Delay Based Analytical Models of Wireless Mesh Networks

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ABSTRACT

This thesis focuses on providing analytical models for the performance evaluation of wireless mesh networks. The main difference from previous work is that we provide accurate analysis for both saturated and unsaturated loads, and closed form expressions for end-to-end delay. This allows for an analysis of routing optimization. Additionally, throughput studies with various congestion control mechanisms can also be performed. As a further extension, analytical models for express forwarding and variations of MAC protocols proposed for mesh networks will be provided, and special characteristics and knowledge of multi-hop networks will be explored to further improve efficiency.

1. INTRODUCTION

Mesh networks are being deployed and used in more and more cities. However, the existing models for performance analysis in mesh networks are still far from being satisfactory. Most of them are not accurate enough, and generally are too complex to be tractable.

My preliminary work makes assumptions similar to Boorstyn et al . [1], who study classical nonpersistent CSMA brought out by Kleinrock and Tobagi [5]. Boorstyn's work is the first to analyze multi-hop networks with arbitrary topology by employing "independent sets" idea. However, the complexity of the algorithm is prohibitive, and their method can only be used for throughput and fairness analysis for saturated loads. Analysis about delay, which requires an unsaturated load analysis, was lacking. In contrast, my dissertation work [6] has the advantage in providing delay-based analysis under an unsaturated load case, and has much lower computing complexity since a single-node decomposition has been employed.

Tobagi's work [2] studies the practical 802.11 based multi-hop network by extending Bianchi's work [4] to consider hidden terminals and unsaturated loads situation, and provides a delay based analysis using an *M/M/1* assumption. However, a tractable expression for delay was lacking. Knightly's work [3] has higher accuracy, but a delay-based analysis also was not provided.

Tobagi and Knightly et al. have presented solid analytical work on practical protocol (like 802.11) based multi-hop networks, and have shown interesting findings like inherent unfairness due to lack of coordination, and the limited effect of Binary Exponential Backoff compared with the minimum contention window. However, they also do not provide tractable expression of delay, which is required to explore better use of mesh networks. We consider a more basic MAC protocol in order to build an accurate model, and explore special characteristics of multi-hop networks using close-form expressions for delay. Moreover, when we start from the original form of the CSMA/CA protocol, it might give us a better look at what kind of MAC protocol should we have in order to address issues in multi-hop networks (like fairness), rather than restricted by what we have in 802.11.

The second stage of my thesis work will extend the current model and method to study more practical MAC protocols, and analyze express forwarding that is used to improve the fairness of long-hop flows and the efficiency of the whole network.

2. FINISHED WORK

2.1 Basic model

Fig. 1 depicts the queueing model for a single node, which is a continuous Markov chain. For each state (l, S) or (l, B), S represents that the node is sending (transmitting), B means that it is backing off, and l represents the number of frames waiting in the queue. The buffer size is L. When $l = 0$, the node is in idle state. This is an $M/G/1/L$ model from which the steady state, busy probability, blocking probability, etc. can be derived.

Frames generated at each node with a Poisson distribution at rate λ. All message transmission times are exponentially distributed with mean $1/\mu$. We assume an ideal collision avoidance mechanism that can always detect if the medium is busy or free at the end of a transmission attempt waiting period. Besides, each node backs off after a successful transmission to ensure other nodes can get fair chance to transmit. All waiting periods between transmission attempts (backoff periods) are exponentially distributed with

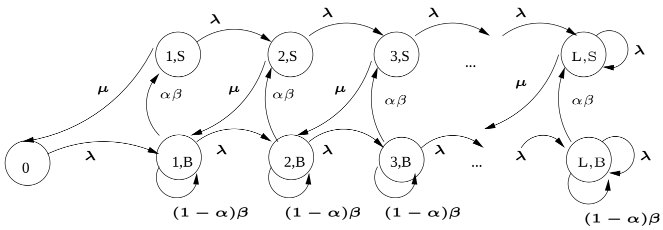

Figure 1: Markov chain diagram of a single node.

