THE NOMINAL CAPACITY OF WIRELESS MESH NETWORKS

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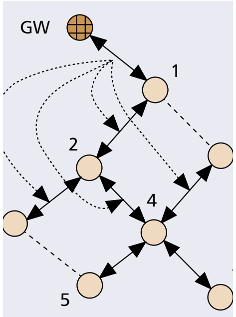

Wireless mesh networks (WMNs) are an alternative technology for last-mile broadband Internet access. Despite the recent start-up surge in WMNs, much research remains to be done before WMNs realize their full potential.

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ABSTRACT

Wireless mesh networks are an alternative technology for last-mile broadband Internet access. In WMNs, similar to ad hoc networks, each user node operates not only as a host but also as a router; user packets are forwarded to and from an Internet-connected gateway in multihop fashion. The meshed topology provides good reliability, market coverage, and scalability, as well as low upfront investments. Despite the recent startup surge in WMNs, much research remains to be done before WMNs realize their full potential. This article tackles the problem of determining the exact capacity of a WMN. The key concept we introduce to enable this calculation is the bottleneck collision domain, defined as the geographical area of the network that bounds from above the amount of data that can be transmitted in the network. We show that for WMNs the throughput of each node decreases as $O(1/n)$, where n is the total number of nodes in the network. In contrast with most existing work on ad hoc network capacity, we do not limit our study to the asymptotic case. In particular, for a given topology and the set of active nodes, we provide exact upper bounds on the throughput of any node. The calculation can be used to provision the network, to ensure quality of service and fairness. The theoretical results are validated by detailed simulations.

INTRODUCTION

The wireless mesh network (WMN) [1, 2] is a new broadband Internet access technology drawing significant attention these days. The competition with other broadband technologies, including cable, digital subscriber line (xDSL), broadband wireless local loop ,and satellite Internet access, is stiff, but WMNs have significant advantages, making them a viable alternative. Upfront investments are minimal, because the technology can be installed incrementally, one node at a time, just as needed. As more nodes are installed, the reliability and network coverage increase.

Figure 1 depicts a possible scenario where users (the small gray nodes) are provided with broadband Internet access using seven gateways (the larger red nodes) connected to the Internet. In WMNs, each user node operates not only as a host but also as a wireless router, forwarding packets on behalf of other nodes that may not be within direct wireless transmission range of a gateway. The gateways are connected to the Internet (the backhaul connection itself may also be wireless). The network is dynamically self-organizing and self-configuring, with the nodes in the network automatically establishing and maintaining routes among themselves. Users can be stationary or comparatively mobile [3]. The main difference between a WMN and an ad hoc network is perhaps the traffic pattern: in WMNs, practically all traffic is either to or from a gateway, while in ad hoc networks the traffic flows between arbitrary pairs of nodes. If desired, repeater nodes (pure wireless routers) may be used to extend the coverage or improve the performance of the network. A repeater node is a layer 3 device, similar to a client node except that it is never the source or destination of a traffic flow.

The gateways in WMNs are added one at a time as needed. Adding more gateways will increase not only the capacity of the network but also its reliability. The mesh structure ensures the availability of multiple paths for each node in the network. If one or multiple nodes fail, the packets will be rerouted around the failed node(s). Similarly, if one gateway fails, the others will take over its traffic, while the network as a whole will continue to function with (slightly) reduced performance. This provides a very appealing "graceful degradation" feature. Mobile users can connect to the WMN and have untethered connectivity as they roam within the coverage area of the WMN.

It is conceivable, and in fact quite desirable, that quality of service (QoS) guarantees can be offered to customers. If the network is designed carefully and enough Internet gateways are placed at key points, each customer can enjoy guaranteed bandwidth and/or delay (at least in the access network). The guarantees enable multimedia applications such as voice over IP and video on demand. Moreover, different classes of service (e.g., premium, enhanced, and basic) can

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be offered, each with different priorities and guarantees.

Because the network is built one node at a time, the technology allows providers to better match incoming revenues to outgoing expenses — a major challenge in DSL and cable-based services (and seemingly an insurmountable one for low Earth orbit, LEO, satellite services), especially at this time. Furthermore, many versions of WMNs are largely deployable by consumers themselves.

