Analysis of Capacity Improvements in Multi-Radio Wireless Mesh Networks

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Abstract— **In this paper, we argue that additional radios should be placed according to the distribution of traffic load in WMN. We show that the capacity of a WMN is constrained by the bottleneck collision domain; hence, placing an equal number of radios at all nodes is not necessary. Only collision domains that need to support higher traffic load should be given more bandwidth by setting up additional radios, so that interfering wireless links would operate on different channels, avoiding interference and enabling multiple parallel transmissions. Furthermore, we determine the upper bound on capacity improvements, and show that much less radios are required compared to conventional *k*-NIC architectures.**

Keywords- Wireless Mesh Networks, Capacity, Multi-Radio, Multi-Channel

I. INTRODUCTION

Wireless is well established for narrowband access systems, but its use for broadband access is relatively new. Wireless mesh architecture is a first step towards providing high-bandwidth network coverage. Mesh architecture sustains signal strength by breaking long distances into a series of shorter hops. Intermediate nodes not only boost the signal, but cooperatively make forwarding decisions based on their knowledge of the network. Such architecture provides high network coverage, spectral efficiency, and economic advantage.

Recently, interesting commercial applications of wireless mesh networks (WMN) have emerged. One example of such applications is "community wireless networks" [1] [2]. Several vendors have recently offered WMN products. Some of the most experienced in the business are Nortel [3], Tropos Networks [4], and BelAir Networks [5].

Although the IEEE 802.11 MAC protocol has been initially designed to operate in wireless local area networks, it has been adopted as the de facto standard for WMN. IEEE 802.11b/g and 802.11a standards provide 3 and 12 non-overlapping channels, respectively, which could be used simultaneously within a neighborhood.

Although IEEE 802.11 standard promises high bandwidth broadband access, many factors contribute to lower the effective throughput with respect to the advertised data rates. The IEEE MAC protocol suffers from control frames overhead such as RTS/CTS handshake and preamble exchange. But the main problem facing wireless multihop networks remains the reduction in total capacity due to interference between simultaneous neighboring transmissions, in addition to fading and environmental noise.

The use of WMN as a backbone for large wireless access networks imposes high bandwidth requirements, making the bandwidth issue most limiting. It is therefore necessary to use bandwidth aggregation techniques whenever possible. The ability to utilize multiple channels, benefiting from the whole available spectrum, would substantially increase the effective bandwidth.

Using however one-NIC architecture inherently limits the whole network to operate on a single channel; otherwise, the WMN would be clustered, disconnecting subset of nodes using a particular channel from others. Since cost of radios and battery consumption are not limiting factors in a WMN, it seems natural to consider using multiple commodity 802.11 hardware per node.

In this paper, we argue that additional radios should be placed according to the distribution of traffic load in a WMN, as opposed to placing an equal number, *k*, of radios per node, known as a *k*-NIC architecture. We show that the capacity of a WMN is constrained by bottleneck collision domains. Hence, placing the same number of radios per node is not necessary. Rather, only collision domains that need to support higher traffic load should be given more bandwidth by setting up new radios, so that interfering wireless links would operate on different channels, avoiding interference and enabling multiple parallel transmissions.

The rest of the paper is organized as follows. We discuss related work in Section 2 and study the traffic profile of WMN in Section 3. We identify bottleneck collision domains, and derive the capacity of WMNs in Section 4. In Section 5, we present a scheme to add radios to WMN by breaking down bottleneck collision domains into multiple domains each operating on different non-interfering channels. In Section 6, we validate our analysis and compare to other alternatives. We conclude our study in Section 7.

II. RELATED WORK

To date and to the best of our knowledge, no other works have addressed the impact of incremental addition of radios, on the capacity of WMN. Instead, they considered *k*-NIC

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architecture, and the number of radios per node was never justified in the context of capacity improvement.

As a first step to take advantage of the full available spectrum, many proposals suggested the use of channel switching for cross-channel communication [6] and [7]. They considered a single-NIC architecture, modifying the MAC layer to support dynamic channel switching. However, this introduces significant end-to-end delays and would require a fine grained synchronization scheme. In addition, with only one radio, the capacity of relay is halved, since nodes would not be able to transmit and receive simultaneously. Hence, the improvements that can be done using a single radio are limited.

On the other hand, many suggested the use of two radios per node for operational reasons. [8] and [9] suggested to use one radio for monitoring on a dedicated control channel and use the other radio for data transmission on remaining channels. Roy et al. [10] proposed a two-radio architecture where one radio operates on the common channel, used for inter-cluster communications, and the other radio operates over different channels for intra-cluster communications. Those approaches don't solve the problem since the major load in the WMN is the traffic of data packets in intra-cluster communications.

