# Modeling TDMA-Based USAP in JTRS MDL for Multicast and Unicast Traffic

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***Abstract*—In this paper, we develop loss network models for the hard scheduling mode (virtual circuit mode) of the reservation-based USAP scheduling protocol as used in the Mobile Data Link (MDL) of the Joint Tactical Radio System (JTRS). These models are used to find performance metric estimates for both multicast and unicast traffic. USAP (Unifying Slot Assignment Protocol) is a dynamic distributed resource allocation protocol for mobile multihop wireless networks where the channel is partitioned in time and frequency. MDL creates a backbone sub-network and routes all traffic through this sub-network. For the backbone sub-network, we consider algorithms that form Connected Dominating Sets. We use loss network models that couple the physical, MAC, and routing layers effects. The effect of the MAC layer is modeled by approximating available capacity at a node. The available capacity to transmit is computed based on the USAP reservation rules and the node's 2-hop neighborhood traffic. For a given time varying scenario, we compute the performance metrics of blocking probability and throughput for both multicast and unicast traffic as a function of time. We compare the results of our model against simulation.**

## I. Introduction

Mobile Data Link (MDL) [1] provides the channel access for the JTRS (Joint Tactical Radio System) Wideband Networking Waveform. MDL uses the Unifying Slot Assignment Protocol (USAP) to schedule transmissions so as to achieve contention free transmissions. USAP is a dynamic distributed reservation based MAC that operates in two modes: hard scheduling mode (virtual circuit connection-oriented mode) where nodes reserve a session's link capacity end-to-end over the entire path; and soft scheduling mode (datagram scheduling) where nodes perform per-hop scheduling of links for single packets after the packet's arrival at the node.

In this paper, we develop models of USAP hard scheduling mode as used in MDL for both multicast and unicast traffic. We use these models to approximate the performance of a multihop wireless adhoc network. Our approach to performance evaluation is based on fixed point methods and reduced load approximations for loss network models [2]. Loss network models [3] were originally used to compute blocking probabilities in circuit switched networks [4] and later were extended to model and design ATM networks [5]–[7]. The main challenge in developing loss network models for wireless networks is coupling between wireless links due to sharing of the wireless medium between a node and its neighbors. This results in a node's average link capacity to be dependent on its neighborhood traffic. We model this effect via reduced capacity available to a node for transmission. This reduced available capacity is calculated using USAP reservation rules and traffic among 2-hop neighboring nodes.

We assume we know the exogenous traffic rate for any source transmitting to either a single destination or a set of destinations in a multicast group. Traffic is routed through a backbone network to the destination/s. The reduced load loss network model coupled with the reduced wireless link capacity estimation model and the specified routing, give us a set of non-linear equations that are run iteratively to obtain fixed point estimates of blocking probability and throughput.

The paper is organized as follows. Section II introduces MDL and USAP. Section III describes our modeling of MDL and the fixed point models used for USAP Hard Scheduling. Finally, in section IV we present the time varying scenario used and the results of our fixed point model for USAP Hard Scheduling including its comparison with simulation.

## II. MDL and USAP

USAP is the distributed resource allocation protocol used in MDL ( [1], [8], [9]). MDL partitions the communication channel in time and frequency and constructs a periodic frame structure called Orthogonal Domain Multiple Access (ODMA). The MDL frame structure is shown in Fig. 1. The Synch, NiB and CNiB slots are used for management traffic while the RBS/FRS slots are used to send user traffic.

MDL uses a concept called Channelized Neighborhoods (CNs) which segregates nodes onto different frequency channels for spatial frequency reuse within the network. Each node is assigned to a default frequency channel called Default ODMA channel (DOC) and a node assigned to the $k^{th}$ channel is denoted as belonging to *DOCk*. Nodes in a neighborhood that exchange a lot of traffic between one another usually belong to the same *DOCk*. Nodes belonging to a particular *DOCk* use this $k^{th}$ frequency channel, in the portion of the frame called Rotating Broadcast Slots (RBSs), to send and receive traffic (multicast, broadcast and unicast) by *broadcasting* the traffic (all neighboring nodes have to listen to a node's transmission) amongst each other (Intra-DOCk communication). Intra-DOCk communication, is routed via a set of backbone or artery nodes. These nodes are selected by a heuristic algorithm [8] in MDL to form an interconnected backbone within a CN. Ideally the artery nodes should form a minimal Connected Dominating Set (CDS) within a CN.

