Delay Based Analytical Models in Wireless Mesh Networks

Jiazhen Zhou
University of Missouri - Kansas City, Kansas City, MO, 64110

ABSTRACT

This thesis work is focusing on providing analytical models for performance evaluation of wireless mesh networks. The main differences from previous works are that we can provide accurate analysis for both saturated and unsaturated load cases, and can provide closed form expression for end-to-end delay, which opens a door for routing optimization, throughput study with congestion control applied etc. As a further extension, analytical models for express forwarding and more practical MAC protocols in mesh networks will be provided, and special characters and knowledge of multi-hop networks will be explored to further improve the efficiency of mesh networks.

1. INTRODUCTION

Mesh networks are being deployed and used in more and more cities. However, the existing analytical models for performance evaluation about mesh networks are still far from being satisfactory. Most of them are far from being accurate, and generally are too complex to be tractable.

There are two representative styles of research in this field, one is represented by Boorstyn et al . 's work that employs node-group based decomposition [Boorstyn-Tran-Comm'87], and considers ideal nonpersistent CSMA as MAC protocol; another one focuses on 802.11 based MAC protocol, represented by Tobagi et al . [Tobagi-Infocom'06] and Knightly et al . [Knightly-Infocom'06], both of which are based on the analytical model for WLAN provided by Bianchi [Bianchi-JSAC'00].

Our first period of work takes similar assumptions as Boorstyn's work, which is classical nonpersistent CSMA brought out by Kleinrock and Tobagi [Kleinrock-Tran-Comm'75]. Boorstyn's work is the first to analyze multi-hop networks with arbitrary topology. The key idea is to decompose large networks into smaller groups, called "independent sets" that consists nodes that can transmit simultaneously. Due to the need to compute all possible independent sets in the network, the complexity of the algorithm is prohibitive. Furthermore, this method can only be used for throughput and fairness analysis for saturated load case, and analysis about delay, which requires unsaturated load analysis, can not be done.

Compared with Boorstyn's work, our work [Zhou-ITC'07] has the privilege in providing delay-based analysis under unsaturated load case, and has much lower computing complexity since we use single-node decomposition similar to what has been employed by Bianchi, Tobagi and Knightly.

Tobagi's work studies the practical 802.11 based multi-hop network by extending Bianchi's work to consider hidden terminals and unsaturated load situation, and provides a delay based analysis using an *M/M/1* assumption. However, the accuracy of the analytical result about throughput is rather poor compared with simulation result, even though they just use single-hop communication pairs. Similarly, Garcia's result [Garcia-Mobicom'04] is also far from being accurate even it just considers saturated load case. Knightly's work has higher accuracy, but still not good enough, especially compared with what we have shown in [Zhou-ITC'07]. Although they also address the unsaturated load case, a delay-based analysis is lacking.

It is no doubt that Tobagi and Knightly et al. have done solid work on pushing analytical research 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 have obvious shortcomings in lacking accuracy and tractable expression of delay, both of which are required to explore better use of mesh networks. This is why we would like to backward a little bit in terms of complexity of the MAC protocol, but can build an accurate model, and explore special characters of multi-hop networks using close-form expression of delay. For example, provide ways to improve the performance of the network by choosing the best routing paths and traffic distributions. Moreover, when we start from the original form of CSMA/CA protocol, it might give us a better look at what kind of MAC protocol should we have to address issues in multi-hop networks (like fairness), rather than restricted by what we have in 802.11.

The second stage of our work will extend our 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 efficiency of the whole network.

2. MAIN 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 easily derived [Lipsky-Book'92].

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

Advisor: Dr. Ken Mitchell, mitchellke@umkc.edu
.

