WiFi-Mesh throughput validation

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1 Introduction

Wireless Mesh Network, an emerging technology, is a special type of wireless ad-hoc network that effectively provides broadband Internet Access and network connectivity using existing inexpensive technology [1]. Information is relayed in a multi-hop fashion from one mesh node to another. These mesh nodes are stationary and can be used to provide connectivity to stationary or mobile clients.

Mesh nodes with multiple radios and multiple channels can be employed to increase the throughput for each client. This can be achieved through good channel assignment making sure that a node can send and receive at the same time, hence increasing the throughput. The nodes in a mesh network are mostly stationary which makes it simpler to determine the throughput and other characteristics.

Since mesh network is essentially multihop, and throughput can be increased using multiple channels and multiple radio, a validation of the throughput for different topologies on the real mesh testbed will provide a good understanding and analysis of theoretical concepts. Using simulation to understand the ideal circumstances and comparing these with the actual characteristics of the testbed will be a good hands-on learning experience.

The goal of this project is to simulate various topologies for the mesh network which includes various combinations of single hop, multiple hop, multiple radio and multiple channels and analyze the behavior for each , based on theoretical concepts. Then we setup the same scenarios in the actual testbed and analyze its behavior compared to the ideal behavior generated by simulation. This will help us to understand the differences in the ideal and practical circumstances due to the unpredictable wireless medium.

2 Related work

There has been much research carried out in addressing throughput analysis in wireless mesh networks. As wireless mesh nodes typically have no mobility and employ carrier sense multiple access protocols in a multihop environment, interference is the main obstacle in achieving high capacity. In [2], the authors study interference together with carrier sensing in a single-channel WMN and also investigate the impact of traffic load on link performance. For the multiple links analysis in WMN, many researchers have recently focused on the performance of wireless chain structure; chains are a fundamental communication structure in a multihop wireless networks.

The work in [3] studied the performance of chains as the number of hops are increased and analyzed the effect of MAC 802.11 behavior on the performance of multi-hop chains but do not categorize interference

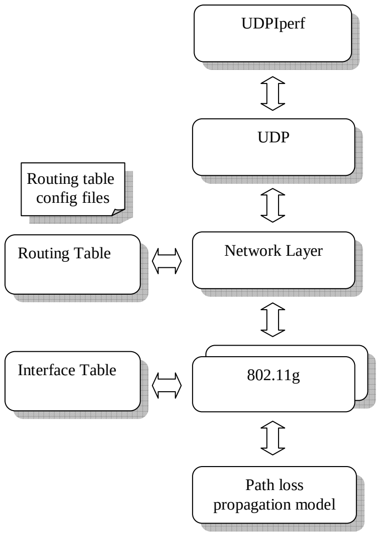


Figure 1: Simulation module structure for multi-radio mobile host in OMNet++.

patterns that govern network performance in terms of throughput and bandwidth utilization. In [4], the authors present a hop by hop analysis of a multi-hop chain and study the effects of hidden nodes on the throughput of a chain topology. They also provide two main observations about flows in a chain. First, the presence of hidden nodes cause packet drops that reduce the throughput of the chain directly. Second, packet drops cause reporting of broken links to the routing protocol and hence reducing the throughput indirectly. Another work in [6] studies the factors that determine chain behavior and then evaluates the effect of these factors on chain performance. They show that MAC level interactions play the primary role in determining the behavior of chains and present most frequently occurred interaction categories.

In order to determine the exact capacity of a WMN, the authors of the work in [1] introduce bottleneck collision domain concept that is defined as the geographical area of the network that bounds from above the amount of data that can be transmitted in the network. They Assume that each node generates traffic to be forwarded to the gateway and provide exact upper-bounds on the throughput of any node.

In summary, most of the work that analyzed chains concentrates on observing the behavior of chains and then identifying and evaluating the effects that cause these behaviors in a single radio and single channel WMN. Our approach extends this behavior of wireless multihop chains into multi radio and multi channel WMN by using real 802.11g testbed, which is presented in section 4. We also compare the testbed results with simulation results.