Traffic between two *DOCk*s (Inter-DOCk communication) is managed by setting up unicast links between nodes in the different *DOCk*s using the receiver's frequency channel (or receiver's DOCk) in the section of the frame called Fixed Reservation Slots (FRSs). FRS and RBS share the same portion of the frame with FRS given priority over RBS. So traffic that needs to be routed between two neighboring channelized neighborhoods (see Figure 2) $CN1$, operating on frequency $F1$, and $CN2$, operating on frequency $F2$, is first broadcast via backbone nodes to reach an edge or border node of CN1 using the RBS on frequency $F1$. Then the traffic is unicast from the edge node in CN1 to an edge node in CN2 uses FRSs on $F2$. Finally the traffic is broadcast via backbone nodes in $CN2$ using the RBS on frequency $F2$ to reach the intended destination/s in $CN2$.

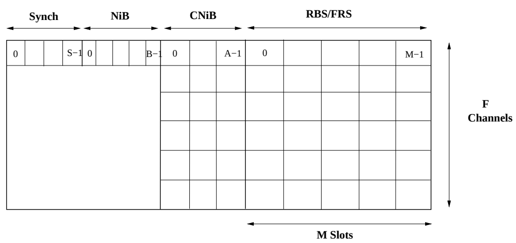


Fig. 1. MDL TDMA Frame Structure

The various slots in the periodic frame (figure 1) include:
**1)** Synch slots: are on a network-wide common channel. These slots are used to convey information needed to allow partitioned networks to merge.
**2)** Neighborhood Bootstrap (NiB) slots: are pre-assigned to nodes on a network-wide common channel. These slots are used to send slot assignment information (USAP records) necessary to reserve FRSs (for inter-DOCk communication). They also contain information to identify which *DOCk* a node belongs to as well as a node's CNiB slot.
**3)** Channelized Neighborhood Bootstrap (CNiB) slots: occur on particular DOCk's frequency. These slots are used to convey USAP slot assignment information for this *DOCk*'s RBSs and USAP information for assigning the CNiBs themselves.
**4)** Rotating Broadcast Slots (RBSs): are used to broadcast packets to all neighbors on a particular *DOCk* and are assigned via the CNiB slots. All nodes belonging to a particular *DOCk* must listen to broadcast slots on that *DOCk*, and are therefore prevented from doing anything else in that timeslot. Every RBS repeats from frame to frame but a particular RBS time slot shifts by one slot every frame period. This is done to somewhat mitigate the effect of FRS slots (that also repeat every frame but do not shift) which may be on a same *DOCk* channel but have higher priority.
**5)** Fixed Reservation Slots (FRSs): unicast packets to a specific neighbor (on the *DOCk* of the receiving node) and are assigned via the NiB slots. FRSs are primarily reservations between different *DOCk*'s (inter-DOCk); thus the idea is that these inter-DOCk connections would not require updating much faster than the NiB cycle. FRSs share the same slots as RBSs but have higher priority and override any RBSs assigned to the same slot. Since the RBS shift 1 slot every frame, the effect of the FRS on RBS traffic is somewhat mitigated.

A node listens/transmits on the common channel during Synch slots and NiB slots; and then switches to its *DOCk* for the CNiB section of the frame and for broadcast traffic in the RBSs, and switches to the receiver's *DOCk* for transmitting inter-DOCk unicast communication using FRSs.

