IEEE 802.11s Wireless Mesh Networks for Last-mile Internet Access: An Up-Down Link Approach

1 Mohamed Riduan Abid, 2 Taha Ben Brahim, 3 Maen Al Assaf, 4 Tajjeeddine Rachidi, 5 Saad Biaz
1, 4 Alakhawayn University in Ifrane, Morocco
2, 5 Auburn University, AL, USA
3 University of Jordan, Amman, Jordan
{1 R.Abid, 4 T.Rachidi}@aui.ma
{2 benbrah, 5 biazsaa}@auburn.edu
{3 m_alassaf@ju.edu.jo

ABSTRACT

Being multi-hop wireless networks, Wireless Mesh Networks (WMNs) are witnessing limited network capacity, mainly due to the contention among nodes in multi-hop paths. Several techniques have been proposed to cope with the limitation, e.g., using multi-channels. These techniques, however, do not account for the very specificity of traffic flow in WMNs when used for last-mile Internet access.

In this paper, we propose a multi-channel scheme that mitigates the network capacity limitation by accounting for the nature of traffic direction. This latter is mostly flowing towards/from the gateway connecting the WMN to the Internet, and forms a tree with the gateway as a root. The scheme assigns two separate interfaces/channels: one for communicating traffic coming/going from/towards nodes up in the tree and the other for communicating traffic coming/going to nodes down in the tree.

Using extensive simulations, and using non-overlapping IEEE 802.11g channels, we show that our scheme improves the network capacity by 33% in two-hop WMNs, and by 508% in three-hop WMNs.

Keywords: Wireless Mesh Networks, Multi-channels, IEEE 802.11s, Network Capacity.

1. INTRODUCTION

Wireless Mesh Networks [1] are emerging as a promising technology with a rich set of applications. IETF (Internet Engineering Task Force) [14] is actively working to finalize the IEEE 802.11s standard [15] which will pave the way towards a successful worldwide industrialization of the technology. The last TG (Task Group) meeting was held in July, 2011[15]. However, as multi-hop wireless networks, IEEE 802.11 WMNs are witnessing major limited network capacity [2, 3]. This is mainly due to the shared medium access: In IEEE 802.11 DCF (Distributed Coordination Function) mode, when a node has data to transmit, it senses the medium/cARRIER. If the medium is idle, or the sensed signal is under the CS (Carrier-Sense) threshold, the transmission occurs, otherwise, it waits for the medium to be idle for a time determined by the NAV (Network Allocation Vector) duration. If a collision happens, the station backs-off using the well-known exponential back off algorithm.

Thus, when multiple stations are trying to send at the same time, the (shared) medium becomes contended and the network capacity decreases. Besides, in the case of multi-hop wireless networks, the network capacity becomes further limited because of the contention among nodes in the same path: In a multi-hop path, adjacent links cannot be active at the same time, and exposed nodes cannot be either because of the well-known exposed nodes problem.

To cope with these limitations, several techniques have been proposed, most of which do not account for the very specificity of traffic flow in WMNs when used for last-mile Internet Access.

When WMNs are used for last-mile Internet access, the traffic is always directed towards/from the gateway connecting the WMN to Internet. Thus, a mesh node is always communicating uplink or downlink in the tree hierarchy. In this paper, we propose a simple and efficient scheme that copes with the problem of contention, among nodes in a multi-hop path, by assigning separate interfaces with separate non-overlapping channels. Nowadays, the cheap cost of NICs makes affordable the equipping of mesh nodes with multiple interfaces.

The proposed scheme handles the problem of adjacent links and exposed terminals as follows:

1. By using two interfaces, anode can simultaneously send and receive frames in both directions, i.e., uplink and downlink. This totally eliminates the problem of contention between adjacent links.
2. By using non-overlapping channels, exposed nodes can simultaneously send data since they will not be visible to each. The exposed nodes will not carrier-sense each other since they will be using different non-overlapping channels.

Using extensive simulations, we prove that our scheme substantially increases the network capacity. The
rest of this paper is organized as follows. In Section 2, related work is presented. Section 3 overviews the WMN technology. The multi-Interface approach is presented in Section 4. In Section 5, we present the experimental settings, results, and analysis. We finally conclude in Section 6.

