Reducing Throughput-delay Analysis of Conflict–free Scheduling in Multihop Adhoc Networks

N.Mallikharjuna Rao[1]*, D.J.Samatha Naidu*[2]*, J.Mithun Kumar*[3]*, S.NoorJahan*[4]
APGCCS, Rajampet.[1,2,3,4]
samramana44@gmail.com[2], kumar_aasc9396@yahoo.co.in[3], noor.deevani@gmail.com[4]

ABSTRACT- An Adhoc networks is a self organized and distributed entity, consisting of n mobile stations (MSs) without the co-ordination of any centralized access point. Initialization is one of the fundamental tasks to set up an adhoc network, which involves assigning of each of the n MSs a distinct ID number from 1 to n, distributedly. In randomized initialization protocols are developed for single-hop adhoc networks under different conditions. This study investigates the performance of an analytical approximation for the throughput-delay charac-teristic of a multihop ad-hoc network employing conflict-free time division multiplex (TDM) scheduling with half-duplex transceivers. The approximation models traffic at each link as an independent M/D/1 queue and its perfor-mance is measured by comparing to simulation results for various topologies, traffic loads, and network sizes. Re-sults indicate that the approximation is most appropriate for a tandem network but is also reasonable for other two-dimensional topologies. In the two-dimensional topologies, the approximation clearly improves at high traffic loads but does not exhibit distinguishable trends over the network sizes observed.

Keywords: *Introduction, Network Delay Approximation, Simulation Method, Experimental Scenario, Results & Discussion.*

I. INTRODUCTION

Ad hoc networks are connection-less networking systems, a collection of interconnected networks without communication channels like fiber optic cables, copper wires, twisted pairs, etc., are not required to communicate. Collection of mobile stations transmits the information through the base stations without communication lines. Scheduling and routing protocols for multihop ad-hoc net-works are constantly being proposed or modified, and results in this area of research rely on the chosen performance anal-ysis method. In these complex networks, an exact analysis of throughput-delay characteristics is difficult and often limited to small networks with simple topologies [1]. Simulation studies are the commonly used alternative, but are often time consum-ing. Analytical approximations are an attractive option. This work investigates an approximation to the throughput-delay for a guaranteed access scheduling protocol. Guaranteed access is one type of scheduling method that allows for control over the packet delay [3]. The ability to directly influence the delay through scheduling is critical to real-time applications and is a means for providing quality of service (QoS) guarantees in a multihop ad-hoc network.

In other work on multihop networks, approximations have been used for the throughput-delay for time division multi-plex (TDM) scheduling. Upon introducing the channel access protocol Spatial - Time Division Multiple Access (S-TDMA), Nelson and Klein rock used a fluid approximation to evaluate the mean system delay of messages. They approximated the random length of the backlog on a link by its expected value and evaluated its growth through a regenerative process consisting of input, service, and idle modes. The delay on that link can be found by dividing the average backlog length by the average ar-rivals to the link. The average delay can be found by summing link delays weighted by their relative traffic loads. The results of the fluid approximation were shown to match closely with simulation results, but the mean delay varied widely accord-ing to assumptions about the ordering and size of input, ser-vice, and idle intervals. This type of analytical analysis based on regenerative processes is often employed for complicated protocols [3], but for TDM scheduling, a more simple queuing analysis may suffice. This was the approach taken by Ju and Li in their work proposing that TDMA scheduling be based on Latin Squares. They evaluated the average packet delay for this protocol using an M/M/1 queuing model with bulk arrivals. Though transmission times for TDM scheduling correspond to discrete length slots, the inter-departure times were assumed to be stochastic to account for the fact that collisions may occur on the channel for the scheduling technique being evaluated. Sim-ulation results attested to the accuracy of this analytical method. A similar approximation with deterministic service times can be used for conflict-free schedules.

