Medium Access Control Protocols for Space and Satellite Communications: A Survey and Assessment

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Abstract

Medium Access Control (MAC) protocols are designed to coordinate transmission of packets, retransmission of damaged packets, and resolution of collisions during contention periods among stations. In recent years, a wide range of MAC protocols have been proposed or developed for different operating environments with different user requirements. Part of the explanation for having many different MAC protocols is that protocols that are suitable for some applications often would not meet the requirements for other applications. Fundamental objectives in the design of MAC protocols are high channel throughput, low transmission delay, channel stability, protocol scalability, channel reconfigurability, and low complexity of the control algorithm. This paper presents a survey, classifications and performance assessments of MAC protocols for satellite communications. A group of hybrid and adaptive protocols have been investigated and their performance have been compared for a Mars Regional Network (MaRNet) model.

1 Introduction

MAC protocols are at the core of all forms of electronic communications involving voice, data and video. These protocols enable stations at diverse locations to regulate the movement of their packets and manage the network bandwidth in order to utilize the network resources as efficiently as possible. They are foundations in networks architecture and play a significant role in the performance of higher-level protocols. All commonly used *high-level* protocols on the Internet, such as FTP (File Transfer Protocol), HTTP (Hyper Text Transfer Protocol), NV (Network Video for video conferencing) and TFIP (Trivial File Transfer Protocol), TCP/IP (Transmission Control Protocol/Internet Protocol) and ATM (Asynchronous Transfer Mode) protocol, use one or more *low level* MAC protocols. Several important factors that directly affect the performance of a MAC protocol for a satellite network are described below.

Propagation Delay: In satellite networks, the forward and backward propagation delays are major limiting factors on the performance of a MAC protocol. Consider a TDMA protocol with $M/D/1$ queuing system over a geostationary satellite link with 0.278 sec round-trip delay. Let B represents the packet size in bits and C represents the channel bandwidth in bits per second, then the packet transmission time $T = B/C$. The end-to-end delay that a packet suffers has four components. First, the access delay, which is the time between its arrival and the end of the frame time during which it arrives. This is simply because we measure the queue size only at the end of each frame. Second, the queuing delay which is the amount of time that the packet must wait in the queue. Third, the packet transmission time. Forth, the propagation delay (τ) which is the time that takes for a bit to reach its destination excluding access time and queuing delay. The total delay for an M/D/1 model [22] can be derived as,

$$D = \frac{1}{2}NT + NT\frac{\rho}{2(1-\rho)} + T + \tau, \qquad (1)$$

where, ρ is the traffic load and N is the number of stations sharing the TDMA channel. Figure 1 depicts the impact of the channel bandwidth and the throughput on the total delay. It indicates that in a high-speed satellite network, any improvement on the channel bandwidth (e.g., OC-3 to OC-12) would not reduce the total delay significantly, while the total delay is significantly reduced with an improvement over a low bandwidth channel (e.g., T1 to T3 improvement).

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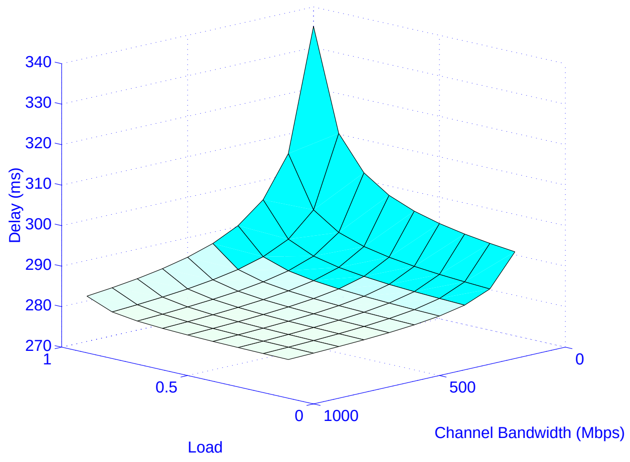

