Performance Evaluation of Single Channel Virtual-Circuit MAC Protocols for MANETs

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***Abstract*—In this paper, we develop and evaluate models for estimating various performance metrics for unicast traffic using a single frequency channel virtual-circuit Medium Access Control (MAC) protocol in mobile wireless ad-hoc networks. Time is divided into periodic frames with a portion reserved for control traffic and the rest divided into timeslots for data traffic. In order to avoid interference between neighboring links, the virtual-circuit MAC protocol uses a set of reservation rules to assign timeslots to links. One such virtual-circuit MAC protocol is the hard scheduling mode of the reservation based Unifying Slot Assignment Protocol (USAP) with the number of frequency channels in a frame set to one. USAP uses a set of generic reservation rules to avoid interference between neighboring links. We model the performance of a single frequency channel virtual-circuit MAC protocol using reduced load loss network models that couple the physical, MAC, and routing layers effects. The blocking probability of a call at a particular link is calculated by considering cliques of neighboring interfering links that cannot transmit simultaneously. These neighboring interfering links and the conflict graph are calculated using the virtual-circuit reservation rules. We compare our results with simulation and show good match for large networks across various offered loads.**

I. Introduction

Wireless Mobile Ad Hoc Networks (MANETs), where nodes form and maintain a wireless multihop network without any central infrastructure, require an efficient Medium Access Control (MAC) layer in order to access the wireless channel. MANETs using virtual-circuit MAC protocols, where a node reserves the wireless channel along the entire multi-hop path before transmitting data, promise easy provisioning of quality of service and better utilization at high loads. Any virtual-circuit MAC protocol requires a set of reservation rules to be observed at every link so as to avoid interference with neighboring links. Unifying Slot Assignment Protocol (USAP) [1] is a particular dynamic distributed reservation-based MAC protocol that uses a generic set of reservation rules in order to ensure that a link does not interfere with its neighboring links.

In this paper, we develop and evaluate models for estimating various performance metrics for unicast traffic using a virtual-circuit MAC protocol. The virtual-circuit MAC protocol sends data traffic over a single frequency channel and divides time into periodic frames with a portion reserved for control traffic and the rest divided into timeslots for data traffic as shown in figure 1. We assume that the virtual-circuit MAC

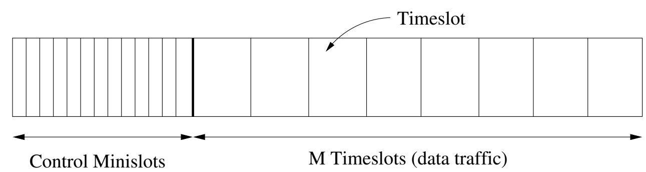

Fig. 1. Single Channel TDMA Frame Structure

protocol enforces a generic set of reservation rules at each link so as to ensure that the transmission at a particular link does not interfere with transmissions and reception among neighboring links. We use the generic reservation rules of USAP. Our approach to performance evaluation is based on fixed point methods and reduced load approximations for loss network models. Loss network models [2] were originally used to compute blocking probabilities in circuit switched networks [3] and later were extended to model and design ATM networks [4]–[7]. The main challenge in developing loss network models for wireless networks is coupling between wireless links due to sharing of the wireless medium between a node and its neighbors. We model this sharing of the wireless medium between a node and its neighbors by considering cliques of neighboring interfering links around a particular link and calculating the blocking probabilities for each such clique. These neighboring interfering links and their conflict graph are calculated using the virtual-circuit reservation rules.

We assume we know the exogenous traffic rate for each source-destination pair and use multiple paths with a set of routing probabilities to forward traffic between a source and destination. The reduced load loss network model coupled with individual link blocking probability calculation using cliques around the link give us a set of non-linear equations that are run iteratively to obtain fixed point estimates of performance metrics like blocking probability and throughput. We can then use the reduced load loss network model to calculate throughput sensitivities which are used to compute the optimal load distribution among multiple paths to maximize network throughput.

The paper is organized as follows. The next section briefly goes over the generic reservation rules that are enforced at each link in order to ensure that the link's transmission does not interfere with neighboring transmissions and receptions.