3 Simulation

In this section, we present the simulation environment we used to study the throughput characteristics of wireless mesh networks. Our simulation is based on the INETMANET framework [8], which is an open-source communication networks simulation package written for the OMNeT++ [7] simulation system. It contains models for TCP, IP, UDP, Ehternet, PPP etc. The INETMANET framework also includes support for mobility and IEEE 802.11-based wireless simulations for MANET. Fig. 1 shows the structure of simulation modules for a multi-radio host.

In order to set the topology of the network to be a simple chain topology we calculated a received signal

Transmitter power	2mW
Thermal noise	-110dBm
Sensitivity	-85dBm
Path loss alpha	2
SNIR threshold	4dB

Table 1: configuration in the `omnetpp.ini` file

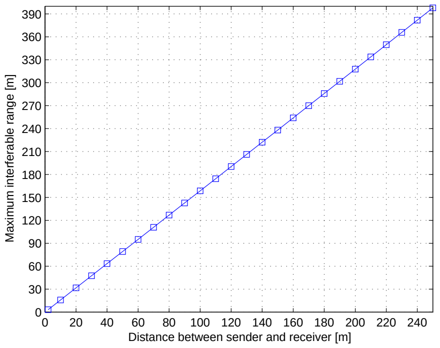


Figure 2: Maximum effective interferers range for each distance between sender and receiver in the simulation environment.

strength based the path loss propagation model with $\alpha = 2$:

$$P_{rx} = \frac{P_{tx}\lambda^2}{16\pi^2 d^\alpha}. \tag{1}$$

As per equation (1) and set of configurations show in table 1 we determined that the transmission range is 250 meter and the maximum effective interferers' range for each distance between sender and receiver in Fig. 2. Based on this relationship, we design the x and y co-ordinates for each node such that one hop nodes are within transmission range and two hop nodes are out of transmission and interference range, while creating a multi-hop topology.

In order to set up multi-radio multi-channel network, we need to check that the orthogonality of channels is maintained. This is done in the ChannelControlExtended Module which is the last point when a packet leaves a machines and the first entry point when the packet enters the machine. Thus when a packet enters the machine on a particular radio, his module will check the channel of the incoming packet and compare with its own. If it is not equal, the packet is discarded. In this way we are ensured that in simulation all different channels are absolutely orthogonal.

In order to create multiple radios, we created an array of MAC layer modules and statically configure the routing table configuration file. In the simulation, the orthogonality of channels is implemented in `ChannelControlExtended`, which is responsible for delivering packets between hosts. When packets enters in this module, it decides radios which is in transmission range and is configured with the same channel as being delivered. Although all different channels are absolutely orthogonal in the current simulation, we also can implement the impact of interference from adjacent channel by extending this module.

In order to generate traffic, we created a module (`UDPIperf`) in the application layer. This application module generates the amount of data scheduled at regular intervals as specified by the user in the omnetpp.ini file, which is similar to iperf [5]. Since this application is run on UDP, it is comparative to the real testbed iperf experiment running over UDP.

As the packet traverses each layer, we added a tracking function which collect the statistics on each layer such as the number of packets received, dropped, transmitted and forwarded and queued. This helps us to analyze the simulation result and account for the throughput in each scenario.

4 Testbed

Centennial Outdoor Wireless Mesh Network Testbed is an on-going development software for mesh networking. It is a modular and extendable testbed platform for supporting wireless mesh network research at NC State.

4.1 Software Architechture

We conducted the throughput tests with the help of Meshbed API. The Communicator, Neighbor Discovery, Neighbor Manager, Reporter and Disseminator modules on the ath0 interface were used. The detailed description of each module is as follows:

4.1.1 Communicator

The communicator is a messaging system that allows network management processes to send and receive messages based on the publish/subscribe mechanism. It enables reliable and loosely coupled distributed network management system.

4.1.2 Neighbor Discovery

Discovers neighbor nodes using hello packets.

4.1.3 Neighbor Manager

Neighbor Manager collects the neighbor information from neighbor discovery process and passes this information to the other modules.