Figure 1. The effects bandwidth and load on delay

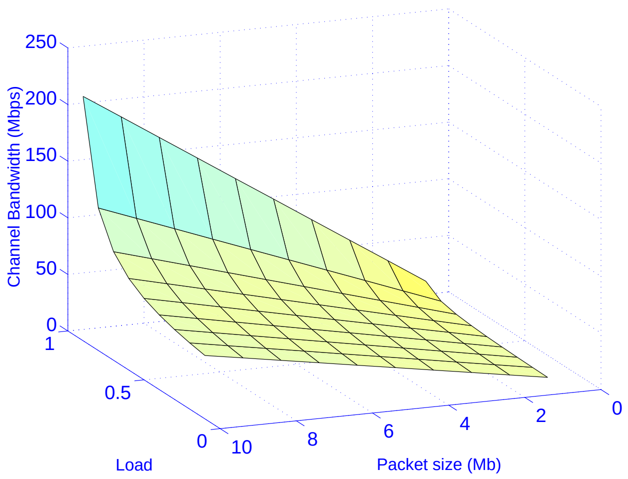

Figure 2. The bandwidth-critical plane

Packet Size: In all packet switching networks, the maximum and the average packet size have a crucial role on the overall performance of the system. The first three components of the overall delay in equation (1) can be improved with more efficient MAC protocols, however, the last component would dominate the total delay at higher speeds. Here we are looking for a sharp boundary on the bandwidth line where these first three components of equation (1) two delays are equal. By substituting $T = B/C$ in (1), this boundary can be computed as,

$$\widehat{C} = \frac{B}{\tau}\left\{1 + \frac{1}{2}N + \frac{N\rho}{2(1-\rho)}\right\}. \tag{2}$$

Figure 2 illustrates this boundary for an $M/D/1$ model. Above this boundary plane, more bandwidth will have negligible effect in reducing the end-to-end delay in equation (1) since D is dominated by τ, while below this boundary we can take the advantage of having more bandwidth to reduce the end-to-end delay. Furthermore, the packet size influences the maximum buffer size at each station. Packets tie up buffers and must not be too long. For extremely long packets, the network response time becomes erratic. This problem is due to instability in queuing process, which is sensitive to high variance in transmission time.

Coordination: A distributed control algorithm in which each individual station makes a decision as to when and how it can transmit is more robust and reliable, particularly in satellite communications. The robustness inherent in a distributed control mechanism for dealing with stations failure and network reconfiguration, and the downlink broadcast property by eliminating the channel overhead for scheduling announcements, make this approach more attractive than a central coordination. Therefore, in this article we focus on the protocols with a distributed control mechanism.

Traffic Model: The performance of a MAC protocol depends strongly on the nature of the traffic transmitted on the multiple access channel. The traffic includes the message arrival distribution, message length distribution and the traffic burstiness. Several definitions for traffic burstiness are given in [4]. Traffic burstiness is an important characteristic that influences the design or selection of a MAC protocol for a satellite network. Large bursts require extra buffers and higher processing capability to support reliable communications. For bursty users, MAC protocols using either fixed assignments or demand assignment over a period of time are going to be very inefficient. To improve the throughput of a broadcast channel shared by users with random bursty traffic, it is desirable to dynamically allocate transmission capacity on a per message (or packet) basis while keeping the end-to-end delay minimal. This can be achieved by hybrid protocols that take the advantages of random access and TDMA-based protocols. Random access protocols provide low latency when the traffic is light while TDMA-based protocols provide high throughput when the traffic load is high. These protocols are analyzed later in this paper.