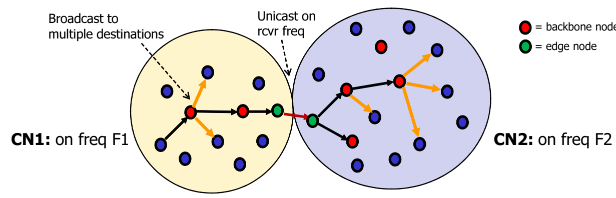


Fig. 2. Multicast Tree Routing between CNs in MDL

RBS slots for a particular *DOCk* are assigned with a 3-hop constraint if possible. The 3-hop reuse rule is included so that a node can borrow its neighbor's assigned slots that the neighbor is currently not using without violating 2-hop reuse. If no slots are available based on the 3-hop constraint rules, then the 2-hop reuse is used. We do not model borrowing of neighbor's slots and hence use the 2-hop reuse constraints. The 2-hop reuse constraint specifies those slots that cannot be used by node $i$ to broadcast (on the RBSs) to its neighbors on frequency $k$ (*DOCk*) and is the following: Node $i$ cannot reserve slots that already have scheduled incoming and outgoing transmissions to and from itself and *all* its neighbors. The FRS unicast Inter-DOCk reservation is based on the following three rules for 2 hop reuse that specify those slots that cannot be used by node $i$ to transmit to node $j$ on node $j$'s DOCk channel: **1**) $i$ cannot reserve those time slots which already have scheduled incoming or outgoing transmissions to and from $i$ and $j$; **2**) $i$ cannot reserve slots containing incoming call transmissions (on $j$'s DOCk) to the neighbors of $i$; **3**) $i$ cannot reserve those slots containing outgoing call transmissions from the neighbors of $j$ (on $j$'s DOCk). These broadcast and unicast reservation rules specify the capacity (i.e., slots) available at a node to broadcast (within a DOCk) or unicast (inter-DOCk) and form the basis of our capacity estimation model.

## III. MDL and USAP Hard Scheduling Models

Let there be $M$ time slots and $F$ frequency channels in the RBS/FRS portion of an MDL frame (figure 1). We consider MANET scenarios where the nodes are divided into a set of groups (e.g., platoons). All the nodes in a group move together (i.e, form a connected sub-network) and exchange a lot of traffic amongst each other. The MANET scenario is specified as a sequence of time snapshots. At each time snapshot, node locations, src-dest traffic flows, and environmental conditions (path loss between nodes) are specified.

### *A. Assign Frequencies to Groups (across all time snapshots)*

Since all the nodes in a group move together and exchange lot of traffic amongst each other, all nodes in a specific group are assigned the same frequency id (an integer from $0$ to $F-1$). Based on the initial location of the groups (using a group reference point location) and the total number of frequency channels $F$, the groups are assigned frequencies from the pool of available frequencies so that as far as possible neighboring groups have different frequency channels. If $F = 1$, all groups are assigned frequency id of $0$. If total number of groups $G \leq F$, then each group is assigned a different frequency id. But if $G > F$, then assign that group, which has lowest average distance to its closest $F - 1$ neighboring groups (using group reference points), the frequency id of 0 and assign its closest $F - 1$ neighboring groups frequency ids $1$ to $F - 1$. And as long as some group is not assigned a frequency id, choose that unassigned group that has lowest average distance to its closest $F-1$ groups that have been assigned different frequencies and assign it the frequency id not assigned to these $F - 1$ groups.

### B. Discover CNs (at each time snapshot)

A Channelized Neighborhood (CN) is a collection of nodes that share the same frequency and are connected. If the number of groups in the scenario is greater than the number of frequency channels $F$, then as the scenario evolves neighboring groups change and hence two groups with the same frequency channel can become disconnected (i.e., there is no path from one group to the other that passes through other groups with the same frequency channel) or connected. Hence it is necessary to find the CNs at each time instance of the scenario. At each time snapshot, groups assigned the same frequency channel and which are connected to each other (either directly or through other groups assigned the same frequency channel) form a single CN.

### C. Find Artery Nodes within Channelized Neighborhood

Traffic within a Channelized Neighborhood (CN) is routed through a set of Artery Nodes (ANs). These artery nodes are chosen to form a Connected Dominating Set (CDS) so that any CN node not in this set is a neighbor of a node in the CDS. We use Algorithm I of Guha and Khuller [10] to form a CDS that approximates a Minimal Connected Dominating Set (MCDS). An MCDS is a CDS that has a minimum number of nodes. Algorithm I of Guha and Khuller yields a CDS of size at most $2\,(1 + H(\Delta))\,|OPT|$, where $H$ is the harmonic function, and $OPT$ refers to an optimal solution, i.e., a MCDS.

