A Single Node Decomposition Based Analytic Model for Multiclass Route Optimization in Wireless Mesh Networks

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***Abstract*— In this paper we present a single node decomposition based model for the analysis of wireless mesh networks. With knowledge of the network topology and routing strategy, the performance of each node, including throughput, delay, etc., can be analyzed using a simple M/G/1 model that takes into account the interference due to neighbor transmissions. With this basic analytic framework, closed form expressions for delay in terms of multipath routing variables are presented. A flow deviation optimization algorithm is used to derive the optimal flow over a given set of routes for both single and multiple classes of traffic. Numerical results are presented for different network topologies and compared with simulation studies.**

Keywords: Wireless mesh network; nodal decomposition; queueing model; delay; optimization; multiclass routing

I. INTRODUCTION

Wireless mesh networks are multi-hop access networks used to extend the coverage range of current wireless networks [1]. They are composed of mesh routers and mesh clients, and generally require a gateway to access backhaul links. Access to the medium is either centrally controlled by the base station or distributed, typically using some form of CSMA/CA protocol.

Critical research topics for wireless mesh networks include network capacity and scalability, QoS support, performance analysis, medium access control (MAC) schemes, error control schemes, routing, reliability, and security. Among those works related to the performance of wireless mesh networks, a number have appeared addressing network capacity. P. Gupta and P.R. Kumar [2] derive the upper and lower bounds of the capacity of a multi-hop wireless network based on the density of the nodes in network. Their analysis is based on uniform distribution of nodes in the network with ideal transmission characteristics. In a more recent work [3], N. Gupta and P.R. Kumar address throughput and delay in single- and multi-hop 802.11 networks under saturated conditions. Jun and Sichitiu [4], study the impact of long-hop routing on the throughput with homogeneous traffic and no frame loss. Mukherjee, Li, and Agrawal [5], provide a layer based analysis for the performance of 802.11 based multi-hop infrastructure networks. The interference caused by nodes in adjacent layers of the routing tree are considered, but a more general interference model, including hidden terminals is not addressed. Throughput and fairness issues have been addressed by Kar, Sarkar and Tassiulas in [6], where they incorporate the time taken for RTS/CTS, and by Wang and Kar [7], who present a model for optimal min/max fairness and throughput.

Multipath routing can improve performance by setting up paths that avoid the most congested regions of the network. A number of multipath routing algorithms have been proposed [8], [9] that have been shown to improve throughput by avoiding interfering nodes. Recently, Du et al. [10], presented protocols for multiclass routing in heterogeneous ad hoc networks.

The contributions of this paper include: 1) A single node decomposition based model for the analysis of wireless mesh networks. The performance of each node can be analyzed in isolation based on the knowledge of interfering neighbors, which has much lower complexity than methods that maintain state of the complete network. An iterative method is presented to calculate backoff probabilities due to interference from neighboring nodes. Results are accurate not only for the saturated node case (the limitation of most studies), but at all loads. 2) Under an infinite buffer assumption, the Pollaczek-Khinchin (P-K) formula is used to derive closed form expressions for the mean waiting time in terms of path flow variables. We solve the optimization problem using a flow deviation algorithm to find the optimal path flows. 3) For networks supporting multiple classes of traffic, a two step optimization method is presented to protect high priority traffic while guaranteeing the performance of the whole network.

The rest of this paper is organized as follows: In section II we describe the basic model and exploit the neighbor relationships to derive solutions using iterative algorithms. The optimization model and a two-step optimization method is also introduced. Examples using our method for the analysis and optimization of wireless mesh networks are shown in section III, and section IV concludes this paper.

II. BASIC MODEL

The basic model is based on a generic carrier sense multiple access protocol with collision avoidance (CSMA/CA) similar to non-persistent CSMA [11], which is the foundation for the 802.11 standard. One major difficulty encountered in model development is how to handle the correlation induced in multi-hop paths. Kleinrock and Tobagi [11], [12] and later Boorstyn et al. [13] and Tobagi [14] give conditions under which the analysis of CSMA systems results in product form solutions.

