A SYNC-LESS TIME-DIVIDED MAC PROTOCOL FOR MOBILE AD-HOC NETWORKS

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ABSTRACT

Approaches to Medium Access Control (MAC) in mobile ad hoc networks (MANETs) can be broadly classified into TDMA and CSMA/CA. In principle, TDMA offers superior performance as well as better capacity guarantees compared to CSMA/CA. In practice, however, the need to provide network-wide synchronization without centralized control, and to accommodate mobility makes TDMA very hard to design and implement. Consequently, CSMA/CA variants are generally preferred. While the proliferation of real-time multimedia applications demands a protocol with TDMA-like features, the problem of doing so in a practically viable manner remains unsolved.

We present SITA (Sync-less Impromptu Time-Divided Access), a MAC protocol for real-time applications over MANETs. SITA combines the advantages of TDMA with the simplicity and robustness of CSMA/CA. SITA provides on (traffic) demand, reserved access to the channel and automatic admission control, while it does not require slot synchronization. The main idea behind SITA is to set up an impromptu, loose, conflict free schedule relative to an initial control exchange. We study the performance of SITA when implemented as an overlay over 802.11 in the ns-2 simulator. Our results show that, with real-time like traffic, SITA provides significant improvement in the end-to-end throughput, by as much as 300%, and on order of magnitude or more decrease in the end-to-end delay and jitter when compared with the vanilla 802.11.

I. INTRODUCTION

Medium Access Control (MAC) is a critical component of any mobile ad hoc network (MANET). The MAC sublayer converts raw physical capacity into usable network capacity, and thus the choice of a MAC protocol significantly impacts MANET performance. In today's MANETs this choice is overwhelmingly in favor of *contention-based* protocols, in particular, the IEEE 802.11 DCF [2]. This is partly due to the cheap availability of IEEE 802.11 cards, and partly due to the fact that its simplicity, robustness and flexibility are a ready fit for MANETs.

The unfolding future, however, presents a challenge: real-time multimedia applications are increasing their dominance in the Internet, and spilling over into MANETs and Mesh Networks. To support this, the MAC architecture needs to be fundamentally reservation-oriented, that is, provide capacity guarantees and admission control. Unfortunately, the 802.11 DCF is not such a protocol, and while the community has invented several ingenious variations [1], [17] to make it real-time friendly, it is clear that these are not long term solutions.

In contrast, *contention-free* access as exemplified by Time Division Multiple Access (TDMA) is widely acknowledged as being an excellent fit for providing requisite QoS for real-time applications, as it enables allocation of dedicated channel capacity to flows. However, broadly speaking, TDMA needs two things that 802.11 doesn't: *synchronization* of frames and slots, and *allocation* of slots to nodes/links. In MANETs, unlike in cellular networks, the lack of centralized control and mobility of nodes makes both of these extremely hard. Even when solved, the need for guard times between slots and control messages for allocation both lead to low efficiency that negates the advantages provided by TDMA over 802.11. Furthermore, synchronization is inherently not scalable with network size. Despite numerous efforts [15], [10], [12], the problem of providing practically viable solutions to these two challenges has not been satisfactorily solved, resulting in the community being stuck in sub-optimal solutions.

In this paper, we present SITA – Sync-less, Impromptu, TdmA, a MAC protocol for MANETs that combines the real-time friendliness of TDMA with the simplicity and robustness of 802.11. Instead of trying to *solve* the MANET synchronization and distributed dynamic allocation problem, SITA simply *bypasses* them by using short-lived, impromptu and local reservations using signaling as lightweight as 802.11's. Specifically, a demand for capacity from the higher layers is reserved with a simple handshake, that also serves as the basis for relative sync for ensuing data packets. If the reservation is successful the node transmits data packets contention-free periodically on the reserved allocation for as long as there are ready packets. The

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transmitter, the receiver and the interfering nodes keep track of the reservation using their local clocks only - no clock synchronization across the nodes is necessary.

In summary, SITA has the following features:

1) SITA does not require clock synchronization, or network-wide slot synchronization.
2) It provides on (traffic) demand reserved channel access.
3) The signaling control overhead is even less than that of 802.11 (amortized over all packets).
4) It is conceptually simple and easy to implement.
5) It can be implemented as a stand-alone MAC or as a software overlay on top of the widely deployed 802.11 MAC.

