Performance analysis of distributed time division multiple access protocols in mobile ad hoc environments

Performance Analysis of Distributed Time Division Multiple Access Protocols in Mobile Ad Hoc Environments

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ABSTRACT

Tactical wireless mobile ad hoc networks rely upon distributed medium access control (MAC) protocols for coordination and assignment of channel resources among dispersed and mobile users. One such protocol is the distributed time division multiple access (TDMA) scheme where different users contend for time slots via a signaling mechanism. Several key performance criteria for such protocols are the convergence time, average packet delay, and throughput. The convergence time is defined as the duration of time within which all nodes across the network collaboratively and in a distributed manner obtain conflict-free slots. The convergence time can be further exacerbated by mobility of the users. The average packet delay and throughput are important to the application layer quality of service (QoS) requirements. In this paper, the authors will quantify the aforementioned performance metrics for a distributed TDMA protocol.

INTRODUCTION

[1]In tactical Mobile Ad Hoc Networks (MANET), communicating nodes have to collaborate, cooperate, and contend for resources in order to construct routing and forwarding tables and obtain communication links. In Figure 1, a group of mobile communications nodes equipped with packet-switched devices and MANET signaling protocols coordinate and reserve resources at the link layer in order to construct routing and communications path throughout the network for delivery of application layer traffic. One of the challenges in the MANET communications systems is the design of efficient and robust medium access control (MAC) protocols. Generally speaking, the MAC schemes fall into two broad categories, the random access based and the reservation based. Many existing MAC protocols are suitable to operate in environments with a central control (e.g., cellular systems with the base stations) [1 and 8]. When operating in infrastructureless, distributed, and dynamic environments such as the tactical operations, the MAC protocol plays two key roles: 1) provide a signaling mechanism for the communications nodes for exchanging information for neighbor discovery and resource allocation (e.g., TDMA slots) in a timely and conflict-free manner; and 2) satisfy latency and throughput performance requirements.

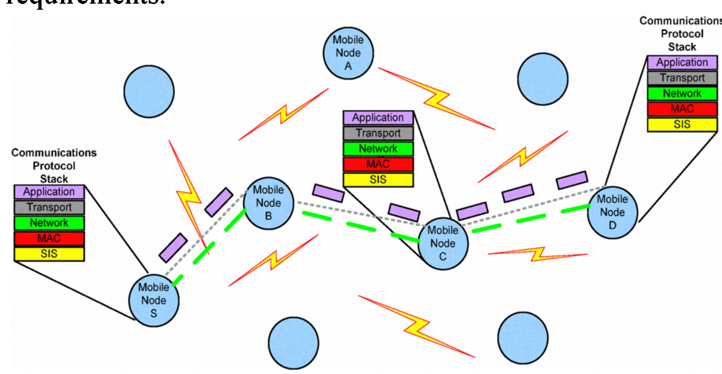

Figure 1: Topology of a distributed Ad Hoc Network.

As a proposed MAC protocol for the Joint Tactical Radio System (JTRS) described in [2-5], the unified slot assignment protocol (USAP) is a distributed TDMA scheme that allows for spatial reuse of the link layer resources. This MAC protocol provides a distributed signaling mechanism for the communicating nodes to exchange information for making resource reservations for packet transmissions. The published papers on this MAC protocol provide a qualitative description of its functions. To better understand the behavior of the TDMA protocol, a modeling and simulation and to the extent possible analytical approach is needed to derive quantitative performance results.

In this paper, the authors will use OPNET modeling and discrete event simulation as well as analytical techniques to analyze the behavior and quantify the performance of

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the TDMA protocol. The next section provides a brief description of the functions and features of the USAP protocol followed by a parametric performance evaluation of the protocol.