2. RELATED WORK

As multi-hop wireless networks, WMNs did largely benefit from the valuable research led so far in multi-hop wireless networks in general, and in MANETs (Mobile Ad hoc Networks)\[35, 32\] in particular. These latter, which failed to attract good civil applications, have tremendously contributed to the proliferating success of WMNs: many WMNs protocols have been borrowed from MANETs, e.g., Hybrid Wireless Mesh Protocol (HWMP) \[5\], Radio-Metric Ad hoc On-demand Distance Vector (RM-AODV) \[18\], Dynamic Source Routing (DSR) \[19\], Optimized Link State Routing (OLSR) \[20\]. The successful adoption of these protocols benefits from the exemption on the stringent constraints of mobility and power consumption which are inherent in MANETs.

In general, multi-hop wireless networks have been extensively addressed in literature, especially in routing \[16, 17, 20, 23, 25\]. However, the capacity of such networks is still deemed limited mainly because of interference and the shared nature of the medium \[2, 3\]. In an attempt to improve the capacity, different techniques have been proposed: load-balancing \[28, 30\], packet scheduling \[34\], directional antennas \[42, 43\], network coding \[37, 38\], and multi-channel/radio \[24, 26, 27, 33, 36, 17, 4, 6, 7, 8, 9\]. The scope of this paper is related to multi-channel/radio techniques.

In \[24, 26, 27\], the MAC protocol is adjusted to support multi-channel on a packet basis. This mainly consists on seeking the best channel that minimizes interferences, and thus allowing parallel transmissions from different channels. In \[33\], the Hyacinth WMN architecture is proposed. This consists on a multi-channel approach that equips each mesh node with multiple network interface cards (NIC). The approach is dynamic and assigns channels on a link load basis, which renders it quite complicated in terms of implementation overhead. In \[36\], a joint channel allocation and interface assignment is formulated. This uses multiple NICs as well. In \[17\], authors used 2 NICs per node and assigned the same channels for every node without differentiating between the uplink and downlink channels. In \[28\], multiple interfaces are used along with directional antennas. This induces more overhead as a separate radio is needed for synchronization between neighbors. In \[4, 6\], a clique-based proportional fair scheduling algorithm is proposed. This explores the multi-channel and multi-radio capability in order to reduce the collisions and interference caused by intra-flows and inter-flows. In \[7\], a hybrid multi-channel multi-radio approach is proposed whereby each mesh node has both static and dynamic interfaces. In \[8\], authors focused on the connectivity problem and the neighbor discovery issue when using multiple channels. In \[9\], a broadcast algorithm that fits any channel and interface assignment strategy has been proposed.

All the approaches above, except \[33\], and without minimizing their added value, do not account for the very specificity of the traffic flow in WMNs when used for last-mile Internet access. In this paper, we propose a simple scheme that accounts for the traffic flow specificity by identifying an uplink and a downlink channel. Using 2 NICs, and profiting from the available non-overlapping channels in IEEE 802.11, we demonstrate that our scheme can substantially mitigate the limitation on network capacity.

3. WIRELESS MESH NETWORKS: AN OVERVIEW

WMNs are emerging as a promising technology with a rich set of applications, e.g., wireless community networks, wireless enterprise networks, transportation systems, home networking and last-mile wireless Internet access. However, providing last-mile wireless Internet access is the most promising application as WMNs are tremendously reducing the cost and the configuration overhead when compared with current solutions, e.g., Wi-Fi (IEEE 802.11) LANs: Thanks to their self-organizing and self-healing nature, plugging the WMN nodes and turning them On is all what is required to operate the network.

Albeit a new technology, several WMNs solutions are already commercialized (e.g., by Strix Systems, Cisco, Nortel, Tropos, Bel Air). Besides, valuable real-world research deployments are in place as well, e.g., the MIT Roof net \[29\] and the Microsoft Mesh Networking project \[31\]. In parallel, IETF is actively working on the standardization process of the technology: The IEEE 802.11s standard started initially as a study group in 2003, and became a Task Group (TG) in July 2004. The first draft was accepted in March, 2006, and the last TG meeting was held in July, 2011 \[15\]. The IEEE 802.11s standard is concerned with five main areas:

1. Architecture,
2. Routing,
3. MAC enhancements,
4. Internetworking,

IEEE 802.11s defines three types of stations:

1. MPs (Mesh Points): MPs are wireless stations that perform routing only.
2. MAPs (Mesh Access Points): MAPs are MPs with additional access point capabilities. Besides performing routing, MAPs aggregate traffic.
from/towards legacy 802.11 stations; a MAP can be thought of as a legacy access point which performs routing as well.

3. **MPPs (Mesh Portal Points):** MPPs are MPs that serve as gateways to other non-mesh networks, e.g., Internet. MPPs aggregate traffic from/towards the non-mesh networks.