### D. Find Edge Nodes of Channelized Neighborhoods

If the artery nodes of neighboring connected CNs are not connected to each other, edge nodes need to be added to the CNs (as necessary) in order to route flows across the CNs. We use a simple heuristic to add the required edge nodes. Consider two neighboring channelized neighborhoods CN1 and CN2 that are connected. If any artery node of CN1 is connected to any artery node of CN2, we do not add edge nodes. If the artery nodes of the two CNs are not directly connected but some artery node of CN1 (or CN2) is connected to some non-artery node of CN2 (or CN1), we add this non-artery node of CN2 (or CN1) as an edge node. Finally if none of the artery nodes of CN1 or CN2 are directly connected to any node of CN2 or CN1 respectively, we add the closest connected nodes of CN1 and CN2 as edge nodes.

### E. Construct Multicast Routing Tree and Unicast Routing Path

Once artery nodes in each CN are chosen and edges nodes chosen (if necessary) to connect neighboring CNs, traffic from a source is routed through these nodes, either to a set of receivers (defining a multicast group) in the case of multicast traffic or to a single destination in the case of unicast traffic. For multicast traffic, we construct a Steiner tree from the source to the multicast group receivers using as Steiner points (i.e., intermediate nodes) the set of artery nodes and edges nodes selected. In the Steiner tree problem, given a graph $G(V, E)$, and a set $R \subseteq V$ of required nodes, we want to find a minimum cost tree connecting all nodes in $R$. The set of nodes $R$ includes the source and the multicast group receivers while the set V includes $R$, the artery nodes and the edge nodes. We use the heuristic proposed in [11] (called the KMB heuristic) to construct the Steiner tree. The KMB heuristic has a performance guarantee of at most twice the size of the optimum Steiner tree. For unicast traffic, we use the shortest path between the source and the destination to route traffic using as intermediate nodes the chosen artery and edge nodes.

### F. Modeling USAP Hard Scheduling Mode for Multicast and Unicast Traffic

We divide the modeling of USAP Hard Scheduling mode used in MDL into two parts. First we use the USAP reservation rules and average traffic amongst neighboring nodes on various channels to estimate the distribution of the available capacity at each node on specific channels to broadcast to other nodes within a *DOCk* or unicast to a destination across DOCks (on the receiver's frequency channel). We then use the available capacity distribution per channel at each node to find the blocking probability for multicast or unicast traffic flows using a modified form of the reduced load approximation for multiservice loss networks (section 5.6 of [12]). These two sets of equations are then iterated over to find a fixed point solution for the blocking probabilities of each traffic flow.

For a source transmitting to a multicast group, the traffic is routed over a multicast tree while for a source unicasting to a single destination, the traffic is routed over a single path. We can consider this single path for unicast traffic also as a tree with the root being the source and with only a single leaf comprising the single destination. Hence let there be $G$ destination groups $M_1, \ldots, M_G$ (consisting of either a set of receiving nodes or a single destination). We assume that calls originate at source $s$ for group $M_g$ (routed via tree $T(s, M_g)$) as a Poisson process with rate $\nu_{T(s,M_g)}$, with each call holding time having finite mean $1/\mu_{T(s,M_g)}$, and with the call demand being $n_{T(s,M_g)}$ cells per frame.

*1) Reduced Load Loss Network Model:* We briefly go through the key equations in the reduced load loss network approximation for computing the blocking probability of an incoming virtual circuit connection (unicast or multicast).

The children of node $i$ in tree $T(s, M_g)$ can be on different CNs and hence node $i$ needs to transmit on all the frequencies corresponding to the CNs that its children belong to. We calculate the blocking probability $B_{i(f),T(s,M_g)}$ for a node $i$ broadcasting on channel $f$ to its $DOCf$ neighbors along tree $T(s, M_g)$ and the average number of slots $\eta_{i(f)}$ reserved by node $i$ to broadcast on channel $f$ to its neighbors using a modified form of the reduced load approximation for multiservice loss networks. When calculating $B_{i(f),T(s,M_g)}$ and $\eta_{i(f)}$, we average over the available capacity distribution on that channel $f$.