The last point is significant in practical terms and penetration potential. Unlike many proposals that need changing the 802.11 card firmware, overlaying SITA over 802.11 allows compatibility with existing 802.11 networks and incremental deployment.

We describe and analyze the performance of SITA using ns-2 simulations. We have implemented a high fidelity model of SITA as an overlay over the ns-2 802.11 DCF implementation. Our simulations show that the throughput of real-time like traffic with overlay-SITA is improved by as much as 300%, while the end- to-end delay and jitter are decreased by an order of magnitude or more when compared with vanilla 802.11. Furthermore, we show that SITA continues to perform well with bursty traffic and in the presence of mobility.

The rest of the paper is organized as follows. In Section II we describe SITA. In Section III we show how SITA can be implemented as overlay on a off-the-shelf 802.11 card. In Section IV we present simulations results. Finally, in Section V we describe the previous work.

II. SITA DESIGN

SITA is designed to provide TDMA-like capacity guarantees without requiring global synchronization. Furthermore, the capacity allocation is based on traffic demands and it is negotiated using random access. This makes SITA friendly to bursty traffic and more robust to mobility than traditional TDMA.

SITA works as follows. A request for capacity from the higher layers is converted into a time-periodic, fractional share of the channel capacity. To reserve the specific share, SITA negotiates with its neighbors using random access. If the reservation is successful, it will be used for data transmission for as long as there are ready packets. The transmitter, the receiver and the interfering nodes will keep track of the reservation using their local clock, which need not be synchronized with each other, and by exploiting the time periodicity of the share.

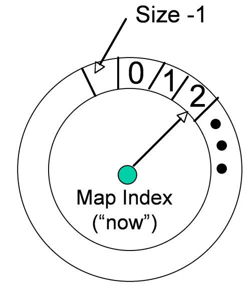


Fig. 1. The reservation map.

All the SITA functionality is based on a novel concept we refer to as the *Reservation Map*. We start the description of SITA by first presenting the Reservation Map. Following that, the SITA procedures for capacity reservation, data transmission and recovery are presented.

A. The Reservation Map

The Reservation Map (RM or simply "map") is a novel concept that provides a simple layer of abstraction between the physical channel and SITA and provides the following capabilities:

a. The reservation map allows describing an arbitrary capacity request as a time share of the channel. This description is succinct and universal across the network.

b. It greatly simplifies admission control. The available capacity at any point in time, which is necessary for performing admission control but at the same time notoriously difficult to estimate in MANETs, is readily provided by the reservation map.

c. Unlike the traditional TDMA frames, it has no synchronized frame boundaries.

The RM is best visualized as a circular strip (see Fig.1) with circumference representing time, and capacity shares represented by "slices" of the strip. All nodes have the same RM length (circumference and hence radius). The Reservation Map is divided in time units, equal in length for all the nodes. The total number of units on the Reservation Map represents the total capacity of the channel. A transmission that requires half the capacity of the channel would occupy half its units. A *Map Index* is used to "tell" the current unit at any point in time. The Map Index "moves" clockwise (without loss of generality) by making use of the local clock. A RM "tick" occurs when the difference between the current time, as indicated by the local clock, and the time of the last "tick" is equal to the unit size.

The map in every node has three regions: *allocated period* (AP), indicating shares that are allocated for this node's transmission; *occupied period* (OP) indicating shares that are allocated for transmission by neighboring nodes; and *free period* (FP), which is not allocated or occupied and can be used for new transmissions.

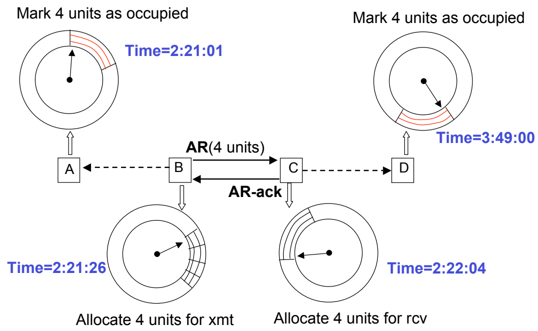


Fig. 2. Clocks at each node may be unsynchronized. Nodes set up impromptu reservations relative to AR and AR-ack

The RM is utilized by the reservation procedure, described below, to perform TDMA like channel reservation without the need for time synchronization. In particular, the reservation procedure updates the AP/OP/FP state of the map units in response to capacity requests.

