# TWO NEW MEDIA ACCESS CONTROL SCHEMES FOR NETWORKED SATELLITE COMMUNICATIONS

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## ABSTRACT

*This paper introduces a pair of new media access control (MAC) protocols for a broadcast satellite network. Specifically, it has been designed to efficiently utilize the available bandwidth over a single channel satellite environment. The protocol enables more efficient use of the bandwidth during low loading periods, and a more equitable distribution of the bandwidth during high loading periods. Determination of access and management of the bandwidth is decentralized; therefore, each terminal can independently determine and schedule bandwidth, which eliminates a single point of failure inherent to a centrally controlled network. In addition, the decentralized approach reduces setup delay for reserving bandwidth, and thus helps to minimize the required satellite resources. This paper describes the operating environment, the MAC protocols, conduct of the modeling and simulation that emulates the network, and results of the simulation analysis. A comparison is also made to a simulation model of a Time Division Multiple Access (TDMA) network and the theoretical ALOHA and Slotted ALOHA throughputs. Observations are made on the simulation results of the protocol performance along with recommendations.*

## INTRODUCTION

The United States Army is in the process of improving its information architecture by digitizing the battlefield. This encompasses examining ways in which it will connect maneuver units' tactical operation centers (TOC) within the division, so they can exchange command, control, and intelligence information such as friendly and enemy positions, operation orders, collaborative planning, logistics, etc. Because the units are very mobile and can easily extend beyond line of sight (BLOS), terrestrial communication resources experience difficulties in maintaining contact. Therefore, satellite resources are being planned to bridge this shortfall.

If these limited, beyond line of sight resources are to be used efficiently, the communication layer (transport network, data link and physical) protocols need to be examined for their performance to deliver unicast, multicast and broadcast addressed messages.

This paper focuses on the data link layer and extends a previous investigation on candidate channel access protocols for broadcast satellite networks. More specifically, this paper concentrates on the channel access portion of the data link layer because this is the area that has the greatest impact on channel bandwidth efficiency.

When the protocols described within were being designed and built, the focus was on identifying the technical parameters that had the largest impact on bandwidth utilization. The three dominant parameters identified during the design are elimination of a single point of failure (distributed operation), handling of propagation delays (delay and delay jitter), and maximizing usage of available bandwidth during both high and low loading (resource adaptation, reliability, overhead and implementation complexity).

## OPERATING ENVIRONMENT

The satellite terminals analyzed within this paper are intended to be deployed by the Army at the Brigade and Battalion TOCs. Their primary mission will be to provide continuous and extended range communication links between these command and control elements. Associated with each satellite terminal will be a subnetwork of radios and host platforms (i.e. Force XXI Battle Command Brigade and Below (FBCB2), Advanced Battlefield Command System (ABCS)) that will use the satellite services. These hosts and radios comprise the Tactical Internet connected to the satellite terminals through terrestrial radio networks such as Enhanced Position Location Radio System (EPLRS) and Single Channel Ground Airborne Radio System (SINCGARS). Figure 1 shows an example geographical layout of the satellite network.

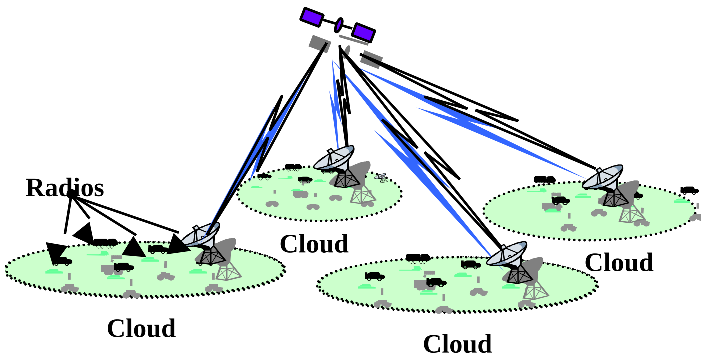


Figure 1. Satellite Network

The satellite network is assumed to be fully connected with low mobility relative to the underlying terrestrial network. The satellite terminals serve as gateways between communicating terrestrial radios from one TOC to another. There will be an uplink channel and a separate downlink channel to the satellite that performs essentially a "bent-pipe" or processing type of service for the analysis presented within this paper. The uplink channel will have a maximum capacity of 128 kbps information throughput at the data link level that is shared among the terminals. The satellite will be in geosynchronous orbit and have total propagation and processing delays from terminal to terminal of 500 milliseconds. The system will provide a $1 \times 10^{-5}$ bit error rate (BER) link quality.