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Section III describes our models for the single frequency channel virtual-circuit MAC protocol. Section IV discusses how we calculate throughput sensitivities and use them to maximize network throughput by computing optimal load distribution among multiple paths of a source-destination connection. Finally, in section V, we present the time varying scenario used and the results of our model as well as its comparison against simulation.

II. Generic Reservation Rules

The single frequency channel virtual-circuit MAC protocol uses the periodic frame shown in figure 1. The control mini slots are used for exchange of network management information and are used to reserve time slots. These control minislots are also used by a node to broadcast the timeslots that are reserved for transmission and reception by itself and its neighbors. In this way, every node acquires information about the reserved slots in its 2-hop neighborhood. To avoid collision, the protocol enforces certain generic reservation rules at every transmitting node. The generic reservation rules specify those time slots that cannot be used by the transmitting node i of link $l = (i, j)$ to send traffic to node j and are as follows:

- Node i cannot reserve those time slots which already have scheduled incoming or outgoing transmissions to and from i and j.
- Node i cannot reserve those time slots already used by incoming call transmissions to the neighbors of i.
- Node i cannot reserve those time slots already used by outgoing call transmissions from the neighbors of j.

We do not model the control portion of periodic frame and only model the performance of the data traffic send in the M timeslots (figure 1). We use the reservation rules and the traffic in neighboring links of link l to estimate the blocking probability of traffic in link l as detailed in the next section.

III. Single Channel Virtual Circuit MAC Model

Assume that there are K classes of calls in the wireless network. Each class k call consists of calls along a route R_k and with a particular service type (voice, video, etc.). The calls from the K classes arrive according to independent Poisson processes with rates λ_k, $k = 1, \dots, K$. The holding times of the calls are independent of each other and independent of the Poisson arrival processes. The holding times of each class k are identically distributed with mean $1/\mu_k$. The offered load ρ_k of each class k call is λ_k/μ_k. Each class k call requires b_k timeslots per frame so that the call demand in terms of number of slots per frame is b_k.

The number of calls in the wireless network form a Markov process (K independent birth death processes) with the state space $\mathcal{S}$ characterized as follows. Using the reservation rules of section II, for each link $l = (i, j)$ in the network that has calls going through it, we can find those neighboring links $f = (m, n)$ (carrying traffic) that cannot share slots simultaneously with link l. These links f include those that are such that node n (receiver of link f) is a neighbor of i (transmitter of link l) or such that node m (transmitter of link f) is a neighbor of j (receiver of link l). The calls in those links that cannot transmit simultaneously have to share the M total timeslots. Thus for each traffic carrying link l, we can build a conflict graph whose vertices are the links that cannot share slots with link l and with edges between those links that cannot share slots with one another. These edges are again determined using the reservation rules. From this conflict graph, we can find all the cliques, i.e., all the maximal set of links that cannot share slots simultaneously. We use the Bron and Kerbosch algorithm [8] to find all the cliques. The calls in link l and the links of each clique should be such that the sum of the slots used is less than or equal to the total number of slots M. Thus each entry in the state space $\mathcal{S}$, i.e., each set of the number of (valid) calls in the wireless network has to satisfy these constraints for each link along their route in the network.

Let $\mathcal{K}_l$ be the set of call classes that use link l. Let there be L clique link sets around link l and let $\mathcal{M}_l^p$ (called closed clique link set, $p = 1, \dots, L$) denote the union of link l and a clique link set p around link l. For each closed clique link set $\mathcal{M}_l^p$ $(p = 1, \dots, L)$ of link l, we have

$$\sum_{f \in \mathcal{M}_l^p} \sum_{k \in \mathcal{K}_f} b_k n_k \leq M \qquad \forall p = 1, \dots, L \tag{1}$$

We can combine the state space constraints for link l as

$$\sum_{k \in \mathcal{K}_l} b_k n_k + \max_{p=1,\dots,L} \left(\sum_{f \in \mathcal{M}_l^p / \{l\}} \sum_{d \in \mathcal{K}_f} b_d n_d \right) \leq M \tag{2}$$

