Tree-based Wireless Mesh Network Architecture: Topology Analysis

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Abstract

Wireless Mesh Networks (WMNs) represent an effective solution to the "last mile" connectivity issue. However, to satisfy users' requirements in terms of quality of service, a clear understanding of the capabilities of WMNs is necessary. As we believe that traffic streams will mainly be oriented towards/from the network gateway therefore forming a tree-based architecture, we provide analytical evaluation of the network performance in this context and validate our results through simulations.

1 Introduction

Technological innovations in optical technologies have significantly increased the transport capacity of network backbone infrastructure, rendering access networks the bottleneck in high-speed data communication today. Due to cost and environmental factors, the deployment of optical networks remains infeasible at the access. Henceforth, Wireless Mesh Networks (WMNs) are sought as an effective alternative solution [1]. WMNs can significantly extend network coverage to regions that are difficult to reach with conventional wired networks (e.g. presence of environmental obstacles) while offering data rates up to 108Mbps. Many novel challenges are put forth by WMNs, including routing, mobility management, admission control, etc. To effectively address these issues, it is crucial to establish a clear understanding of the characteristics of wireless mesh networks, and the possibilities and limitations they present.

In this paper, we evaluate the performance of wireless mesh networks in tree-based architectures. We believe that most traffic streams in the network will flow between mobile nodes and the network gateway, as the users will be accessing the wired infrastructure for Internet access more than exchanging information with peers in the same wireless network. By deriving analytical formulation of the end-to-end delay, we provide network designers with approximations of expected network performance for specific network topologies.

The remainder of the paper is organized as follows. Section 2 provides background information on wireless mesh networks. The network performance analysis is described in Section 3 and assessed through simulations in Section 4. Section 5 concludes this paper.

2 Wireless Mesh Networks

2.1 Architecture

Wireless Mesh Networks are composed of three distinct network elements (Figure 1):

- Network Gateway: one (or more) gateway can be deployed to allow access to a different IP subnetwork (usually wired infrastructure).
- Access Points: the access points form a wireless backbone, providing connectivity in places otherwise difficult to access through traditional wired infrastructure. The wireless communication between the access points can use different technologies such as IEEE802.11a/b/g or IEEE802.16 and different hardware (directional or omnidirectional antennae).
- Mobile Nodes: any device embedding wireless capabilities (e.g. PDAs, laptops, etc.) can access the network gateway through direct or multi-hop communication (using the access points as relays).

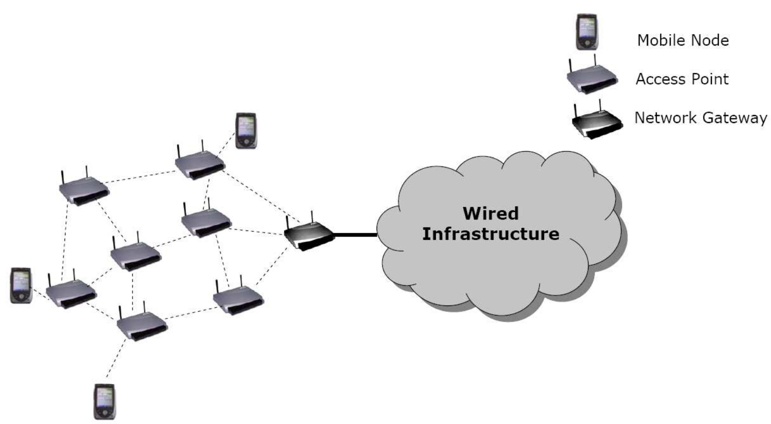

Fig. 1: Wireless Mesh Network Architecture

2.2 Routing in WMN

Whereas each mobile node can possibly communicate with any other mobile node in the network, most expected traffic streams will occur between the mobile nodes and the network gateway (e.g. to further access the wired infrastructure) [6]. An example of traffic pattern is depicted in Figure 2. The multi-hop nature of WMNs raises the question of end-to-end delay bound and therefore, an understanding of the impact of this type of topology on performance criteria such as end-to-end delay is a key element that can greatly facilitate the work of network designers.

