Approximating Flow-Based Proportional Fairness in Ad-hoc Wireless Networks

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***Abstract*— In this paper we present a distributed flow-based access scheme for slotted-time protocols, that approximates proportional-fairness in ad hoc wireless networks and does not have a significant implementation overhead. We say a medium access control algorithm is *proportionally fair* with respect to individual end-to-end flows in a network, if the product of the end-to-end *flow-success probabilities* is maximized.**

The proposed scheme is implemented using a slotted-time protocol – *ST-MAC* [17]. We then compare the performance of the ST-MAC protocol with that of the 802.11-MAC using *ns2* simulations [15] of random networks of various sizes. For dense-networks, in terms of packet-delivery-ratios and throughput, the ST-MAC protocol presents an improvement over 802.11-MAC, with comparable end-to-end delay.

I. Introduction

In this paper we address the issue of providing end-to-end flow based proportional fairness [8] where each node accesses the wireless medium with a probability so as to maximize the end-to-end *flow-success probabilities* of all flows in the context of proportional fairness. As the node's access of wireless channel is dependent on the underlying MAC protocol being used, the problem of providing proportional fairness must be considered in context of a specific protocol.Keeping this in mind, we define a family of protocols, and analyze the proportional fairness problem with respect to this specific family of protocols.

The literature contains several references to fairness and its impact on the network performance [5]. For example, references [16], [19] present a list of modifications that eliminate the unfairness that is commonly seen in the 802.11-MAC. The literature also contains a large volume of references (cf. [8], [9], [11], [12], for example) where it is supposed that each network flow/link is associated with a concave utility-function that could be maximized by . In this context, it is of interest to schedule individual transmissions on the links so as to maximize the sum of the utilities of the consumers. Specifically, for proportional fairness it is assumed that the above mentioned utility function has the form of $\log x$, where x denotes the flow rates [8]. To achieve fairness, all of the above mentioned schemes also include a penalty function which is updated by some form of feedback from the network. In this paper the algorithm presented does not requires any estimations for penalizing the flows such as the loss rates or queue-lengths and just works on the local two-hop information.

Slotted-time protocols have had a rich history starting from the ALOHA protocol for packet-radio networks [1], and have found numerous applications in the context of mobile radio networks. TDMA-based protocols for ad-hoc wireless networks have been proposed by various researchers (for e.g. ADAPT [3], RRA protocols [4], D-PRMA [6], HRMA [18] and FPRP [20]). Using Global Positioning System (GPS) technology, synchronization between terminals in mobile ad hoc environments becomes feasible at a low cost. Thus, TDMA-based protocols for ad-hoc wireless networks, now present an interesting alternative to the widely used 802.11-MAC protocol. We investigate the notion of proportional fairness in context of slotted time MAC protocols. The proposed algorithm is implemented using ST-MAC protocol [17], which is a slotted time MAC-protocol where every station contends for each data-slot using RTS-CTS exchange similar to one used in HRMA [18], over a single channel.

The rest of the paper is organized as follows. Section II presents analysis of flow-based proportional fairness, where we derive the expressions for transmission probabilities stations under the assumption that no retry of data-packets is allowed after a failed transmission attempt. Section III discusses approximation of flow-based proportional fairness, when every station is allowed to retransmit packets. Section IV contains the formal specification of the ST-MAC protocol, and section V contains the details of the experimental comparisons of the ST-MAC protocol and the 802.11-MAC. The paper concludes with section VI, which includes a list of future research topics.

II. Notions and Definitions of Proportional Fairness

We assume the following facts about the protocol (how we implement this in the *ST-MAC* protocol is described in brief in the later section)(1) Time is divided into slots of equal duration. (2) A successful transmission in a slot implies collision free data transmission in a time-slot. (3) The transmitting nodes always have data packets to transmit (i.e. we do not consider the arrival rates of packets for different flows, and assume that all flows have packets to transmit at all times). (4) All nodes in the network are assumed to have infinite-length buffers. (5) No retransmission of data-packets is permitted (this condition will be relaxed later; for the present, a data-packet is dropped following an unsuccessful attempt at transmission). (6) We only consider unicast flows for our derivations. Specifically, we assume there is a unique route for each flow within the network (which would be the case if we used AODV [14] as the routing protocol, for example) A wide variety of slotted-time protocols, like the *S-Aloha* [1], *ST-MAC* [17], etc., fit this description. We denote this family of protocols as *protocol-family A*.