TDMA SYSTEM DESCRIPTION

This section provides a brief description of the components and features of the USAP protocol. Given a network of mobile nodes, each having line of sight RF capabilities, USAP provides a spatial-reuse TDMA time slot schedule for the participant nodes in a distributed manner. This is the underlying protocol used by [2-5] to handle link-level connectivity. The schedule is comprised of data slot assignments. A subset of slots is used for signaling and exchange of user information in order to schedule data slots. The signaling slots are pseudo-randomly and intermittently distributed throughout the frame. Each node is assumed to be preconfigured with a signaling slot as depicted in Figure 2. This signaling slot becomes available to a node once every cycle (a cycle is some number of frames). The length of a cycle is determined by the number of nodes in the network and the number of signaling slots per frame. Each node has a different schedule, since it only holds information about itself and its local neighborhood[2]. USAP assigns data slots either for node activation or link activation.

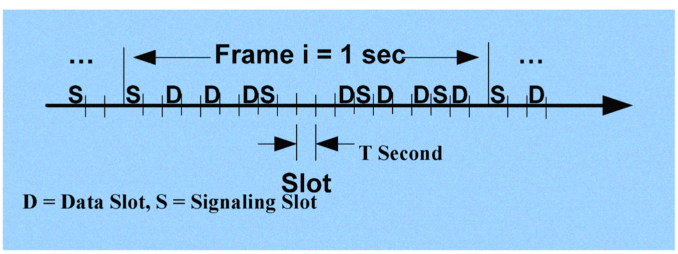

Figure 2: A generic USAP TDMA frame.

A slot assignment in node activation indicates that the timeslot is assigned to a single node. During the assigned data slot, the node can choose to do nothing, (if it has no data pending) and then the timeslot is wasted, to send data to any one of its neighbors during the slot, or to broadcast to all of them. A slot assignment in link activation indicates that the timeslot is assigned to an ordered pair[3] of nodes. During the data slot the node can choose to do nothing, (if it has no data pending) and then the timeslot is wasted, or to send data to the receiver. In this paper we only address the node activation scheme.

It is assumed that the nodes contain a simplex transceiver with an omni-directional antenna. A node cannot both transmit and receive in a single timeslot. When in transmit mode, a node will not notice incoming transmissions. A node cannot receive from more than one node in a single timeslot. When in receive mode, a second transmission reaching the node will interfere with or corrupt the other. For a given node, its neighbors are the nodes whose transmissions can be heard or are strong enough to prevent reception of other neighbors' signals. A good neighbor is a neighbor where communication is bidirectional and probability of correct reception is above a certain threshold. A bad neighbor is a neighbor where communication is receive-only and/or the probability of correct reception is below the good neighbor threshold.

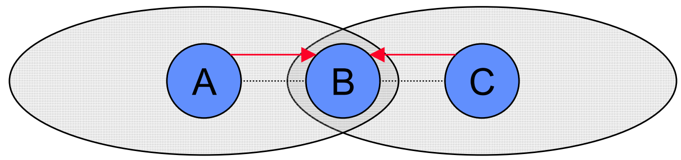

Figure 3: The hidden terminal problem. Nodes A and C are hidden terminals.

In wireless environments, the hidden terminal problem occurs when two nodes are hidden from each other but visible to a third node. An example of this is shown in Figure 3. Nodes A and C are hidden terminals and do not hear each other when broadcasting because they are too far away. However node B, which is between, hears both. Since the hidden nodes cannot hear each other, without a schedule, they will not be aware that the other one is transmitting. This can cause them both to transmit simultaneously to node B and prevent either's transmission from being heard. This is a problem because it causes packets to be collided and therefore lost. USAP attempts to mitigate the hidden terminal problem by creating a transmission schedule before allowing data transmissions. It uses signal slots to coordinate schedules. The signal slots have a pre-assigned schedule so they cannot cause collisions. USAP schedules data slots using information from the local neighborhood. It attempts to ensure that collisions do not occur.

As the data slots are assigned per frame, the USAP algorithm makes use of spatial reuse of timeslots, see Figure 4. This capability enables for distant users that are not subject to each other's interference to schedule the same data slots for transmission and therefore allowing for the network to scale.

