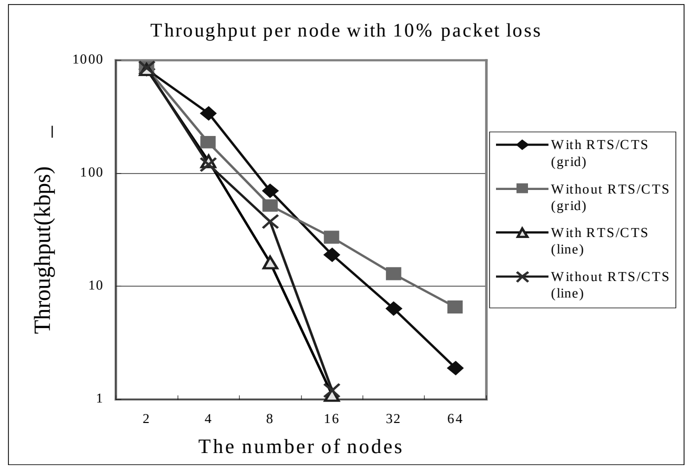

Fig 6: Throughput per node with 10% packet loss

From Fig. 6, 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

$S = 14.845 / N^{3.43}$ **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 estimate 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: 4.27kbps, 2.25kbps, and 1.44kbps, respectively.

IV. The Throughput of Multi-channel Multi-hop Ad Hoc Networks

In the commercial 2.4GHz and 5GHz ISM and in the U-NII frequency bands, there are a lot of channels available for use. Thus use of multi-channels at the MAC layer is, in principle, possible. We need to verify that it is advantageous as well.

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 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 under multi-channel multi-hop environments, we assume 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 discussed next.

For the linear topology, assume that there $N=2K$ nodes, numbered as $1, 2, \ldots, K, K+1, \ldots, N$. Assuming a symmetrical, equally distributed traffic model, bi-directional communications among the nodes, the link between node K and node $K+1$ is the bottle 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: $(N-1)C \big/ 2K^2$. 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 linear topology under multi-channel (M_CH) environment is: $S = (N-1)C \big/ 2K^2 = 2(N-1) \big/ N^2$ [Mbps] and as shown in the Fig. 7. For the comparison, the single-channel (S_CH) throughputs per node with 10% packet loss rate by simulation are also shown in Fig. 7.

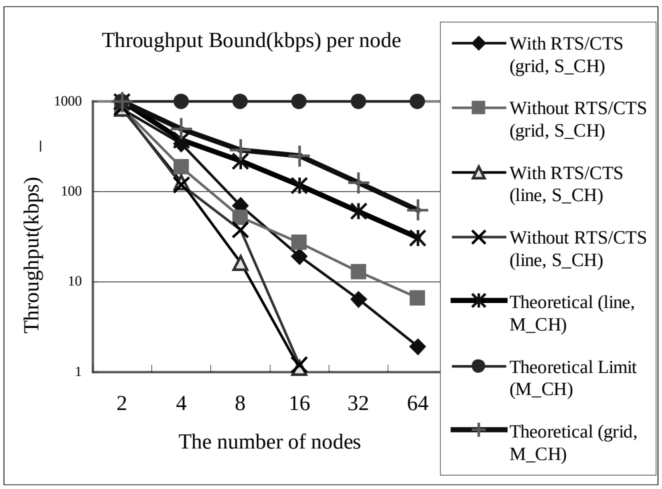

Fig.7: The throughput bound for multiple channels

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 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 and the shortest route algorithm the network can balance the traffic well, the number of routes through link (i, j) will equal to the number of route through link (j, i). Thus the bottle link will be at the center of the network, so that half of the routes uses the bottle links. However, each node will have six possible route directions. Thus, the maximum number of one-way routes through a bottle link is: $N \cdot (N-1)/(2 \cdot 2 \cdot 6)$. Thus 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 the summary, the guaranteed throughput bounds per node for a grid topology with different N are shown in the Figure 7. Take the number of nodes as 100, 200, and 300. Then the limits of the guaranteed throughputs 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 can be increased 9.23~9.36 times.

V. Conclusions

In this paper, the performances of multi-hop ad hoc networks are evaluated. In particular, the throughputs for different network sizes are given.

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

The theoretical guaranteed throughput bounds for multichannel ad hoc networks are 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 40~13.3 kbps with the 2Mbps channel rate for grid topology – an increase of 9.23~9.36 times relative to the single channel case.

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