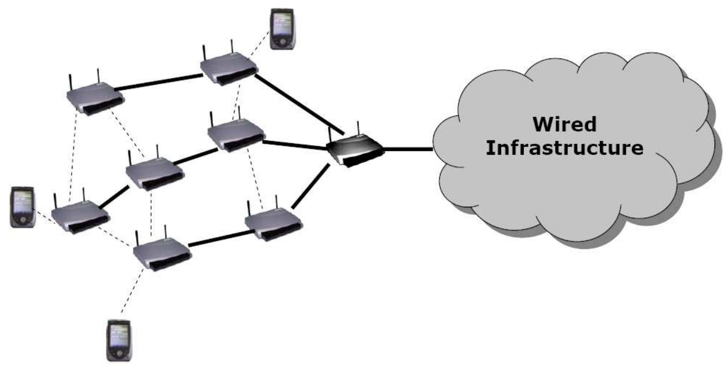

Fig. 2: Example of routing tree: the paths are represented by bold lines

3 Performance Analysis

The following analysis aims at providing an approximation of the end-to-end transmission delay. The results are then validated through simulations (Section 4). For the analysis, we make the following assumptions:

- The wireless backbone network and the wireless access network operate on different channels. Therefore we assume that there is no interference between the data transmissions between the access points and the transmissions between the mobile nodes and the access points.
- The access points are uniformly distributed.
- All the access points have similar transmission capabilities. This assumption makes the analysis more tractable by alleviating the computation from the specifics inherent to each access point.
- The medium access is performed according to a CSMA/CA protocol with Request To Send / Clear To Send (RTS/CTS) mechanism (IEEE802.11).
- Time is slotted and synchronization is maintained by the access points through the periodic transmission of beacon messages.

- Delays due to processing and propagation operations are negligible compared to transmission and queuing delays.

Our computation differs from previous approaches [3] in that for a multitude of source nodes (mobile nodes), there exists only one destination, the network gateway. To compute the end-to-end transmission delay we need to evaluate:

- 1-hop transmission delay between mobile nodes and access points
- 1-hop transmission delay between access points

The main difference in the computation of these two delays resides on the number of interfering nodes. The interference area between a mobile node and an access point is restricted to the coverage area of the access point, while in an access point to access point communication, all the neighbouring access points of the sender and receiver access points have to be considered.

3.1 1-Hop Transmission Delay

3.1.1 Between Access Points

The computation of the 1-hop transmission delay between access points follows a similar approach as in [3]. We denote r the transmission radius of an access point and N the number of access points distributed over an area of diameter k. The data transmission process involves the exchange of four different messages: RTS (Request To Send), CTS (Clear To Send), DATA packets and ACK (Acknowledgment). To each type of packet is associated a transmission duration respectively referred to as T_{RTS}, T_{CTS}, T_{DATA} and T_{ACK}. An additional waiting period SIFS (Short Inter Frame Space) has to be considered between the transmission of two successive packets. The time unit, *Time Slot*, is referred to as T_{TS}. Each access point can be in one of the four states:

- **Idle**: No transmission occurs. The access point decrements its backoff timer. The duration of this state is referred to as T_i.
- **Transmit**: Successful Transmission. The duration of this state T_t corresponds to $T_{RTS} + T_{SIFS} + T_{CTS} + T_{SIFS} + T_{DATA} + T_{SIFS} + T_{ACK}$.
- **RTS-Coll**: Collision on an RTS. The duration of this state T_r corresponds to the transmission duration of an RTS message.
- **CTS-Coll**: Collision on a CTS consecutive to the successful reception of an RTS. The duration of this state T_c can be expanded as $T_{RTS} + T_{SIFS} + T_{CTS}$.