We generalize on their work to include a finite number of nodes, multiple hops, and interference caused by routing. Nodes having frames to transmit can access the network if the medium is idle. If the medium is detected as being busy, a node will reattempt to access the medium after a specified time interval. We assume that there is some mechanism (such as RTS/CTS in the 802.11 standard) that allows the node to determine if the medium is available or if it must wait and reattempt access to the channel.

For model development, we make the following assumptions:

1) Messages at each node i are generated according to a Poisson distribution with mean rate λ_i.
2) All message transmission times are exponentially distributed with mean $1/\mu$.
3) We assume an ideal collision avoidance mechanism that can always detect if the channel is busy or free at the end of a transmission attempt waiting period.
4) All waiting periods between transmission attempts (backoff periods) are exponentially distributed with mean $1/\beta$, resulting in a geometrically distributed number of backoff attempts (see Cali et al. [15]).
5) An infinite number of backoff periods are possible.
6) Each node backs off after a successful transmission to ensure fairness.
7) The probability that node i finds the channel free and is able to successfully transmit a message is denoted as α_i.
8) If node A interferes with node B, then node B also interferes with node A (symmetrical transmission range.)
9) Non-preemptive priority queue mechanism is used for the scheduling of different classes of traffic at the same node.

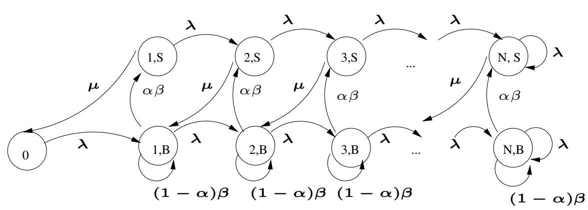

Fig. 1. Markov chain diagram of a single node.

Fig. 1 depicts the queueing model for a single node. For each state (i, S) or (i, B), S means the node is sending, B means it's backing off, i represents the number of messages waiting in the queue, and N is the queue length. The steady state, sending probability, blocking probability, etc. can be easily derived [16]. Strictly speaking, for internal nodes in the network that relay messages, the arrivals will not be Poisson, but under the conditions stated above, the model produces surprisingly accurate results compared to simulation.

A. Calculating successful transmission probabilities

We have defined α_i as the probability that node i successfully accesses the medium during a transmission attempt. Now consider the state of the medium in the region around node i. There are three possible states: 1) node i is idle with probability $P_I[i]$, 2) node i is sending with probability $P_S[i]$, 3) node i is in backoff with probability $P_B[i]$. When a node is transmitting frames, we note this node as being in its "sending" state. Obviously, α_i is decided by the "sending" probability of node i itself and its neighbors. In multi-hop networks, some nodes directly interfere with each other, some indirectly interfere (hidden terminal problem [12]), and some nodes do not interfere with each other at all. Those nodes that directly interfere or are hidden terminals to each other cannot send messages at the same time. We refer to these nodes as "neighbors" in this paper.

Let ρ_i be the queuing system utilization of node i, which means this node is either in its "backoff" or "sending" state, so $\rho_i = P_S[i] + P_B[i]$. Only when it is in "backoff", will node i sense the medium (attempt to transmit). The corresponding probability is $\rho_i - P_S[i]$. To make sure node i's attempt is successful, no neighbor of node i can be sending at that moment, so the probability of a successful attempt is $\rho_i - P_S[i] - \rho_i \cup_{k\in\omega_i} P_S[k]$, where ω_i represents all nodes that are neighbors of node i, and $\cup_{k\in\omega_i} P_S[k]$ represents the "sending" probability of neighbors as viewed by node i. We denote this as the medium "busy" probability in the neighborhood of i.

The parameter α_i can be interpreted as the probability that node i transmits successfully given that it *attempts* to do so.

$$\begin{aligned} \alpha_i &= \frac{\rho_i - P_S[i] - \rho_i \cup_{k\in\omega_i} P_S[k]}{\rho_i - P_S[i]} \\ &= \frac{1 - P_S[i]/\rho_i - \cup_{k\in\omega_i} P_S[k]}{1 - P_S[i]/\rho_i}. \end{aligned} \tag{1}$$

α_i is determined by the "sending" probability of node i itself 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.