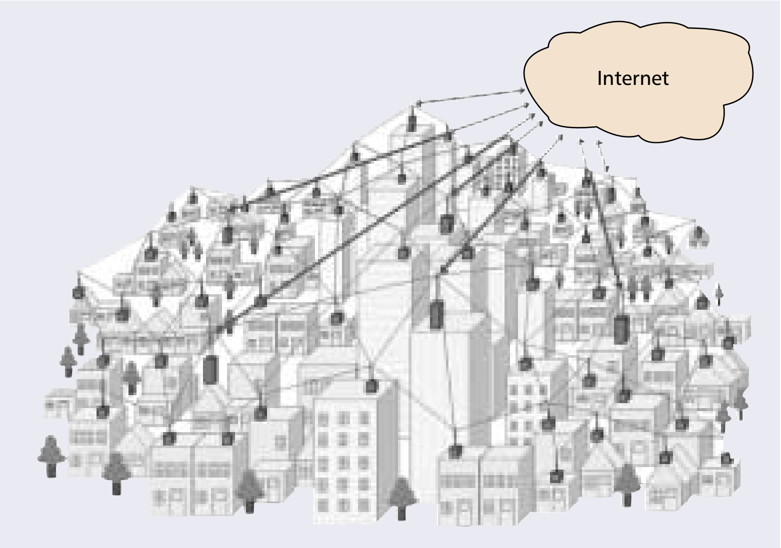
The technology is "radio agnostic" [3] (i.e., independent of the underlying radio technology). Fixed nodes can act as triangulation beacons for mobile users, and a Global Positioning System (GPS)-less geolocation feature can be implemented within the coverage area of a WMN.

Several vendors have recently offered WMN products. Some of the most experienced in the business are Mesh Networks [3] and Nokia Rooftop. There are more than 20 other startup companies that plan to offer similar products. A comparison of the product offerings of these companies reveals that the research needed to back up the products was largely passed over in the rush to capture the market. While the technology is sound, more research is needed before WMNs can reach their full potential.

One of the most hyped ideas is that the capacity of a WMN exceeds the capacity of a fixed wireless broadband Internet access (or that of a wireless LAN) based on similar technology. Some even claim that the capacity of the network increases with the number of clients. The intuition to support these claims comes from the spatial reuse possible in WMNs: two nodes at opposite ends of the network can transmit simultaneously without a collision; however, in a multihop environment, most of the transmissions are just forwarding traffic, which, as will be shown, effectively eliminates the gain from spatial reuse.

Although there are significant research results on the capacity of wireless ad hoc networks [4–10], these results are focused on the general case where the traffic streams flow between arbitrary pairs of nodes. Moreover, the existing results hold in the asymptotic case when the number of nodes n is very large. It was shown [4] that for stationary networks, the capacity for each node decreases as $O(1/\sqrt{n})$; while for mobile networks, if long delays are tolerated, the capacity may remain constant with the number of nodes: $O(1)$ [6]. Another study related to this article considers the capacity of regular ad hoc networks [5]. An interesting probabilistic model is used in [7] to compute the capacity of a chain of wireless nodes.

We will show that the existence of gateways in WMNs introduces hot spots in the network that act as bottlenecks. Due to the presence of these bottlenecks, the available capacity for each node is reduced to $O(1/n)$ where n is the number of users for one gateway. Most important, in our analysis we not only treat the asymptotic case, but also compute exactly the minimum and maximum data rates available for each node in a WMN for a given network topology and link layer protocol. The key concept enabling this computation is the *bottleneck collision domain*, which is the geographical area that limits the overall throughput of the network. We analyze the capacity of WMNs based on traffic behavior at the medium access control (MAC) layer. Since our approach is not limited to a specific MAC scheme, we can compute the exact capacity of a WMN for any MAC layer implementation.