The equilibrium distribution of the number of calls, $\pi(\vec{n} = \{n_1, \dots, n_K\})$, is given by

$$\pi(\vec{n}) = \frac{1}{G} \prod_{k=1}^{K} \frac{\rho_k^{n_k}}{n_k!}, \quad \vec{n} \in \mathcal{S} \tag{3}$$

where, the partition function G is given by

$$G = \sum_{\vec{n} \in \mathcal{S}} \prod_{k=1}^{K} \frac{\rho_k^{n_k}}{n_k!} \tag{4}$$

There is a combinatorial explosion of the state space $\mathcal{S}$ with respect to the number of links, routes, and link capacities [2], [9] which makes the calculation of blocking probabilities via equations 3 and 4 impractical. We therefore use a reduced load loss network approximation [2] for computing the blocking probability of a class k call in the network. The reduced load loss network approximation assumes that links block independently and that the calls arrive at links along the route as independent Poisson processes. Then the offered load of class k calls arriving at a link l (where $l \in R_k$) is reduced due to blocking at other links in the route R_k and is given by

$$\rho_{k,l} = \frac{\lambda_k}{\mu_k} \prod_{p \in R_k / \{l\}} (1 - B_{k,p}) \tag{5}$$

where, $B_{k,p}$ is the probability of blocking a class k call on link p that is along route R_k. The blocking probability, L_k, of a class k call is given by

$$L_k = 1 - \Pi_{l \in R_k}(1 - B_{k,l}) \tag{6}$$

To compute the blocking probability $B_{k,l}$, consider each closed clique link set $\mathcal{M}_l^p$ ($p = 1, \ldots, L$) around link l. Let the number of links in $\mathcal{M}_l^p$ that are also along route R_k be $n_{k,\mathcal{M}_l^p}$. For this clique set $\mathcal{M}_l^p$, we can compute the blocking probability $B_{k,\mathcal{M}_l^p}$ of a class k call as

$$B_{k,\mathcal{M}_l^p} = 1 - \sum_{c=0}^{M - b_k * n_{k,\mathcal{M}_l^p}} q_{\mathcal{M}_l^p}^M(c) \tag{7}$$

where the $q_{\mathcal{M}_l^p}^M(c)'s$, are the probabilities of having exactly c slots occupied in a frame with a total of M slots (i.e., knapsack occupancy probabilities) for the closed clique link set $\mathcal{M}_l^p$. These occupancy probabilities can be computed easily using following recursive stochastic knapsack algorithm [10]:

1) Set $g_{\mathcal{M}_l^p}^M(0) \leftarrow 1$ and $g_{\mathcal{M}_l^p}^M(c) \leftarrow 0$ for $c < 0$
2) For $c = 1, \ldots, M$, set $g_{\mathcal{M}_l^p}^M(c) \leftarrow \frac{1}{c} \sum_{f \in \mathcal{M}_l^p} \sum_{k \in \mathcal{K}_f} n_k \, \rho_{k,f} \, g_{\mathcal{M}_l^p}^M(c - n_k)$
3) Set $G_{\mathcal{M}_l^p}^M = \sum_{c=0}^M g_{\mathcal{M}_l^p}^M(c)$.
4) For $c = 0, \ldots, M$, set $q_{\mathcal{M}_l^p}^M(c) \leftarrow g_{\mathcal{M}_l^p}^M(c)/G_{\mathcal{M}_l^p}^M$.

If a class k call is blocked in any of the closed maximum clique link set $\mathcal{M}_l^p$ ($p = 1, \ldots L$), then the call is blocked. We approximate the link blocking probability $B_{k,l}$ to be the maximum of the closed clique blocking probabilities $B_{k,\mathcal{M}_l^p}$ ($p = 1, \ldots, L$), i.e.,

$$B_{k,l} = \max_{p=1,\ldots,L} B_{k,\mathcal{M}_l^p} \tag{8}$$

IV. Throughput Sensitivities

Total throughput $TH(\mathbf{C_l})$ for the single frequency channel virtual-circuit MAC protocol is the total call demands that are not blocked and depends on the vector of free capacities $\mathbf{C_l}$ over all the links l , i.e.,

$$TH(\mathbf{C_l}) = \sum_{s \in S} \sum_{r=1}^{k_s} n_s \alpha_{r_s} \frac{\lambda_s}{\mu_s}(1 - L_{r_s})$$

where S is the set of all source-destination connections, k_s is the total number of routing paths for a connection s, n_s is the call demand (number of reserved cells per frame) for connection s, and α_{r_s} is the fraction of calls that are routed over path r for connection s.