4.1.4 Disseminator

Using the process of flooding, the control packets from the control node are delivered to the mesh nodes. During the process of Dissemination, the reverse path back to the communicator node (routing entry) is set for each node on its path.

4.1.5 Reporter

Reporter process responds to the control packet sent by the communicator. It traverses back the path taken by the disseminated packet. On its way, it also sets the routing entries for the forward direction i.e. control node to the mesh node.

The routing entries are only set for ath0 interface in Disseminator and Reporter processes.

4.2 Hardware Architecture

We used off-the-shelf desktops, Atheros a/b/g cards and Extended antenna cables. We initially used push-cards with desktops running on the batteries to find locations in EBII for building a 4-node chain topology. On deciding the locations, the power supply was provided from the power line. One card per node was used for scenarios involving single channel testing and two cards per node for scenarios involving multiple channel testing.

4.3 Test Automation

The cards are activated and assigned IP during the boot. The usage of various meshbed modules are scenario dependent. The scenario file specific to our test is also invoked during the boot and the necessary modules are started. During the experiment, Iperf and other commands are issued to the nodes from the control node using the disseminator module. Every node executes the command destined to it and saves it in the log file which is collected at the end of the experiment. No Ethernet cables were used. The routing table was auto-set by the disseminator and the reporter modules on ath0 network, thus enabling debugging/datacollection using SSH. 10.2.[card number].[Node ID]/24 is the IP format used. Since cards are on /24, ath0 and ath1 form network with different subnets.

5 Experiments and Analysis

In this section we run all the emulation scenarios on our testbed to validate the simulation results. We set up test scenarios with features as summarized in Table 2. The details of single channel scenarios (1-3) are presented in Section 5.1, and those fo multi-channel ones (4-5) are in Section 5.2.

Table 2: Scenario Features

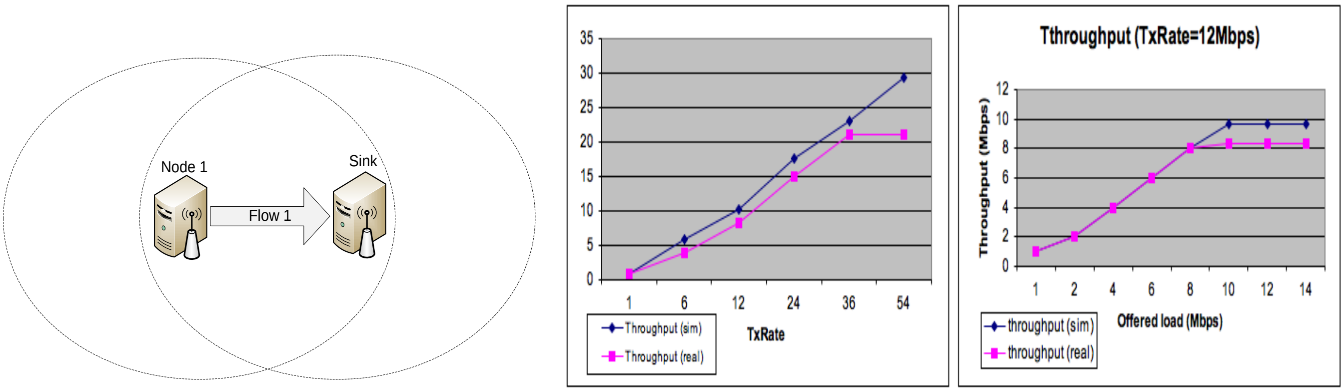
Scenario Number	Hop Count		Channel		Flow		Hidden Terminal		
	Single	Multi	Single	Multi	Single	Multi	Yes	No	N/A
1	√		√		√			√	
2		√	√			√		√	
3		√	√			√	√		
4	√			√		√			√
5		√		√		√			√

5.1 Single Channel Scenarios

We start our experiments from the single channel scenarios. When all links are transmitting at the same channel, with a properly designed MAC protocol the links will equally share the medium, but may suffer hidden terminal problems when not all nodes are in transmission range of each other.