The traffic traversing the satellite network is assumed to consist of Situational Awareness (SA), Command and Control (C2) messages, and voice. The packets at the network layer will be Internet Protocol (IP) and addressed to both unicast and multicast destinations. The packet lengths assumed were SA packets of 100 bytes in length, C2 packets of 1500 bytes in length and voice packets around 720 bits in length. A review of the limited user test (LUT)[1] C2 data from the Near Term Data Radio (NTDR) testing provided a distribution of loading from the participating 5 TOCs to be as shown in Table 1. This distribution, as well as a uniform traffic loading was simulated.

| Unit Type | Percent of Loading |
|---|---|
| BDE TAC | 39% |
| BDE TOC | 13% |
| BN TOC 1 | 18% |
| BN TOC 2 | 18% |
| BN TOC 3 | 12% |

Table 1. Unit Traffic Load Distribution

## PROTOCOL OVERVIEW

The next few sections introduce both of the MAC layer protocols developed and analyzed. The two protocols are the Windows Overlapping Reservation Protocols (WORP) and the Dynamic Assignment Time Division Multiple Access (DA-TDMA) protocol. The fundamental premise behind each protocol is that each terminal within the network will periodically transmit its bandwidth requirements in a control frame to all other terminals. Each terminal will then periodically process these requests, and run a common algorithm to assign bandwidth for the next finite duration of time.

## FRAME STRUCTURE

For the purposes of the analysis presented within, time has been divided into several groupings; time slots, frames, and epochs; where a time slot is the lowest increment for allocation. A frame is assumed to consist of M number of slots, and an epoch is the number of frames that a given terminal bandwidth allocation will remain in effect. The epoch length is required to be at least as long as the one way link delay to ensure synchronization between terminals bandwidth/time slot allocation. Figure 2 depicts the frame structure.

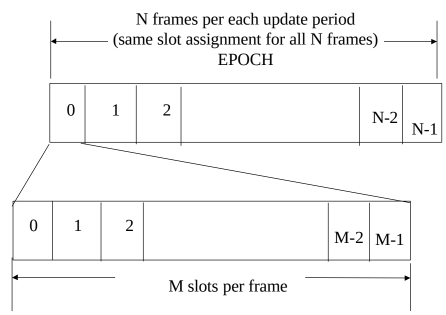


Figure 2. MAC Frame Structure

## WORP PROTOCOL

WORP can be categorized as a reservation based type of channel access protocol, though it also has some characteristics of a round robin and contention resolution protocol. In order to describe the protocol, this section will first present the frame and control structure assumed, followed by examples of the protocol's operation.

The protocol has the cyclic, round robin characteristics similar to TDMA. Each terminal must periodically transmit its bandwidth requirements to every other terminal. The control packet contains the following information:

- Terminal's unique identification (i.e. Terminal ID)
- First frame number that it is being considered for transmitting data
- Number of frames considered within its window of opportunity or reservation window
- Number of time slots that it knows are used within each frame of its reservation window

The control packet is 28- 60 bytes in length and is shown in the following figure.

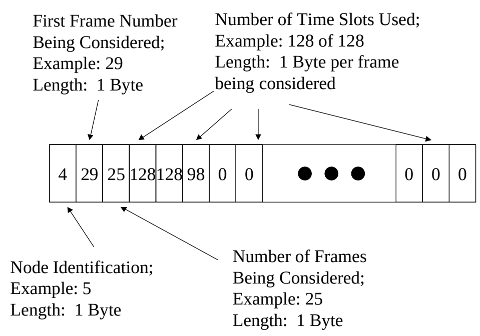


Figure 3. Control Packet Structure

Each terminal, at a minimum, will transmit a control packet twice an epoch. Terminals will also have a fixed sequential order in which these packets are transmitted. Before a terminal transmits its control packet, it updates a table that it uses to track the number of used time slots within each frame of an epoch. After it receives its preceding terminal's control packet, the terminal will determine the total number of packets within its queue and calculate the required number of time slots within its reservation window to transmit the queued data. The reservation window is the maximum number of frames it considers for transmitting data. The window size is normally the same for all terminals, such as 25 frames in a 50-frame epoch. The first frame it considers available for transmission can be designated based upon many factors, but it must be at a minimum the propagation delay to allow other terminal's to receive its control packet. For this analysis, the window was set equal to the one-way propagation delay plus processing time.