An ad hoc wireless network carrying a collection of CBR-flows, is represented as an undirected graph $G = (V, E)$, where V represents the set of *nodes*, and $E \subseteq V \times V$ is a symmetric[1] relationship that represents the set of bi-directional *links*. We assume all links of the network have the same capacity, which is normalized to unity. The 1-hop neighborhood of node $i \in V$ is represented by the symbol $N(i)$. When a node i communicates with a node $j \in N(i)$, we can represent it as an appropriate orientation of the link (i, j) in G, where i is the origin and j is the terminus.

Each flow has a source $i \in V$ and a destination $j \in V$, and there is a directed path in G from i to j representing the route assigned to the flow. As noted earlier, there is a single route between source-destination pairs in our network. When there are many flows in the network, each link may be used by multiple flows in any of the two orientations that can be assigned to it. We denote the set of flows that use link $(i, j) \in E$ by the symbol $\mathcal{F}(i, j)$.

When node i intends to transmit data to node $j \in N(i)$ for the l-th flow ($l \in \mathcal{F}(i, j)$) under a protocol from protocol-family A, it would transmit data in the appropriate time-slot with probability $p_{i,j,l}$. These probabilities are to be chosen such that $\mathcal{P}_i = \sum_{j \in V} \sum_{l \in \mathcal{F}(i,j)} p_{i,j,l}$, which is the probability that node i will be transmitting to some node in its 1-hop neighborhood for some flow, is not greater than unity for any node $i \in V$.

In this paper, we adopt the the logarithm of the success probability of each flow as the utility-function. We will derive an expression for the sum of the individual utility functions in an ad hoc network that uses a protocol from the protocol-family A, under the assumption that there are no retries of data-packets (as mentioned in assumption 5, earlier). For instance, flows encoded using *digital fountain codes* [2], [10] are robust to erasures. These codes guarantee that the receipt of $K(1+\epsilon)$ coded-packets, sent over a channel with an erasure probability of ϵ, at the receiver is sufficient to decode K-many source-packets with high probability. If a particular packet transmission is unsuccessful at some link in the route, there is no need to attempt a retransmission.

Theorem 2.1: For a flow l, and a fixed i, j where $j \in N(i)$, any proportionally fair protocol from the protocol-family A will assign the same value for $p_{i,j,l}$.

Proof: Let us suppose that the l-th flow starts at host i_1 and terminates at host i_n and uses the (loop-free) route: $i_1 \to i_2 \to i_3 \to \cdots \to i_{n-1} \to i_n$, where $\{i_1, i_2, \ldots, i_n\} \subseteq V$ are the hosts of G that appear on the route. If we assume the flows do not require retries after each unsuccessful transmission the probability of success for a packet of the l-th flow, is given by the expression

$$\underbrace{p_{i_1,i_2,l}(1-\mathcal{P}_{i_2}) \prod_{j_2 \in N(i_2)-\{i_1\}} (1-\mathcal{P}_{j_2})}_{\text{Prob. of success at } i_1 \to i_2 \text{ link}}$$
$$\times \underbrace{p_{i_2,i_3,l}(1-\mathcal{P}_{i_3}) \prod_{j_3 \in N(i_3)-\{i_2\}} (1-\mathcal{P}_{j_3})}_{\text{Prob. of success at } i_2 \to i_3 \text{ link}} \times \cdots$$
$$\cdots \times \underbrace{p_{i_{n-1},i_n,l}(1-\mathcal{P}_{i_n}) \prod_{j_n \in N(i_n)-\{i_{n-1}\}} (1-\mathcal{P}_{j_n})}_{\text{Prob. of success at } i_{n-1} \to i_n \text{ link}}$$

Of the total of k-many flows in the network, let us suppose m-many of them either originate, or, get routed through node $i \in V$. If we computed the product of the k-many flow success probabilities using instances of the above equation, and restricted our attention to the flows that either originate, or, get routed through node $i \in V$, we would get an expression that has the form $\underbrace{p_{i,j_1,k_1}\ p_{i,j_2,k_2}\ \cdots\ p_{i,j_m,k_m}}_{m\text{-many terms}} \times$ (*An expression that involves $\mathcal{P}_i$-terms and probability-terms of other nodes*)