Calls belonging to tree $T(s, M_g)$ arrive at node $i$ for transmission on channel $f$ with offered load reduced due to blocking at other nodes in the tree and also on other channels at node $i$ and is given by

$$\rho_{i(f),T(s,M_g)} = \frac{\nu_{T(s,M_g)}}{\mu_{T(s,M_g)}} \prod_{\substack{j(p)\neq i(f),\\ j\in T(s,M_g),\\ p\in[0,F-1]}} (1 - B_{j(p),T(s,M_g)}) \quad (1)$$

where, $B_{j(p),T(s,M_g)}$ is the probability of blocking a call at node $j$ of tree $T(s, M_g)$ on channel $p$. The overall blocking probability, for a call traversing tree $T(s, M_g)$, is given by

$$L_{T(s,M_g)} = 1 - \prod_{i\in T(s,M_g), f\in[0,F-1]} (1 - B_{i(f),T(s,M_g)}) \quad (2)$$

Denote by $Q_{T(s,M_g)}\left[f, C_{i_f}; \rho_{i(f),t'}, t' \in T_i\right]$ the blocking probability for calls on tree $T(s, M_g)$ at node $i$ on channel $f$ with available capacity $C_{i_f}$ which has a set of trees $T_i$ going through it. We have,

$$Q_{T(s,M_g)}\left[f, C_{i_f}; \rho_{i(f),t'}, t' \in T_i\right] = 1 - \sum_{c=0}^{C_{i_f} - n_{T(s,M_g)}} q_{C_{i_f}}(c) \quad (3)$$

where the $q_{C_{i_f}}(c)'s$, are the probabilities of having $c$ slots occupied at node $i$ with available capacity $C_{i_f}$ on channel $f$ (i.e., knapsack occupancy probabilities). These knapsack occupancy probabilities can be calculated easily by a recursive algorithm as per [12] (chapter 2).

If we assume that the available capacity at node $i$ on channel $f$ is between $C_{i_f}^{\min}$ and $C_{i_f}^{\max}$ with some given probability distribution, we have

$$B_{i(f),T(s,M_g)} = \sum_{m=C_{i_f}^{\min}}^{C_{i_f}^{\max}} \big(Pr[C_{i_f} = m] \\ Q_{T(s,M_g)}\left[f, m; \rho_{i(f),t'}, t' \in T_i\right]\big) \quad (4)$$

From the occupancy probabilities, we also compute $\eta_{i(f)}$, the average number of slots reserved by $i$ for transmission on $f$

$$\eta_{i(f)} = \sum_{m=C_{i_f}^{\min}}^{C_{i_f}^{\max}} Pr[C_{i_f} = m] \sum_{c=0}^{m} c q_m(c) \quad (5)$$

*2) Available Capacity Estimation:* We calculate a low ($C_{i_k}^{\min}$) and high ($C_{i_k}^{\max}$) estimate of the number of slots available to a node $i$ for either broadcasting to its neighboring nodes $j$ within a DOCk or for unicasting to a node on a neighboring DOCk. We calculate these estimates based on the USAP reservation rules (section II), the average number of slots reserved by neighboring nodes $j$ of node $i$ for transmission ($\eta_{j(k)}$), and the average number of slots reserved by neighbors $l$ of the neighbors $j$ of node $i$ for transmission ($\eta_{l(k)}$). We then assume a uniform distribution for the available capacity between these low and high estimates and use this distribution in the reduced loss model.