Each terminal's window is also shifting a period of time that is equal to the size of the control information. In this system, a control message requires one frame. The protocol also guarantees that each terminal obtains at least one frame per epoch because the windows of two sequential terminals are separated by at least one frame.

Currently, the channel access protocol only attempts to reserve bandwidth based upon bits to transmit and does not consider packet prioritization. The data link or higher layers determine if the highest priority packet is transmitted first.

## PROCESSING EXAMPLES

The following example helps to illustrate how the protocol performs during a low loading scenario. A similar analysis can be performed for high loading where the protocol performance approaches TDMA. For the example shown, a five terminal broadcast network is assumed as shown in the following figure. The terminals are full duplex allowing for simultaneous transmit and receive.

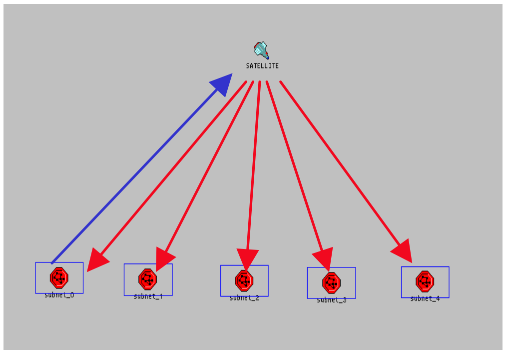

Figure 4. Satellite Network Example

The framing sequence figure that follows shows the processing for WORP at low loading. Each terminal will transmit a control packet every fifth frame. The following is the sequence of events that explain what is occurring as terminal R1 and R3 have traffic to send while terminals R2, R4 and R5 do not have any packets.

- At $t_{eo}(0)$ terminal R1 sends a control message that requests 4 frames and will start at $t_{eo}(N/2)$.
- At $t_{eo}(1)$ terminal R2 sends a control message that does not request any frames or show used frames that it previously recorded from other terminals.
- At $t_{eo}(2)$ terminal R3 sends a control message that requests 5 frames and will start at $t_{eo}(N/2+2)$.
- At $t_{eo}(3)$ terminal R4 sends a control message that does not request any frames. The terminal also does not show any used frames since it has not received terminal R1-R3's control information yet.
- At $t_{eo}(4)$ terminal R5 sends a control message that does not request any frames.

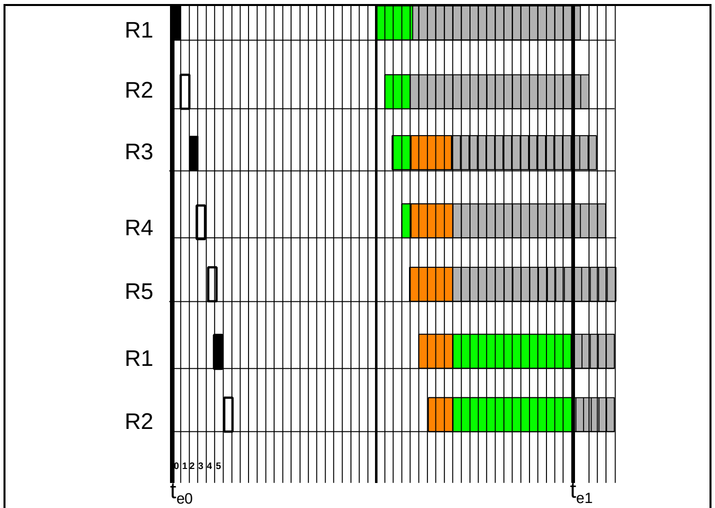

Figure 5. Low Loading Framing Sequence

- At $t_{eo}(5)$ terminal R1 sends a control message that requests 14 frames and starts at $t_{eo}(N/2+5)$.
- At $t_{e0}(N/2)$ all terminals receive R1's control message and assign the first 4 frames beginning at $t_{e0}(N/2)$ for R1. Terminal R3 adjusts its transmission to begin at $t_{e0}(N/2+4)$. Terminal R1 starts transmitting data at this time.
- At $t_{e0}(N/2+2)$ all terminals add R3's reserved frames as terminal R3 previously had done at $t_{e0}(N/2)$ and R1 adjusts its next transmit frame for $t_{e0}(N/2+9)$.
- At $t_{e0}(N/2+4)$ terminal R1 completes its first transmission and R3 starts transmitting data at this time.
- At $t_{e0}(N/2+5)$ all terminals add R1's additional requested frames as R1 previously had done as explained at $t_{e0}(5)$.
- At $t_{e0}(N/2+9)$ terminal R3 completes transmission and terminal R1 starts its next transmission.
- At $t_{e1}(1)$ terminal R1 completes its second transmission.