2 All nodes within two hops.
3 (Transmitter, Receiver).

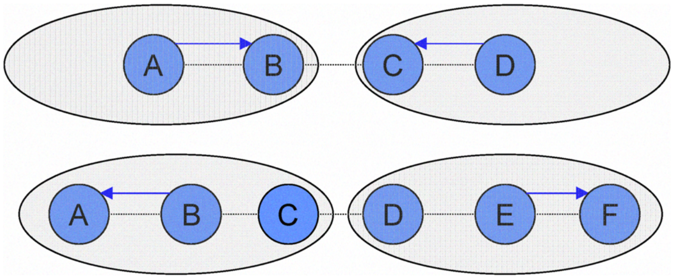

Figure 4: Multiple nodes can transmit in the same data slot as long as they do not interfere.

The USAP protocol can incur additional overhead associated with the signaling slots where no data (from upper layers) can be transferred and no spatial-reuse can occur. USAP has an additional challenge of coming up with the schedule quickly. There is a minimum level of convergence before upper layers can send data, and global convergence may be required for layer 3 (routing) to converge properly. Both the scalability and the convergence performance of the USAP protocol will be further investigated in the next section.

Signaling Performance of the Distributed TDMA Systems

In this section, we will investigate the performance of the signaling protocol of the distributed TDMA scheme. This analysis is based on a model of USAP protocol implemented in the OPNET simulation environment. As a key measure of performance, we consider the convergence time of the USAP protocol. The convergence time is defined as the interval of time during which the communications nodes in the network attempt to obtain conflict-free data slots.

Table 1: Example system parameters for the simulation experiment;

System Parameters	Fixed Parameters	Variable Parameters
Frame length (Sec)	$T_C = 1$	
Number of nodes in the system		N = 2, 4, 9, 16, 25, 49, 64, 81, 100
Number of slots per frame	100	
Number of signaling slots per frame		S = 5, 10
Hop constraint for spatial reuse	H =3	
Transmission range constraint for spatial reuse (Hops)		1, 10
Number of data slots each node tries to reserve and de-conflict		1, 2, 3, 4
System bandwidth BW = (M Hz)	5	
Data rate per slot R= (kbps)	(~43)	
Offered Load, ρ		0.1-1
Mobility		Static and 100% of nodes are mobile

The convergence time is a key metric that plays an important role in the convergence time of the upper layer protocols (e.g., routing) and depends upon many system parameters. To better understand the sensitivity of the convergence time to various system parameters, we have enumerated a few important ones in Table 1. The network topologies considered in the following analysis are of Manhattan Grid (MG) type with static and mobility cases as depicted in Figure 5. As the number of possible experiments based on the combinations of parameters in Table 1 is very large only a subset of the experiments are selected.

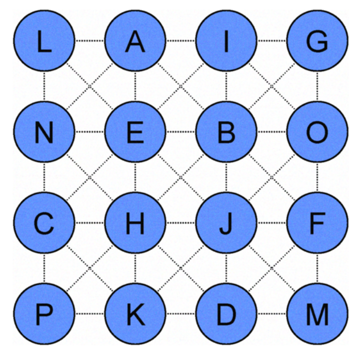

Figure 5: A sample grid network topology.

Figure 6 illustrates the convergence time of the USAP protocol as a function of the number of nodes in the network. Both dense and sparse topologies are considered in this experiment. Each node in the network is assigned a single data.

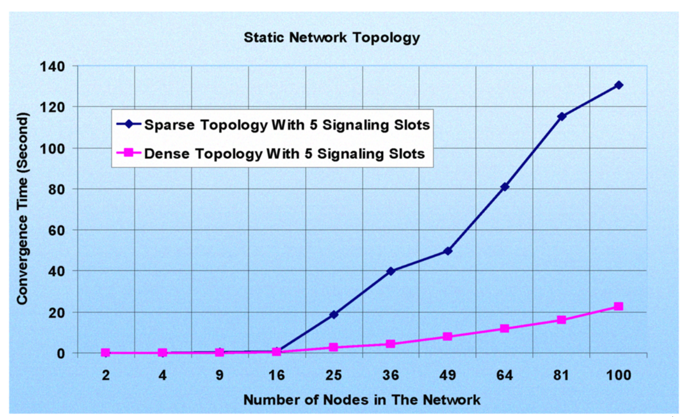

Figure 6: Convergence time as a function of the number of nodes in the network for dense and sparse static topologies.