■ Figure 1. *A wireless mesh network for broadband Internet access.*

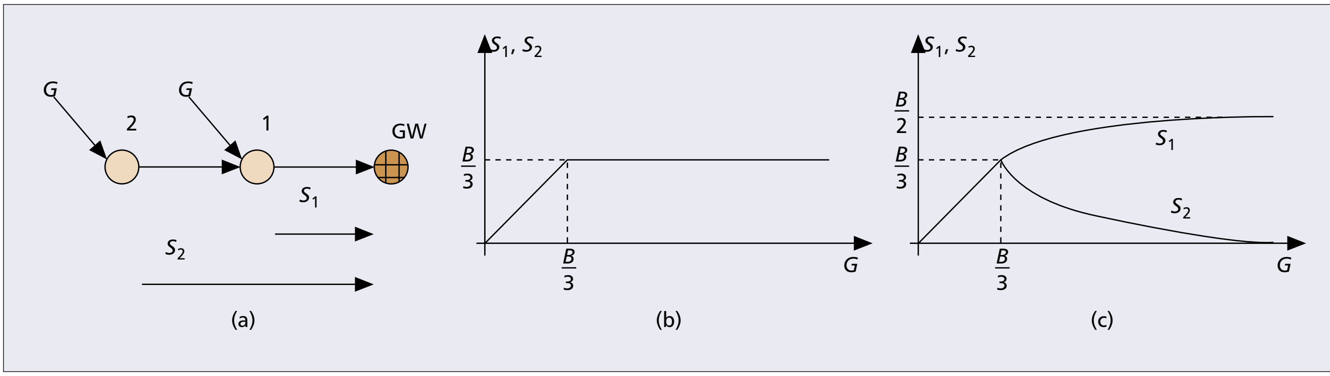
Problem Formulation

Before determining the capacity of WMNs, we will comment on the fairness of multihop networks. We will also define MAC capacity and collision domains as essential building blocks for WMN capacity calculation.

Relayed Traffic and Fairness

The question of the capacity of the network cannot be properly addressed without discussing the issue of fairness. Note that a user node in WMNs has to transmit relayed traffic as well as its own. Therefore, besides contention with other nodes for the same destination node, there is inevitable contention between its own and relayed traffic. This type of contention does not occur in fixed wireless local loops or wireless LANs in infrastructure mode where user nodes are always at one-hop distance from the base station or access point.

Consider the simple case depicted in Fig. 2a where two nodes (1 and 2) have the same offered load G sent to the gateway (GW). Ideally, as the offered load at each of the nodes (G) increases, both nodes receive the same share of the MAC layer throughput, B (Fig. 2b). In practice, without a modified MAC or network layer, as the offered load increases, the node closest to the gateway (node 1 in Fig. 2a) gradually but completely starves the node further away from the gateway (as shown in Fig. 2c). The results in Fig. 2c are obtained under the assumptions that the MAC layer is "fair" and that the traffic to be forwarded by node 1 (from node 2 to the gateway) is queued together (either in the forward-



■ Figure 2. *a) Fairness study of a two-node network forwarding packets to a gateway GW; b) the ideal and c) real throughputs of nodes 1 and 2 as a function of offered load* G.

ing engine or at the MAC layer) with the traffic originating at node 1.

The unfair behavior observed in Fig. 2b can be explained theoretically, and was verified using both OPNET and ns-2. A detailed analysis of the phenomenon is beyond the scope of this article. It is clear that unless *absolute fairness* is somehow enforced, the capacity of the network will depend on the offered load. Therefore, without describing how it may be achieved, in what follows we assume that there exists a mechanism enforcing absolute fairness in the WMNs under study. Under the assumption of absolute fairness for equal offered loads, the user nodes in the network will receive an equal share of the available throughput. An interesting, practical mechanism providing *proportional fairness* is presented in [11].

Nominal MAC Layer Capacity

In Fig. 2, *B* denotes the nominal MAC layer capacity. We define *B* as the throughput that can be achieved at the MAC layer in a *one-hop* network with infrastructure (e.g., 802.11 in infrastructure mode). The exact value of *B* depends on many parameters [12]:

- The radio technology (i.e., the raw physical layer data rate).
- The efficiency of the considered MAC layer.
- The size and distribution of the packets sent through the gateway is also important, as the MAC layer overhead can be very big for wireless communications.
- The error rate of the channel should be taken into account, if significant.
- The MAC layer throughput may also depend on the number of nodes in the system. For IEEE 802.11, on one hand, as the number of nodes increases, the time wasted in a collision avoidance phase decreases; on the other hand, the number of collisions increases.