The calculation of α_i in equation (1) can be verified by a simple example: for a wireless LAN with n nodes that are all saturated, a Markov chain can be built to solve the sending probability for each node. When the backoff rate β is equal to the service rate μ, the sending probability of each node will be $1/(n + 1)$, and the probability that all nodes are in their idle state (overlapped backoff probability) is also equal to $1/(n + 1)$. Knowing that $\rho_i = 1$, $P_S[k] = 1/(n + 1)$, by using equation (1) we have $\alpha_i = 1/n$. Since that $P_I[i] = 0$ for saturated node i, we have $P_S[i] = \alpha_i/(1 + \alpha_i) = 1/(n + 1)$.

For nodes that are not neighbors and don't have shared neighbors, their transmission probabilities are independent. If they have shared neighbors, their transmission probabilities are independent only during the period when no messages are being sent to or from the shared neighbors. In the latter case, we call these nodes "conditionally independent", and their overlapped sending probabilities can be calculated using conditional probabilities for random events.

With the overlapped sending probability known, the medium busy probability around each node $\cup_{k\in\omega_i} P_S[k]$ can be easily derived. Now we can use equation (1) to iteratively calculate α_i and the sending probability of each node.

B. Path delays

The service time distribution at each node consists of both the backoff delay and the transmission time. We use a matrix exponential distribution representation

$$F(t) = 1 - \boldsymbol{p} exp(-\boldsymbol{B}t)\boldsymbol{e}', \tag{2}$$

where $\boldsymbol{p}$ is the starting vector for the process, $\boldsymbol{B}$ is the progress rate operator for the process, and $\boldsymbol{e}'$ is a summing operator consisting of all 1's. The moments of the matrix exponential distribution are

$$E[X^n] = n!\boldsymbol{p}\boldsymbol{B}^{-n}\boldsymbol{e}'. \tag{3}$$

Based on the Markov chain of Fig. 1, the matrix exponential representation of the service distribution at each node i is

$$\boldsymbol{p} = \begin{bmatrix} 1 & 0 \end{bmatrix}, \quad \boldsymbol{B} = \begin{bmatrix} \beta\,\alpha_i & -\beta\,\alpha_i \\ 0 & \mu \end{bmatrix}. \tag{4}$$

Using equation (3), the mean of the service distribution at node i is

$$E[S_i] = \frac{\mu + \alpha_i\,\beta}{\alpha_i\,\beta\,\mu}, \tag{5}$$

and the second moment of the service time distribution is

$$E[S_i^2] = 2\,\frac{\mu^2 + \alpha_i\,\beta\,\mu + {\alpha_i}^2\beta^2}{{\alpha_i}^2\beta^2\mu^2}. \tag{6}$$

If we assume infinite buffers at each node, we can express the mean waiting time in the queue at each node using the P-K formula for M/G/1 queues,

$$E[W] = \frac{\lambda E[S^2]}{2(1 - \lambda E[S])}. \tag{7}$$

By substituting the expressions for the mean and second moment of the service times (equations (5) and (6)) into equation (7), the expected waiting time in the queue at node i is

$$E[W_i] = \frac{\left(\mu^2 + \alpha_i\,\beta\,\mu + {\alpha_i}^2\beta^2\right)\lambda}{\alpha_i\,\beta\,\mu\,\left(\alpha_i\,\beta\,\mu - \lambda\,\mu - \lambda\,\alpha_i\,\beta\right)}. \tag{8}$$

The mean total time spent at node i is $E[T_i] = E[W_i] + E[S_i]$, resulting in

$$E[T_i] = \frac{\alpha_i\,\beta + \mu - \lambda}{\alpha_i\,\beta\,\mu - \lambda\,\mu - \lambda\,\alpha_i\,\beta}. \tag{9}$$

If we assume (as in [3]), that $\beta = \mu$ and that they take on unit values, the expression for the mean delay at node i simplifies to

$$E[T_i] = \frac{1 + \alpha_i - \lambda}{\alpha_i - \lambda - \lambda\,\alpha_i}. \tag{10}$$

Assume each a node i has P classes of arrivals, where class 1 has the highest priority and class P has the lowest priority. We denote the arrival rate of each class r as $\lambda_{i,r}$. According to Cobham's formula [17], the waiting time of each class can be expressed as

$$E[W_{i,r}] = \frac{E[T_{i,P}]}{(1 - \sigma_{i,r})(1 - \sigma_{i,r-1})}, \tag{11}$$

where $E[T_{i,P}] = \sum_{k=1}^{P} \lambda_{i,k} E[S_{i,k}^2]/2$, $\sigma_{i,r} = \sum_{k=1}^{r} \rho_{i,k}$, and $\rho_{i,k} = \lambda_{i,k}/E[S_{i,k}]$. The first and second moment of the service times for each class can be computed using equations (5) and (6).