If we choose values for $p_{i,j_1,k_1}, p_{i,j_2,k_2}, \ldots, p_{i,j_2,k_m}$ that maximize the above expression, subject to the condition that $\mathcal{P}_i (= p_{i,j_1,k_1} + p_{i,j_2,k_2} + \cdots + p_{i,j_m,k_m})$ is a constant, we get

$$p_{i,j,k_1} = p_{i,j,k_2} = \cdots = p_{i,j,k_m} = \frac{\mathcal{P}_i}{m} = p_i. \tag{1}$$

■

So, if we are interested in enforcing proportional fairness, node i should assign the same transmission-probability to each flow that either originates from i, or, is routed through it.

Before we write down the expression for the product of the success probabilities of the k-many flows, it would be useful to identify (the not necessarily disjoint) subsets of these flows vis-á-vis an arbitrary node $i \in V$. As mentioned in the previous paragraph, let us suppose

1) m_i-many of the flows either originate, or, get routed through node $i \in V$,
2) n_i of them either have i as their final-destination, or, are routed through i, and,
3) q_i of them are flows that either terminate, or, get routed through some member in $N(i)$.

Theorem 2.2: For protocol from protocol-class A to be proportionally fair, the probability with which a node $i \in V$ will transmit data for any flow that either originates, or, gets routed through it is given by $\mathcal{P}_i = \frac{m_i}{n_i + q_i}$.

Proof: The expression for the product of k-many flow success-probabilities would be

$$\Delta = \prod_{i \in V} (\frac{\mathcal{P}_i}{m_i})^{m_i} \times (1-\mathcal{P}_i)^{n_i} \times (1-\mathcal{P}_i)^{(q_i - m_i)}$$

[1]That is, $(i, j) \in E \Leftrightarrow (j, i) \in E$.

$$\Rightarrow \log\Delta = \sum_{i\in V}(m_i \log \mathcal{P}_i - m_i \log m_i$$
$$+n_i \log(1-\mathcal{P}_i) + (q_i - m_i)\log(1-\mathcal{P}_i)) \quad (2)$$

The above mentioned expression is strictly concave with respect to the $\mathcal{P}_i$'s ($i \in V$). The value of $\mathcal{P}_i$'s that maximize the above concave expression can be obtained by differentiating the expression for $\log\Delta$ with respect to $\mathcal{P}_i$'s and equating the result to zero. This results in

$$\begin{aligned} \frac{m_i}{\mathcal{P}_i} - \frac{n_i}{1-\mathcal{P}_i} - \frac{q_i - m_i}{1-\mathcal{P}_i} &= 0 \\ \Rightarrow \frac{m_i}{\mathcal{P}_i} &= \frac{n_i + q_i - m_i}{1-\mathcal{P}_i} \\ \Rightarrow \mathcal{P}_i = \frac{m_i}{n_i+q_i} \Rightarrow \frac{\mathcal{P}_i}{m_i} &= \frac{1}{n_i+q_i} \end{aligned} \quad (3)$$

■

The expression shown above is the probability that $i \in V$ will send a data packet for any flow that either originates, or, gets routed through it. Note that the terms n_i and q_i can be inferred from exchanges between i and nodes in $N(i)$. A single-hop interpretation of equation (3) would result in the expression derived in the literature for proportional fairness in S-ALOHA networks [7]. Since every flow that originates, or, gets routed through a host $i \in V$ is also a flow that either terminates, or, gets routed through a member in $N(i)$, it follows that $m_i \le q_i$, which in turn guarantees $\mathcal{P}_i \le 1$.

III. Approximating Proportional Fairness

In Theorem 2.2 the equation derived for transmission probability assumes that each nodes transmits the packets only once, i.e. there is no retransmission of the data-packets. However, in an ad-hoc wireless network this will result in very low packet-delivery and therefore we would want to allow a certain number of retries in case of unsuccessful transmissions. In this section we will show that the formula presented in theorem 2.2 gives us a good approximation for achieving proportional-fairness in terms of flow-success probabilities for networks where a fixed number of retries are permitted.