5.1.1 Scenario 1

As shown in Fig. 3(a), in Scenario 1 there are simply two nodes transmitting packets between each other. The purpose of this scenario is to find the achievable throughput given the data transmission rate. In both OMNET simulation and testbed experiments, we use the 802.11g MAC protocol without CSMA/CA (same



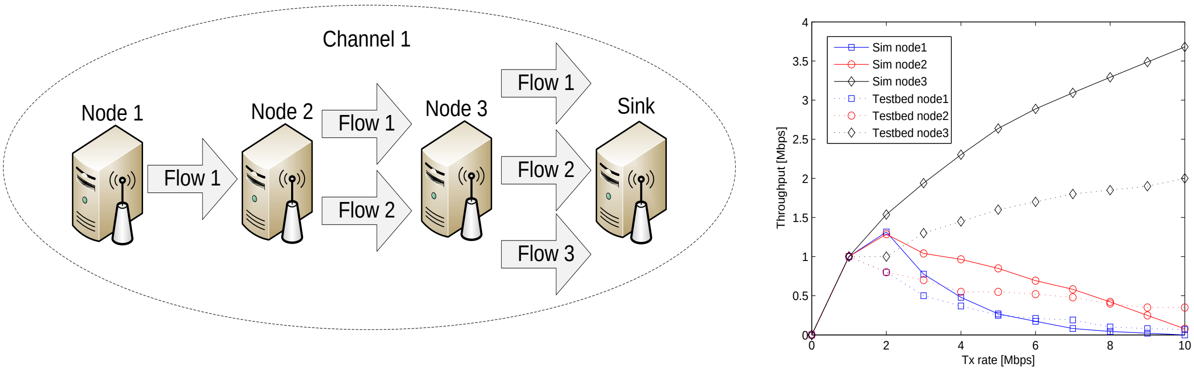
(a) (b) (c)

Figure 3: (a) Scenario 1 Setting. (b) Actual throughput vs. transmission rates. (c) Throughput vs. offered load.

for all the following scenarios). In our lab the two test nodes are placed around only 4-5 meters apart, which ensures excellent signal reception. We run a saturated data flow using iperf between the two nodes with varying transmission rates, and plot the corresponding actual throughput from both simulation and testbed against the transmission rates in Fig. 3(b). Later we fix the transmission rate at 12 Mbps and plot the goodput against the offered load in Fig. 3(c).

From the results in Fig. 3(b) and 3(c) we see that the actual payload throughput is around 8Mbps when the transmission rate is set to 12Mbps. The throughput on the testbed is a bit lower than that of simulation due to non-ideal channel conditions (especially background noise from office networks).

5.1.2 Scenario 2



(a) (b)

Figure 4: (a) Scenario 2 Setting. (b) Actual goodput vs. offered load.

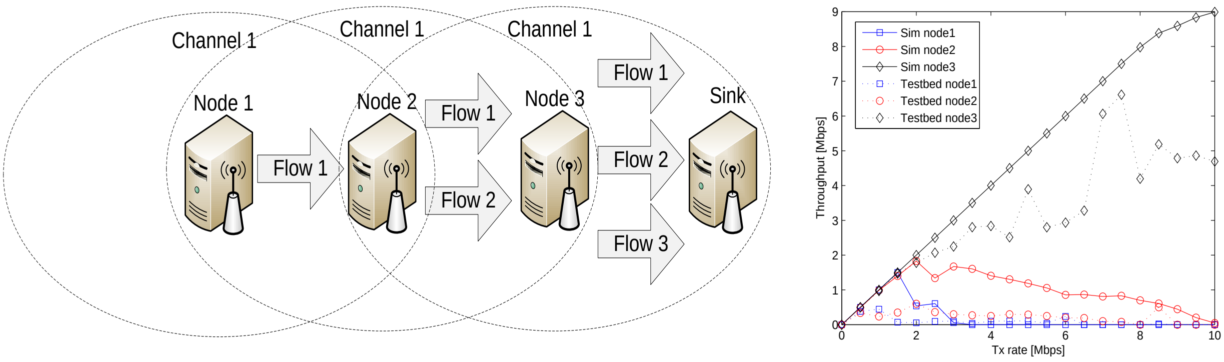
Having obtained the achievable one-hop throughput, we set up the chain topology as shown in Fig. 4(a) since it is the most common mesh network structure. All the nodes are operating on the same channel without hidden terminals, therefore it is essentially an 802.11g broadcast domain with multi-hop transmission: in our testbed we put all the four machines inside our lab with around 5 meters apart from each other, thus all nodes can perfectly hear each other. All the three nodes have the same offered load of G to be sent to the sink. When the offered load is low and the media is unsaturated, almost all traffic should be delivered. However, once the media reaches saturation, packets will be getting dropped at queues. Depending on the queueing fairness scheme implemented on the relaying nodes, data flows with more hops may suffer lower goodput. Assuming the media is about to reach saturation, the threshold offered load in this scenario could be calculated as:

$$G_O = \frac{B}{1+2+3} = B/6, \tag{2}$$

where B is the channel capacity.

We fix the transmission rate at 12 Mbps and plot the actual goodput of each flow against the offered load in Fig. 4(b). As expected, when the offered load is below the saturation point, all flows have the same goodput which is close to the offered load. When the offered load is high, the flows from node 1 and 2 are penalized and eventually almost only packets from node 3 are delivered to the sink. Similar to Scenario 1, the testbed results are lower in total throughput than in simulation due to imperfect channel condition.

5.1.3 Scenario 3



(a)

(b)

Figure 5: (a) Scenario 3 Setting. (b) Actual goodput vs. offered load.

Since the purpose of mesh network is to extend the wireless communication range, in real deployments nodes are often only able to communicate with several nearest neighbors and unable to carrier sense other transmissions hops away, therefore creating hidden terminal situations. In the following scenario shown in Fig. 5(a) we setup the same chain topology as in Scenario 2, but each node now has limited range so that it can only hear from its immediate neighbors, thus creating a hidden terminal situation between node 1 and node 3. With low offered load, packets will eventually get through since the channel is unsaturated. However since there are hidden terminals packets are more likely to get corrupted, thus the saturation point of the offered load will be lower than the previous scenario. As the offered load increases the packets from node 3 will gradually win the whole channel and the other flows are starved.

We deployed our testbed nodes 1-3 near the stairway on the three floors of the Engineering Building respectively and the sink in our lab. Under such deployment the nodes are able to communicate with their direct neighbors but not any further. We plot the actual goodput from both the testbed and simulation in Fig.

5(b). As expected, the flows from node 1 and node 2 starved while the flow from node 3 wined the channel as the offered load increases. Also, the saturation point in Fig. 5(b) is smaller compared to the one in Fig. 4(b). Both the simulation and testbed results suggests that proper traffic engineering is crucial to achieve fairness and avoid starvation in wireless networks.

5.2 Multiple Channel Scenarios

Since in 802.11 there are three orthogonal channels, properly utilizing the different channels may enhance the system performance at the cost of additional hardware. Therefore we carry out the multi-channel scenarios to explore its actual impact upon system performance.