Let CW be the size of the contention window and p the probability that a saturated access point transmits at a given time slot. It has been proven that for a fixed contention window size [2], p can be derived as:

$$p = \frac{2}{CW + 1}$$

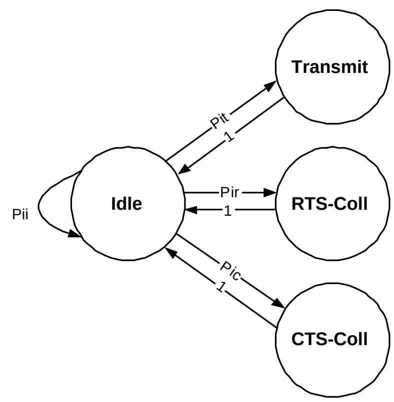

Fig. 3: FSM of data transmission process

Let N' be the number of nodes in the coverage area of an access point. N' can be expressed as $N' = \rho \Pi r^2$ with a network density $\rho = \frac{N}{\Pi R^2}$. By considering the equilibrium state, each transition can be straightforwardly computed as follows (Figure 3):

$$\begin{cases} P_{ii} = (1-p)^{N'} \\ P_{it} = (N'-1)\Pi_s(1-p)^{N'-1} \\ P_{ir} = 1-(1-p)^{N'} - N'p(1-p)^{N'-1} \\ P_{ic} = 1 - P_{ii} - P_{it} - P_{ir} \end{cases}$$

with Π_s the probability that a node successfully sends its resource request and receives its acknowledgment.

To compute Π_s, we consider that a node can be in three different states:

- **Wait**: no transmission occurs. The probability P_{ww} to remain in this state corresponds to the situation where no node initiates a data transmission process and can be computed as:

$$P_{ww} = (1-p)^{N'}$$

- **Succeed**: the node accesses the medium and successfully transmits its data.

- **Fail**: after accessing the transmission medium, data collision occurs necessitating a subsequent retransmission.

For a transmission to be successful, there should be no collision on the RTS and CTS messages. Therefore, the nodes in the transmission range of the source node and the receiving node should not initiate a data transmission process at the same time as the source node and the receiving node. For a given transmission, the area $B(d)$ where nodes may potentially interfere with the transmitting node can be computed as (d is the inter-nodes distance) [7]:

$$B(d) = \Pi r^2 - 2r^2 \arccos(\frac{d}{2r} - \frac{d}{2r}\sqrt{1-(\frac{d}{2r})^2})$$

As the distance between two nodes may vary between ϵ (we assume that two nodes are not exactly at the same location) and r, the average inter-nodes distance d_a can be computed as follows:

$$d_a = \sqrt{\frac{r^2-\epsilon^2}{2}}$$

$$d_a \approx \frac{\sqrt{2}r}{2}$$

Consequently, the probability of a successful transmission can be derived as follows:

$$\Pi_s = \frac{P_{ws}}{2-P_{ww}}$$

$$\text{with} \begin{cases} P_{ww} = (1-p)^{N'} \\ P_{ws} = p(1-p)^{N'-1}[(1-p)^{\rho B(d)}]^{\frac{(T_{RTS}+T_{SIFS}+T_{TS})}{T_{TS}}} \end{cases}$$

The percentage of time in the transmit state is derived as the time spent in the transmit state over the time spent in all the possible states

$$perc = \frac{P_{it}T_t}{P_{it}T_t + P_{ir}T_r + P_{ic}T_c + T_i}$$

Therefore, the delay $delay_{AP-AP}$ can be expressed as:

$$delay_{AP-AP} = \frac{1-perc}{perc}T_t$$

3.1.2 Between Mobile Nodes and Access Points

We assume that different neighbor access points are allocated different channels to communicate with the mobile nodes located in their vicinity. Therefore, they do not interfere with each other when communicating with the mobile nodes in their coverage area.