## DA-TDMA PROTOCOL

The DA-TDMA protocol is also a decentralized protocol (i.e. no master controller) that requires a common algorithm to be run at each terminal to allocate/deallocate bandwidth dynamically based upon user bandwidth requirements. The protocol takes advantages of the TDMA approach applicable for an equal loading network and extends it to a dynamic protocol applicable to a non-uniform, bursty traffic load.

The DA-TDMA protocol maintains a decentralized control of channel resources that are assigned to users based upon relative demand. The resource management function, called the Network Resource Manager (NRM) is run on each terminal participating in the network, and is responsible for monitoring a terminal's queue sizes & QOS requirements, and allocating bandwidth accordingly. Each terminal maintains both a global slot table that lists the time slots assigned to each terminal for the current epoch, and a global queue table that lists the queue sizes within each terminal's buffers. Other terminal's queue sizes in the global queue table are obtained by listening to each terminal's queue size advertisement within a control packet. The entry for a terminal's own queue size must be delayed to account for the satellite delay and ensure all terminals are synchronized. Each terminal consults the global slot table at each update interval (i.e. epoch) for its slot assignment for the current epoch. Details of the global queue table and global slot table are described in the following section.

## NETWORK RESOURCE MANAGER

As described in the preceding section, the NRM is responsible for assigning time slots within a frame based on the global slot table and global queue table. This algorithm employs a weighted average of five queues maintained within each terminal to allocate bandwidth. Each of the five queues manages messages of a pre-assigned precedence level: Priority_1, Voice/Urgent, High, Medium and Low. The four precedence levels (Voice/Urgent, High, Medium, and Low) are obtained via the IP precedence field within the IP header. Queues will be cleared from the top priority down. An additional requirement was added such that a packet can not be held in a queue for more than "x" number of frames (default set to 30 seconds), so that high priority traffic can not completely prevent any lower priority traffic from being transmitted. Any packets held in a queue for more than "x" number of frames would be put into the Priority_1 queue. A queue weighting scheme is used that provides the Priority_1 queue with a weight of 7, the Voice queue 5, the High queue 3, the Medium queue 2, and the Low queue 1, and is intended to give priority to a terminal with higher precedence traffic. The overall reported queue size to other terminals in the control packet is the weighted average of the five queues. For example, using the queue sizes shown in Table 2, terminal 1 through 3 would report the following queue sizes:

- Terminal 1: (10*7)+(42*5)+(100*3)+(40*2)+(100*1) = 760 bytes
- Terminal 2: (20*7)+(24*5)+(20*3)+(20*1) = 380 bytes
- Terminal 3: (5*7)+(19*5)+(10*3)+(10*2)+(10*1) = 190 bytes

| Terminal | Priority_1 Queue (bytes) | Voice Queue (bytes) | High Queue (bytes) | Medium Queue (bytes) | Low Queue (bytes) |
|---|---|---|---|---|---|
| 1 | 10 | 42 | 100 | 40 | 100 |
| 2 | 20 | 24 | 20 | 20 | 20 |
| 3 | 5 | 19 | 10 | 10 | 10 |
| 4 | 0 | 0 | 0 | 0 | 0 |
| … | 0 | 0 | 0 | 0 | 0 |
| N | 0 | 0 | 0 | 0 | 0 |

Table 2. Global Queue Statistic Table

The hop assigned algorithm would then assign bandwidth to each terminal based on queue sizes relative to the other terminals.

- Terminal 1 would receive 760/1330 of each frame
- Terminal 2 would receive 380/1330 of each frame
- Terminal 3 would receive 190/1330 of each frame

## DA-TDMA PROTOCOL ILLUSTRATION

This section presents an example of the DA-TDMA protocol operation for the 5 terminal network depicted in Figure 4. Assume for this example there are 50 slots per frame, and N frames per epoch. Note that it is assumed that all 5 terminals join the network at the same time, and no mechanism for join and leaving is presented within. For the purposes of assessing the steady state performance of the protocol this assumption is satisfactory.