This work considers an approximation for the expected end-to-end packet delay based on the assumption that the traffic at each link acts as an independent M/D/1 queue [6]. A queuing model for traffic is used for wired networks [7] and is appli-cable to a wireless network by accounting for operation of the hardware in half-duplex mode. Research in ad-hoc networks makes use of this traffic model [2], but this study is the first known to the authors to focus on the performance of the M/D/1 approximation. The approximation can be applied for a known fixed routing and a conflict-free schedule defined by a repeating frame of equally-sized time slots. This represents the state of a mobile network at the time of route and schedule updates, and the performance may change as nodes move.

In the following section, the delay approximation is derived and necessary assumptions are discussed. A network simula-tor used for performance comparisons is then described in de-tail. The scenarios used in evaluating the approximation are presented, followed by a discussion of the suitability of the ap-proximation for various traffic loads, topologies, and network sizes.

II. NETWORK DELAY APPROXIMATION

The ***end-to-end packet delay*** is defined as the time between the arrival of a packet at the buffer of the *source* node and its successful reception at the *destination* node. The end-to-end packet delay allows for evaluation of the quality of service (QoS) under low, moderate, and high traffic. For this dis-cussion the following assumptions are needed.

- The external traffic source attached to each node generates Poisson distributed packet arrivals with average traffic load *ë/N* (packets/slot) where *N* is the number of nodes in the network, and ë is **the *total external traffic load.***
- Packet destination is equally likely among nodes. The initial source *(S)* and final destination *(D)* of a packet is denoted by an *(S, D)* pair. In a multihop ad-hoc network a routing algorithm must be used to select a set of intermediate links (path) between *(S, D)* pairs to route the packet. There-fore, the average traffic load passing through a link *(i, j), ëij,* is the result of external and internal traffic [2].

$$\lambda_{ij} = \sum_{\substack{\forall (S,D) \text{ routed} \\ \text{through link } (i,j)}} \frac{\lambda}{N(N-1)} = \frac{\lambda}{N(N-1)} T_{ij} \qquad (1)$$

Tij are the elements of the *relative traffic load* matrix T given by the cardinality of the set of *(S, D)* pairs routed through link *(i,j)*. In other words, Tij represents the number of route paths that traverse link *(i, j)*. The assumption of Poisson ar-rivals to a node does not represent busty traffic or capture the effects of relayed packets through a slotted-time system, but it is used in [6], in the approximation here, and in other studies of ad-hoc networks due to its simplicity, ease of analysis, and reproducibility of the results it provides.

A randomly selected packet transmitted from node *S* to node *D* experiences a random delay D_{SD} that is the sum of the de-lays on every link traversed in the selected path. Averaging over all the equally likely *(S, D)* pairs in the network, the expected end-to-end delay is given by

E[Dij] is the expected packet delay over link (i,j) and is a function of the external traffic load, internal traffic load, medium access control (MAC) protocol, and the multiple ac-cess interference (MAI). An exact analysis for E [Dij] in the wireless scenario appears to be very difficult [9, 3].

Neverthe-less, the above equation can be rewritten in terms of the relative traffic load.

$$E[D] = \frac{1}{N(N-1)} \sum_{\forall (S,D)} \sum_{\substack{\forall \text{ links } (i,j) \text{ in path} \\ \text{selected to route } (S,D)}} E[D_{ij}] \qquad (2)$$

Since coordination among nodes exists, it is possible to esti-mate the relative link capacity assigned to each link after cre-ating the link schedule. Through the scheduling algorithm the number of slots assigned to a link is more or less controlled. However, in general, the resulting number of slots assigned to a link depends on several factors including the topology and loca-tion of a particular node. For instance, links at the network edge will be subject to less MAI than those at the center of the net-work. In addition, nodes at the center of the network may carry higher relative traffic. Nevertheless, the capacity assigned to a given link *(i, j)* after creating the schedule can be computed. Let *nij* be the number of slots within a period of the schedule, *NF*, allocated to link *(i, j);* then the relative link capacity *Cij* is given by (4).

$$C_{ij} = \frac{n_{ij}}{N_f} \ . \qquad (4)$$

In order to estimate *E[Dij]* the following assumptions are needed:

A. Each node uses a different infinite length buffer for every feasible outgoing link.
B. Packet arrival times to be transmitted over each link are Poisson distributed with arrival rate *ëij* given by (1).

$$E[D] = \sum_{\substack{\forall \text{links } (i,j) \\ \text{in the network}}} \frac{T_{ij}}{N(N-1)} E[D_{ij}] \qquad (3)$$

C. The *nij* slots assigned to link *(i,j)* are uniformly distributed within the schedule.
D. Packet reception is error free.