To illustrate the functionality of the IEEE 802.11s mesh node types, we depict in Fig. 1 a scenario where an end-user, with a Wi-Fi enabled station, is browsing the Internet: The end-user, at station Sta1, is connected to a legacy IEEE 802.11 network through the mesh access point MAP1 which serves as an interface between the Wi-Fi network and the WMN. Besides, MAP1 is responsible for routing frames towards the destination, using an appropriate routing protocol. MAP1 selects mesh point MP1 as a next-hop. This latter performs only routing and forwards the data towards the mesh portal point MPP1 who serves as a gateway between the WMN and the Internet where the server resides. Ideally, MPPs should interface WMNs with whatever type of non-mesh network, e.g., 3G network.

IEEE 802.11s did set HWMP (Hybrid Wireless Mesh Protocol) as a routing protocol [5] and Airtime as a routing metric [10]. HWMP is to determine the best sequence of hops for a data frame to get to its final destination. This is carried out by selecting the path that has the best (least) Airtime value. HWMP is an adaptation of the well-known AODV (Ad-hoc On-demand Distance Vector) protocol [25], and it hybrids two protocols: 1. Reactive On-demand, and 2. Proactive Tree-based Routing.

RM-AODV (Radio-Metric Ad hoc On Demand Distance Vector) [18] is the reactive protocol in HWMP. RM-AODV is an adaptation of the well-know AODV [25] protocol that uses Airtime [10] as a link quality metric. Reactive routing protocols initiate route discovery requests only when needed, such as in case of a route failure or a route time-expiration.

The HWMP proactive mode [5] is a tree based routing [11, 33] whereby every root mesh point (i.e., MPP) periodically broadcasts PREQ (Path Request) messages bearing unique sequence numbers. By comparing the routing metrics of the different received PREQ messages, MAPs select the best MPP and thus adhere to the tree whose root is the selected MPP. The proactive protocol is ideal for the scenario where WMNs are used for last-mile Internet access since most of the traffic is directed towards/from the gateway MPPs that connect the WMN to the Internet.

### 4. MULTI-CHANNEL/RADIO APPROACH

In multi-hop wireless networks, the network capacity is limited basically due to the contention among nodes constituting adjacent links in the same multi-path. To illustrate the fact, we consider a node S (source) that is transmitting towards node D (destination) along the three-hop route S-A-B-D, see Fig. 2.

When S is transmitting along the first hop (i.e., S-A) towards node A, this latter cannot simultaneously send along the second hop towards node B (i.e., A-B). This is due to the fact that the NIC of node A is busy receiving frames from node S. As such, node A will be forced to buffer the received frames till S finishes the transmission. This is very likely to result in a buffer overflow situation especially if the node S is transmitting at a high rate, and hence inducing frames dropping which will be deemed as losses, a fact that substantially limits the network capacity.

On the other hand, when node B is transmitting towards node D, node A cannot respond/transmit towards node S since node A is in the transmission range of node B and thus will sense the medium busy. This is the well-known problem of exposed nodes.

To cope with the two problems above, we suggest the use of non-overlapping channels along with the use of multiple interfaces. IEEE 802.11 provides 12 and 3 non-overlapping frequency channels for the 802.11a and 802.11b/g standards. The channels can be simultaneously used within a node neighbourhood, and this should substantially increase the effective bandwidth.
As depicted in Fig. 3, every node is equipped with 2 NICs each using a different channel from the set of non-overlapping channels. This way, and unlike situation in Fig. 2, node A can send towards node B using the uplink interface (using channel-2) while node S is simultaneously sending towards node A using the uplink interface (using channel-1). Similarly, and coping with the well-known exposed nodes problem, node B can send towards node D using its uplink interface (using channel-3) while node A is transmitting back towards node S using its downlink channel (using channel-1).

Accordingly, and by accounting for the very specificity of the traffic direction in WMNs when used for last-mile Internet access, we would have eliminated the well-known problem of exposed nodes and the persisting problem of contention among adjacent links, a fact which is of great input to mitigating the limitation on network capacity in multi-hop wireless mesh networks. However, the current scheme suffers from the constraint that channel-to-interface binding should be done at the time of booting up the mesh nodes. Still, we are setting as a future work an automated binding scheme where a mesh node would pick the appropriate channel by counting the hop-distance from the gateway. Thus, nodes that are one-hop from the gateway will be assigned channel-1, and then hops at two-hop distance from the gateway will have channel-2 assigned and so forth.