We use the same model as in section II to model the ad-hoc wireless network, only now, each node is allowed r number of retries per data-packet. The expression for product of flow-success probabilities now have additional terms which take into account the success-probability over r retries denoted by Δ is given by the expression

$$\begin{aligned} \Delta &= \prod_{(i,j)\in E, l\in\mathcal{F}(i,j)} \{1-(1-\mathcal{P}_{i,j,l})^{r+1}\}, \\ \Rightarrow \log\Delta &= \sum_{(i,j)\in E, l\in\mathcal{F}(i,j)} \log\{1-(1-\mathcal{P}_{i,j,l})^{r+1}\} \end{aligned} \quad (4)$$

where $\mathcal{P}_{i,j,l}$ denotes the link-success probability of flow l over link $(i,j) \in E$, which is dependent (among other terms) on the probability $p_{i,j,l}$ introduced in the previous section.

If we approximate $\log(1-(1-\mathcal{P}_{i,j,l})^{r+1})$ as $\log(c\mathcal{P}_{i,j,l})$ for some constant c, equation (4) can be written as

$$\log\Delta = \sum_{(i,j)\in E, l\in\mathcal{F}(i,j)} \log\{c\mathcal{P}_{i,j,l}\}$$

It can be verified that the $\mathcal{P}_{i,j,l}$'s that maximize the above equation are the same as the one given in theorem 2.2. Thus, if error from the above mentioned approximation can be bounded we can guarantee an efficient distributed solution to equation (4) within some error range of the ideal solution, which uses only local information to provide a proportionally fair protocol.

Consider the approximation $\log(1-(1-\mathcal{P}_{i,j,l})^{r+1})$ as $\log(c\mathcal{P}_{i,j,l})$, $\mathcal{P}_{i,j,l} \in (0,1)$ for some constant c. If we choose r to be 4 (Default long-retry limit used in 802.11-MAC), then depending on the value of $\mathcal{P}_{i,j,l}$ we can get a relatively good, or poor, approximation. For example, a network consisting of only two nodes, $\{1,2\}$, each transmitting one flow to each other has $\mathcal{P}_{1,2,1} = \mathcal{P}_{2,1,1} = 0.25$ for proportional fairness. A dense network where every node has at least one neighbor, and has at least one flow to transmit, will result in $\mathcal{P}_{i,j,l} \le 0.25$ for proportional fairness, for all $(i,j) \in E$ and $l \in \mathcal{F}(i,j)$. Thus for a network with the above mentioned properties we can use $c = 3.4$ and get an approximation error ≤ 0.25. This gives us a bound on the approximation error. It is important that the choice of c is only needed to arrive at an upper bound of the approximation error.

It should be noted that if the network is uniform in terms of flows and number of neighbors, i.e. the $\mathcal{P}_{i,j,l}$'s are close to each other, the value of transmission probabilities obtained from zero-retry formula will be very close to the ideal solution as $\log(c\mathcal{P}_{i,j,l})$ can very closely approximate $\log(1-(1-\mathcal{P}_{i,j,l})^{r+1})$ in a small interval for any number of retries. The approximation is poor only if the values of $\mathcal{P}_{i,j,l}, \mathcal{P}_{i,j,l} \in (0,1)$ take on diverse values.

IV. ST-MAC Protocol Specification

In this section we present a brief overview of the *ST-MAC* protocol, which is a subset of HRMA protocol [18]. Additional details can be found in [17]. The proper execution of this protocol requires the following: (1) when multiple packets arrive at a host, the host hears noise (i.e. there is no packet-capture mechanism in the physical-layer); (2) all links are bi-directional; (3) host cannot transmit and receive packets simultaneously; and (4) all nodes in the network are synchronized.

A single super-frame of the *Slotted-Time MAC* (ST-MAC) protocol consists of a fixed-number of sub-frames and a SYNC frame consisting of three SYNC-slots as shown in Figure 1. Each sub-frame consists of a *Request-to-send* slot (RTS-slot), a *Clear-to-send* slot (CTS-slot) and a *data* slot (DATA-slot). The RTS- and CTS-slot within a sub-frame correspond to the DATA-slot within the same sub-frame. The structures of the RTS-, CTS- and DATA-packets are identical to that of 802.11-MAC [13]. The SYNC-packets, are used to broadcast the time for the start of new super-frame. A new node only joins the network at the beginning of new super-frame after it has this information of when the new super-frame is going to begin. Let us suppose the maximum single-hop transmission delay of the network is w; the transmission/reception time for a packet of size m is $x(m)$; the maximum turnaround time (i.e. the