Several other proposals considered mainly *k*-NIC multihop wireless networks. They focused on the problem of channels assignment without any consideration of the required number of radios. Draves et al. [12] presented a new metric for routing in WMN and assumed an equal number of radios per nodes. Similarly, Tang et al. [13] presented heuristics for channel assignment and formulated a routing protocol for QoS, assuming each node is equipped with the same number of NICs which should be less than the number of available channels.

The work closest to ours is perhaps the work of Raniwala et al. [14]. Although they considered a *k*-NIC architecture, they took into account the traffic profile of WMN to optimize the aggregated throughput, by proposing routing and channel assignment algorithms. We similarly consider the traffic profile of WMN, but to derive the number of radios required and its direct impact on capacity.

III. TRAFFIC PROFILE

As opposed to an ad hoc network, a wireless mesh network offers predictability in term of traffic pattern. This permits capacity optimization based on “computed” traffic profiles. WMNs have a relatively stable topology except for occasional node failures or additions. Practically all the traffic is either to or from a gateway, while in ad hoc networks the traffic flows between arbitrary pairs of nodes.

As a result, the traffic is skewed as flows are aggregated and directed to the gateways that are connected to the Internet. Gateways would form bottlenecks as more and more packets contend for the channel as they are forwarded closer to the gateways. Since the traffic inside a WMN is skewed, it is not reasonable to assign an equal number of radios per node, without taking into account the load they carry. In addition, flows originating farther away could not benefit from the enhanced capacity without first reducing the bottleneck wireless links along the path to the gateway.

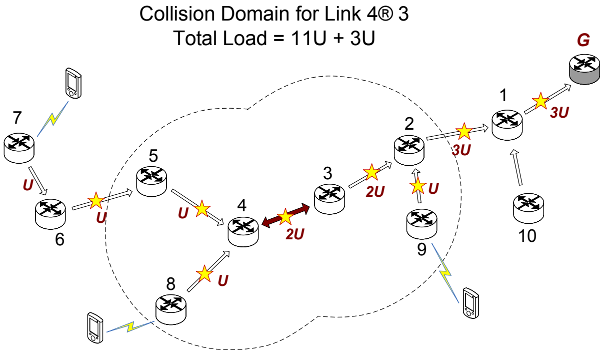

Figure 1. Collision domain

Given WMN's characteristics, dynamic routing is not necessary, making shortest path proactive routing the routing of choice. A tree-based routing scheme would easily allow flows aggregation and would minimize overhead, ensuring an optimal utilization of bandwidth [15]. Hence, a spanning tree rooted at the gateway is used for traffic forwarding. Each node is mainly associated to one tree, and would attach to another tree as an alternative route in case of path failure.

IV. CALCULATING THE FAIR CAPACITY

A. *Wireless Channel and Collision Domains*

In a wireless network, the resource of interest is not a link but a wireless channel in a geographic space. Contending nodes share the capacity of the local channel and form a *collision domain*.

Although the broadcast nature of the wireless medium implies that *no receiving node can be in the reception range of more than one simultaneously transmitting node*, the IEEE 802.11 standard imposes more strict constraints on channel access in order to mitigate the “exposed” and “hidden” node problem [16]. The MAC layer has to ensure that *no node that is a one-hop neighbor of either the sender or the receiver of a data packet may be engaged in any communication activity (either transmitting or receiving) during the entire 4-way (RTS-CTS-DATA-ACK) exchange*.

The hidden node problem still exists in multihop networks. In addition to the constraints imposed by the 802.11 standard, the collision domain should also include wireless links causing hidden node problems.

Fig. 1 shows the collision domain of the link 4→3; the links are labeled by a *star*. There are 3 flows in the network, generated at nodes 7, 8 and 9. Flows are aggregated and forwarded towards the gateway. The two semi-circles contain the nodes that are one-hop neighbor of either the sender or the receiver. The collision domain would therefore consist of all the wireless links included in or intersecting the two semi-circles, in addition to link 1→G which introduces a hidden node problem. The collision domain could be computed similarly for each wireless link in the network.

Every collision domain is bounded by the capacity of the MAC layer and should be able to forward the traffic of its links. From Fig. 1, we observe that the total traffic to be forwarded inside the collision domain is 11U, imposed by the coordinated channel access (RTS/CTS), and an additional 3U due to the hidden node problem, for a total of 14U where U is the unit of fair traffic we shall compute.