*Intra-DOCk Transmission:*

For intra-DOCk communication on frequency channel $k$, a node broadcasts its traffic on frequency $k$ in the RBS portion of the frame. All neighboring nodes must listen to this communication and hence are prevented from doing anything else on this timeslot. A node cannot transmit on those time slots that it is already using to transmit on other frequencies $f$. Denote this by $R^0$ and it is given by

$$R^0 = \sum_{f\in[0,F-1]/k} \eta_{i(f)} \quad (6)$$

As per the 2-hop RBS constraint (section II), node $i$ cannot transmit on those time slots reserved by its neighbors $j$ for transmission and is required to listen to all these transmissions. Let $R_{\min}^1$ and $R_{\max}^1$ represent the low and high estimate for the number of these time slots. Since a neighbor $j$ of $i$ on the same DOCk is required to listen to node $i$'s transmission, node $i$ cannot transmit on all those time slots that $j$ transmits in including ones in which it transmits on other frequencies. The high estimate $R_{\max}^1$ for node $i$ transmitting on frequency $k$ is therefore the sum of the average time slots used by all its neighbors to transmit on channel $k$ and the sum of the time slots used by those neighbors $j$ that are part of the same DOCk to transmit on other frequencies. Hence

$$R_{\max}^1 = \sum_{j\in N(i)} \eta_{j(k)} + \sum_{\substack{j\in N(i), j\in DOCk\\ f\in[0,F-1]/k}} \eta_{j(f)} \quad (7)$$

Node $i$ has to listen to transmissions from all its neighbors on frequency $k$ (which therefore cannot overlap). Also for each DOCk neighbor $l$ of $i$ that transmits on other frequencies, node $i$ cannot transmit on those time slots used by $l$ to transmit on all frequencies and those time slots used by common neighbors of $l$ and $i$ to transmit on frequency $k$ (which cannot overlap). Hence $R_{\min}^1$ is given by

$$R_{\min}^1 = \max\{\sum_{j\in N(i)} \eta_{j(k)}, \max_{\substack{l\in N(i),\\ l\in DOCk}} (\sum_f \eta_{l(f)} + \sum_{\substack{j\in N(i),\\ j\in N(l)}} \eta_{j(k)})\} \quad (8)$$

Node $i$ is also prevented from transmitting on those time slots that correspond to its neighbors $j$ in DOCk receiving transmissions from its neighbors $l$. We denote by $R_{\min}^2$ and $R_{\max}^2$ the low and high estimate for the number of time slots used by neighbors $j$ of $i$ on DOCk to receive transmissions from its neighbors (that are also strictly not neighbors of node $i$). $R^2_{\max}$ is just the sum of these transmissions. Therefore,

$$R^2_{\max} = \sum_{(j \in N(i), j \in DOCk)} \; \sum_{(l_j \in N(j), l_j \notin N(i))} \eta_{l_j(k)} \quad (9)$$

where we make sure that these neighbors of neighbors are included only once. $R^2_{\min}$ is the low estimate of the number of slots used by neighbors $j$ of $i$ on DOCk to receive transmissions from its neighbors (that are also strictly not neighbors of node $i$) and corresponds to finding the maximum of the sum of average cells transmitted by these neighbors of neighbors of $i$ that cannot transmit simultaneously. Hence we create a conflict graph whose vertices are these neighbors of neighbors of $i$ (set containing nodes $l$ where $l \in N(j)$ and $l \notin N(i)$ with $j \in N(i)$ and $j \in DOCk$) and with edges between those nodes that cannot transmit simultaneously. An edge is drawn between two nodes $m$ and $n$ if either $m \in N(n)$, $n \in N(m)$, and $n$,$m \in DOCk$ or both $n$ and $m$ are neighbors of some common neighbor $j$ of $i$ that is part of DOCk. From this conflict graph, we find all the maximal cliques using Bierstone's method [13]. We choose $R^2_{\min}$ to be the maximum of the sum of the average transmitted cells of each clique.

$C^{\min}_{i_k}$ and $C^{\max}_{i_k}$ are then given by

$$C^{\min}_{i_k} = \max\{0, M - (R^0 + R^1_{\max} + R^2_{\max})\} \quad (10)$$
$$C^{\max}_{i_k} = \max\{0, M - (R^0 + R^1_{\min} + R^2_{\min})\} \quad (11)$$

*Inter-DOCk Transmission:*
We do not model the priority of FRS over RBS and assume that when a node in a CN with frequency $f_1$ unicasts to a node in a neighboring CN with frequency $f_2$, the transmission uses the same time slots as the RBS with same priority. So as to have no traffic loss, we also assume that all the source's neighboring nodes on the receiver's DOCk need to listen to this transmission. We use similar methods as in the Intra-DOCk modeling to model this inter-DOCk unicast traffic.