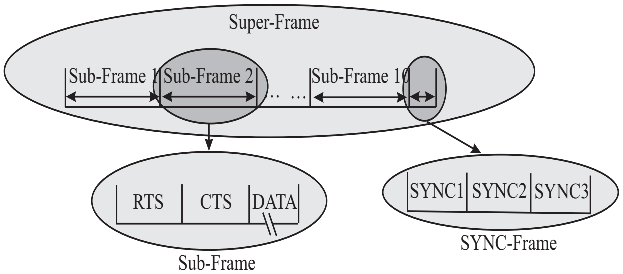

Fig. 1. A Super-Frame in the ST-MAC Protocol.

time it takes for a host to switch between transmitting and receiving modes) is y; and the processing time for a packet of size m is $z(m)$. We set the slot-time for the packet of size m to $(2x(m)+y+w+z(m))$. The ST-MAC protocol assumes the network satisfies the inequality $y + w + z(m) < x(m)$. That is, the sum of the turnaround time, transmission delay and processing time is strictly less than the transmission/reception time of a packet. All data packets are assumed to be of the same size. The slot-lengths of the RTS-, CTS-, DATA- and SYNC-slots are $(2x(m) + y + w + z(m))$, for an appropriate value of m.

A host that is in receipt of a clear CTS-signal that is not meant for it, or noise, during the CTS-slot of a sub-frame will remain silent for the duration of the DATA-slot in the same sub-frame. If a source intends to multicast data during a specific sub-frame, it sends an appropriately structured multicast RTS signal with the same probability as when it sends an unicast RTS, and proceeds with the transmission of data in the DATA-slot of the frame, without paying heed to the signals it might receive in the CTS-slot. Additionally, a host that is in receipt of a multicast RTS-signal does not respond with a CTS-signal in the CTS-slot of the sub-frame. While there can be collisions at any given receiver on multicast transmissions, we can show that for unicast transmissions, following the RTS-CTS exchange there can be no collisions at the receiver [18].

A source intending to send unicast data to any destination in the DATA-slot on a sub-frame issues an RTS-signal in the corresponding RTS-slot with a probability determined by equation 3 in section II. After successful reception of the RTS-signal, the destination responds with a CTS-signal in the CTS-slot of the sub-frame. On hearing a clear CTS-signal from the destination, the source proceeds with the transmission of data in the DATA-slot of the sub-frame. Specifically, the probability that an RTS-signal is followed by the receipt of a CTS-signal is equivalent to the probability of data-transmission alluded to earlier in section II. If it is of interest to improve the link-layer reliability of the network, the destination can be made to acknowledge the receipt of data on the previous data-transmission, the next time it sends a CTS-signal to the source. That is, there is scope for a delayed link-layer acknowledgment within the CTS-slot, if necessary. By eliminating the immediate acknowledgement of proper receipt of data, we are in effect eliminating the exposed-terminal problem that is found in the 802.11-MAC.

V. Performance Evaluation of the ST-MAC Protocol

In this section we describe the experiments that show how ST-MAC protocol performs when the RTS-signal in the corresponding RTS-slot is transmitted with a probability as determined by equation 3. For this we compare the performance of the ST-MAC protocol against 802.11-MAC protocol. A detailed implementation of the 802.11-MAC protocol [13] already exists as a part of the simulation model. These experiments involved the implementation of the ST-MAC protocol within the NS2 network simulator [15]. As there is no notion of proportional fairness in the 802.11-MAC, it is unfair to compare ST-MAC with 802.11-MAC in terms of fairness. However, the results presented in this section give a clear picture of how the approximately-proportional fairness scheme combined with no exposed terminal problem, performs in a wireless network involving random hosts.

A. Traffic and mobility models used in the experiments

A constant-bit-rate (CBR) traffic was generated for each source-destination pair. We chose AODV [14] as the ad hoc routing protocol as it requires less information to be exchanged and does not require enumerating paths within the packets.