B. Reservation Procedure

The channel reservation procedure takes as input a request for capacity in bits/sec for a specific flow[1]. Depending on the available channel capacity, it either reserves enough floor to satisfy the flow request or it turns it down and the flow is denied admission.

The procedure is executed in two steps. First, the capacity request is converted into a share of the reservation map. After that, if possible, the share is reserved by the random access based negotiation procedure.

1) Capacity to map share conversion: The conversion is a function of the capacity demand, reservation map size and the link[2] capacity. If D is the capacity demand, map_size, the RM size, and C, the link capacity, then,

$$req\_units = \lceil \frac{D}{C} \times map\_size \rceil$$

where req_units is the share size in terms of RM units.

2) Negotiation procedure: The negotiation procedure has two objectives: (1) to ensure allocation of time shares at the receiver, if available; and (2), to get interfering nodes to update their RM to reflect this allocation as an Occupied Period.

The procedure is identical to the RTS/CTS exchange employed by IEEE 802.11 for reserving channel capacity. We desribe the steps followed by all the nodes involved during a channel reservation negotiation with a specific example (see Fig. 2). Note that we deliberately assume that the clocks of the four nodes are not synchronized with each other and thus their respective map indexes "tell" different units.

Source Procedure: Let us assume that node B needs to allocate 4 units for a flow that crosses the link $B \rightarrow C$. Node B first looks for a FP share of size 4 on its RM. If such a share is not found the process is terminated and the flow is denied admission. Otherwise, B sends an Access Request (AR) packet to the C indicating a request for channel access. The AR packet consists of three fields: the source (B) and destination (C) addresses and the $req\_units(4)$. B then waits for an AR-ACK from C. If it receives an AR-ACK, the share of its RM starting at the unit the map index currently "tells", say x_B, up to $x_B + 4$ is marked as allocated for the particular flow. The data exchange component (described later in this section) will be invoked to transmit data packets contention free every time the map index "tells" between x_B and $x_B + 4$. If B does not receive an AR-ACK within a certain amount of time, it will assume the AR failed and the above process will be repeated after a randomly selected time period. If the process fails for a pre-defined number of times, it is terminated and the particular flow is denied admission.

Destination Procedure: Upon receiving an AR packet, the destination (node C) node will check its Reservation Map, starting at the unit the map index tells at the moment, say, x_C. Note that x_C can be, and in our example is, different from x_B. If, starting from x_C, there are 4 FP units available, C will update its reservation map by setting the units from x_C up to $x_C + 4$ as Allocated Period (OP) and will reply with a AR-ACK. The AR-ACK contains the same field as AR. Node C will be expecting data from node B every time C's map index is between x_C and $x_C + 4$.

If C does not possess the amount of free units required, the AR is silently discarded.

The rest of the network: Every node, in our example nodes A and D, that receives an AR or AR-ACK packets which is not destined at them reads the field containing the req_units and updates their respective RMs. Starting at the unit their map indexes tell, the next req_units will be set to Occupied Period (OP) status.

3) Reservation tracking procedure: When a node allocates or occupies a chunk of the RM it initiates a reservation tracking procedure for this chunk. The sole purpose of this procedure is to check whether any transmission takes place during the respective chunk. If no transmission takes place for a predefined number of cycles, the status of the chunk will be set to Free Period (FP). New flows may now allocate this chunk.

C. Data Transmission Procedure

The main task of the data exchange component is to reliably transmit data packets on the allocated shares, as

[1]Best effort packets are treated as belonging to a single flow called "best effort".

[2]The same node may realize different capacities with different neighbors.