## IV. Results

### A. Scenario with 60 nodes divided into 5 groups

The scenario considered is a time varying fast moving network of 60 vehicles divided into 5 groups (platoons) of 12 vehicles each. Figure 3 shows the movement of the five groups over the entire scenario of 575 seconds. Initially all the 5 groups are connected. Groups 3 (nodes 25 to 36), 4 (nodes 37 to 48), and 5 (nodes 49 to 60) start moving immediately with groups 1 (nodes 1 to 12) and 2 (nodes 13 to 24) following groups 4 and 5 respectively after some initial amount of time (120s). The groups have to go around two hills in their paths and hence groups 3, 4, and 5 lose connectivity with each other. Three Aerial Platforms (APs) then need to be brought in so that communication between the platoons is maintained at all times. We use a Deterministic Annealing algorithm [14] to determine the AP locations for full network connectivity.

The scenario is specified every 5 seconds. At every 5 second interval the following are input to the USAP Hard Scheduling model: ground node positions, traffic demands (offered load), traffic routes, environment conditions. All ground nodes and APs have identical omni-directional radios with receiver sensitivity of -95dBm, receiver threshold of 10dB, and transmit power of 5W. The environment is modeled as a fading channel with $1/R^{\alpha}$ power attenuation. $\alpha$ is taken to be 4.5 between ground nodes, 3.9 between ground and aerial nodes, and 3.0 between the aerial nodes. The radio specification and path loss $\alpha$ result in a maximum connectivity distance of 857m between ground nodes, 2423m between ground-aerial nodes, and 25099m between aerial nodes.

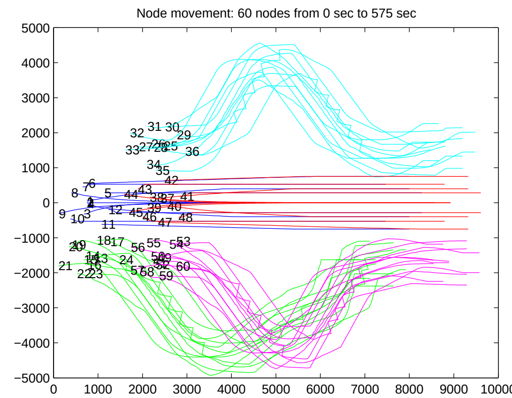


Fig. 3. Movement of 5 groups (with 12 nodes each) for 575 seconds

There are 6 multicast groups considered: 5 of them are intra-group and each includes all the nodes of a group. The sixth multicast group spans all the 5 scenario groups and includes 2 nodes in each group. All IERs, i.e., traffic flows in the scenario are assumed to be voice (using 1 cell per frame) with a holding time of 2 minutes. The traffic is chosen so that 70 percent of total offered traffic are from multicast flows while the rest are from unicast flows. There are 15 multicast IERs: 10 of them intra-group (with arrival rate of 1.5 calls/minute) and 5 inter-group (with arrival rate of 0.5 calls/minute). There are 5 unicast intra-group IERs with arrival rate of 1.5 calls/minute.

The USAP frame period is set to 125ms and the combined capacity of all the frequency channels is set to 1 Mbps. Only half of the USAP frame period is used for the RBS/FRS slots. The RBS/FRS portion of the frame has a total of 50 cells.

### B. Results of USAP MDL Hard Scheduling Model

Figure 4 shows the total network throughput using the models developed for the scenario described previously as the total number of cells is held constant at 50 but the number of time slots $M$ (and correspondingly $F$) is changed. We observe that since the traffic is mostly intra-group, the network throughput increases as the number of time slots $M$ increases.

To find out the effect of offered load on throughput, we ran the scenario at time snapshot 0 but with all offered loads scaled by a common scale factor $\delta$. Figure 5 shows the effect of offered load on total throughput (total carried load) using the developed models for various ($F$, $M$). We see that the total carried load in all cases saturates to some constant as offered load is increased and the carried load increases with $M$.