5. EXPERIMENTATION

To assess the limitation on the WMN network capacity, and to prove the performance of the new scheme, we run extensive simulations with different topologies and scenarios. The chosen topologies were drawn within the context of a project where we are intending to deploy a real-world test bed at our university campus. A former deployment was carried in another campus [12, 13].

In the first two scenarios, we deployed a two-hop WMN and we compared the network capacity using the single-channel and multi-channel approaches. In the two last scenarios we deployed a three-hop WMN instead, and we conducted the same comparison. Next sections illustrate the experiments.

5.1 Scenario 1: Two-hop WMN, using Single Radio

In this first scenario, we simulated a two-hop WMN that spans the academic area of our university campus. See Fig. 4. The transmission range of stations was adjusted via the tweaking of the “power transmission” attribute (in the OPNET simulator) in order to approximate the target real-world deployment.

Mesh Access Points MAP_1 and MAP_2 are sources transmitting CBR (Constant Bit Rate) traffic towards the destination SERVER. This latter resides in the Internet. The WMN is connected to Internet via the gateway (MPP_Gateway). MAP_3 is a mesh access point that serves as an intermediate node routing/forwarding sources traffic towards destination.

a. Experimental Settings

The sources transmission rate is set to 1000 packets per second, where a packet is 1024 bits long. This corresponds to a rate of 1 Mbps. The routing protocol is set to AODV [25], See Fig. 5.
b. Experiments

Using OPNET [22], we run extensive simulations for a period of 10 min, and we clearly noticed that the network capacity is degrading when compared to the expected network throughput. Ideally, the destination should receive 2000 packets per second, as this is the aggregate packets' transmission rate originating from sources MAP_1 and MAP_2 (Each MAP is sending 1000 packets per second).

As such, we tracked the variance on the number of received IP packets at the intermediate node (MAP_3) and at the gateway (MPP_Gateway), See Fig. 6.

From the last figure, we clearly notice the difference between the aggregate throughput at intermediate node MAP_3, and at the gateway. On average, MAP_3 is receiving 1948 packets/sec, and the gateway is receiving 1496 packets/sec. This corresponds to a network efficiency of 76%, which is a poor performance especially when we consider the fact that this is a two-hop WMN.

Fig 6: Scenario1 - IP Traffic Received (Packets/sec)

Fig 7: MAP_3 Queue Size and Retransmission Attempts

At this stage, a possible venue to cope with this problem raises. This suggests the dynamic adjusting of the buffer size in order to mitigate the congestion problem. However, this has been proved in efficient [21], and we did further ascertain the fact. Indeed, adjusting the buffer size affects only the delay and not the throughput.

c. Analysis

Theoretically, the observed network throughput degradation should mainly stem from the fact that MAP_3 cannot simultaneously receive traffic from downlinks (i.e., from MAP_1 and MAP_2) and forward the received traffic towards the MAP_Gateway destination. This fact has been discussed in Section 4. As such, MAP_3 will buffer packets received from downlinks while waiting to grasp the uplink channel. This is very likely to induce a buffer overflow, which will result in packets dropping and thus throughput degradation. Besides, and due to the fat tree nature of the traffic flow when WMN are set for Last-mile Internet access, the top link (i.e., from MAP_3 to Gateway) will be witnessing high loads and this is another factor aggravating the buffer overflow condition.

To assess the last assumptions, we tracked the variance on the queue sizes as well as the number of retransmission attempts at both MAP_3 and the gateway, see Fig. 7: We found that MAP_3 is indeed suffering congestion as the buffer size is growing high, whereas the gateway is not.

Indeed, in Fig. 7 we clearly notice that MAP_3 is suffering congestion as the retransmission attempts levels are high: 850 retransmissions per second. In parallel, we notice also that the queue/buffer size levels are high as well: The average is 202 packets per second. This corresponds to a buffer size of 200 * 1024 = 206848 bits. When checking the value of the buffer size of node MAP_3, we found that it is 256000 bits (See Fig. 8). This clearly shows that the buffer is indeed overflowed. As such, we can ascertain the former assumption about the throughput degradation due to buffer overflow, which stems from the contention among adjacent links.
5.2 Scenario 2: Two-hop WMN, using Multiple Interfaces

In this scenario, and while keeping the same topology as in the previous scenario, we configured the intermediate node (MAP_3) to have two separate interfaces (instead of 1), and we used two separate non-overlapping channels in the IEEE 802.11g spectrum.

a. Experiments

We run exactly the same experiments as in previous scenario and we tracked the variance on the received IP packets at intermediate node MAP_3, and at the gateway (MPP_Gateway), see Fig. 9.