Assumption B implies that packet arrivals to each link are independent from the delay and queue process over the previ-ous relaying link. This is similar to Klein rock’s principle of independence [2]. For low traffic this is not always true. For example, one packet from a source to a destination will find basically empty queues over each relaying node, making the Poisson distributed arrival process assumption to each link in-valid. Assumption C depends on the scheduling algorithm uti-lized and could be difficult to achieve. It has been shown in [4] that Assumption C is a desirable property of a good schedule as it minimizes packet delay. Assumption D is reasonable since the schedule ensures sufficiently low interference between links scheduled to transmit during the same slot.

If the above assumptions are used, the expected packet de-lay through link *(i,j), E[Dij]* can be modeled as the resulting packet delay in a TDMA system (M/D/1 queueing model) with a frame length *Nf/nij* and packet transmission time of 1 slot [[3], page 13]. Hence, (3) can be approximated by (5).

III. SIMULATION METHOD

In order to investigate the performance of the approximation in (5), a simulator based on MATLAB® and ANSI C is used for comparison. In the simulator, external packets arriving at each node are generated according to a Poisson process using the procedure described in [5]. Poisson arrivals and destination node are generated using a linear congruential pseudorandom number generator as implemented in ANSI C. Simulation of equally likely packet destinations is done following the recom-mendation given in [6]. The statistical properties of these pro-cesses have been verified to ensure that the random generator works well for the number of packets generated in the network. According to [7], this improves credibility of the results. First-In-First-Out (FIFO) buffers of length 500 packets are used for each outgoing link where packets were placed after their recep-tion to be forwarded using information from the routing table. The simulation is run until each node transmits 1000 packets to every other node in the network. This is repeated and the mea-sured delays are averaged until the 95% confidence interval lies within 0.1% of the average.

IV. EXPERIMENTAL SCENARIO

Routing: A minimum-hop algorithm (MHA) is used and ties are broken by selecting the last path found. This corresponds to the minimum-hop path with the largest sum of node ID num-bers.

Scheduling: The Degree Algorithm introduced by Shor and Robertazzi [9] is adapted for link assignment scheduling and used to generate a conflict-free schedule. This algorithm ac-counts for traffic load when creating the schedule in order to increase network throughput. All links in the network are first numbered according to traffic load so that heavily loaded links are given higher priority in access to the channel. Sets of non-interfering links, or cliques, are then constructed by attempting to add links in order of priority. Through this process, the fol-lowing assumptions are used.

- A node can either transmit or receive a single packet in a given slot as shown in fig 1.
- The channel can be spatially reused. Links located two hops apart produce negligible interference. Compatible links, or links that can be enabled without violating these assumptions, are added to each clique. Once all cliques are constructed, a schedule is defined by a fixed-length repeat-ing frame where each clique is assigned a number of slots pro-portional to its traffic load.

$$E[D] \approx \hat{D} = \sum_{\forall \text{ link } (i,j)} \frac{\lambda_{ij}}{\lambda} \left[\frac{}{2(} \right. \text{slots} . \quad (5)$$

Fig 1. Examples of tandem, ring, and grid-mesh network topologies.

All links are assumed to be of the same quality and the net-work is represented by a connected graph. Once the sched-ule is generated, slot assignments are scrambled in an effort to distribute link access to the channel uniformly within the frame. The random generator used for scrambling is a lagged Fibonacci generator combined with a shift register random in-teger generator as implemented in MATLAB ®.

Network topologies: Ring, tandem, and mesh-grid topologies of various sizes *N* nodes are considered. Fig. 4.1 shows examples of these topologies. Ring networks consisting of odd numbers of nodes allow for perfect balancing of the traffic load over links with the MHA. This is not true for the other topologies.