B. Spatial Reuse in Collision Domains

Any subflows that are not interfering with each other can potentially transmit simultaneously. Therefore, the amount of traffic to be forwarded individually by the collision domain is less than or equal to the sum of the traffic on its links. Simultaneous transmissions should be considered, and deducted from the total load on the channel.

In Fig. 1, we can see that link 6→5 can transmit simultaneously with link 2→1 and 1→G. Similarly, link 5→4 and link 8→4 can transmit simultaneously with link 1→G. To account for spatial reuse, we remove the load of the least congested link among the pair of simultaneously transmitting links. Hence, we remove a total of 3U, corresponding to the combined load of links 6→5, 5→4 and 8→4 which can transmit simultaneously with others. The effective load of the collision domain is therefore reduced to 11U.

We are left with 11U contending for the channel and sharing the effective capacity of the MAC layer, W. The local upper bound on the unit of traffic U is therefore W/11.

C. Bottleneck Collision Domain

Since packets are forwarded by intermediate nodes along the path to the gateway, the throughput is limited by the capacity of subsequent wireless links; $U_i = \min_{l \in L^i} U_l$, where L^i is the set of wireless links forming the path of node *i* to the gateway. The traffic in a WMN tends to be skewed as flows are aggregated and directed to the gateway. Collision domains are therefore most congested around nodes closer to the gateway, acting as bottleneck for system throughput.

In Fig. 1, the bottleneck collision domain corresponds to link 4→3's collision domain and carries an effective load of 11U. Since all the 3 flows, 7→G, 8→G and 9→G, contribute to the load of the bottleneck collision domain, no flow can increase its throughput without decreasing the capacity available to other flows.

V. OPTIMAL ADDITION OF RADIOS

A. Baseline Topology

For illustration, we consider a multi-flow chain topology consisting of 9 nodes in addition to the gateway, as shown at the first row in Fig. 2. Each of the 9 nodes generates a flow of bandwidth U, flowing towards the gateway, G.

For example, the link 6→7 has a load of 6U since it forwards flows 1 to 5 as well as the flow generated by node 6 itself. Similarly, for each wireless link we compute the corresponding collision domain. For example, the collision domain of link 6→7 corresponds to links 4→5, 5→6, 6→7, 7→8, 8→9 imposed by the coordinated channel access (RTS/CTS), in addition to link 9→G due to the hidden node problem. The nominal load of the collision domain would correspond to the sum of the load on those links. However, the effective load is much lower due to spatial reuse: link 4→5 can transmit simultaneously with link 8→9 and 9→G, similarly, link 5→6 can transmit simultaneously with link 9→G. Therefore, the loads of links 4→5 and 5→ 6 do not contribute to the effective load of the collision domain which is reduced to 6U+7U+8U+9U=30U. The load of collision domains for each link is computed and shown above that link in Fig 2.

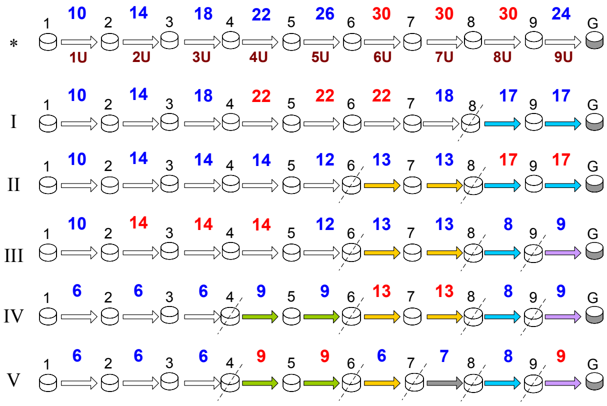

Figure 2. Chain topology and its subsequent 5 configurations

In this single-NIC chain topology, the bottleneck collision domain corresponds to any of the links 6→7, 7→8 and 8→9, and limits the throughput U of each flow to W/30. The load of bottleneck collision domains is shown in red in Fig. 2.

B. Breaking down Bottlenecks

We have shown in the previous section that the capacity of WMN is constrained by the bottleneck collision domain which needs to support higher traffic load. The throughput can therefore be increased by giving them more bandwidth by setting up new radios, breaking bottleneck collision domains into multiple collision domains each operating on a different non-interfering channel. Interfering wireless links would operate on different channels, avoiding interference and enabling multiple parallel transmissions. Wireless links that contribute to the effective load of bottleneck collision domains are called *critical* wireless links.