2 MAC Classifications

MAC protocols have been studied and classified for different applications and environments. A survey of MAC protocols for wireless ATM networks is given in [44]. A survey and analysis of MAC protocols for high-speed LANs

- *MAC protocols*
  - *Passive Users*
    - Polling .... [19]
    - Adaptive Polling .... [19]
  - *Active Users*
    - *Contention–Free Protocols*
      - *Fixed Assignment*
        - *Orthogonal*
          - FDMA .... [40]
          - TDMA .... [40]
        - *Quasi – Orthogonal, CDMA* .... [31]
      - *Demand Assignment*
        - *Reservation*
          - MSAP .... [45]
          - BBM .... [48]
          - BRAP/BRAM ... [48, 13]
          - MLMA .... [41]
          - BCD .... [48]
          - GSMA .... [32]
          - FPODA .... [57]
        - *Token – Passing* .... [46]
    - *Contention–Oriented Protocols*
      - *Random Access*
        - *Asynchronized*
          - Pure-Aloha .... [3, 8]
          - TACRA .... [11]
          - Sel. Rej. Aloha
        - *Synchronized*, Slotted Aloha ...... [37, 1, 23]
        - *Sensing*
          - CSMA . [51, 24, 33, 17, 28, 53, 29]
          - CSMA/CD
      - *Reservation*
        - R-Aloha .... [14, 27, 30]
        - PODA .... [52]
        - SCRMA .... [54]
        - ASLBT .... [18]
      - *Hybrid*
        - Aloha-R .... [38]
        - RRR .... [7]
        - IFFO .... [58]
        - RUC .... [9, 56]
        - SRUC .... [9, 56]
        - ARRA .... [35]
        - SRMA .... [61]
        - PDAMA .... [34, 15]
        - A Stellite-Controlled Algo. ... [47]
    - *Limited Contention Protocols*
      - Probing protocol .... [48]
      - Adaptive Tree Walk .... [12, 11]
      - URN .... [25, 60]
      - MDMA .... [59]
      - Group Random Access Protocol .... [42]

Figure 3. Classification of MAC protocols

and MANs is given in [56]. Modeling and analysis techniques for key classes of MAC protocols are reviewed and described in [43]. In this article, MAC protocols for satellite communications are classified based on their functionality with respect to the static or dynamic nature of the channel, the centralized or distributed control mechanism of the channel assignments, and the adaptive behavior of the control algorithm. This classification is shown in Figure 3. Each class has its advantages and limitations. There exists no protocol that performs better than all others over the entire range of performance criteria.

As far as MAC protocols are concerned, the space environment possesses some major constraints that eliminate a large number of MAC protocols from considerations. First, the performance impact of the long propagation delay imposes certain limits on some classes of MAC protocols, such as a large class of protocols proposed for local area and wide area networks. Second, because of the difference in propagation delay in satellite and terrestrial links, the impact on any previously calculated performance of a protocol could be significant and hence these protocols need to be reevaluated for satellite communications. Third, physical changes to the controllers in space are limited if not impossible and this necessitates a simple control mechanism for the MAC protocol under consideration. Fourth, to provide fault tolerance and network survivability, a MAC protocol is expected to easily accommodate topological changes such as adding or deleting a station, activating and deactivating a station from the network. Finally, limitation in power implies stringent use of buffer memory and processors.

2.1 Active versus Passive Users

Protocols with active users actively seek access to the channel instead of waiting to be polled. This class includes contention-free and contention-oriented protocols. A MAC protocol can be made contention-free either by static allocation or dynamic allocation of the channel. An important advantage of contention-free access protocols is the ability to control the packet delay and hence the worst case delay can be determined. This important feature is essential for real-time applications. In contention-free protocols, a channel can be configured either as a fixed assigned channel, or a demand assigned channel. With demand assignment, a channel needs to be set aside for signaling. Access to the signaling channel itself is another multiple access problem. Contention protocols can be grouped into random access protocols, reservation via contention protocols, and hybrid of random access and reservation protocols.

In MAC protocols with passive users, stations may access the channel only when specifically polled by the central controller. This group of MAC protocols consists of fixed polling and adaptive polling protocols. In fixed polling, stations are polled one after the other. A very important parameter determining the efficiency of polling protocols, during a polling cycle, is the total *walk time* which is a portion of cycle time including channel propagation delay, polling transmission time, messages response time, modem synchronization time, etc. For a lightly loaded network, fixed polling is not efficient since all stations are polled regardless of their readiness. In adaptive polling [19], stations are probed during a polling cycle. This protocol is discussed later.