For the reduced load approximation of a multi-service loss network, it is possible to analytically calculate the throughput sensitivities using the implied cost formulation (see section 5.7 of [10]). In order to connect to the implied cost formulation, n_s is equal to the rate at which a call on route r for connection s earns revenue. Consider adding a single call to route r of connection s in equilibrium. This call is admitted with probability $1 - L_{r_s}$; if admitted the call uses an average of n_s/μ_s cells or earns an average revenue of n_s/μ_s, but reduces the future expected revenue or throughput due to the additional blocking that its presence causes. This expected loss in future revenue or throughput is called the implied cost (c_{r_s}) of route r call of connection s. Hence throughput sensitivities are given by:

$$\begin{aligned} \frac{\partial}{\partial \alpha_{r_s}} TH(\mathbf{C_l}) &= \lambda_s(1 - L_{r_s})\Big(\frac{n_s}{\mu_s} - c_{r_s}\Big) \\ \text{where, } c_{r_s} &= \frac{1}{\mu_s}[TH(\mathbf{C_l}) - TH(\mathbf{C_l} - \mathbf{n_{lr_s}})] \end{aligned}$$

and $\mathbf{n_{lr_s}}$ is a vector specifying the call demand for route r of connection s over all the links l. The implied costs are approximated using the link independence assumption. Thus the total implied cost for route r of connection s is approximated to be the sum of individual link implied costs along all links l of route r of connection s and is given by:

$$c_{r_s} = \sum_{l \in r_s} c_{lr_s}$$

A fixed point approximation procedure is used to find the link implied costs similar to that in [10] (section 5.7). The equations are:

$$c_{lr_s} = \sum_{r'_{s'} \in R_l} \frac{\Delta_{r'_{s'}, lr_s} \, \rho_{l, r'_{s'}}}{\mu_s} \left[n_{s'} - \mu_{s'} \sum_{i \in r'_{s'} - l} c_{ir'_{s'}} \right]$$

where, $\Delta_{r'_{s'}, lr_s}$ is the difference in blocking probabilities for a call of route $r'_{s'}$ at link l when the total capacity, i.e., time slots is reduced by the demand of a single call of connection s and when there is no reduction in slots.

Having obtained the throughput sensitivities with respect to routing probabilities, we use the gradient projection method to find the optimal values for routing probabilities to maximize total network throughput.

V. Results and Validation

A. Scenario

The scenario considered is a time varying fast moving network of 30 vehicles heading towards a rendezvous point. The scenario duration is for 500 seconds with vehicles moving at speeds between 22-60 mph. The vehicles start together, then branch into 3 clusters of 10 nodes each due to obstructions (2 steep hillocks), and finally rejoin (see figure 2). Two Aerial Platforms (APs) are used to maintain communication connectivity when the clusters become disconnected. The number and location of the APs are determined by a fast Deterministic Annealing algorithm [11]. From 0-30s, the ground nodes move together forming a connected network. From 30-420s, the nodes form 3 clusters as shown in figure 2 with clusters 1 (nodes 0-9) and 3 (nodes 20-29) going around the hills. The clusters start to lose communication connectivity around 75s, then become disconnected from each other, and finally reconnect around 400s. APs are brought in to provide communication connectivity between the otherwise disconnected clusters from 75-400s.

The scenario is specified every 5 seconds (the ground nodes move an average of 100 meters in 5s). At every 5