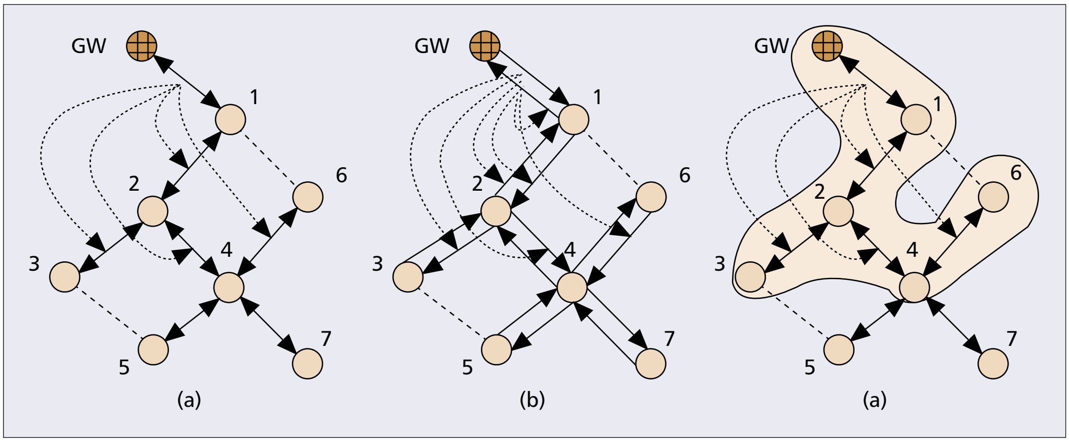
Given all the relevant parameters, the nominal MAC layer capacity *B* can be determined [12]. This capacity will be used in the following sections as the upper bound for the throughput of a network in a collision domain (defined in the next section).

Link Constraints and Collision Domains

The model used for the capacity analysis of WMNs takes into account the interactions at the MAC layer. Since wireless networks inherently use a shared medium for communication, the MAC protocols' primary goal is to avoid collisions, while maintaining good efficiency, delay, and fairness. The only way to achieve these goals is to ensure that only one node in a given geographical region transmits at a time (assuming a single frequency channel and no code-division multiple access, CDMA). Different MAC protocols avoid collisions in different ways. In ad hoc networks, many random access schemes have been proposed and have been shown to perform well under a variety of network topologies and traffic loads [13, 14]. Some of the most popular MAC protocols have been incorporated in the IEEE 802.11 [15] standard. Practically all MAC protocols avoid collisions by preventing simultaneous transmissions.

In Fig. 3, the solid arrows denote active links used to forward the traffic to and from the gateway. The dashed lines connect nodes that can receive each other's transmissions. Finally, the dotted arrows represent transmission constraints. In Fig. 3a, a MAC protocol that protects both ends of a link (e.g., request to send/clear to send, RTS/CTS [13]) is considered. When the link between the gateway and node 1 (link GW-1) is active, none of the other links connected by a constraint should be active in order to avoid a collision. In Fig. 3b an asymmetric MAC protocol is considered (e.g., carrier sense multiple access with collision avoidance, CSMA/CA [15]); and it is assumed that nodes 2 and 6 are aware of transmissions from the gateway, by either sensing the medium or receiving a CTS. In the case of an asymmetric protocol, the direction of the links should be taken into account when determining the constraints. Practically, for any MAC protocol (and physical layer parameters), given the topology of the network, a list of such constraints can be computed or determined experimentally.

We define the *collision domain* of the *i*th link as a set of links formed by the *i*th link and all other links that have to be inactive for the *i*th link to transmit successfully. Figure 3c depicts the collision domain corresponding to link GW-1 under the assumption of a symmetric MAC protocol. The notion is similar to the collision domain of an Ethernet network. In a WMN, each link has a collision domain that may partially overlap with the collision domains of other links.



■ **Figure 3.** *Link constraint models for (a) symmetric and (b) asymmetric MAC schemes, and (c) the wireless collision domain corresponding to the link GW-1.*

Once the link constraints are determined, the method presented in the next section can be used for any model to determine the capacity of the network.

Similar constraints can be imposed on the *nodes* of the network instead of the *links*. For example, node 2 should not transmit while the gateway transmits; however, the node constraints also depend on the destination node of the transmission, which eventually boils down to link constraints. Therefore, to make our presentation as clear as possible, only collision domains resulting from link constraints will be further considered.