5.2.1 Scenario 4

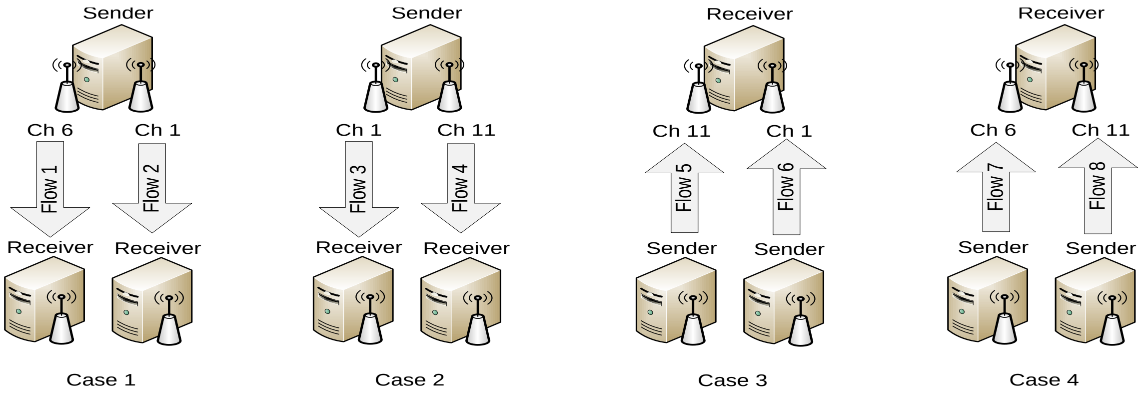
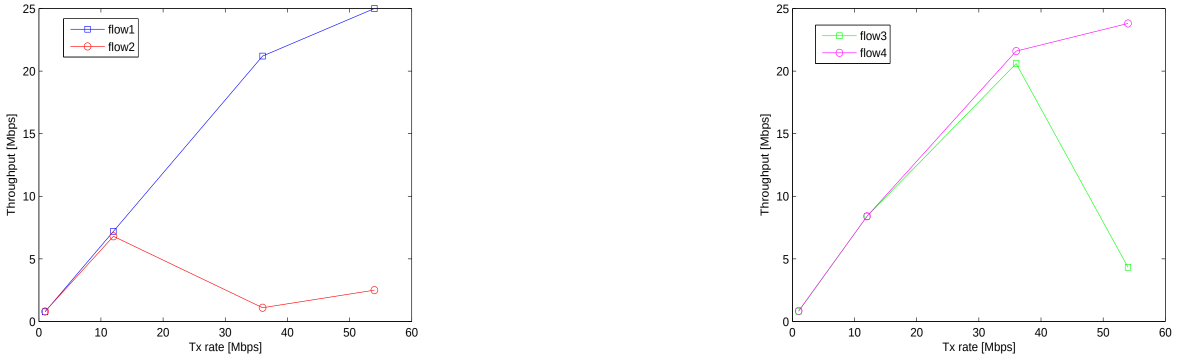


Figure 6: Scenario 4 Settings.

Before deploying multiple radios on the multi-hop testbed, we set up simple test scenarios to validate the orthogonality between channel 1, 6, and 11 in the 802.11g system. We set up the scenarios in our lab with one node equipped with 2 antennas separated 1 meter apart. The validation is run on four cases as shown in Fig. 6 and we plot the saturated throughput against different transmission rates in Fig. 7. If both flows have similar throughput which is close to the corresponding achievable throughput in Fig. 3(b), the channels could then be considered as orthogonal. In case 1 where a common sender sends 2 flows at channel 6 and channel 11, the channel maintains good orthogonality when transmission rate is under 12 Mbps. In case 2 where the channels are 1 and 11, they have even better orthogonality which lasts until transmission rate is around 36 Mbps. In case 3 and 4 where a common receiver receives from 2 channels, the channel maintains good orthogonality throughout all transmission rates, although it is better between channel 1 and 11 than between 6 and 11. As a conclusion from the test in our lab, when transmission rate is below 12 Mbps, the channel orthogonality is ideally good when the two channels are 10 channels apart (1 and 11), and acceptably good when they are 5 channels apart (6 and 11).