The pause-time is kept constant and equal to the simulation time (i.e. there is no mobility) in all our experiments. Lucent's WaveLAN with 2Mbps bit rates and 250m-transmission range is used for the radio model. An omnidirectional antenna is used by the mobile/wireless nodes.The carrier sense range is the same as the transmission range in our simulation experiments, i.e. the packets are assumed to interfere with each other only when a receiver is within the transmission range of two sources that are transmitting simultaneously . Simulations are run for 500 simulated seconds.

In the simulations the retry limit for data packets is set to 4 for both the protocols which is the default 802.11-MAC long-retry limit. In our derivation we assumed infinite buffer space, however, in simulations, Drop Tail Queue of size 50 packets was selected as an interface queue for both these protocols, unless mentioned otherwise. It is interesting to note that even though we are restricting the buffer space, approximately-proportional fairness scheme performs quite well.

B. Performance Metrics

The following metrics are used in the various scenarios to evaluate the two protocols:

1) *Average Network throughput*: This is defined as the total data received at traffic destinations over the simulation period divided by the simulation time (in Mbps).
2) *Packet Delivery Ratio*: This is defined as the ratio of the total number of data packets received by the destinations to those sent by the CBR sources over the simulation period.
3) *Average End-to-End delay of data packets*: This is defined as the average delay between the time at which

the data packet was originated at the source and the time it reaches the destination. Data packets that are lost en route are not considered. Delays due to route discovery, retransmissions and queuing are included in the delay metric.

C. NS2 Implementations of Equation 3

Using the IP-addresses of the packets, a host is made aware of the number of CBR-flows that either originate, terminate, or, are routed through it. For these simulations,these numbers are counted over the past ten super-frames (cf. figure 1) and presented as an estimate for the next ten super-frames. The choice of optimal number of super-frames to be counted to present an estimate of number of CBR-flows depends on the traffic and mobility pattern of any network. However we are not considering these factors for the reported simulations and fixed this number to be ten at random.

This information is then made available to the 1-hop neighbors of the host by an appropriate field in the RTS/CTS packets. Each host $i \in V$ estimates its value for $\mathcal{P}_i$ as per equation 3.

D. Simulation Experiments

To compare the performance of 802.11-MAC protocol and ST-MAC protocol we first considered a scenario involving only two hosts and a single CBR-flow. The maximum average throughput (i.e. when the source has packets to transmit all the time) obtained by 802.11-MAC protocol is 0.699 Mbps. In comparison, ST-MAC protocol achieved a maximum throughput of 0.580 Mbps.

We then compare 802.11-MAC protocol with ST-MAC protocol in a scenario with three nodes and two flows, to show that ST-MAC protocol does better than 802.11-MAC even without eliminating exposed terminal problem (as there is no exposed terminal problem in a network with three nodes). In this scenario, three nodes A, B and C are used where nodes A and C are one hop neighbors of node B and nodes A and C are not one hop neighbors of each other(A↔B↔C). Flow 1 is from A to B and flow 2 is from A to C. Every station has a buffer space sufficient to store all the packets it receives and A has data to transmit all the time for both flows. Each CBR-flow generates 12.5 data packets (of 512 bytes) to keep the link saturated (The notion of fairness comes into play only when the network resources are scare than the demand). The maximum throughput obtained in this experiment by ST-MAC for flow 1 (A →) B) is 0.290 Mbps and for flow 2 (A →B→C) it is 0.238 Mbps. 802.11-MAC obtains average throughput of 0.234 Mbps for both flows. The average delay for both protocols is very high because of huge buffers.We can observe that even for a simple 3-station network, ST-MAC is performing better than 802.11-MAC.

If we fix the queue length to be 50 for the above mentioned 3-station experiment, then the average throughput for each link varies as a function of start time of flows, as the queue overflows and depending on the start times either packets of flow 1 or flow 2 get dropped more frequently using Drop Tail Queue.Table I summarizes the observation. The delays are comparable for both these protocols. If we implement a more fair queuing scheme in place of Drop Tail Queue, the average throughput in case of ST-MAC protocol will be similar to the one obtained when every station has a buffer space sufficient to store all the packets. Ongoing work includes implementing approximation algorithm together with a fair queueing scheme.