Although the presented model only considers the constraints at the MAC layer, the model can be infinitely improved to take into account a large number of parameters (partial obstructions, Rayleigh fading [7], MAC protocol parameters, radio technology, transmission errors, etc.). Once the link constraints are determined, the method presented in the next section can be used for any model to determine the capacity of the network.

Determining the Nominal Capacity

In this section the assumptions concerning the capacity analysis of WMNs will be summarized. To improve the clarity of our presentation, a simple chain topology will be analyzed first, and later the results will be generalized to an arbitrary topology.

Assumptions

We assume that there is only one gateway in the network. If there are multiple gateways, the problem can be separated into multiple simpler problems by separating the nodes associated with one gateway from those associated with other gateways.

We also assume that there is an infinite amount of data to be sent from every node in the network. The scheme we present works well even if some of the nodes are idle (i.e., they are just repeaters and do not originate or receive traffic) or send data only a percentage of the time. We make this assumption for the sake of clarity.

We assume that there exists a mechanism for enforcing absolute fairness for all nodes sending data to the same gateway. In other words, the throughput of the nodes in the network is the same for any node for any offered load (the same offered load for all active nodes). Under this fairness scheme, every node in the network will receive an equal share of the bandwidth available in the network.

Furthermore, we assume the employment of an RTS/CTS type of MAC layer that protects both the sender and receiver from collisions. As mentioned earlier, under this assumption the link constraints are symmetric. If an asymmetric MAC layer is employed (e.g., CSMA/CA), the presented method still works, but the link constraints have to be carefully defined for each traffic direction.

For clarity, we assume that the traffic is unidirectional from the nodes to the gateway. This assumption can be trivially eliminated if the paths from the gateway to the nodes are the reverse of the paths from the nodes to the gateway. The presented scheme works well even if the traffic is bidirectional, but more care is needed when defining the link constraints.

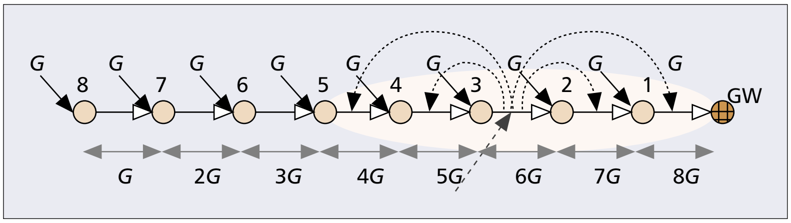
Finally, we assume that the nodes are stationary. Obviously, the capacity of WMNs depends on topology. If the topology changes, the capacity itself will change. Our computation holds for periods of time when the nodes are stationary or, if mobile, when mobility does not affect the topology of the network.

Chain Topology

In Fig. 4 a chain of $n = 8$ nodes generate and forward traffic to the gateway. The case where only the node farthest away from the gateway generates traffic was considered before [5]. Assume that each node generates traffic to be forwarded to the gateway and that each node can only receive packets from its immediate neighbors.

In the first step, the traffic that has to be forwarded by each link is computed. It is clear from the picture that nodes closer to the gateway have to forward more traffic than nodes farther away. In Fig. 4 node 1 has to forward $n - 1$ times the traffic it generates; thus, link 1-GW has to be able to forward traffic equal to nG.

In the second step, the collision domain of every link in the network is constructed. Consid-



■ Figure 4. *A chain of* n = *8 nodes generating and forwarding data to a gateway.*

ering a specific MAC layer model, link constraints can be determined for each of the $n = 8$ links of the chain. In Fig. 4, the constraints of link 2–3 are represented as dotted arrows. Similar constraints may be determined for every link but are not depicted to avoid cluttering the figure. Each link in the chain is constrained to transmit only when the other links in its vicinity are inactive.

For example, the collision domain of link 2-3 is composed of links {2-3, GW-1, 1-2, 3-4, 4-5}. Each collision domain has to be able to forward the sum of the traffic of its links. The collision domain of 2-3 has to forward $4G + 5G + 6G + 7G + 8G = 30G$. The collision domain corresponding to each link cannot forward more than the nominal MAC layer capacity B; therefore, there exists a collision domain that throttles the capacity of the entire network.

We define the *bottleneck collision domain* as a collision domain that has to transfer the most traffic in the network. There may be multiple bottleneck collision domains in a network (in which case they all have to transfer the same amount of traffic).