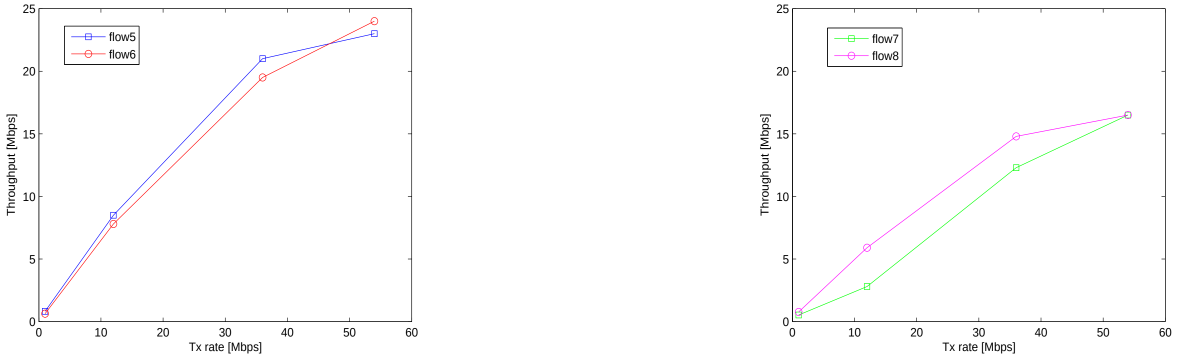
5.2.2 Scenario 5

Based on the conclusion from Scenario 4, we deploy the same testbed as in Scenario 3 but with multiple radios as shown in Fig. 8(a), where all the three links are on different channels which ideally should be orthogonal to each other. Similar to Scenario 3, we plot the actual goodput against the offered load in Fig.



(a) Case 1

(b) Case 2



(c) Case 3

(d) Case 4

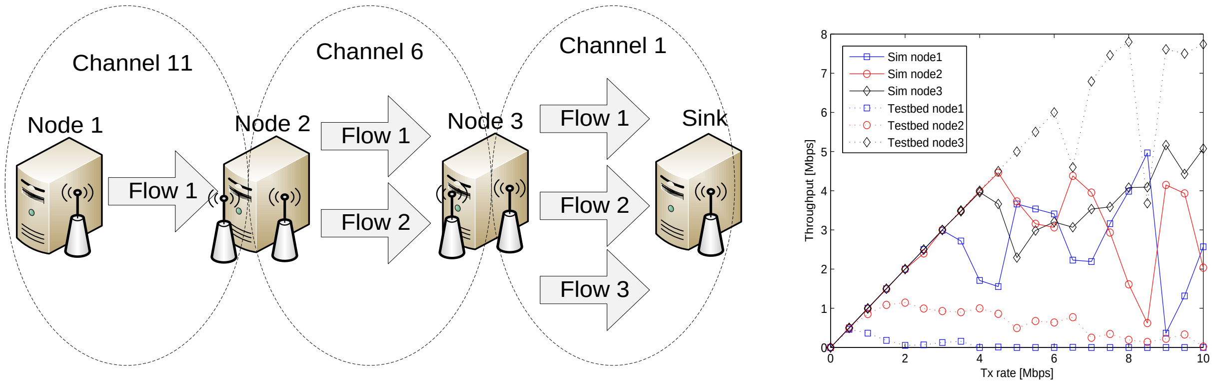
Figure 7: Actual throughput vs. transmission rate.

8(b). If the channels are perfectly orthogonal, the actual goodput of this scenario will look like as if in a wired network where there is no intra-flow interference. There will also be no starvation due to hidden terminals, and the average goodput would be much higher.

However, to our surprise, the actual testbed goodput shows a clear trace of starvation which is similar to Scenario 3 as if the channels are not orthogonal. To find out whether it is the inter-flow interference that caused this, we remove the inter-flow interference by running several single flow simulations on the same testbed with saturated offered load and summarize the average goodput in Table 3:

From the results in Table 3 although the goodput is much better without inter-flow interference, the goodput is still too low if the channels are supposed to be orthogonal, where multi-hop goodput should be close to the single hop goodput. Since the goodput on each single link exceeds 4.5 Mbps while the 2-hop flows have about half of that value, and the 3-hop flow from node 1 to the sink has less than one third of that, the intra-flow interference significantly affects performance just as in the single channel scenarios. Therefore all the testbed results seems contradicting with the conclusion of Scenario 4.

Since Scenario 4 was deployed in our lab where all nodes are close to each other (within 4 or 5 meters), for comparison purpose, we deployed a similar two hop multi-channel testbed as shown Fig. 9 in our lab where the nodes are all close to each other. Surprisingly, the average two hop goodput is 7.85 Mbps while the single hop goodput is 8 Mbps, which shows high orthogonality. Since Scenario 5 is deployed in the



(a) (b)

Figure 8: (a) Scenario 5 Setting. (b) Actual goodput vs. offered load.