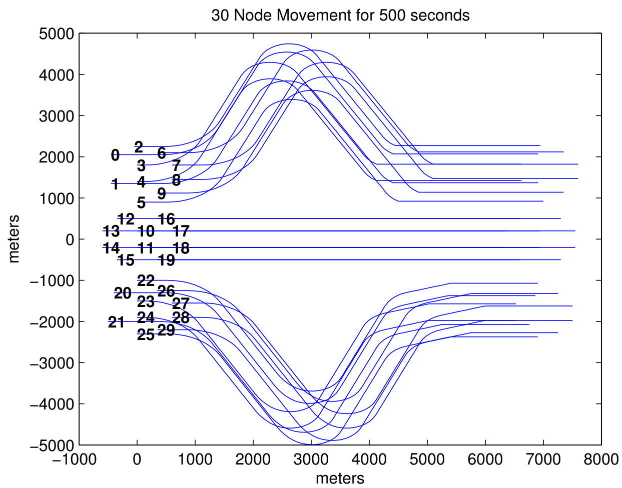

Fig. 2. 30 node movement for 500 seconds

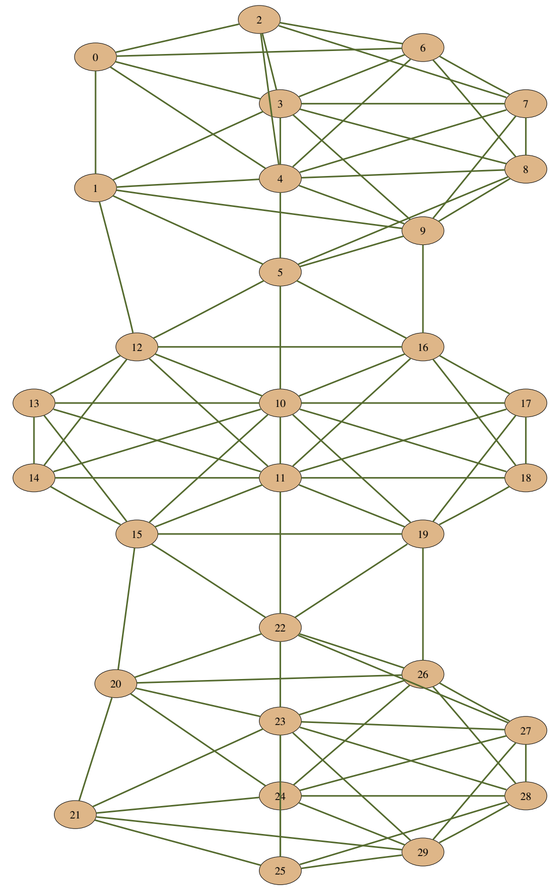

Fig. 3. Node connectivity at time 0

second interval, the ground node positions, the traffic demands (offered load) & routes between source-destination pairs, and the environment conditions are input to the single frequency channel wireless virtual-circuit performance model. All ground nodes and APs have identical omni-directional radios with receiver sensitivity of -95dBm, receiver threshold of 10dB, and transmit power of 5W. The environment is modeled as a fading channel with a $1/R^{\alpha}$ power attenuation. The radio specification and the path loss exponent α together determine a maximum connectivity distance between nodes. α is taken to be 4.5 between ground nodes, 3.9 between ground and aerial nodes, and 3.0 between the aerial nodes. This results in a maximum connectivity distance of 857m between ground nodes, 2423m between ground-aerial nodes, and 25099m between aerial nodes. Node connectivity at time (snapshot) 0 is shown in figure 3.

The frame period is 125ms and the maximum channel rate is set to 1 Mbps. Only half of the frame period is used for reservation slots. Based on the capacity of the channel, the number of time slots in a frame M and the fraction of frame period used for reservation slots, 1250 bits can be carried per reservation cell. Hence for a connection to have a call demand (b_k) of 1 reservation slot per frame, the call demand rate (for e.g., the voice coder rate) is 10 kbps. We assume that the voice coder rate is 10 kbps (hence voice calls use 1 reservation cell per frame) and the voice coder frame period is 125ms. All chosen source-destination pairs have a call demand of 1 reservation slot per frame.

There are 17 source-destination connection pairs chosen in this scenario. The traffic between each source-destination pair is routed via the first S shortest hop paths. All the connections have holding time of 2 minutes. Table I lists the chosen source-destination pairs, the corresponding number of paths and the traffic generation parameters. There are 13 intra-cluster connections (4 each in cluster 1 and 2; and 5 in cluster 3) each of which have call arrival rate of 2.5 calls/minute and with S, the number of paths per connection, equal to 2 or 3. The remaining 4 connections span clusters with S ranging from 3 to 4 paths and call arrival rate ranging from 0.5-2.5 calls/minute. Connection 11 between source node 20 and destination node 0 is the longest connection (with $S = 4$).