In the dense scenario each node in the network can hear every other node. In the sparse case, each node can hear a subset of the nodes (e.g., on average 7 nodes depending where in the network it is located.) There are 5 signaling slots per frame of 1 second long and 1 signaling slot per node therefore in a 100 node network each node gets to transmit its signaling information once per cycle which is about 20 frames or 20 seconds long. As expected the convergence time of the dense topology is much shorter (22.5 seconds = 1 signaling cycle) than the sparse topology. This is due to the ability of the nodes hearing all their neighbors and hence deconflicting any potential conflicts in the slot assignments. On the other hand, in a sparse topology the convergence time (about 130 seconds = less than 6 signaling cycles) may take much longer since nodes have to deconflict their slot assignments without the ability to hear from every other node directly.

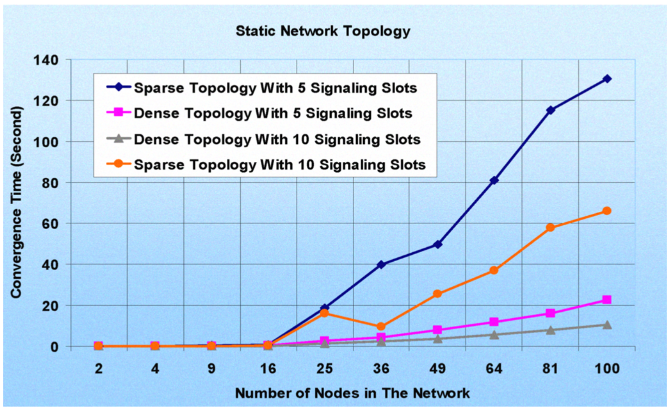

Figure 7: Convergence time as a function of the number of nodes in the network for dense and sparse static topologies for different number of signaling slots per frame.

In Figure 7, we depict the convergence time of the protocol as a function of the number of nodes in the network for both dense and sparse static topologies where we increase the number of signaling slots per frame by a factor of two. As expected, the convergence times for both the dense and sparse topologies are reduced by half.

As the bandwidth demand per node increases, the fixed number of data slots has to be shared among the nodes in the network. When dealing with a dense network, this can result in some nodes being deprived from obtaining any data slots.

In Figure 8, the convergence time of the protocol is depicted as a function of the number of nodes in the network where each node is assigned two data slots (where the previous results had one data slot per node). Under a highly dense topology, at most 50 nodes can obtain 2 data slots each. But the same network can provide 2 data slots per node to 100 nodes when it is sparse. This is primarily due to spatial reuse feature of the USAP protocol.

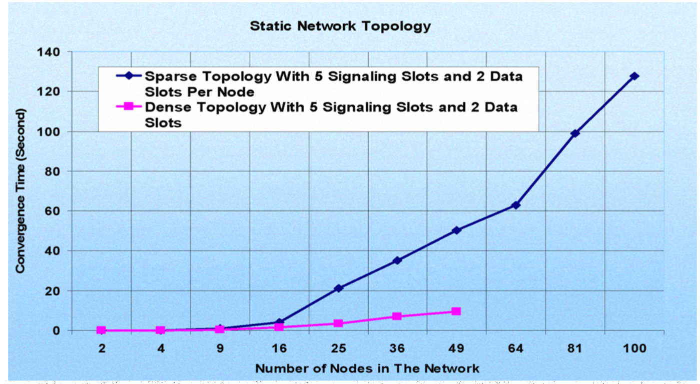

Figure 8: Convergence time as a function of the number of nodes in the network for dense and sparse static topologies for different number of required data slots per node.

When network operation under dense topologies is required higher slot allocation can be achieved only with additional bandwidth. This can be achieved by taking advantage of several frequency channels using frequency division multiple access (FDMA) technique. The USAP protocol is equipped with this capability however that analysis is postponed to a future paper.