Time	802.11-MAC Throughput(Mbps) Flow 1, Flow 2	ST-MAC Throughput(Mbps) Flow 1, Flow 2
Flow 1 starts first	0.044, 0.329	0.135, 0.238
Flow 2 starts first	0.454, 0.124	0.440, 0.136

TABLE I

COMPARISON OF CBR-FLOW THROUGHPUTS, WHERE FLOWS START AT A DIFFERENCE OF 0.2 SEC FROM EACH OTHER.

Finally, we considered randomly generated networks consisting of 100 hosts within a $1000m \times 1000m$ field. Each source generates 4 data packets per second of 512 bytes each. The CBR-connections start and end at random times during the simulation period. The number of CBR-flows is varied from 10 to 50 in intervals of 10 for these randomly distributed hosts. All results presented are averaged over 20 random simulations,each run involving random CBR-connections over randomly distributed nodes. Figures 2, 3 and 4 show the plots of the average network throughput, packet-delivery ratio and end-to-end delay as a function of the number of connections within the above mentioned scenarios. On an average, the ST-MAC protocol provided an 26.6% improvement in average network throughput; a 14.5% improvement in the packet-delivery-ratio, with a comparable end-to-end delay over 802.11-MAC.

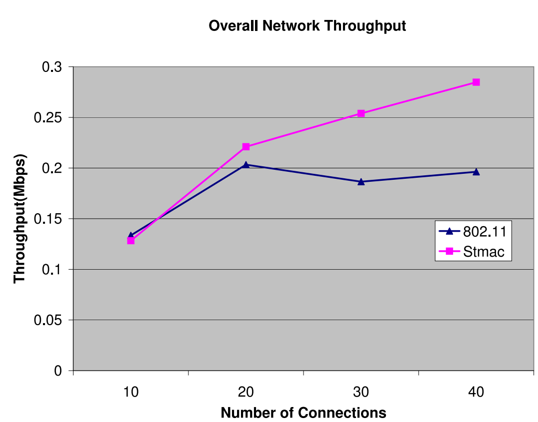

Fig. 2. Network throughput as a function of the number of connections.

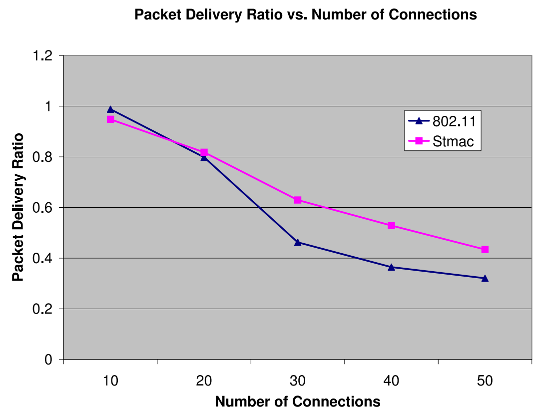

Fig. 3. Packet-delivery-ratio as a function of the number of connections.

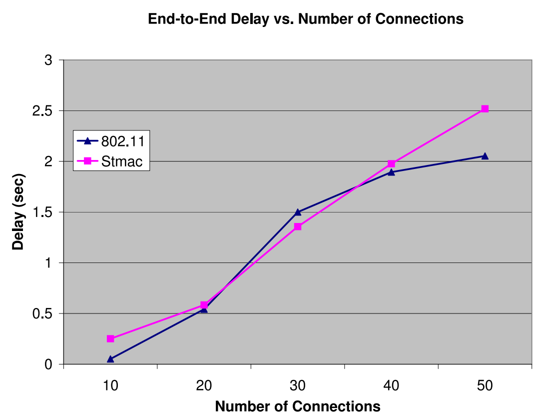

Fig. 4. End-to-end-delay as a function of the number of connections.

VI. Conclusion

In this paper we presented an algorithm to approximate proportional fairness for slotted-time MAC-protocols for ad-hoc wireless networks. We then implemented the approximation scheme using ST-MAC protocol and showed that it performs better in terms of average network throughput and packet-delivery ratio when compared to the 802.11-MAC protocol.

Extensions to the current work include using the latency between the start of a sub-frame and the arrival of a signal from a host as a measure of separation-distance. This measure can then be used to determine the appropriate transmit power so as to permit the spatial reuse of frequencies during the data slots in the ST-MAC sub-frame. Our ongoing research includes work related to providing distributed solution for achieving proportional fairness in terms of throughput using only the local information.

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