TABLE I
SOURCE-DESTINATION TRAFFIC REQUIREMENTS

Conn Number	Src-Dst	#. of Paths	λ_k (calls/min)	hold time (min)
0	1-18	4	0.5	2
1	1-3	2	2.5	2
2	2-9	2	2.5	2
3	4-6	2	2.5	2
4	7-5	2	2.5	2
5	10-1	3	2.5	2
6	14-17	2	2.5	2
7	16-11	2	2.5	2
8	17-18	2	2.5	2
9	19-12	2	2.5	2
10	20-11	3	1.25	2
11	20-0	4	1.25	2
12	20-29	2	2.5	2
13	21-10	3	2.5	2
14	21-22	2	2.5	2
15	23-28	2	2.5	2
16	23-25	2	2.5	2

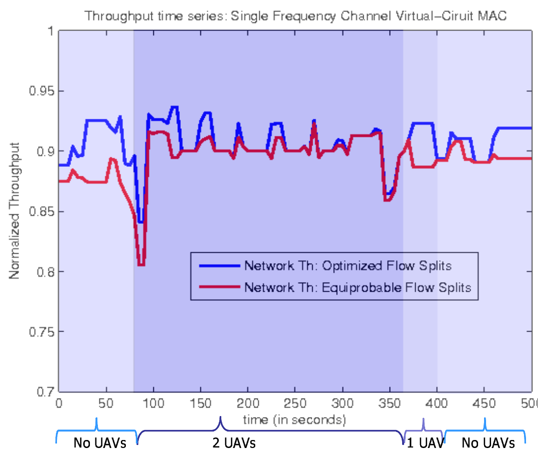

Fig. 4. Throughput Time Series for Scenario

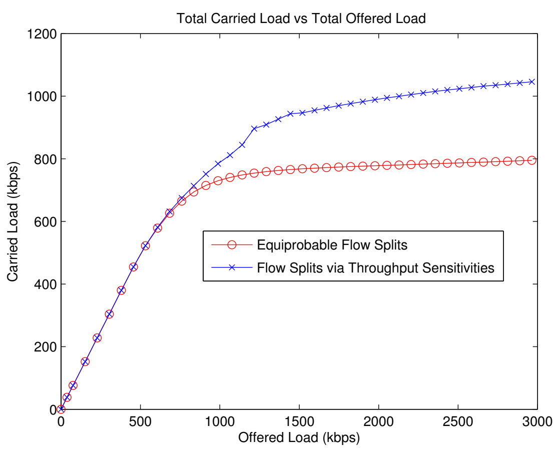

Fig. 5. Total Carried Load vs Total Offered Load

TABLE II
TOTAL THROUGHPUT: SIMULATION VS MODEL

Load Factor	0.5	0.75	1.0	1.5	2.0
Sim Th	0.9983	0.9593	0.8742	0.6928	0.5561
Model Th	0.9999	0.9678	0.8749	0.6566	0.5054

Fig. 6. Simulation (sim) VS Model (fpa): 0.75 load scaling factor

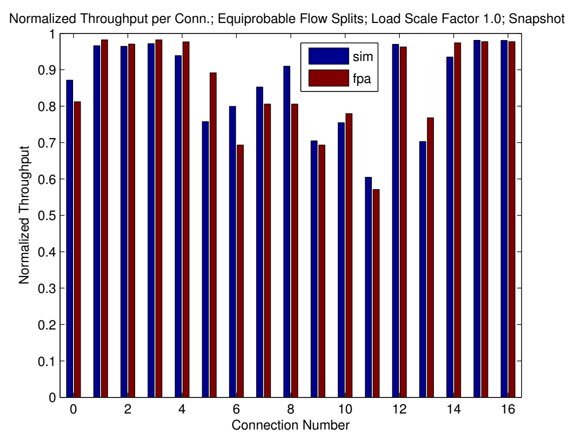

Fig. 7. Simulation (sim) VS Model (fpa): 1.0 load scaling factor

B. Results

We run the entire scenario first with equiprobable flow splits among the various paths of a connection and then with flow splits optimized using throughput sensitivities (section IV). Figure 4 shows the variation of total throughput for the two cases. Note the increase in total throughput for flow splits chosen to maximize total throughput.