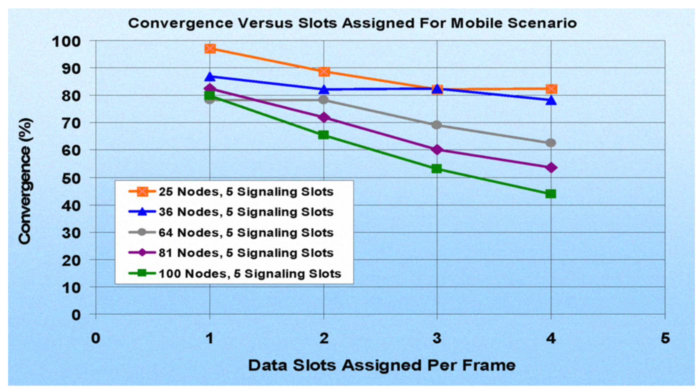

Figure 9: Convergence percentage as a function of the number of data slots assigned per node for dynamic topologies.

We conclude the performance analysis of the USAP signaling protocol with the convergence behavior for mobile nodes where random mobility pattern of nodes is considered. In Figure 9, the convergence of slots of different network sizes is plotted as a function of the number of slots assigned per node. This quantity is defined as the ratio of data slots that are conflict free for the total number of data slots. An absolute convergence can not be achieved when network nodes are constantly moving around. Mobility results in the network to oscillate between a sparse state and dense state. In a sparse state, spatial reuse can be leveraged to provide better delay and throughput performance. On the other hand, a dense state limits the spatial reuse gain. This is manifested in Figure 9 where the percentage of slots with conflict free schedule decreases with the slot demand per node. In the next section, we will address the delay and throughput performance of the distributed TDMA system.

Throughput and Delay Performance of the Distributed TDMA Systems

The previous section dealt with the performance of the TDMA convergence of the signaling protocol as a function of various system parameters. Once the data slots are allocated to different users and routing and forwarding tables are established throughout the network then each node can send its application traffic to the intended destinations. Two key performance measures that the application traffic is sensitive to are the expected delay and the throughput that each packet would experience throughout the network. In this section, we will address the access delay incurred and throughput obtained per node by the TDMA scheme. Using both simulation and closed form stochastic models, we will quantify these performance metrics as a function of offered traffic load.

For the TDMA system it is assumed that the network load is uniformly distributed among the network nodes. It should be noted that for the TDMA system the number of nodes in the system impacts the total delay as each node is given a fraction of the resources and as more nodes are added the fraction of resources decreases (or the time between permission to access the resources is increased).

As each node acquires a single data slot per frame, the latency can be computed based on the expression in (1) where D is the average message delay ($\hat{D}$ is normalized to a packet transmission time of T) of the packet transmission (slot) time where each packet is of fixed size of P bits, N is the number of nodes sharing a TDMA channel, L and $\overline{L^2}$ are the mean and mean square values of the message length, R is the total transmission rate in bits/sec, and finally $\rho = \lambda NP/R = \lambda LT_c < 1$ is the offered traffic load as the ratio of Poisson message arrival rate, λ, over the departure rate of messages out of the system.

$$\hat{D} = \frac{D}{T} = 1 + N\left(L - \frac{1}{2}\right) + \frac{N\overline{L^2}}{L}\frac{\rho}{2(1-\rho)} \qquad (1)$$

The three different terms in equation (1) represent a packet transmission time T, the time between the packet generation time and the end of the current frame $T_C/2$, and the queueing time incurred for all the packets already queued to be transmitted.

When the user data rate requirements in the system are asymmetric, the channel resources will be more effectively utilized if users with higher demand obtain more data slots. In a hypothetical example depicted in Figure 10, a user is assigned 4 data slots per frame. In a general case when a particular user that has been assigned K slots in each frame, then we can define $d(k) \geq 1 \; (1 \leq k \leq K)$ to be the distance between the $(k+1) \bmod K$ allocated slot and the $k \bmod K$ allocated slot where, $\sum_{k=1}^{K} d(k) = T_C$ where T_C is defined to be the duration of the frame.

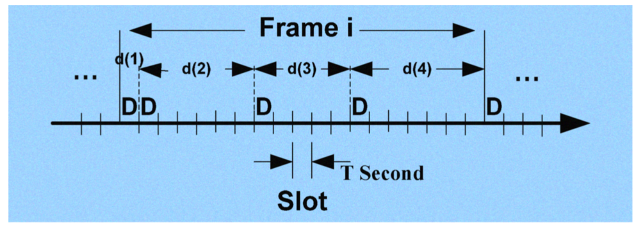

Figure 10: Data slot allocation for distributed TDMA.