C. Optimization algorithm

To express the delay as an optimization problem, we use the following notation:

$\mathcal{K}$	Set of all origin-destination nodes that have traffic.
$\mathcal{I}$	Set of communicating nodes in the network.
Λ_k	Average arrival rate for origin destination pair k.
Λ	Total arrival rate to the network, $\Lambda = \sum_{k\in\mathcal{K}} \Lambda_k$.
$\mathcal{P}_k$	Set of possible paths for o-d pair k.
λ_{kj}	Amount of flow on path j for pair k.
α_i	Transmission success probability at node i, which is expressed as a function of the path flow variables λ_{kj} using equation (1).
δ_{jk}^{ℓ}	Node path indicator: 1 if path j for pair k passes through node n.
F_i	Total flow through node i, $F_i = \sum_{k\in\mathcal{K}} \sum_{j\in\mathcal{P}_k} \delta_{kj}^i \lambda_{kj}$.

The optimization problem for minimizing the mean delay a frame experiences in the network is

$$\min_{\lambda_{kj}, F_i} \frac{1}{\Lambda} \sum_{i\in\mathcal{I}} F_i \frac{1 + \alpha_i - F_i}{\alpha_i - F_i - F_i\,\alpha_i} \tag{12}$$

such that

$$\sum_{j\in\mathcal{P}_k} \lambda_{kj} = \Lambda_k, \quad k \in \mathcal{K} \tag{13}$$

$$\sum_{k\in\mathcal{K}} \sum_{j\in\mathcal{P}_k} \delta_{kj}^i \lambda_{kj} - F_i = 0, \quad i \in \mathcal{I} \tag{14}$$

$$\lambda_{kj} \geq 0,\ F_I \geq 0 \tag{15}$$

All the variables α_i can be expressed in terms of the flow variables λ_{jk} using equation (1), where, in the case of infinite buffers, $P_S[i] = \lambda_i/\mu$. The objective function is rational, with polynomials in both the numerator and denominator. The constraints are linear, so we use a flow deviation algorithm using the projection method [18] to solve this problem. Convergence is very fast for the examples we present under the assumption that the network is stable and the starting point is feasible.

For wireless mesh networks that support multiple classes of traffic based on priority queue scheduling, we need to optimize the route for each class to get the best performance for both the whole system and each class. A straightforward way to do this is to optimize the cost function we get in equation (12) based on the traffic rate of each class at each node. However, if we use the average network delay as our objective function, the higher volume of the lower class traffic will tend to dominate, possibly resulting in greater path delays for the higher priority traffic, which must be avoided.

One approach is to optimize the delay for each class, from high to low priority independently. While this works well for wired networks, it is not suitable for CSMA/CA networks because of the interdependence of path delays caused by interference.

As a solution, we propose the following efficient algorithm:

(1) Optimize the system delay for all O-D pairs as a single class.

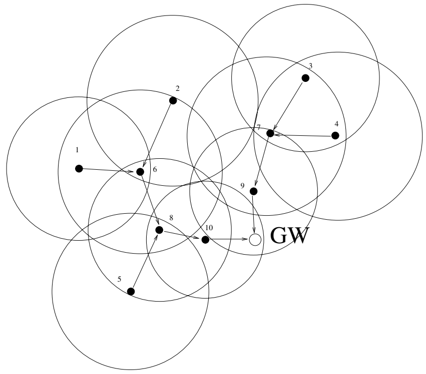

Fig. 2. Ten node multi-hop network.

(2) Among paths chosen for each O-D pair, optimize for each class.