2.2 Fixed Assignment Multiple Access (FAMA)

In fixed assignment protocols, the allocation of the channel bandwidth to a station is a static assignment, and it is independent of stations activities. This can be done by partitioning the bandwidth space into slots which are assigned in a predetermined fashion. In FAMA, the channel assignment is tightly controlled and is not adaptive to traffic changes. This can be wasteful of capacity when the traffic is asymmetric. These techniques can be classified as *orthogonal* FAMA assignment protocols such as Time Division Multiple Access (TDMA) and Frequency Division Multiple Access (FDMA) or *quasi-orthogonal* FAMA such as Code Division Multiple Access (CDMA).

The FAMA protocols are the most effective techniques for satellite networks composed of a small number of ($<$ 10) stations with stable and predictable traffic patterns. A FAMA protocol can be implemented either by means of frequency division multiple access or time division multiple access. FDMA was the first technique used in early multiple access for satellite communications, while TDMA has been used in recent years.

In FDMA, no coordination or synchronization is required among stations. Each station can use its own band without interference. However, FDMA is the cause of waste especially when the load is momentarily uneven [40]. When a station is idle, its share of the bandwidth cannot be used by other stations. FDMA is also not flexible; adding a new station requires equipment modifications. This technique has the advantage of simplicity, but lacks flexibility and reconfigurability.

TDMA, on the other hand provides better channel throughput. However, the stations must be synchronized so that each station knows exactly when to transmit. The major disadvantage of TDMA is the requirement that each station must have a fixed allocation of channel time whether or not it has data to transmit. In most applications transmission requirements are bursty and a fixed allocation of channel time to each station is wasteful.

Neither FDMA nor TDMA allow any time overlap of the stations transmissions. A conflict-free protocol that allows overlap transmission, both in frequency division and

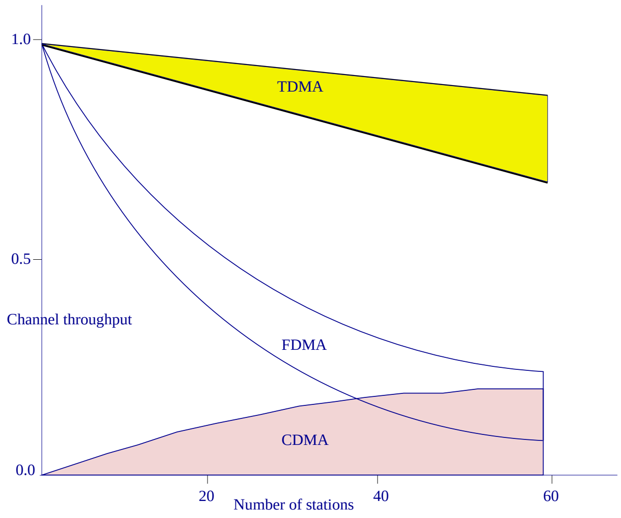

Figure 4. Throughput of the basic access techniques

time division techniques, is Code Division Multiple Access (CDMA) or Spread Spectrum Multiple Access (SSMA). The conflict-free property of CDMA is achieved by using quasi-orthogonal signals in conjunction with matching filters at the receiving stations. The main advantage here is the benefit of *capture* in asynchronous SSMA. The main disadvantage is the low throughput. Figure 4 illustrates the approximate throughput behavior of the three basic access techniques [31].