Referring to the initial single radio configuration in Fig. 2, *critical* wireless links consist of links 6→7, 7→8, 8→ 9 and 9→G. We note that the same set of critical wireless links make up the load of the 3 bottleneck collision domains of 30U shown in red. The optimal placement of an additional radio would therefore be at node 8, setting up the links 8→9 and 9→G to operate on a different channel than the remaining *critical* wireless links. Hence, each bottleneck collision domain is broken into 2 collision domains operating on different frequencies. We adopt the *Min-max* approach; that is, we subdivide the bottleneck collision domain into two sets, such that the maximum load of any of the two resulting collision domains is minimized. Since the load on neighboring collision domains changes as well, we continuously update the load on all collision domains and identify new bottlenecks, as we add new radios. The resulting topology is shown in Fig. 2 configuration I.

We can clearly see that the bottleneck has shifted to links 4→5, 5→ 6 and 6→7, and consists of 22U. We therefore give them more bandwidth by setting up a new radio at node 6, separating the critical wireless links 6→7 and 7→8 from the remaining *critical* links. The resulting configuration is shown in step II. Fig. 2 shows subsequent configurations as we add new radios, breaking the resulting bottleneck collision domains.

C. *Upper Bound on Capacity Improvement*

At configuration V, we reach a stage where the load of the bottleneck collision domain, 9U, consists of the load on the link, 9→G, itself. No additional improvements could be done using channel diversity as the bottleneck collision domain can not be further subdivided.

Hence, the load on the bottleneck wireless link imposes an upper bound on flows' throughput in the multi-radio architecture. This upper bound constitutes a stopping criterion to the incremental addition of radios, contrasting our configuration to other *k*-NIC architecture. Recall that all previous work on multi-radio WMN considered a *k*-NIC configuration, placing *k* radios at each node, and not taking into account the upper bound on the capacity which can be reached with less radios.

D. *Channel Assignment*

Once non-interfering channel regions have been identified, any graph coloring approximation algorithm [19] could be used to identify the number of non-interfering channels required for that purpose. A channel region is a set of wireless links which operate on a single channel and is represented by a unique color in Fig. 2. Ideally, a graph coloring algorithm is applied to the last configuration and channels assigned appropriately. However, if the number of channels is not enough, previous configurations would be considered iteratively (backward) until the number of required non-interfering channels is available.

E. *Generalization*

It is not difficult to extend the analysis to a more general topology. We consider a spanning tree routed at the gateway used for proactive routing. We can therefore use the traffic profile on the WMN, calculating the load on each wireless link then deriving the collision domain for each link. Next, we proceed to identifying bottleneck collision domains and placing additional radios iteratively using the *Max-min* approach, until the load on the bottleneck collision domain is confined to the load of the bottleneck wireless link. The load-aware radio addition technique will automatically form a fat-tree where more relay bandwidth is available on wireless links closer to the roots of the tree, i.e. the gateway.

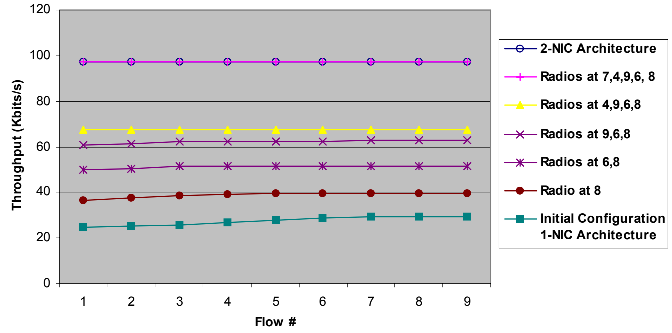

Figure 3. Throughput improvements at each step illustrated in Fig. 2

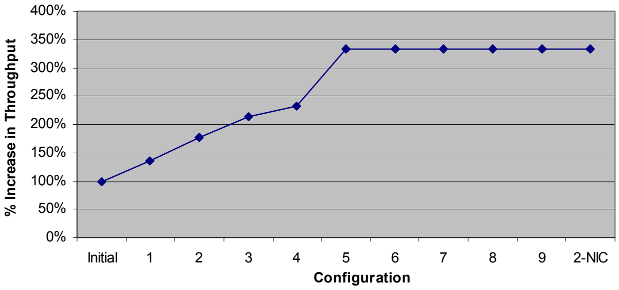

Figure 4. Throughput improvement with respect to the original configuration

VI. RESULTS VALIDATION AND PERFORMANCE ANALYSIS

A. *Experimental Settings*

NS-2 with CMU wireless extensions [20] is used for simulations. The parameters are tuned to the commercially available 802.11-based WaveLan wireless cards. The effective transmission range is 250 meters and the sensing (interference) range is about 550 meters. The simulations involve nodes separated by 200 meters, which allows a node to connect only to neighboring nodes. The bandwidth is set to 1 Mbps and RTS/CTS exchange precedes all data packets. NS-2 is extended to support static routing and multi-radio architectures.