The first step of this algorithm can guarantee optimal system delay and the traffic load for each path. In the second step, the optimal distribution of load among optimal chosen paths is explored for high priority classes.

III. Numerical Results

We will now show some numerical results for the performance evaluation and optimization.

A. Simulation Model

We use CSIM simulation tools to construct the simulation model. If a node has a segment to transmit, it will first wait one backoff period which is exponentially distributed with mean $1/\beta$. Upon completion of the backoff period, the node initiates an RTS to see if the channel is available. We use the same assumption that RTS/CTS communication is instantaneous over a dedicated channel and that there are no errors. If the channel is not available, the node will go into backoff, otherwise the segment is transmitted with a mean time of $1/\mu$. Segments are forwarded based on the route indicated in the segment header.

If there are multiple classes of frames to be sent, all the waiting frames will be put into a queue, and they will be scheduled according to the priority. For the frames with the same priority, FIFO scheduling is applied.

B. Evaluation of wireless mesh networks

In this subsection we show the effectiveness of our single-node decomposition method by comparing analytical results to simulation. In the following examples, we assume the maximum transmission rate is 10 Mbps, and the average frame size is 1250 bytes ($10,000$ bits), resulting in a mean transmission rate of $\mu = 1000$ frames per second (fps).

For the multi-hop mesh topology illustrated in Fig. 2. There is one gateway, nodes 1-5 are actively sending messages, and the other nodes are acting as mesh routers. There is only one class of traffic at each node. The comparison of simulation and analytical results for the delay at nodes 1, 6, 8, and 9 is shown in Fig. 3 and blocking probabilities are shown in Fig. 4. We can see that node 6 and node 8 are the bottlenecks in this network. Note that the results are accurate over a wide variety of offered loads.

C. Path optimization results

The path optimization study in this section is based on the network topology shown in Fig. 5. Wireless mesh networks frequently operate in two modes [19]. In mesh mode, all traffic will be routed through the base station. In ad hoc mode, nodes can route directly to each other. Optimization for both modes will be shown in the following subsections.

1) Mesh mode: For this example, only node 5 and node 1 have traffic to send. From node 5 to the gateway, 5-7-GW is the only path available; for node 1, there can be three different choices: path 1-3-6-GW, path 1-4-6-GW and path 1-4-7-GW. Therefore, we optimize the traffic distribution on the three possible paths out of node 1.

As an example, we assume that the traffic rate out of node 5 is $\lambda_{5,1} = 200$ Kbps, $\lambda_{5,2} = 500$ Kbps, and the traffic rate out of node 1 is $\lambda_{1,1} = 200$ Kbps, $\lambda_{1,2} = 2$ Mbps. The arrival rates in terms of frames per second are: $\lambda_{5,1} = 20$ fps, $\lambda_{5,2} = 50$ fps, and $\lambda_{1,1} = 20$ fps, $\lambda_{1,2} = 200$ fps, with service rate $\mu = 1000$ fps.

We use the two step optimization method introduced in section II. In the first step, we optimize the traffic on different paths without considering the classes of traffic. The total traffic out of node 1 is $\lambda_1 = \lambda_{1,1} + \lambda_{1,2}$. Denote the traffic at

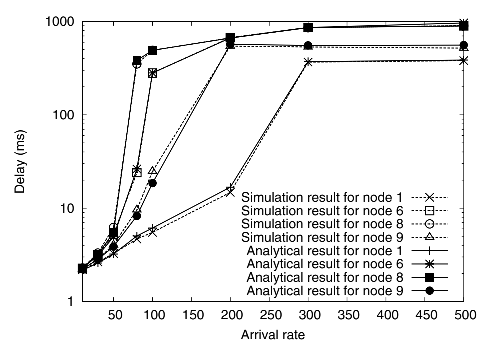

Fig. 3. Comparison for delay at nodes 1, 6, 8, and 9.

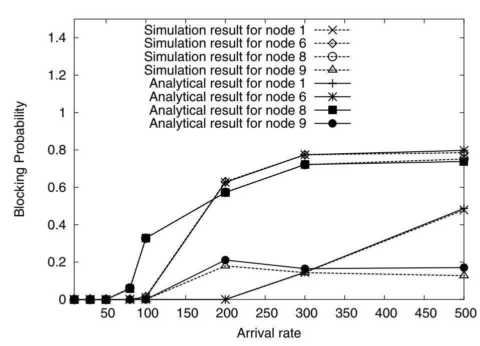

Fig. 4. Comparison for blocking at nodes 1, 6, 8, and 9.