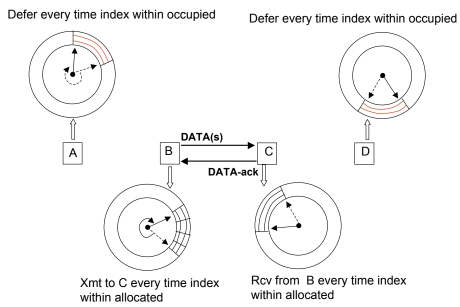


Fig. 3. Node B will transmit data to node C every time its map index "tells" the previously reserved share. Nodes C, A, and D know when B will transmit by virtue of their reservation maps.

indicated by the reservation map. Going back to our example (see Fig. 3), node B will transmit data to node C every time its map index is in the space allocated for the flow $B \rightarrow C$. Nodes C, D, and A will be aware of B's transmissions by simply checking their respective RMs. It is important to point out that during the data transmission procedure only the first and the last unit of the reserved share are relevant. Node B will send data to C as fast as it can until the map index "tells" the last unit of the reserved share.

Although the data transmission is contention-free, SITA employs ARQ to cope with channel errors and with those few cases when the allocation may fail. A SITA transmitter will send a burst of several packets at a time (the burst size is a parameter) and will require only a single ACK in response. If the ACK is not received within a certain time interval, all the packets will be retransmitted. On the receiving side, the SITA node will reply with an ACK if and only if all the data packets of the burst are received.

D. Allocation Failures and SITA Recovery Procedure

The above establishes a pseudo-TDMA regime with each node transmitting at pre-announced times for durations based entirely on its local clock. The initial access rules make it so that in the ideal case the transmissions from different nodes are collision free. However, in reality, a number of things disturb this condition. For example, mobility of nodes may bring a node, whose reservation map does not include current conditions, into conflict; transmissions may get out of sync due to clock drift (we explore the effect of clock drifts in more detail in the next subsection); packets may be lengthened due to the radio dropping its rate down (say from 11 Mbps to 5.5 Mpbs to 2 Mbps etc). For these reasons, SITA includes a recovery and re-sync scheme which is based on re-doing the access.

A recovery/re-sync is initiated whenever there is no ACK in response to a DATA for more than a certain number of attempts. Each node in this situation triggers a fresh access procedure (see above) in the existing FPs (that is, they exclude the time share on which the unsuccessful DATA was sent).

E. Addressing Clock Drifts

In order for SITA to work as described above, all of the nodes that have marked a specific reservation on their RM need to count units at the same speed. This in turn implicitly assumes that clocks on nodes run at the same speed. In practice, however, this is seldom true due to manufacturing variations. Clocks typically run at marginally different speeds resulting in *clock drift*. Clock drift may eventually result in the transmitter and receiver disagreeing on when the reservation starts within their RMs.

To deal with the clock drifts SITA uses guard bands. One RM unit at the beginning and one at the end of every share reservation are left unutilized. For example, if the request for capacity is 4 units, SITA will actually reserve 6 but it does not transmit any packets on the 1st and 6th unit. In the following we show that for practical settings and clock drifts the SITA guard bands are very effective.

If we denote the clock drift with C_{drift}, then, a reservation will spill into either of the guard bands, on every repetition, by:

$$RM_{size} \times C_{drift}$$

where C_{drift} is measured in PPM (parts per million).

Thus, the number of repetitions the guard band will protect the reservation for is:

$$\lfloor \frac{unit\_size}{RM_{size} \times C_{drift}} \rfloor$$

After this number of repetitions is exceeded reservations may start to overlap and are not guaranteed anymore to be contention free. If this happens and it results in packet collisions[3], the SITA recovery procedure described in the previous subsection will kick in.

Let us consider some realistic value for the variables above to get a better sense of the effectiveness of the SITA guard bands. In our simulations we have used $RM_{size} = 100msec$ and $unit\_size = 2msec$. In [14] it is reported that for the Telos mote platform the clock drift is 21 PPM. For these values, a RM reservation will spill $2.1\mu sec$ into the guard band on every repetition. Thus, the guard band will protect the reservation from the clock drift for 952 repetitions or 95 seconds. In our simulations, even with a reservation that was one tenth of the RM, SITA was able to transfer 4 data packets of 500 bytes on every repetition. That translates to 3808 data packets of 500 bytes before the recovery procedure may have to kick in and the reservation be done anew. Alternatively, SITA could be modified so that it proactively reserves a new share and abandons the

[3]Collisions will only happen if there are two reservation separated only by the guard bands

current when it realizes that the current share is about to spill outside the guard band. We leave this for future work.