Table 3: Single Flow Goodput

Sending Node	Receiving Node	Hop Count	Goodput
1	Sink	3	1.30 Mbps
1	3	2	2.17 Mbps
2	sink	2	2.32 Mbps
1	2	1	4.51 Mbps
2	3	1	7.50 Mbps
3	sink	1	8.20 Mbps

aisle of Engineering Building, where nodes could only hear their direct neighbors, one possible reason that caused such contradiction could be the signal strength. In multi-hop transmission, each forwarding node has two antennas: one for sending and one for receiving. When one antenna is sending, it always imposes a certain level of interference on the other antenna. Since in the lab all nodes are close to each other, the received signal strength on the receiving antenna is strong enough to capture the packet, while in Scenario 5, the received signal is much weaker so that the received packet is corrupted, thus result in lower goodput.

6 Discuss

Through the extensive simulation and experiments in our mesh test bed, we make the following observations based on our results:

Channel utilization: Until saturation point, every node can achieve throughput that is requested. However, as offered load increases, throughput starts to decline from the point where bottleneck link's channel utilization is more than 1. To fairly maximize the per-node throughout, we need to have mechanisms such as routing protocol and channel assignment, which properly maintains channel utilization less than 1 at bottleneck links, to prevent links from being exposed to more traffic than its' link capacity.

Unfairness in queue and MAC: Beyond the saturation point unfairness in queue and MAC is oberved. The default linux queueing discipline has a simple FIFO queue serving all locally generated and forwarded packets in which the local packets fill in the queue faster than the forwarded packets. If there exists a hidden terminal in a chain topology, one link would always gain access to the medium while the other is starved

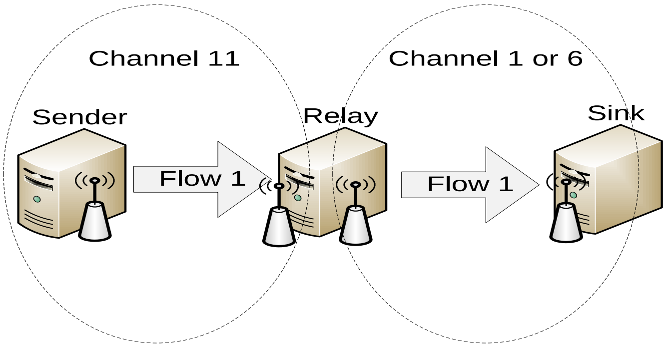


Figure 9: Comparison Scenario Setting.

with increasing backoff. This results in severe unfairness as compared to the non-hidden terminal case.

Channel orthogonality: The channel orthogonality is evident when we have two parallel one hop flows on orthogonal channel. However in the multihop case since we observe decreased throughput as compared to the simulation results, we need to further investigate if orthogonality is effective. This could be done by marking the packets and performing packet-by-packet analysis at appropriate network stacks.

7 Conclusion

The goal of this project was to simulate and emulate the various scenarios for a multihop, multiradio network using the simulation as well as the real testbed to validate the throughput obtained in a chain topology. We have used OMNeT++ to simulate the various scenarios in the mesh network and obtain graphs for the ideal behavior of the network. We setup the mesh testbed for different scenarios of single hop, multihop, multiradio and collected throughput statistics using traffic generating tool like iperf. We compared the graphs obtained from both the simulation and emulation, analyzed and discussed the reasons for the observations.

There is scope for future work following the observation we made during the project. It is uncertain where the packets are dropped when a node injects traffic more than the available bandwidth. There is considerable throughput drop in multihop case with orthogonal channels even when the same nodes in single hop show high throughput. Detailed analysis of packet flow through the network stack needs to be performed using a custom traffic generator and not depend on iperf. This would help us locate where packet losses occur. In order to avoid interference with other networks, 802.11a shall be considered. Also this would clarify if perfect orthogonality between channel (1,6) and (6,11) exists.

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