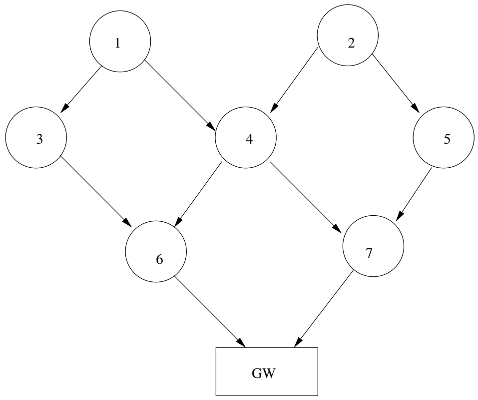

Fig. 5. System architecture of a wireless mesh network.

each possible path as λ_{136}, λ_{146}, and λ_{147} for path 1-3-6-GW, 1-4-6-GW and 1-4-7-GW respectively. We have $\lambda_1 = \lambda_{136} + \lambda_{146} + \lambda_{147}$, and can represent λ_{136} in terms of λ_{146} and λ_{147}, $\lambda_{136} = \lambda_1 - \lambda_{146} - \lambda_{147}$.

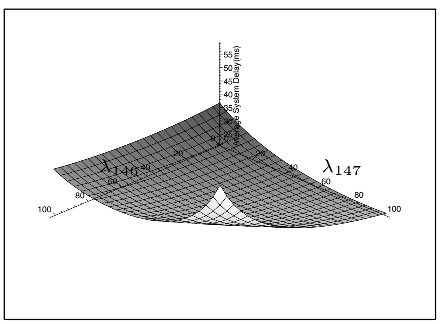

Fig. 6. System delay optimization for mesh mode example.

Now we can represent the optimization problem in terms of λ_{146} and λ_{147} using equation (12). The plot of the objective function on part of the feasible domain is shown in Fig. 6. The cost function is convex, so we use the flow deviation algorithm to get the optimal traffic distribution: $\lambda_{146} = 0$ fps, $\lambda_{147} = 88.295$ fps, $\lambda_{136} = 131.705$ fps. The optimized average system delay is 21.33 ms. We can see that if the route and traffic flow are well chosen, the system delay will be reasonable, otherwise the system delay can be unreasonably high and make frame loss inevitable.

After making sure the total system delay is minimum, we can minimize the delay for each class to make sure high priority traffic has the minimum delay. We have as our linear constraints $\lambda_{136,1} = \lambda_{1,1} - \lambda_{146,1} - \lambda_{147,1}$, $\lambda_{136,2} = \lambda_{136} - \lambda_{136,1}$, $\lambda_{146,2} = \lambda_{146} - \lambda_{146,1}$, and $\lambda_{147,2} = \lambda_{147} - \lambda_{147,1}$.

Using the delay equation for each class (equation (11)), and the above information, we can formulate the optimization problem using equation (12). The optimized traffic distribution is : $\lambda_{136,1} = 13.117$ fps, $\lambda_{146,1} = 0$ fps, $\lambda_{147,1} = 6.883$ fps, $\lambda_{136,2} = 118.589$ fps, $\lambda_{146,2} = 0$ fps, $\lambda_{147,2} = 81.411$ fps. The optimized average system delay for class 1 traffic is 9.994 ms.

Suppose we now have a flow of 200 fps from node 5 to node 7 and vary the flow from node 1 to the gateway from 0 to 200 fps. We assume the amount of class 2 traffic is always 9 times that of class 1 traffic between each O-D pair. The corresponding results are shown in Fig. 7. We can see that when the flow out of node 1 is low, all traffic is routed along path 1-3-6-GW. As the traffic increases, part of traffic begins to take path 1-4-7-GW. Class 1 traffic on node 1 always takes path 1-3-6-GW since interference in the region of 5-7 is high.