III. SITA As Overlay

SITA can be implemented as a stand alone MAC protocol or as a software overlay (sublayer) on top of the widely deployed 802.11 MAC. In the following we show how SITA can be implemented on top of a off-the-shelf 802.11 card without making any modification to its firmware. With our approach, the 802.11 code will remain untouched. A new "sublayer" (overlay) is written on top that uses 802.11 MAC as a data pipe, and all time management and access arbitration is performed within the overlay. To 802.11, the SITA packets are merely higher layer data packets.

Recall from Section II that SITA has four packet types: AR, AR-ACK, DATA and DATA-ACK. The AR packet is to be sent using random access, while the rest of the packets are to be sent contention free. Below we show how each of these SITA packets can be sent the way they should through an 802.11 card.

a) Transmitting AR: To comply with the SITA semantics, the behavior of the 802.11 cards needs be modified to transmit the AR only once, and without the automatic ACK. Both requirements are achieved by forwarding the AR to the 802.11 as a "broadcast" packet type.

b) Transmitting AR-ack, DATA, DATA-ack: SITA requires transmitting these packets contention free. Thus, it is necessary that AR-ack, DATA and DATA-ack cut through the 802.11 and reach the physical layer with no delay. To achieve this, all the packets are forwarded to the 802.11 card as "broadcast" packet types while the carrier sensing and the backoff are disabled [5], [7].

In Section IV, we use the approach describe above to implement SITA as on overlay on top of the 802.11 ns-2 implementation.

IV. Simulations

In this section we present the performance evaluation of SITA. We have implemented SITA in the ns-2 simulator as an overlay over the IEEE 802.11 implementation, following the approach described in Section III. The exact policy for admission control is beyond SITA's scope. However, for the purpose of these simulations we follow a simple first come first serve approach. We make the following main observations in our experiments:

- With real-time like loads, SITA improves the end-to-end throughput by as much as 300%, and decreases the end-to-end delay and jitter by on order of magnitude or more, when compared with the vanilla 802.11.
- SITA continues to perform better than 802.11 in terms of throughput, end-to-end delay and jitter even in the presence of high node mobility and with bursty traffic, albeit by not the same margins.

A. Simulations Settings

In all the experiments, unless otherwise specified, the packet size is set to 500 bytes, the transmission rate to 11 Mbps and the simulation time to 150 seconds. The RM size is set to 100 msec. This bounds the per hop delay by 100 msec, which is deemed acceptable for voice latency [18]. The RM $unit\_size$ needs to be as small as possible to allow SITA good granularity in assigning RM shares. However, it has to big enough to allow for a packet transmission. For out settings this size is 2 msec. For most experiments, we use CBR traffic over UDP, which is similar to the traffic a real-time multimedia application is expected to generate. We also run experiments with bursty traffic and mobile nodes for which reservation based MAC protocols traditionally perform poorly. The metrics of interest are end-to-end throughput, delay and jitter

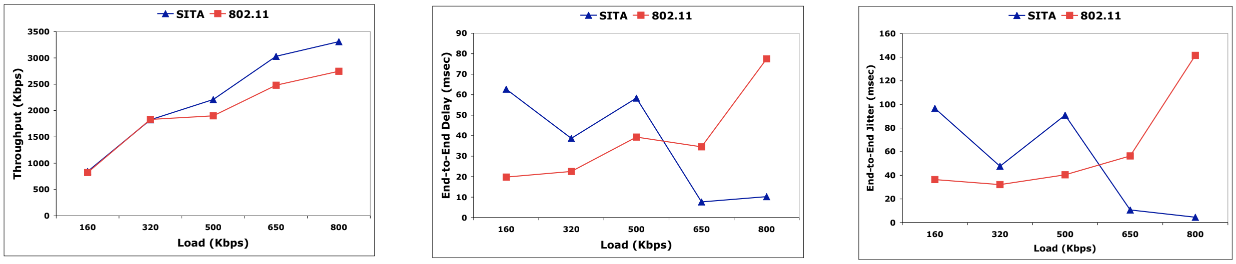
B. Experiment 1: Grid topology

We first analyze the behavior of SITA over long flows that are subject to high interference. For this purpose we use a 64 node Manhattan grid. Eight source destination pairs are selected such that the source is on one side of the grid and the destination on the other side. Every source generates CBR traffic at varying loads.