*At time t = 0.0 (start of 1st epoch)*

Since no information is contained within the global queue statistic table at t = 0.0, initially no time slots are assigned to each of the terminals for the first epoch. A slight improvement in performance could be obtained by distributing the time slots equally amongst the five terminals for the first epoch.

| Global Queue Statistic Table at t=0.0 | | | | | |
|---|---|---|---|---|---|
| Terminal | Priority_1 Queue (bytes) | Urgent Queue (bytes) | High Queue (bytes) | Medium Queue (bytes) | Low Queue (bytes) |
| 1 | 0 | 0 | 0 | 0 | 0 |
| 2 | 0 | 0 | 0 | 0 | 0 |
| 3 | 0 | 0 | 0 | 0 | 0 |
| 4 | 0 | 0 | 0 | 0 | 0 |
| 5 | 0 | 0 | 0 | 0 | 0 |

| Global Slot Table at t=0.0 | |
|---|---|
| Terminal | Slots Assigned |
| 1 | none |
| 2 | none |
| 3 | none |
| 4 | none |
| 5 | none |

Table 3. NRM Tables at t=0.0

*At t = N (start of 2nd epoch)*

The global queue statistic table is populated with latest terminal queue information. The global slot table is updated based on the global queue statistic table. Time slots for frames N to 2N-1 are assigned as shown in Table 4.

| Global Queue Statistic Table at t=N | | | | | |
|---|---|---|---|---|---|
| Terminal | Priority_1 Queue (bytes) | Urgent Queue (bytes) | High Queue (bytes) | Medium Queue (bytes) | Low Queue (bytes) |
| 1 | 0 | 30 | 100 | 40 | 0 |
| 2 | 0 | 20 | 50 | 20 | 0 |
| 3 | 0 | 10 | 25 | 10 | 0 |
| 4 | 0 | 0 | 0 | 0 | 0 |
| 5 | 0 | 0 | 0 | 0 | 0 |

| Global Slot Table at t=N | |
|---|---|
| Terminal | Slots Assigned |
| 1 | 0-27 |
| 2 | 28-41 |
| 3 | 42-49 |
| 4 | none |

Table 4. NRM Tables at t=N

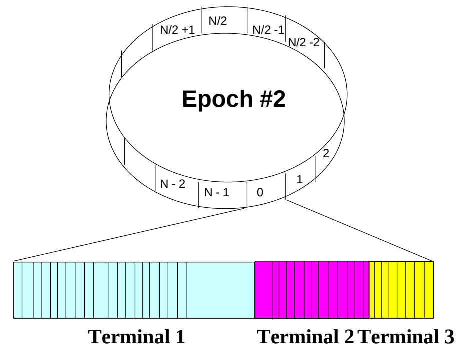


Figure 6. Time Slot Allocation at t=N

## SIMULATION AND RESULTS DISCUSSION

The Optimized Network Engineering Tools (OPNET) simulation package was used to assess the performance of the WORP and DA-TDMA protocol. The primary metrics captured at the data link layer were throughput, packet completion, end-to-end delay, and voice jitter versus loading.

A number of simulations were run to assess the performance of the MAC protocols. The five terminal network model depicted previously in Figure 4 was utilized. For each event simulated, the message loading characteristics were varied as a function of the available bandwidth. Additionally, the input message priority was equally distributed between urgent, high, medium and low traffic types. Unless otherwise noted, the performance shown represents the average performance.

The first set of simulation results compares the WORP and DA-TDMA's performance for packet sizes of 100 bytes.

The results show that WORP, DA-TDMA, and TDMA all performed significantly better than the theoretical ALOHA and Slotted ALOHA.[2] The throughput and packet completion rate results also were very comparable. However, there was a difference in the end-to-end delay results that showed WORP and DA-TDMA performed better. The difference can be attributed to how each protocol delivers its packets. The TDMA protocol must wait for its limited time slot. As the higher layers generate packets and are received by the data link layer, the latest packets must wait to be processed by the TDMA layer during its allocated time slot. The WORP and DA-TDMA protocols reserve as much of the available bandwidth that it can, and therefore, the arriving packets from the higher layers do not wait in the queues as long as in a TDMA scheme.