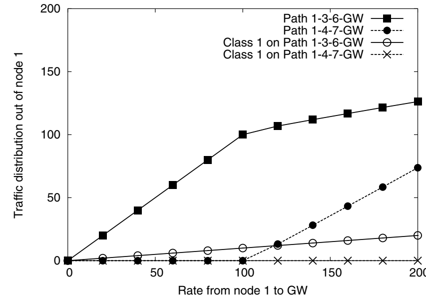

Fig. 7. Change of flow distribution as flow from 1 to GW changes.

If we fix the flow from node 1 to the gateway at 200 fps and increase the flow from node 5 to 7, the corresponding optimization results are shown in Fig. 8. We can see that as the traffic on O-D pair 5-7 increases, less traffic out of node 1 takes path 1-4-7-GW. All of the class 1 traffic takes path 1-4-7-GW when there is no traffic from 5 to 7. But as traffic on O-D pair 5-7 increases, less and less class 1 traffic takes path 1-4-7-GW until there is no flow.

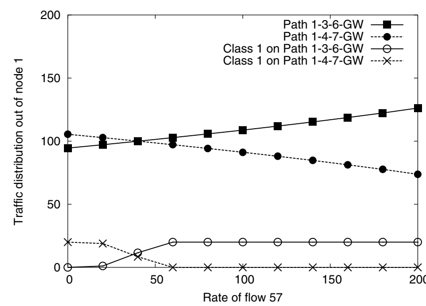

Fig. 8. Change of flow distribution as flow 5-7 changes.

2) Ad hoc mode: For this scenario, we assume that there are two communicating pairs. Node 1 is sending to node 6 and node 2 is sending to node 7. The paths available to O-D pair 1-6 are path 1-3-6 and 1-4-6, and the paths available to O-D pair 2-7 are path 2-4-7 and 2-5-7. The mean arrival rate at node 1 and 2 are denoted as λ_1 and λ_2 respectively. The path flow variables are denoted as λ_{136}, λ_{146}, λ_{247}, and λ_{257}. Similar to the optimization operation for the mesh mode example, we use the methods shown in Section II.

In Table I, we show the optimization results for varying load at nodes 1 and 2. We can see that when traffic at node 2 is low, part of traffic from node 1 will choose path 1-4-6 to minimize the system delay, also part of high priority traffic out of node 1 will also take path 1-4-6. As the traffic at node 2 increases, less traffic from node 1 will take path 1-4-6, and high priority traffic out of node 1 will not choose it because

TABLE I

OPTIMAL ROUTING FOR VARYING OFFERED LOADS.

$\lambda_1,$	λ_2	λ_{146}	$\lambda_{146,1}$	λ_{247}	$\lambda_{247,1}$	Delay	Class1	Class2
300	0	150.0	15.00	0.00	0.00	23.23	10.24	24.67
300	50	90.51	0.00	0.00	0.00	23.44	9.55	24.99
300	100	55.76	0.00	0.00	0.00	22.97	9.05	24.51
300	150	35.03	0.00	0.00	0.00	22.41	8.85	23.92
300	200	20.45	0.00	0.00	0.00	22.32	8.92	23.81
300	250	6.28	0.00	0.00	0.00	23.64	9.20	25.24
300	300	0.00	0.00	0.00	0.00	32.20	9.85	34.68

the delay will be higher than path 1-3-6 due to the increased interference from nodes 2 and 5.

IV. CONCLUSION

In this paper, based on the interfering and routing relationships among the nodes in wireless mesh networks, we used a nodal decomposition analysis where an iterative process was used to find the probability of a successful transmission at each node. For the case with infinite buffers, we derived closed form expressions for the average delay at each node and in the whole network. These expressions were used to formulate an optimization problem solvable with flow deviation methods. We could then identify the optimal multipath flows that minimize the mean delay in the network. For the case where there are multiple classes of traffic, we also introduced a two step optimization method to guarantee optimal scheduling for high priority traffic. The comparison of simulation and analytical results show that our analytical method is accurate under both light and heavy loads.

The evaluation of wireless mesh networks shows that the system performance is sensitive to the number of interfering neighbors and route selection. Based on the analytical framework we have developed, possible future work includes multiclass analysis for varying backoff rates and frame sizes.

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