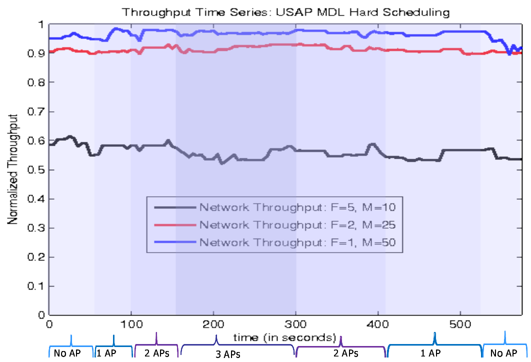


Fig. 4. Total Network Throughput for various combinations of $F$ and $M$

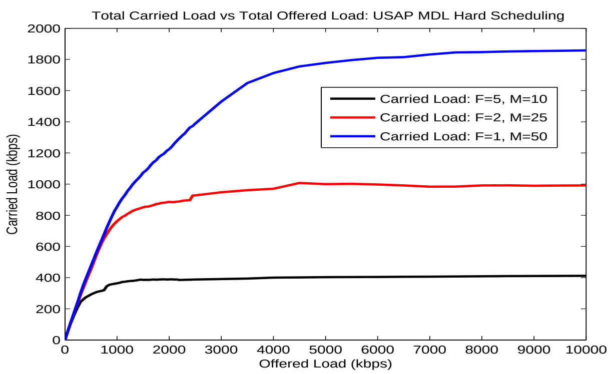


Fig. 5. Total Carried Load vs Total Offered Load for various ($F$, $M$)

Figure 6 compares individual connection throughput of the model against simulation (developed in C++) for $F = 1$, $M = 50$. We see that while most of the connections' throughputs match, the model underestimates the throughput for long connections (numbers 3, 7, 11, 15, 19). Figure 7 shows the results of the comparison for $F = 2$, $M = 25$. We note a better match between simulation and the models. If we replace the model's capacity estimation module with the capacity distribution obtained from simulation, the resultant reduced load model matches simulation. Due to space constraints the relevant graphs are not shown. This shows that we need to improve our capacity estimation method.

## V. Conclusion

We have developed models based on reduced load loss networks and reduced link capacity approximation for estimating blocking probability and throughput for both unicast and multicast traffic using the hard scheduling mode of reservation based USAP in the MDL of JTRS. We compare results of the model against simulation and find that more work needs to be done on improving the available capacity approximation.

## Acknowledgment

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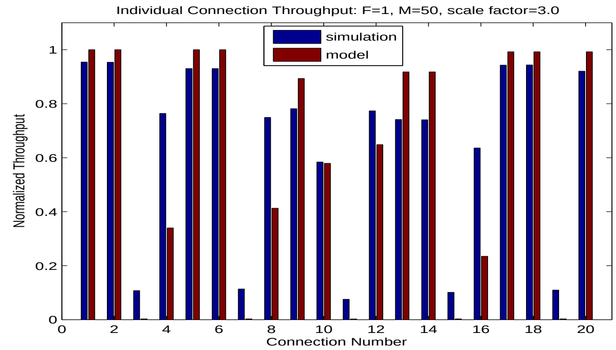


Fig. 6. Simulation vs. Model: $F = 1$, $M = 50$ (scale factor = 3.0)

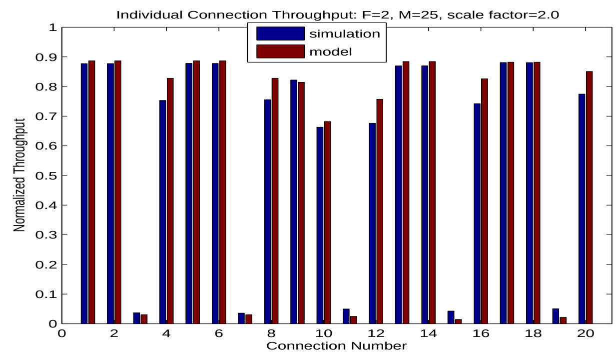


Fig. 7. Simulation vs. Model: $F = 2$, $M = 25$ (scale factor = 2.0)

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