B. *Comparison with 2-NIC Architecture*

In this section we study the performance of iteratively adding radios. Fig. 3 plots the throughput of all 9 flows for each of the 5 configurations (of Fig. 2) in addition to the initial one and the 2-NIC architecture. First we note that the throughputs of configuration number V and the 2-NIC architecture are overlapping. Second, we note that some flows farther away from the gateway experience less throughput than others. This is due to the hidden node problem, resulting from uncoordinated channel access of certain flows, causing collisions. Although the RTS/CTS handshaking works well to prevent the hidden node problem in WLANs, it is not as effective in multihop networks [21]. As the channel diversity increases when placing additional radios, fairness among the flows improves as the hidden node problem disappears gradually. Fig. 4 plots the increase in throughput with respect to the initial configuration in percentage. Each configuration consists of placing an additional radio.

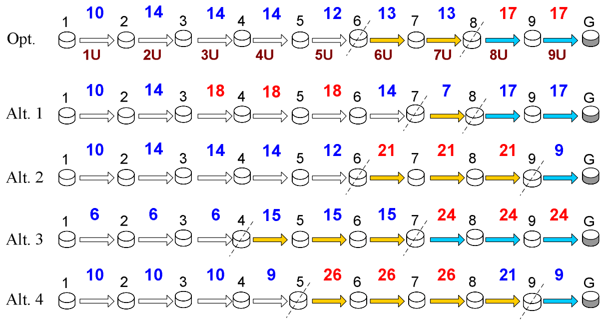

Figure 5. Optimal placement versus 4 other alternatives

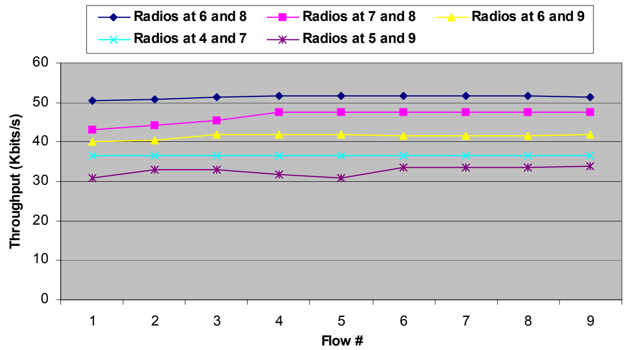

Figure 6. Throughputs' Comparison of configurations in Fig. 5

The first 5 configurations correspond to the 5 steps illustrated in Fig. 2. They consist of placing radios optimally by tracking down bottleneck collision domains. The remaining configurations, 6 and above, consist of placing additional radios, with no specific order, at remaining nodes until all 10 nodes are equipped with 2 radios each, referred to as 2-NIC architecture.

We can clearly see that the improvement in throughput stops beyond configuration 5, as the bottleneck collision domain is confined to the load of the bottleneck wireless link, 9→G, which can not be further reduced. We note that placing the same number of radios at all nodes is therefore not necessary. The 2-NIC architecture throughput can be reached by optimally placing 5 radios, hence saving 50% of the total amount of radios required in the 2-NIC architecture.

C. Comparison with Non-Optimal Radio Placement

By optimally placing one additional radio at node 8, the throughput has increased by 36.64%. Similarly, placing another radio at node 6, increases the throughput further to a total of 76.34%, and the throughput is doubled upon placing a third radio. Although we argued that placing 2 radios at each node was not necessary, here we show that the location of additional radios is also important. Fig. 5 shows the proposed optimal configuration and 4 other possible alternative placements for 2 additional radios. As shown in the previous section, an optimal placement consists of placing additional radios at node 6 and 8. Fig. 6 compares the performance of the five configurations. We can clearly see that our approach leads to the highest throughput. The second best configuration consists of placing an additional radio at node 7 instead of 6, and the third best consists of placing an additional radio at 9 instead of 8. Other alternatives which are not presented here lead to lower throughput and even to no improvements at all if placed for example at node 4 and 5.

VII. CONCLUSION

In this paper, we argued that additional radios should be placed according to the distribution of traffic load in WMN. We showed that placing an equal number of radios per node is not necessary, given that the capacity of a WMN is constrained by bottleneck collision domains. Additional radios should be placed such that bottleneck collision domains are given more bandwidth, benefiting from channel diversity. Moreover, we showed that an upper bound on capacity improvement is reached whenever the load of the bottleneck collision domain is confined to the load of an individual link. As a future work, it would be interesting to study analytically the number and distribution of radios required for a general topology.

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