Results and Discussion: The throughput for each flow is depicted in Fig. 4, while the overall network throughput in Fig. 5. As we can see in Fig. 4, at high loads, IEEE 802.11 becomes extremely unfair, resulting in high variance in the realized throughput among the flows. SITA, on the other hand, thanks to its capacity allocation mechanism is able to always deliver the promised capacity to as many flows as possible, while denying capacity to those flows that simply cannot be accommodated. SITA's approach leads to fairness among those flows that were admitted, as shown in Fig. 4(a), as well as in much higher overall network throughput, by as much as 300%, as shown in Fig. 5. The same behavior is also observed when analyzing the end-to-end delay. SITA's allocation mechanism allows for expedited (contention free) delivery of the packets, as shown in Fig. 6(a), over the pre-reserved capacity. The pre-reserved capacity leads also to very low jitter values, as shown in Fig. 6(c). With IEEE 802.11, at high loads, the unfair sharing of the capacity and the contention leads to certain flows suffering an order of magnitude or more higher end-to-end delay and jitter (Fig. 6(b) and Fig. 6(d)) when compared with SITA.

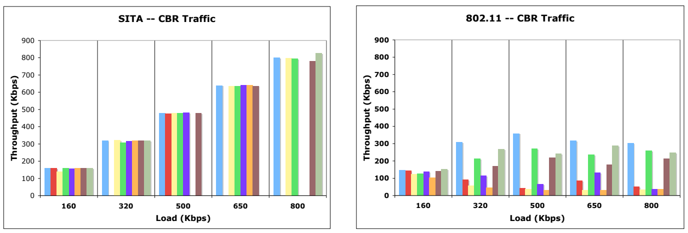
C. Experiment 2: Performance with Mobile Nodes

A major strength of CSMA, including 802.11, is its superior resilience to mobility when compared with a reservation based protocol. In this experiment we evaluate the performance of SITA and compare it to the 802.11 when



(a) Overall throughput . (b) Average End-to-End Delay. (c) Average Jitter.

Fig. 7. **Experiment 2: 50 nodes on a 3 by 3 unit, flat topology; all the nodes move following the random waypoint model. 10 CBR flows are established over 10 source destination pairs selected at random. SITA continues to performs well when compared with 802.11, despite the high node mobility. In terms of throughput, SITA performs just as good or slightly better than 802.11, while dramatically improving the end-to-end delay and jitter at high loads.**



(a) SITA Throughput. (b) IEEE 802.11 Throughput.

Fig. 4. **Experiment 1: 8 by 8 Manhathan grid; 8 flows generating CBR traffic. At high loads, IEEE 802.11 becomes extremely unfair, resulting in high variance in realized throughputs among flows. SITA, on the other hand, delivers fair throughput to as many flows as possible.**

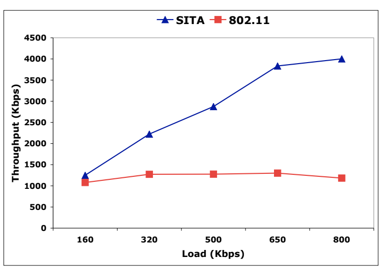
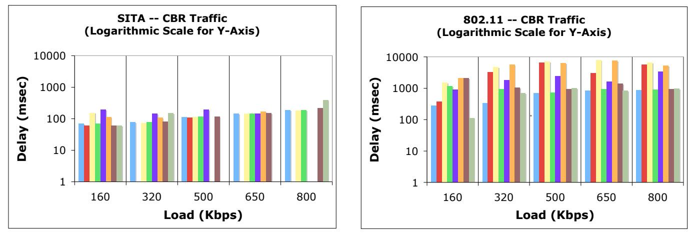