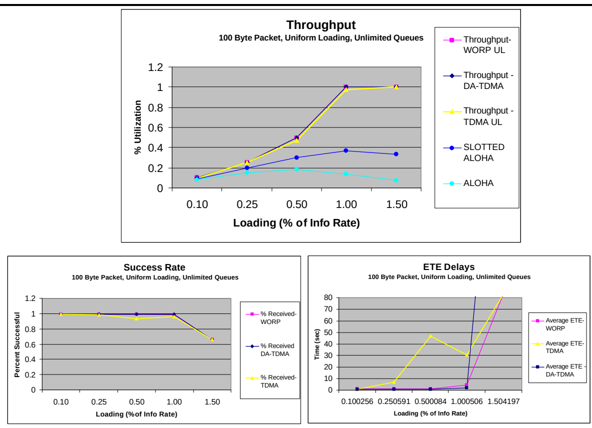


Figure 7. 100 Byte Packets, Uniform Terminal Loading, and Unlimited Queue Sizes

The impact is even more noticeable when the data link queues have limited size constraints. The TDMA scheme will drop packets at the data link layer because the queues have become full, whereas WORP and DA-TDMA adapt the time slot allocation as a terminal's queues fill. This is reflected in the throughput and completion rate results shown in the following figure.

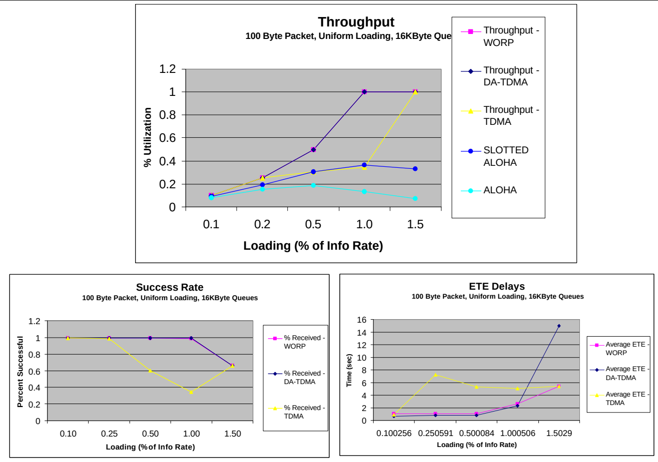


Figure 8. 100 Byte Packets, Uniform Loading, and 16 kbyte Queue Sizes

The next set of simulation results compare the protocols' performance for packet sizes of 1500 bytes. Again, the limited queue size results showed WORP, DA-TDMA, and TDMA performed significantly better as far as throughput than the theoretical ALOHA and Slotted ALOHA. The WORP, DA-TDMA and TDMA throughput and completion rate results also were very comparable. There was a slight difference in the end-to-end delay results that showed WORP and DA-TDMA did better.

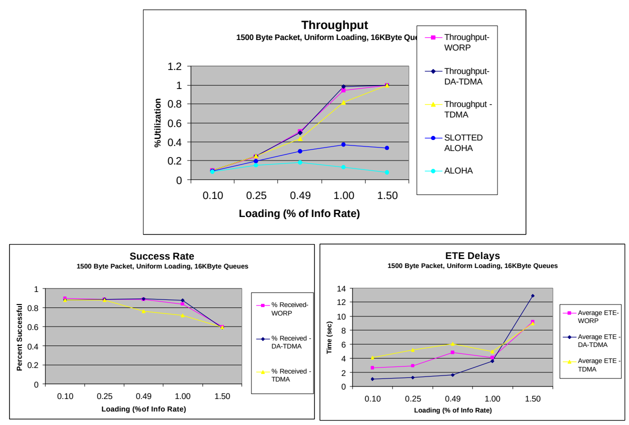


Figure 9. 1500 Byte Packets, Uniform Loading, and 16 kbyte Queue Sizes

The next set of results show the performance of WORP and DA-TDMA for the non-uniform loading scenario highlighted in Table 1. Figure 10 depicts that DA-TDMA still maintains the linear throughput curve despite non-uniform terminal loading, while the TDMA performance does not. Also shown is the delay and completion rate for each of the individual traffic priorities for DA-TDMA. The results indicate that the queue management scheme performs well, optimizing the delay and completion rate for the urgent traffic.