For a chain of length $n \geq 3$, it can be shown that the collision domain corresponding to link 2-3 is the bottleneck collision domain, as shown in Fig. 4. Therefore, for $n = 8$ the throughput available to each node G_{max} is bounded by $G_{max} \leq B/30$.

Similar inequalities can be written for every collision domain. By the definition of the bottleneck collision domain, the maximum throughput G_{max} obtained by solving the inequality for the bottleneck collision domain will satisfy all the other inequalities.

Arbitrary Topology

It is not difficult to extend the same analysis to a regular two-dimensional topology and, further, to an arbitrary topology. Figure 5 depicts an example of an arbitrary topology.

The collision domain corresponding to link 17-18 is composed of the link set {32-GW, 1-GW, 17-GW, 17-18, 18-19, 19-20, 19-21, 21-26, 26-28, 26-27, 9-14, 8-9, 4-8, 8-10}. Similarly, the collision domain corresponding to link 11-12 is composed of the link set {1-3, 1-4, 4-8, 8-10, 10-11, 11-13, 11-12} and partially overlaps with other collision domains. Each collision domain limits the available capacity for each node. By constructing the collision domains corresponding to every link it can be shown that for this topology, the collision domain of link 17-18 is the bottleneck collision domain. Assuming that all the nodes are allowed the same amount of bandwidth G, the maximum throughput available for each node G_{max} is thus bounded by $G_{max} \leq B/97$ because there are $97G$ b/s that have to be transmitted through the bottleneck collision domain.

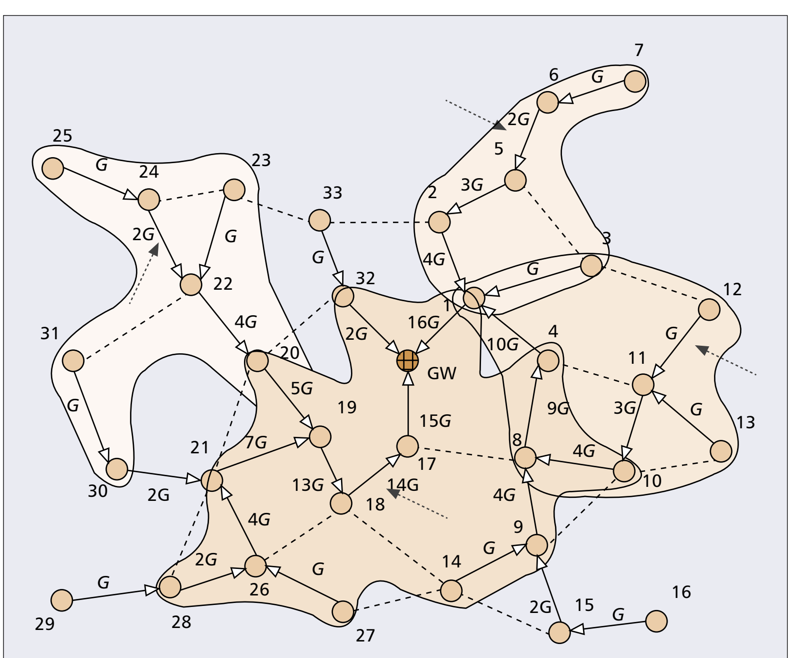
Simulation Results

To validate the results, we simulated a mesh network using the OPNET Modeler. For the MAC layer, we used 802.11b with RTS/CTS as it is well modeled in OPNET, and it is easy to compute the MAC layer throughput B [12]. We used constant bit rate (CBR) User Datagram Protocol (UDP) flows such that traffic behavior is not affected by the TCP's congestion control mechanisms. The same topology presented in Fig. 5 was used for the simulation. We increased the offered load and plotted the average throughput for each user node. We did not enforce absolute fairness.

Three scenarios were considered: in the first scenario, only one node (node 25) is active and forms a seven-hop chain toward the gateway. In the second scenario, three nodes (nodes 7, 25, and 29) send data at the same time. Finally, six nodes (node 7, 12, 16, 20, 25, and 29) are active simultaneously. All the active nodes generate packets toward the GW.