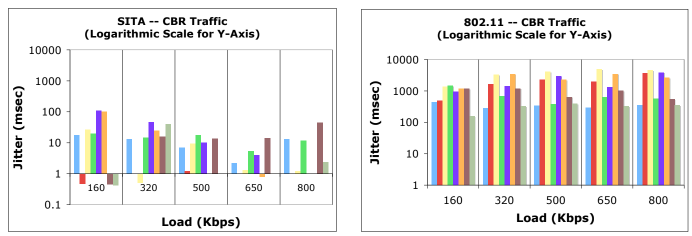
Fig. 5. **Experiment 1: 8 by 8 Manhathan grid; 8 flows generating CBR traffic. SITA offers several times increase in the overall network throughput for moderate to high loads.**

there is a large number of flows and the nodes are mobile. 50 nodes are placed uniformly at random on a 3 by 3 units flat topology. We select at random 10 source destination pairs and generate data flows at constant bit rate (CBR). All the nodes in the network are mobile. We use the random waypoint model. The maximum speed in the simulations is 10 m/s, while the minimum is 0 m/s.

Results and Discussion: The results for the overall network throughput and the average end-to-end delay and jitter are depicted in Fig. 7. At low load the performance of SITA and IEEE 802.11 is similar. However, as the load increases, SITA is able to deliver approximately 25% more throughput, while incurring a much lower end-to-end delay.



(a) SITA End-to-End Delay. (b) 802.11 End-to-End Delay.



(c) SITA End-to-End Jitter. (d) 802.11 End-to-End Jitter.

Fig. 6. **Experiment 1: 8 by 8 Manhathan grid; 8 flows generating CBR traffic. At high loads, IEEE 802.11 becomes extremely unfair, resulting in many flows experiencing very high end-to-end delay and jitter. SITA delivers the data on all the flows at very low end-to-end delay and jitter.**

Two are the reasons that the improvement in throughput achieved by SITA is lower than what was observed in experiment 1. First, the paths here are shorter and, as also observed in the experiment 2, 802.11 performs well over 1 and 2 hop paths. Second, the high node mobility makes the life of any reservation shorter, forcing SITA to invoke the recovery and leading to higher overhead per data packet delivered.

D. Experiment 3: Performance with Bursty Traffic

In this experiment we use the setting of the Experiment 1, except that the nodes generate bursty traffic. To simulate bursty traffic, nodes generate traffic following an on/off pattern. The lengths of pause and traffic generation periods are exponentially distributed. For the data presented here, the mean value for the on (traffic) period is 5 seconds,

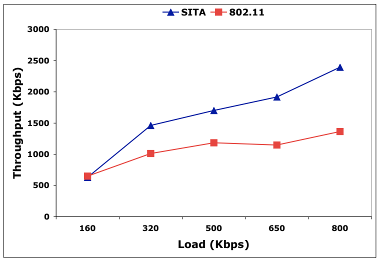


Fig. 8. **Experiment 3: 8 by 8 Manhathan grid; 8 flows generating bursty traffic. SITA offers significant increase in the overall network throughput, by as much as 100%, for moderate to high loads, when compared with 802.11.**

while for the off (pause) period, 10 seconds. The simulation duration is again 150 seconds. Due to space limitations, we depict only the overall network throughput in Fig.8. As the data shows, SITA continues to significantly outperform 802.11, by as much as 100%, albeit not by the margin observed for the CBR traffic.

V. Related Work

There is a large body of work on MAC protocols for MANETs and a complete account is beyond the scope of this paper. Instead, in this section, we describe some representative work.

Random Access MAC Protocols: IEEE 802.11 DCF (based on CSMA/CA) has become the de-facto standard reference for the research and development of MAC protocols for MANETs. However, this protocol was designed and engineered for WLANs. When used in MANETs, it presents numerous shortcomings, such as unfairness [3] and spatial bias [16]. Furthermore, the inherent weakness of CSMA/CA in handling real-time traffic is exacerbated in the multihop setting [9], [11].

TDMA MAC Protocols: TDMA has been largely dismissed in the design of MAC protocol for MANETs mainly due to its demand for tight network wide synchronization and its poor channel utilization under bursty traffic. There are a few exceptions, however, of TDMA MAC especially in the military context [18], and emerging networks [8], [6] where CSMA is not an option.

Protocols Based (in part) on CSMA: These protocols can be broadly classified in two categories: protocols that provide service differentiation, and CSMA/TDMA hybrids.