Performance measures: The expected delay given by the ap-proximation is denoted *I)* while the average value provided by the simulation is denoted *D*, both of which are functions of the total external arrival rate ë. The maximum throughput A* is the maximum value of ë for which *D* remains finite. The *approxi-mation error* is defined as

$$\xi = \frac{\hat{D} - \bar{D}}{\bar{D}}. \qquad (6)$$

These values are expressed as a percentage, and positive values of î indicate that the approximation overestimates delay. For performance comparisons, values of î are found for the low traffic load ë = 0.10A* and a high traffic load ë = 0.75A*. These errors are denoted ξ_{Low} and ξ_{High}

V. RESULTS & DISCUSSION

The end-to-end delay versus offered traffic is shown for tan-dem, ring, and mesh-grid networks in Fig 2, 3, and 4, respec-tively. The approximation follows the trend in the simulated throughput-delay over all traffic loads. It tends to underesti-mate delay at low traffic loads for all topologies considered. At high loads, the approximation provides a clear overestimate for tandem networks and a less-pronounced overestimate for ring topologies. For mesh-grid topologies, the simulated delay con-verges to the approximate value at high traffic loads, providing a close estimate. Though caution should always be taken in applying an approximation, the one examined here is clearly reasonable for the cases considered and thus useful for quick evaluations.

It is interesting to note that the tandem network is the only topology for which the approximation performs better at low traffic loads. This is better revealed by the approximation er-ror at low and high traffic loads as listed for the three topolo-gies in Tables I, II, and III. For tandem networks of the net-work sizes observed the error for low and high traffic is at most 6.3%. Higher approximation error occurs for a tandem network of only 5 nodes. In larger networks, the approximation tends to get worse as network size increases.

The degradation in performance of the approximation for high traffic load in a tandem network is clearly evident in Fig 2. Simulation results have been verified to ensure that buffer over-flows do not occur and that the simulated delay does asymptote as the external arrival rate approaches maximum throughput. For a tandem network, this asymptote is quite sharp, but the approximation does not reflect such sharpness. In the ring networks, it appears from Fig 3 that the approx-imation gets worse at network size increases. However, when more network sizes are considered as shown in Table II, it ap-pears there are no distinguishable trends with changes in net-work size. A relatively high error was found for low traffic but the approximation error for high traffic loads is at most 11%. This leads to the conclusion that the model is better suited for moderate to high traffic load.

Finally, the highest error for low traffic was found for the mesh-grid topology, making the model poor in this situation. However, the approximation improves with increasing traffic load, and the poor performance at low loads is in stark contrast to its convergence with simulated results at maximum through-put. The model can be utilized with greater confidence to pre-dict the throughput-delay performance at high traffic load for mesh-grid.

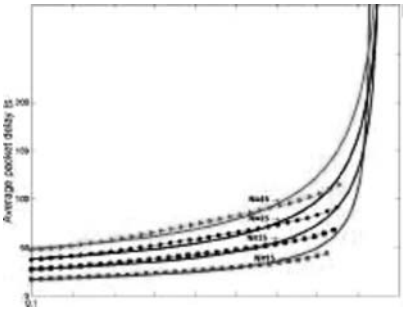

Fig 2. End-to-end delay versus offered traffic for tandem networks of various sizes. The approximate delay is shown in the solid line and simulated delay is shown as points.

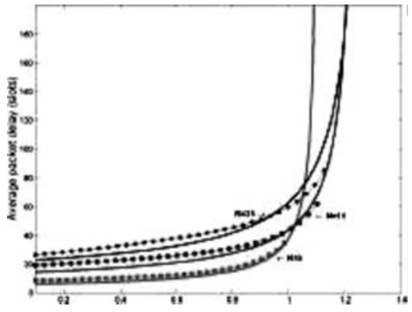

Fig 3. End-to-end delay versus offered traffic for ring networks of various sizes.