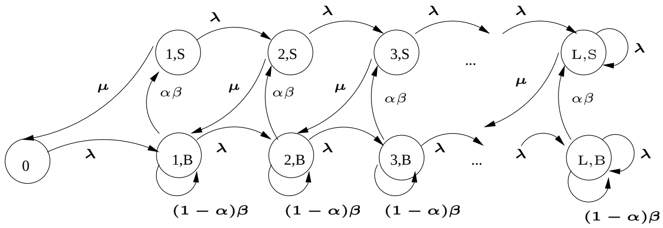

Figure 1: Markov chain diagram of a single node.

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 be 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, which makes it possible to apply our model to large and arbitrary topologies.

2.2 Accuracy of our model

To verify the effectiveness of our analytical model, comparison with the simulation results (using CSIM) for a 10 node tree structure mesh network (in Fig. 2) is shown in Fig. 3 and Fig. 4. Here Nodes 1-5 are sources of traffic (and have the same amount for ease of evaluation), the other nodes are acting as mesh routers.

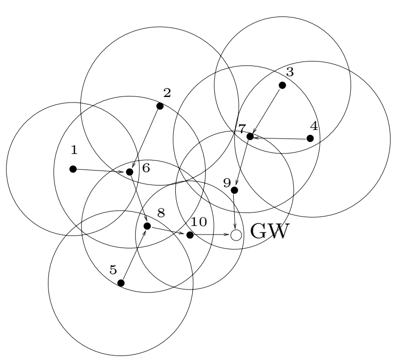

Figure 2: A mesh network with tree topology

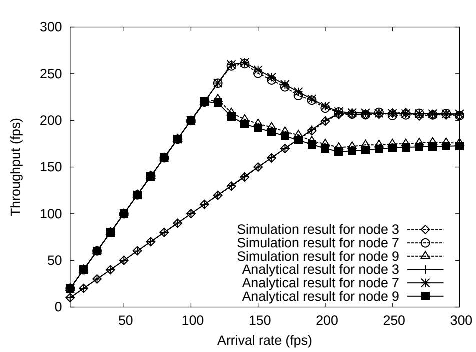

Figure 3: Throughput at nodes 3, 7, 9

As we can see, the analytical results for throughput are almost the same as the simulation for all loads. For the delay, the analytical results match perfectly with the simulation results for low load and heavy load, while there is a slight difference for moderate load. These results show that our model is much more accurate than previous work.

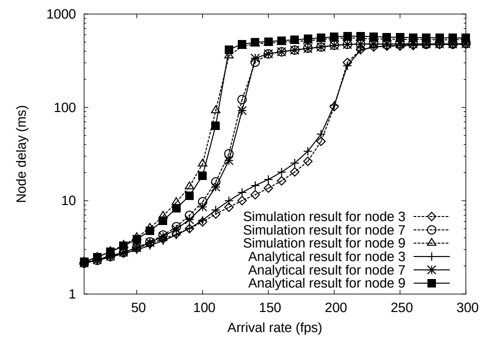

Figure 4: Delay at nodes 3, 7, 9

2.3 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) Get optimal routing for given loads to minimize the average flow delay for both single class and multiple classes of traffic [Zhou-WCNC'07]; (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 we have used can provide nice expressions for delay, how to connect it with the real protocols that are using is a challenge that we should overcome. Possible work include: (1) Build a discrete model for 802.11s MAC (not necessary Binary Exponential Backoff) that utilize the key ideas in our basic model (2) Map 802.11s protocol into our continuous model by detailed analysis of different stages and connections among them; (3)Comparing of our applications in routing optimization and rate control with 802.11s based simulations (using NS-2 or OPNET)

3.2 Express forwarding in mesh network

The biggest problem in wireless mesh network is its efficiency and unfairness for long-hop flows. Express forwarding , which has been proposed to 802.11s working group, is a good strategy to solve these problems. It is just like building a highway rather than have stop signs at each intersection. However, the existing work that we can see are all simulation based, which prevent us from obtaining the insight about the advantage and disadvantage (like unfairness to short-hop flows) of this strategy and exploring better relay mechanisms. We hope to extend our work in multi-hop networks to build a model for express forwarding.