mean $1/\beta$. The probability that node i transmits successfully given that it *attempts* to do so is denoted as α_i and has following expression:

$$\alpha_i \quad = \frac{\rho_i - P_S[i] - \rho_i \cup_{k\in\omega_i} P_S[k]}{\rho_i - P_S[i]}. \qquad (1)$$

Here ρ_i is the queuing system utilization of node i and $\rho_i - P_S[i]$ is the portion of time that node i is in backoff . The value of α_i is determined by the "sending" probability of node i itself ($P_S[i]$) and its neighbors $k \in \omega_i$. Likewise, each neighbor k will have node i as its neighbor, and its successful transmission probabilities will depend on node i. Therefore, we need to use an iterative method to find the value of α_i.

To compute the portion of time that the medium is busy as seen by node i ($\cup_{k\in\omega_i} P_S[k]$), algorithms have been provided to identify hidden nodes and compute the overlapped transmitting probability [6], which makes it possible to apply this model to large and arbitrary topologies. The examples for some arbitrary topologies (20 nodes, up to 6 hops) have shown high accuracy of the analytical results compared with the simulation results (with same assumptions.)

2.2 Closed form expression of delay

When the queue is infinite, based on the Markov chain of Fig. 1 and by using the P-K formula for M/G/1 queues, the mean total time spent at node i can be calculated as:

$$E[T_i] = \frac{\mu + \alpha_i\,\beta - \lambda_i}{\alpha_i\,\beta\,\mu - \lambda_i\,\mu - \lambda_i\,\alpha_i\,\beta}. \qquad (2)$$

In which α_i has simpler expression:

$$\alpha_i = \frac{\mu(1 - \cup_{k\in\omega_i} P_S[k])}{\mu + \beta \cup_{k\in\omega_i} P_S[k]} = \frac{1 - \cup_{k\in\omega_i} P_S[k]}{1 + \beta/\mu \cup_{k\in\omega_i} P_S[k]}. \qquad (3)$$

Note that when no loss is assumed (with infinite queue), $P_S[k] = \lambda_k/\mu$. As a result, a closed form expression for α_i, and more importantly, $E[T_i]$, can be obtained. This will allow us to solve different problems, for example: (1) Use optimal routing for given loads to minimize the average flow delay for both single class and multiple classes of traffic [7]; (2) Study the behavior of nodes when rate control is employed; (3) Study the maximum throughput at the gateway while satisfying certain QoS requirements;

3. ONGOING WORK

3.1 Model with more practical protocols

While the idealized CSMA/CA model has been used can provide accurate expressions for delay, how to associate it with the real protocols that are being used is a challenge that needs to be addressed. Possible work include: (1) Build a discrete model for 802.11s MAC (not necessarily Binary Exponential Backoff) that utilizes the key ideas in my basic model shown in [6]; (2) Map 802.11s protocol into a continuous model by detailed analysis of different stages and connections among them; (3)Compare the applications for routing optimization and rate control with 802.11s based simulations (using NS-2 or OPNET)

3.2 Express forwarding in mesh network

In a IEEE 802.11 based wireless mesh network there are significant problems in maintaining fairness and low delay for long-hop flows. Express forwarding, which has been proposed to the IEEE 802.11s Task Group, is a possible strategy for solving these problems.

The existing work for express forwarding are all simulation based, and the main benefit that has been shown is limited to shortened delay for long-hop flows. My model shown in [6] will be extended in order to analyze express forwarding. Hopefully, good insights about how express forwarding can shorten the response time that a long-hop flow will experience can be provided. Furthermore, the closed form expression of delay can be used for analyzing the throughput of mixed load situations (some nodes always have very limited traffic to transmit) that are common in wireless mesh networks. The main reason why throughput analyses for mixed loads are needed comes from the fact that some mesh routers are just acting as relay nodes (Mesh Points as defined in 802.11s) so their traffic loads are the aggregate throughput of upstream nodes.

In conclusion, given a closed form expression for delay, the throughput of mesh networks can be well analyzed. Thus the efficiency and fairness of different express forwarding mechanisms can be evaluated, and better schemes that can further improve on these aspects are to be explored.

4. REFERENCES

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