Service differentiation. In the first category [1], the modification still maintains the CSMA nature of the protocol but make changes to the backoff procedures so that the probability of accessing the channel depends on some assigned priority. However, in the presence of multiple flows with the same priority the protocol with fall back to pure CSMA.

CSMA/TDMA hybrids: In [4], [13] it is proposed to use CSMA for accessing the channel and then holding it, in TDMA fashion, for as long as it is necessary. Thus, no synchronization is required and the channel allocation is based on traffic demand, while at the same time there are capacity share guarantees. However, both works assume that the real-time traffic packets arrive at a specific and universal rate. This would not hold in scenarios where different kinds of real-time traffic, e.g video, VOIP, are present simultaneously in the network. Finally, both protocol have no efficient way of dealing with node mobility.

References

[1] Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications, Amendment 8: Medium Access control (MAC) Quality of Service Enhancements, IEEE Std. 802.11e-2005 (November 2005).

[2] Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications, IEEE Std. 802.11, January 1997.

[3] Violeta Gambiroza, Bahareh Sadeghi, and Edward W. Knightly. End-to-end performance and fairness in multihop wireless backhaul networks. In *ACM MobiCom '04*.

[4] C. R. Lin and M. Gerla. Asynchronous Multimedia Multihop Wireless Networks. In *IEEE INFOCOM '97*.

[5] M. Neufeld, J. Fifield, C. Doerr, A. Sheth, and D. Grunwald. SoftMAC-flexible wireless research platform. In *HotNets-IV*.

[6] Jim Partan, Jim Kurose, and Brian Neil Levine. A survey of practical issues in underwater networks. In *WUWNet '06: Proceedings of the 1st ACM international workshop on Underwater networks*.

[7] R. Patra, S. Nedevschi, S. Surana, A. Sheth, L. Subramanian, and E. Brewer. WiLDNet: Design and Implementation of High Performance WiFi Based Long Distance Networks. *NSDI*, 2007.

[8] Bhaskaran Raman and Kameswari Chebrolu. Design and evaluation of a new MAC protocol for long-distance 802.11 mesh networks. In *ACM MobiCom '05*.

[9] Ram Ramanathan. Challenges: a radically new architecture for next generation mobile ad hoc networks. In *ACM MobiCom '05*.

[10] S. Ramanathan. A Unified Framework and Algorithm for (T/F/C)DMA Channel Assignment in Wireless Networks. In *INFOCOM '97*, page 900, Washington, DC, USA. IEEE Computer Society.

[11] Ananth Rao and Ion Stoica. An overlay MAC layer for 802.11 networks. In *ACM MobiSys '05*.

[12] Injong Rhee, Ajit Warrier, and Lisong Xu. Randomized Dining Philosophers to TDMA Scheduling in Wireless Sensor Networks. Technical report, Department of Computer Science, North Carolina State University, April 2005.

[13] Sumit Singh, Prashanth Aravinda Kumar Acharya, Upamanyu Madhow, and Elizabeth M. Belding-Royer. Sticky CSMA/CA: Implicit synchronization and real-time QoS in mesh networks. *Ad Hoc Netw.*, 5(6):744–768, 2007.

[14] Hoi-Sheung Wilson So, Giang Nguyen, and Jean Walrand. Practical synchronization techniques for multi-channel MAC. In *ACM MobiCom '06*.

[15] Bharath Sundararaman, Ugo Buy, and Ajay D. Kshemkalyani. Clock synchronization for wireless sensor networks: a survey. *Ad Hoc Networks*, 3(3):281–323, 2005.

[16] Karthikeyan Sundaresan, Hung-Yun Hsieh, and Raghupathy Sivakumar. IEEE 802.11 over multi-hop wireless networks: problems and new perspectives. *Ad Hoc Netw.*, 5(6):744–768, 2003.

[17] Nitin H. Vaidya, Paramvir Bahl, and Seema Gupta. Distributed fair scheduling in a wireless LAN. In *ACM MobiCom '00*.

[18] C.D. Young. USAP multiple access: dynamic resource allocation for mobile multihop multichannel wireless networking. *IEEE MILCOM 1999*.