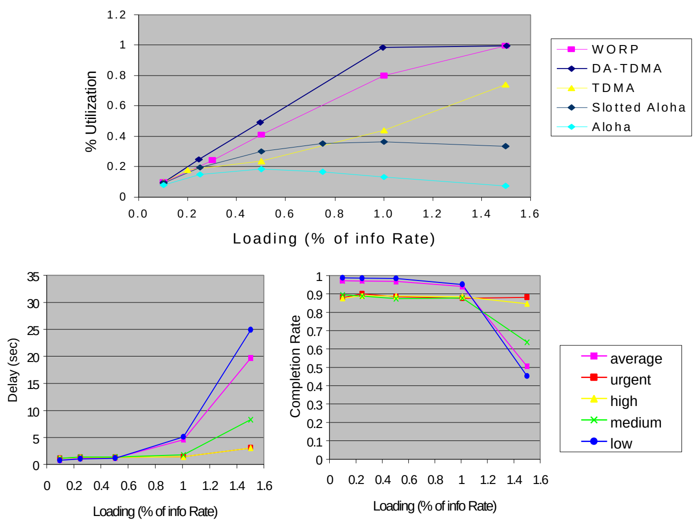


Figure 10. LUT Channel - Non-Uniform Loading

Voice packet delivery performance was also simulated. The application model for voice generated packet sizes of 720 bits once every 100 ms following the initiation of a conversation. Each conversation was 10 – 30 seconds in length. Simulation runs were made with voice only packets, unlimited queue sizes and uniformly distributed loading among all nodes. Packet latency, completion rate, throughput and packet jitter were recorded.

To best understand the results, the definition of jitter and what is an acceptable jitter level need to be described. Jitter is defined as the change in arrival of successive packets. This is important when dealing with isochronous types of traffic such as voice and video. One would like successive packets to arrive at a constant rate. If jitter occurs when transmitting voice, speech seems to be broken up and harder to understand. The acceptable threshold is at approximately 300 ms.

WORP’s and DA-TDMA’s performance was significantly better than TDMA for throughput, completion rate and acceptable jitter. WORP and DA-TDMA did have longer end-to-end delay at higher loading than TDMA though. Because more successful packets could be processed by WORP and DA-TDMA than TDMA, these packets had to wait longer in the data link queues to be processed by WORP. The same packets in the TDMA queues never made it to the top of the queues for processing by the MAC layer, and were thus not completed.

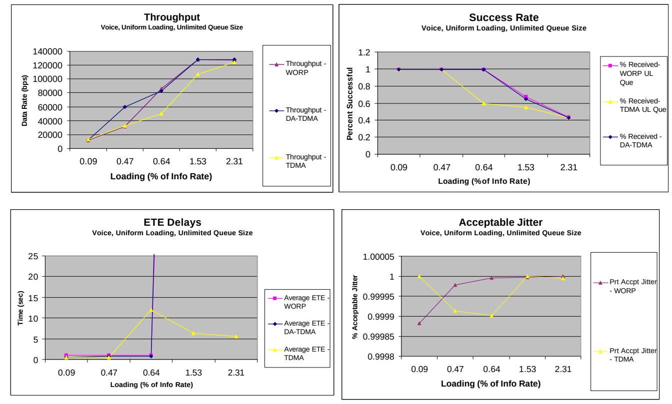


Figure 11. Voice Packets, Uniform Loading, and Unlimited Queue Sizes

## CONCLUSIONS

Results of the simulation analysis show that both MAC protocols presented are viable candidates for a satellite media access control protocol. Their primary advantages are their simplicity to implement, decentralized scheme to reduce vulnerability, maximum use of bandwidth for unevenly distributed loading and low loading situations, and adaptability to high loading.

These advantages are apparent when the protocols' performance is compared to a standard TDMA protocol performance or theoretical ALOHA/Slotted ALOHA. Their throughput is 210% to 250% better than Slotted ALOHA, and 1% to 250% better than TDMA’s throughput performance. The more constraints that are put on the physical system hardware such as limited queue size the better the protocols' perform as compared to TDMA. In addition, the protocols' are able to maximize available bandwidth when the loading of traffic is not uniform. The TDMA results showed that the unevenly distributed loading causes packets to be dropped at the terminals that were heavily loaded and bandwidth not utilized for the lightly loaded terminals. The WORP and DA-TDMA results showed an improvement in completion rate and throughput by allowing the heavily loaded terminals to reserve more bandwidth than the lightly loaded terminals.

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[2] Stallings, William, Data and Computer Communications, 2d Ed, Macmillian Publising Co., 1988, p 296-302.