Following the same computation as performed in the previous section, let N'_s be the number of nodes in the interference area S_i of the sending node (Figure 4). S_i can be computed as follows:

$$S_i = 2r^2 \arccos(\frac{d}{2r} - \frac{d}{2r}\sqrt{1-(\frac{d}{2r})^2})$$

The remaining of the computation is similar to the one presented in the previous section. The state probabilities can then be expressed as follows:

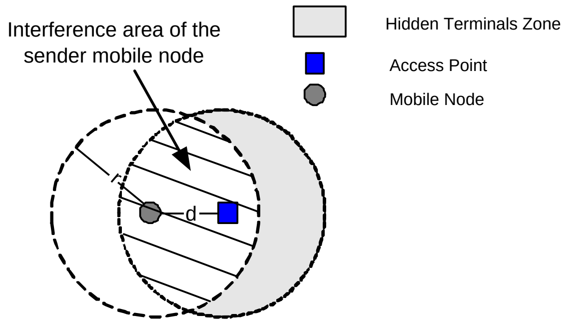

Fig. 4: Transmission area

$$\begin{cases} P'_{ii} = (1-p)^{N'_s} \\ P'_{it} = (N'_s - 1)\Pi_s(1-p)^{N'_s-1} \\ P'_{ir} = 1 - (1-p)^{N'_s} - N'_s p(1-p)^{N'_s-1} \\ P'_{ic} = 1 - P_{ii} - P_{it} - P_{ir} \end{cases}$$

with

$$\Pi_s = \frac{P_{ws}}{2 - P_{ww}}$$

$$\text{and} \begin{cases} P'_{ww} = (1-p)^{N'_s} \\ P'_{ws} = p(1-p)^{N'_s-1}\left[(1-p)^{\rho B'(d)}\right]^{\frac{(T_{RTS}+T_{SIFS}+T_{TS})}{T_{TS}}} \end{cases}$$

$$perc' = \frac{P'_{it}T'_t}{P'_{it}T'_t + P'_{ir}T'_r + P'_{ic}T'_c + T'_i}$$

Therefore, the delay $delay_{MN-AP}$ can be expressed as:

$$delay_{MN-AP} = \frac{1 - perc'}{perc'}T'_t$$

3.2 Queuing Delay

Let's assume that the transmissions are scheduled in a round robin fashion [1]. On a path, each intermediate access point would have to transmit its traffic as well as the traffic of its children. If we consider a network with uniform node distribution, the average number of nodes n_i at each hop level i can be expressed as:

$$n_i = \frac{N}{\pi R^2}\int_{(i-1)r}^{ir} 2\pi x dx$$

[1] The computation of the queuing has to be modified if another scheduling policy is implemented.

$$n_i = \frac{N}{\pi R^2}\pi[x^2]_{(i-1)r}^{ir}$$

$$n_i = \frac{N}{R^2}(i^2 - (i-1)^2)r^2$$

Let k be the hop level in the tree, k_{max} the maximum number of hops and p_k the number of packets that an access point has to forward. Then, for $k < k_{max}$, p_k can be expressed as:

$$\bar{p_k} = \frac{\sum_{k+1}^{R} \frac{Nr^2}{R^2}(k^2 - (k-1)^2)}{\frac{Nr^2}{R^2}(k^2 - (k-1)^2)}$$

$$\bar{p_k} = \frac{\sum_{k+1}^{R} k^2 - (k-1)^2}{k^2 - (k-1)^2}$$

The queuing delay q_k can therefore be approximated by:

$$q_k = \bar{p_k} * delay_{AP-AP}$$

3.3 End-to-end Transmission Delay

3.3.1 Average

The path followed by a packet generated by a mobile node can be divided into two sub-paths:

- Single hop transmission from the mobile node to the nearest access point.
- Multi-hops transmission from the associated access point to the network gateway.