The expected delay of a message can be computed by the expression in (2) and (3),

$$\begin{aligned} D(k) &= \frac{1}{2}d(k) + T \\ &+ \frac{T_C}{K}\left[q(1) + L - 1 - \frac{1}{2}\lambda L d(k) + \sum_{m=1}^{k}\left[\lambda L d(m) - 1 + Q_m(0)\right]\right] \\ &- \frac{T_C(K-1)}{2K} + \frac{1}{K}\sum_{J=1}^{K-1} V(J,k) \\ &+ \frac{T_C}{K d(k)}\sum_{m=1}^{K} h_k(\beta_m)\frac{e^{c_m d(k)} - 1}{c_m}\left[\frac{1}{1 - \frac{a}{\beta_m}} + \sum_{J=1}^{K-1} V(J,k)\beta_m^{-J}\right] \end{aligned} \qquad (2)$$

and

$$\hat{D} = \sum_{k=1}^{K} \frac{d(k)}{T_C} D(k). \qquad (3)$$

For details of the derivation and the definition of the terms in equation (2) see References [7 and 8].

One of the design parameters for this system is how to allocate the K slots available to a user in a frame in order to optimize the delay performance. For heavy offered traffic load conditions (e.g., $\rho \to 1$), the expected message delay is dominated by the large number of whole frames a message must wait before its transmission can begin. When the traffic load is very light (e.g., $\rho \to 0$), the expected message delay is very sensitive to the allocation of slots to the user and described in Equation (4)

$$\hat{D}_{\lambda \to 0} = 1 + \frac{1}{T_C} \sum_{k=1}^{K} \gamma_i \left[\frac{1}{2} \sum_{m=1}^{K} d^2(m) + \sum_{m=1}^{K} \sum_{l=m+1}^{m+k-1} d(m) d(l) \right]. \qquad (4)$$

In (4), $\gamma_i(1 \le i \le K)$ are the probabilities that a message transmission requires i slots beyond the number of whole frames.

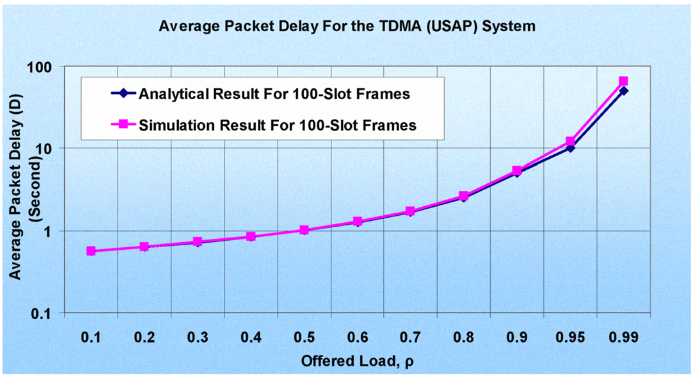

Figure 11: Average packet delay as a function of offered load with one data slot per node per frame.

In Figure 11, the average packet delay is illustrated as a function of the offered load to the network. The offered network load ρ is the ratio of traffic to be transmitted relative to the maximum traffic that could possibly be transmitted. Each node is assigned 1 data slot. Each node generates a message of 1 packet long and each packet fits within one date slot. The results are from the simulation as well as the analytical expression provided in Equation 1. For light network traffic load the length of the frame (1 second) is the main contributor to the delay and as the offered load increase the queueing portion becomes the dominant factor. It is important to note that the delay shown in Figure 11 is a single hop and not an end to end delay. For scenarios where more than one data slots are required per node, Equations 2, 3, and 4 can be used to obtain the access delay per message.