With a basic data rate of 11 Mb/s and a packet size of 1500 bytes, the upper bound for the aggregate throughput B is 5.1 Mb/s [12]. For each case, the network has a different bottleneck collision domain. Based on the calculation of B and identification of bottleneck collision domains, the theoretical throughputs for the three cases are 1.02 Mb/s, 464 kb/s, and 256 kb/s, respectively.

Figure 6 shows the result of the simulation. As the offered load is increased, the resulting average throughput saturates very close to the estimated value.



■ **Figure 5.** *A WMN with arbitrary topology.*

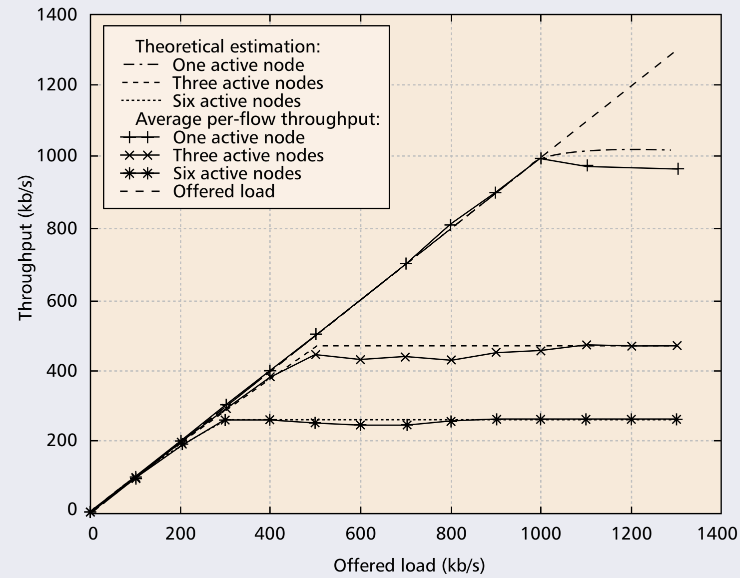
DISCUSSION

For a chain topology, it is obvious that the asymptotic throughput for each node is $O(1/n)$. For the general (arbitrary topology) case, it is clear that the traffic from all nodes *must* go through the links directly connected to the GW. The collision domain for any of these links includes all the links connected to the GW; hence, the sum of the traffic on these links (equal to nG) has to be smaller than or equal to the MAC throughput B. Thus, each node will receive $O(1/n)$ of the bandwidth where n is the total number of nodes. This is the same as the wireless LAN (one hop) case and significantly worse than the classical results of Gupta and Kumar $O(1/\sqrt{n})$ [4] for large values of n. The reason for the decreased performance of WMNs from that of pure ad hoc networks lies in the creation of a hot spot at the gateway that throttles the throughput of each node in the network. Clearly, the available throughput improves directly proportional to the number of gateways in the network.

The $O(\cdot)$ notation hides the real difference between the one-hop wireless LAN and the WMN. In the general case, the collision domain of any of the gateway-connected links will include all first *and* second tier links around the gateway; since most of the traffic in the first tier is forwarded from the second tier, the capacity of the WMN is smaller than the capacity of a wireless LAN with similar parameters by a factor of 2 (up to 3 depending on the exact topology, MAC layer and radio technology). This result is in sharp contrast to the claims of the product vendors. In all fairness, WMNs have other advantages over the one-hop solution: they require considerably less powerful transmitters, have improved reliability and market coverage, and, as preliminary results indicate, probably lower delay. Moreover, in the above analysis we did not take into account the potential increase in bandwidth due to reduced distance between the nodes. Indeed, we assumed that all communications take place at the maximum data rate allowed by the radio hardware; however, if a physical layer that adapts to the conditions of the channel is available (e.g., IEEE 802.11{a,b,g} and IEEE 802.16), the mesh network may have a higher bandwidth resulting from an increase in the signal-to-noise ratio at each receiver [7].

This rather simple but powerful scheme can be extended in several ways:

- For asymmetric MAC environments or networks with bidirectional traffic and different return paths, the direction of the traffic must be taken into account. The procedure we present works well in these cases as well, provided a collision domain is defined for each link *and* direction.
- The model of the network can be improved as well: One may take into account cumulative interferences from neighboring links to redefine the collision domains more accurately.
- Not all nodes have to be active at all times. When assigning traffic to the links, we can take into account only traffic from nodes that transmit/receive traffic.