Form figure above, we clearly notice that the network throughput is increasing, and it reaches 1969 packets per second on average. This corresponds to a network efficiency of 98%. When compared to network efficiency in scenario 1, which was 75%, this corresponds to a 33% increase, and it reaches an optimal value closer to 100% efficiency.

In parallel, we tracked the variance on the queue size at intermediate node MAP_3 as well, see Fig. 10. We clearly observe that the queue is witnessing a very low load (less than 1 packet per second on average) when compared to the queue load in scenario 1 (200 packets per second, see Fig. 5). Thus, we clearly assess our assumption about the buffer overflows being a major contributor to network capacity degradation. We did also prove the impact of using two interfaces, along with two non-overlapping channels, on the network capacity. However, to further assess our proposal, we did further expand the WMN to span 3-hop links instead of 2-hop ones. Next Section illustrates the experiments.

5.3 Scenario 3: Three-hop WMN, using Single Channel

In this scenario, we used the single-channel approach and we expanded the WMN to span 3-hop links, see Fig. 10.
Mesh access points 1, 2, 3, and 4 are all sources transmitting at the same rate as in Scenario 2 and 3, i.e., 1 Mbps. The Traffic type is a CBR (Constant Bit Rate) one as well. MAPs 4, 5, and 6 are serving as intermediate nodes routing/forwarding traffic towards/from destination.

As in previous scenarios, we run extensive simulations where we tracked the variance of received and sent packets at all intermediate nodes and at the gateway. Fig. 11 depicts the results.

![Fig 11: Scenario 3 - IP. Traffic Received at intermediate nodes MAP_5 and MAP_6 (Packets/sec)](image)

From last figure, we observe that nodes MAP_5 and MAP_6 are sharing the available capacity since an increase in MAP_5 received packets corresponds to a parallel decrease in the MAP_6 received packets. This stems from the fact that only one station can be receiving at a time, a fact that ascertain our assumption in Section 4 about contention among adjacent links in the same multi-hop path.

Besides, when tracking the number of received packets at the intermediate node MAP_7 and at the gateway (see Fig. 12), we found that MAP_7 receives 845 packets per sec, and the gateway receives 390 packets per sec. This corresponds to a network efficiency of 9% which is a very poor one.

![Fig 12: Scenario 3 - IP. Traffic Received at intermediate node MAP_7 and at the gateway (Packets/sec)](image)

Besides the contention among adjacent links, and the buffer overflows due to the impossibility for a node to simultaneously send and receive, the interference are playing a major role as well [2, 3]. When using separate channels, the interference should be eliminated as nodes operating in orthogonal frequency channels should not sense each other. The next experiments prove the impact of using such an approach.

### 5.4 Scenario 4: Three-hop WMN using non-overlapping channels

We run the same experiments as in previous scenarios, using separate interfaces and separate non-overlapping channels, and we kept the same experimental settings as well.

When tracking the throughput at nodes MAP_5 and MAP_6, see Fig. 13, we observe that the throughput at these nodes did noticeably increase to reach an average of 1968 packets per second. At the level of nodes MAP_7 and the gateway, see Fig. 14, we note that the throughput reached 3928 (pack/sec) for MAP_7 and 3317 (pack/sec) for the gateway. This corresponds to an increase of 508% when compared to the scenario where we used a single channel.
This clearly ascertains the assumption about interference as another factor substantially impacting the network capacity in multi-hop wireless networks. Indeed, the use of separate non-overlapping channels is largely eliminating the interference, and the use of separate interfaces eliminates the contention among links in the same multi-hop path.

6. CONCLUSION

In this paper, we presented a simple multi-channel and multi-interface approach that mitigates the network capacity limitation witnessed in multi-hop wireless mesh networks. The scheme is simple as it identifies an uplink and a downlink interface that use different non-overlapping channels in the IEEE 802.11g spectrum. In contrast to existing multi-channel approaches, our scheme accounts for the very specificity of traffic flow in WMNs when used for last-mile Internet access. This forms a fat tree whose root is the gateway connecting the WMN to the Internet. The scheme improves the network efficiency by a factor of 5 in three-hop WMNs. However, the scheme suffers from the constraint of static binding of channels to interfaces at the booting stage of the mesh nodes. As a future work, we are researching an automated venue for adjusting the channels binding. As a primary step, we are thinking about assigning non-overlapping channels based on the hop-distance from the gateway. This hop-distance information can be easily extracted from the routing broadcast frames. We plan to deploy the scheme in a real-world WMN campus test bed.

REFERENCES