Let k be the diameter of the network in terms of hops and $\bar{h}$ the average number of hops. $\bar{h}$ can be computed as follows:

$$\bar{h} = \frac{\sum_{i=1}^{k} ih_i}{N}$$

When computing the overall average end-to-end transmission delay, an important factor to consider is the possibility of simultaneous transmissions. By estimating the average surface involved in a data transmission process over the total transmission coverage, we can easily derive the possible number of simultaneous transmissions. Similar to before, we need to consider the area in which hidden terminals are located. The maximum area B_{MAX} is reached when r'=r. Therefore, we can derive B_{MAX} as:

$$B_{MAX} = \Pi r^2 - 2r^2(\frac{\Pi}{3} - \frac{\sqrt{3}}{4})$$

The average number of simultaneous transmissions n_{sim} can then be computed as follows:

$$n_{sim} = \frac{\Pi R^2}{\Pi r^2 + \frac{B_{MAX}}{2}}$$

$$n_{sim} = \frac{2\Pi R^2}{3\Pi r^2 - 2r^2(\frac{\Pi}{3} - \frac{\sqrt{3}}{4})}$$

Finally, by considering the time between two successive transmissions and by averaging this result over the number of access points, the number of successive hops and the number of simultaneous transmissions, we obtain the target estimation of the end-to-end delay.

So in total, the average end-to-end transmission delay can be obtained as:

$$delay_{average} = delay_{AP-AP} \frac{N * \bar{h}}{n_{sim}}$$

3.3.2 Worst Case

If we consider that h is the maximum number of hops, then the maximum end-to-end delay can be computed as follows:

$$del\bar{a}y_{max} = q_h + delay_{AP-AP} + delay_{MN-AP}$$

4 Validation

To assess the accuracy of our analysis, we performed a comparative evaluation using Matlab [4] and QualNet 3.6.1 [5]. We first evaluate the average end-to-end delay between a mobile node and an access point as the communication is assumed to occur on a frequency band different from the ones the access points are using and therefore simulations can be performed separately. Our simulations were performed using the parameters presented in Table 1. The comparison is depicted in Figure 5.

Simulation Parameters	**Values**
Data rate	2Mb/s
RTS	14 bytes
CTS	20 bytes
ACK	20 bytes
packet size	512 bytes
routing protocol	AODV

Tab. 1: Simulation parameters

For the backbone network, due to space limitations, we restricted our simulation to 25-nodes topologies (grid and random topologies) composed of 24 access points and 1 network gateway.

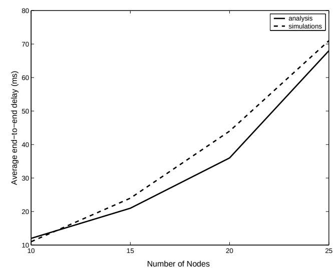

Fig. 5: Average transmission delay between mobile nodes and access point

The results of our simulations including the average end-to-end delay and worse-case delay are presented in Table 2. We therefore show that our analysis represents a good approximation for a tree-based wireless mesh network architecture.

		Theoretical	**Simulation**	**Error**
Grid	Average	177ms	162ms	8.4%
	Worst case	191	209	8.9%
Uniform	Average	69.7ms	78ms	11.5%
	Worst case	101.8ms	99ms	2.7%

Tab. 2: Results

5 Conclusion and Future Research

With the rise of user expectation of anywhere connectivity and quality of service guarantees, new wireless technologies are sought after for their versatility, ease of deployment, and low cost. Wireless mesh networks present a promising solution by extending network coverage based on mixture of wireless technologies through multi-hop communications. As the traffic streams are mainly oriented towards the network gateway, an analysis of the network performance in such a scenario can be very useful for future network deployments.

In this paper, we provided an analytical evaluation of the network performance in terms of average and worst-case end-to-end delay and validated it through simulations. In the future, we intend to perform more evaluations for example with different network topologies.

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