■ Figure 6. *Theoretical and simulation results of the throughput as a function of the offered load* G *for all three scenarios.*

- Not all nodes have to receive an equal share of bandwidth. It is possible that the network supports different classes of service, where, for example, some nodes receive twice the bandwidth of other nodes. This case can be easily handled by our scheme by appropriately assigning the traffic weights on the links (e.g., $G_{\max}$ can be calculated when G is assigned to some nodes, $2G$ to others).

An obvious application of the presented method is provisioning for WMNs. The technique may also be used to achieve fairness and quality of service in WMNs; once how much bandwidth each node can receive is known, this value can be enforced at each node. Furthermore, the presented approach can be applied to any type of wireless networks that have a similar architecture and traffic pattern. For example, in wireless sensor networks data collected from the sensor field is typically forwarded in a multihop fashion to some form of long-haul base station that forwards it to a monitoring station. In wireless sensor networks, the estimated capacity can be used to tune the sampling rate of each sensor node so that the generated traffic does not exceed the available capacity.

CONCLUSION

Wireless mesh networks are a promising new broadband Internet access technology. Despite the recent availability of WMN products, much research is still needed before the technology is ripe. In this article a technique to determine the exact bandwidth of WMNs is presented. A model of the network topology and the number and position of active nodes have to be known (realistic assumptions for WMNs). The key concept introduced to enable the computation is the bottleneck collision domain, which throttles the throughput

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of the entire network. It is also shown that the asymptotic capacity for each node decreases with the number of nodes as $O(1/n)$, where n is the number of nodes in the network. The theoretical results are verified by careful simulations.

References

[1] B. Schrick and M. Riezenman, "Wireless Broadband in a Box," *IEEE Spectrum*, June 2002, pp. 38–43.

[2] J. Garcia-Luna-Aceves *et al.*, "Wireless internet gateways (WINGs)," *Proc. IEEE MILCOM '97*, Monterey, CA, Nov. 1997.

[3] MeshNetworks; http://www.meshnetworks.com

[4] P. Gupta and P. R. Kumar, "The Capacity of Wireless Networks," *IEEE Trans. Info. Theory*, vol. 46, Mar. 2000.

[5] J. Li *et al.*, "Capacity of Ad Hoc Wireless Networks," *Proc. 7th ACM Int'l. Conf. Mobile Comp. and Net.*, Rome, Italy, July 2001.

[6] M. Grossglauser and D. Tse, "Mobility Can Increase the Capacity of Ad Hoc Wireless Networks," *Proc. IEEE INFOCOM*, Apr. 2001.

[7] M. Haenggi, "Probabilistic Analysis of a Simple MAC Scheme for Ad Hoc Wireless Networks," *IEEE Wireless Circuits and Sys. Wksp.*, Pasadena, CA, Sept. 2002.

[8] M. Gastpar and M. Vetterli, "On the Capacity of Wireless Networks: The Relay Case," *Proc. IEEE INFOCOM*, 2002.

[9] Y. C. Tay and K. C. Chua, "A Capacity Analysis for the IEEE 802.11 MAC Protocol," *Wireless Networks*, vol. 7, 2001.

[10] F. Cali, M. Conti, and E. Gregori, "IEEE 802.11 Wireless LAN: Capacity Analysis and Protocol Enhancement," *INFOCOM '98*, vol. 1, 1998.

[11] A. Woo and D. E. Culler, "A Transmission Control Scheme for Media Access in Sensor Networks," *Proc. ACM MOBICOM*, July 2001.

[12] J. Jun, P. Peddabachagari, and M. L. Sichitiu, "Theoretical Maximum Throughput of IEEE 802.11 and Its Applications," *Proc. 2nd IEEE Int'l. Symp. Net. Comp. and Applications*, Cambridge, MA, Apr. 2003, pp. 249–56.

[13] V. Bharghavan *et al.*, "MACAW: A Media Access Protocol for Wireless LAN's," *SIGCOMM*, 1994, pp. 212–25.

[14] C. L. Fullmer and J. J. Garcia-Luna-Aceves, "Floor Acquisition Multiple Access (FAMA) for Packet-Radio Networks," *SIGCOMM*, 1995, pp. 262–73.

[15] IEEE Std. 802.11, "Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specification," June 1999.

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