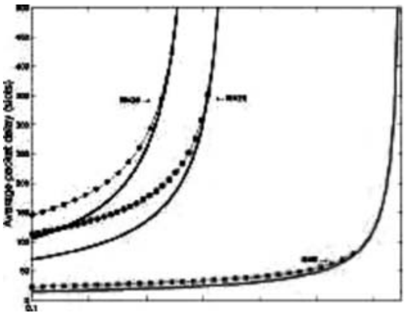

Fig 4. End-to-end delay versus offered traffic for mesh-grid networks of various sizes.

The approximate delay is shown in the solid line and simulated delay is shown as points. Most general and comparable to an arbitrary two-dimensional topology. These results are most extendable to other cases. The performance of the approximation clearly depends on the network topology and size. These two parameters influ-ence traffic and directly affect the packet arrival process to the queue of each link which, together with the uniform slot as-signment distribution, is a key assumption of the model. In the case of tandem networks, the arrival process to each link appears to be renewed by packets entering and leaving the net-work, and the Poisson assumption for the process is reasonable. This agrees with Klein rock's independence assumption for inter-arrival times as noted in [3]. For ring and mesh-grid topolo-gies at low traffic, the approximation does not perform as well, indicating that the Poisson process assumption may not be true to the same degree. As revealed by Fig 4, this renewal process appears to occur to a greater extent in mesh-grid topologies as traffic load increases. The difference in suitability of the model might be better ex-plained by comparing arrivals at nodes in the tandem and ring network. It is noted that the arrival process and destination for any node in the ring is comparable to that of the middle node in the tandem. At these nodes, inter-arrival times may not fol-low the exponential distribution as closely since internal arrivals.

N	$\xi low(\%)$	$\zeta high(\%)$
5	-6.3	3.8
15	-0.04	5.2
25	0.47	4.7
35	1.6	5.1
45	2.5	5.8
55	3.5	6.3

TABLE I

APPROXIMATION ERROR FOR TANDEM NETWORKS.

N	$\xi low(\%)$	$\zeta high(\%)$
5	-29	-11
15	-24	-3.6
25	-14	2.0
35	-26	1.6
45	-12	8.8
55	-26	4.5

TABLE II

APPROXIMATION ERROR FOR RING NETWORKS.

N	$\xi low\ (\%)$	$\zeta high\ (\%)$
9	-37	-17
25	-44	-17

TABLE III

APPROXIMATION ERROR FOR MESH-GRID NETWORKS.

This symmetry in traffic may result in dependencies on the in-terarrival times. However, when moving away from the middle of the tandem network, internal arrivals occur at intervals that are more unevenly distributed. This is a result of the arrivals coming from opposite ends located at different distances from the node. Thus, the assumption of independent Poisson arrivals is more realistic for nodes further from the middle of the tan-dem. The assumption still deviates further from reality for the ring and mesh-grid topologies. This possible explanation of re-sults has not been verified in this study, but future work that measures the distribution of simulated arrivals would be useful for testing this explanation.

VI. CONCLUSION AND FUTURE WORK

The end-to-end delay versus offered traffic follows the trend in the simulated throughput-delay over all traffic loads. It tends to underesti-mate delay at low traffic loads for all topologies considered. At high loads, the approximation provides a clear overestimate for tandem networks and a less-pronounced overestimate for ring topologies. For mesh-grid topologies, the simulated delay con-verges to the approximate value at high traffic loads, providing a close estimate. Though caution should always be taken in applying an approximation, the one examined here is clearly reasonable for the cases considered and thus useful for quick evaluations. The highest error for low traffic was found for the mesh-grid topology, making the model poor in this situation. However, the approximation improves with increasing traffic load, and the poor performance at low loads is in stark contrast to its convergence with simulated results at maximum through-put. The model can be utilized with greater confidence to pre-dict the throughput-delay performance at high traffic load for mesh-grid. Our future work will include analyzing the achievable throughput in an *ad hoc* network with idealized assumptions such as random traffic patterns and uniformly distributed nodes, we show that it is more practical and important to “increase the end-to-end throughput” available to a multihop session connecting a set of sources and destinations in an application

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