To find out effects of offered load on throughput, we ran the scenario at time snapshot 0 but with all connection offered loads scaled by a common factor δ. Figure 5 shows the effect of offered load on total throughput (i.e., carried load) for equiprobable flow splits and flow splits chosen to maximize throughput. The total throughput in both cases saturates to some maximum value which is the maximum total capacity that the single frequency channel virtual-circuit based system can carry. Note that the optimized flow splits carry more load than the equiprobable flow splits for the same offered load.

C. Validation

We developed a simulation of the single frequency channel virtual-circuit MAC protocol with the reservation rules specified in section II and used it to validate the reduced load loss network models for the virtual-circuit MAC. Table II compares the total throughput between simulation (in the row labeled *Sim Th*) and reduced load loss models (in the row labeled *Model Th*) for various load scaling factors. We see that the total throughput of the model matches well with the simulation for low and medium load factors but underestimates the total throughput for high load factors (but not by too much).

Figures 6 and 7 compare the individual connection throughput between simulation and the reduced load model for load factors 0.75 and 1.0 respectively. We see quite a good match between simulation and the models for these low to medium load factors. Figures 8 and 9 compare the individual connection throughput between simulation and the reduced load model for load factors 1.5 and 2.0 respectively. Though most of the connections show a good match between the

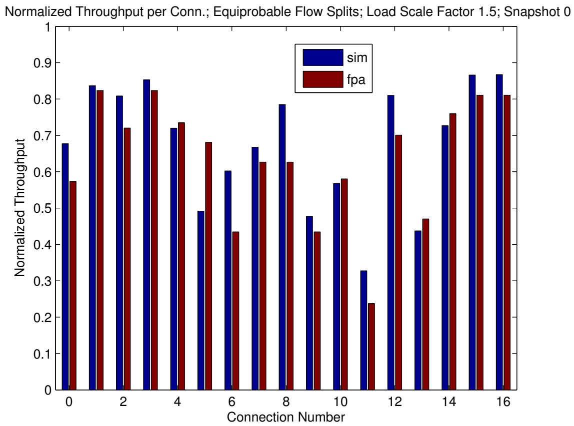

Fig. 8. Simulation (sim) VS Model (fpa): 1.5 load scaling factor

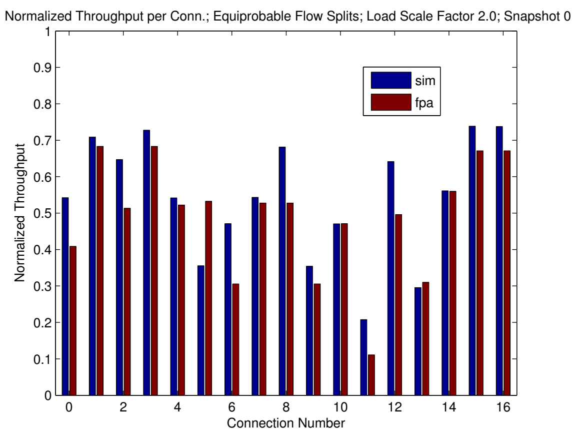

Fig. 9. Simulation (sim) VS Model (fpa): 2.0 load scaling factor

simulation and the model, we see that at these high loads there are a few connections where the model underestimates the individual connection throughput. This is due to approximating the link blocking probability with the maximum of the blocking probabilities among all the closed clique link sets of the particular link. We are looking at ways improve the link blocking probability calculation by taking into account relationships between the cliques.

VI. Conclusion

We have developed and validated models for a single frequency channel virtual-circuit wireless Medium Access Protocol using generic reservation rules. These models are based on reduced load loss network models and estimating the individual link blocking probability using cliques of interfering links. The models can be used to estimate blocking probability and throughput for unicast traffic for such a MAC. The key effect of multiuser interference is modeled by estimating an individual link's blocking probability using cliques of interfering links around this link. The cliques are calculated using the generic MAC reservation rules. The models show good match with simulation for low to medium loads but underestimates the throughput of some links for high loads. We are working on improving the individual link blocking probabilities calculation using relationships between cliques.

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