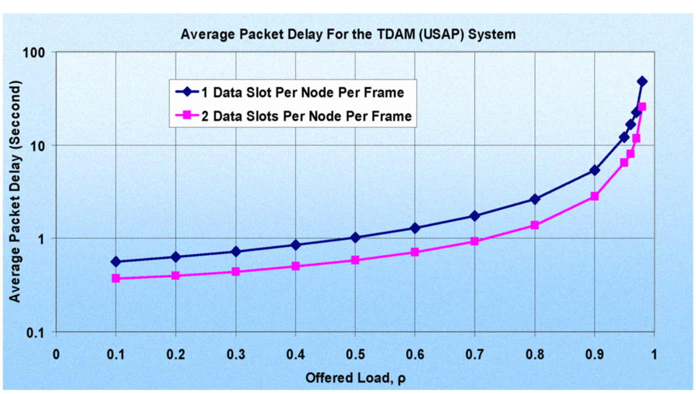

Figure 12: Average packet delay as a function of offered load with different number of data slots per node for a sparse topology.

When more than one data slot per node per frame is considered, the delay performance improves dramatically as depicted in Figure 12. The delay performance is markedly improved when 2 data slots per node per frame is assigned. The average throughput versus offered load is presented in Figure 13. As expected the throughput increases linearly with the offered load. The average throughput is further improved with the allocation of 2 data slots per node. This is only possible because of the sparseness of the network where spatial reuse of the TDMA slots is achieved. Under dense network topologies high throughput performance is only achievable by introducing more frequency channels.

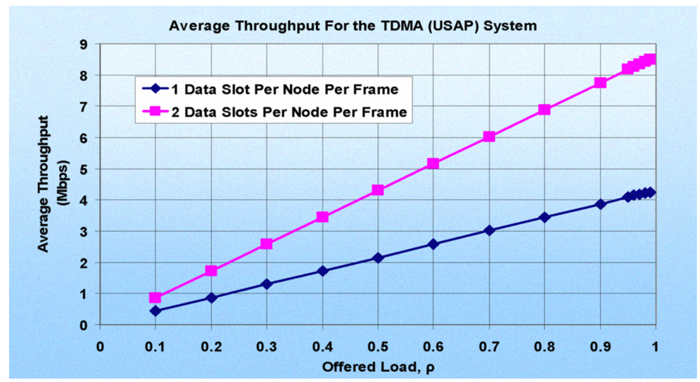

Figure 13: Average throughput as a function of offered load for different number of data slots per node per frame.

Finally, the delay and throughput results provide a good benchmark and gauge for assessing the application layer QoS expectations as well as network planning and capacity analysis.

CONCLUSIONS

Tactical MANET networks present many challenges. One of these challenges is the ability of the network to coordinate, schedule, obtain, and maintain link connectivity and bandwidth resources in a distributed and dynamic environment. MANET networks rely upon MAC layer protocols to achieve these while being able to scale and converge in a highly agile and mobile environment. In this paper, the authors investigate the performance of one of a proposed distributed TDMA MAC protocols for the JTSR systems.

Using modeling and simulation and analytical techniques, a set of system level performance metrics is quantified. In particular, the convergence behavior of the distributed TDMA system is characterized as a function of many systems parameters for static and dynamic network conditions. The convergence behavior of the system is demonstrated to be sensitive to the number of signaling slots per frame as well as the network mobility dynamics. With this modeling and simulation capability, we can optimize this behavior through the right parameter choices.

As important application layer required performance measures, both delay and throughput behavior of the TDMA scheme are evaluated using analytical and modeling and simulation techniques. We illustrate that the TDMA access delay is sensitive to the number of data slots allocated to each node. Using stochastic queueing models, we show the accuracy of our simulation model. Under sparse network topologies, the throughput performance of the USAP system is shown to increase per increase in the offered load.

While performance prediction capabilities are developed it is important to emphasize their utility in providing insight and traffic engineering guidelines to the communications planners. For instance, how many users can one fit into a frequency channel, how many channels to establish, and what will be the delay and throughput per user? The analytical tool provides instantaneous results while simulation tool offers more flexibility in terms of degree and variations of the system parameters. The verification of these two capabilities and the closeness of the results should give further confidence to the users.

Finally, to the best of the authors' knowledge the USAP numerical performance analysis presented in this paper is of its first kind that has ever been published. Even though further analysis and investigation are recommended, the overall insight gained here is that the USAP protocol can perform well and this can be further improved with the appropriate optimization of its various parameters.

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