2.3 Demand Assignment Multiple Access (DAMA)

In situations where the traffic pattern is random and unpredictable, fixed allocation of the channel bandwidth leads to inefficient use of transponder capacity. It is desirable to design MAC protocols that allocate capacity on demand in response to the station request for capacity. DAMA can be divided into reservation and token passing protocols. Dynamic allocation using reservation based on demand increases the transmission throughput. The reservation process can be *implicit* or *explicit* [36]. In explicit reservation, a single reservation slot is assigned to each station in every frame. Each frame contains a control subframe that consists of a sequence of bits serving to reserve or announce upcoming transmissions. In implicit reservation, stations use Slotted Aloha to compete for the reservation slots. In networks with a large number of stations, contention is used to keep the number of reservation slots small. The boundary between the control subframe and the data subframe can be movable which expands the control subframe to fill unused frame time, reducing the actual contention for the control slots. The following protocols were initially designed for satellite communications, however, they are of interest in LANs and MANs because of similar conditions especially for large geographical distance and higher bit rates. In all these protocols, fixed frame length is used.

Mini-Slotted Alternating Priorities(MSAP): The MSAP is a distributed contention-free reservation multiaccess protocol [18] suitable for a small number of data stations. MSAP can be viewed as a ”carrier-sense” version of polling with distributed control. The time is slotted such that the size of the minislot is greater than or equal to the propagation delay. All stations are synchronized and may start transmission at the beginning of a minislot. an alternating priorities (AP) scheme is used to provide fairness among stations. In MSAP, a single reservation preamble is used to schedule more than a single reservation. All participating stations are aware of the reservation made in the preamble. The MSAP represents a family of contention-free reservation protocols. An improvement to the MSAP protocol is the Basic Bit-Map (BBM) protocol [48].

Basic Bit-Map Protocol (BBM): In BBM scheme [48], each contention period consists of exactly N minislots. Each minislot is one bit long. A station may announce that it has a frame to send by inserting a 1 into its minislot. After N slots have passed by, all stations have complete knowledge of which stations wish to transmit. The channel efficiency at low load is $d/(N+d)$ and at high load is $d/(d+1)$, where d is frame length in bits. The mean delay for a frame is queuing delay plus $N(d+1)/2$ minislots. The BBM protocol is more sophisticated than the MSAP protocol in a sense that it requires synchronization among stations. However, the overhead per transmitted packet is less than the overhead in the MSAP protocol.

Broadcast Recognition with Alternating Priorities (BRAP): The BBM scheme has two drawbacks. First, higher numbered stations get better service than lower numbered stations. Second, for light load, a station has to wait for the current scan to be finished before it gets a chance to transmit. The BRAP [48] eliminates both these drawbacks. In BRAP, a station begins transmission as soon as it inserts a 1 into the minislot. In addition, the station following the one just transmitted now has the opportunity to insert a 1 into the minislot. Therefore, the alternating priority in BRAP is a round-robin rotation. The channel throughput is the same as provided by the BBM method. However, the delay characteristic is better. At low load, a station only waits $N/2$ minislot on average, where N is the number of stations. At high load, BRAP and BBM have the same delay characteristics.

Broadcast Recognition Access Method (BRAM): One of the most efficient distributed reservation protocols is Broadcast Recognition Access Method (BRAM) [13]. This protocol combines the BBM and MSAP protocols. A reservation preamble is used to reserve the channel for a single station as in the MSAP. Under heavy load BRAM reduces to regular TDMA. The channel throughput for low load and high load are computed as $d/(N+d)$ and $d/(d+1)$, respectively [48], where the mean delay for a frame is queuing delay plus $N(d+1)/2$ minislots.

Multi-Level Multi-Access (MLMA): The problem with BRAP is the delay when the channel is lightly loaded. When there is no frame to be transmitted, the N-bit headers just go on and on until a station inserts a 1 into its mini slot. On average, the waiting time would be $N/2$. MLAM scheme [41] is nearly as efficient under high channel load, but has shorter delay under low channel load. In MLAM, a station wants to transmit a frame sends its identification in a particular format. A group of 10 bits (called decade) is used to represent a digit of the station number [48].

Binary Count Down (BCD) In MLMA, for N stations, the number of levels needed is $\log_2 N$. In BCD protocol, a station wants to transmit, writes its identification into the header in binary digits. An arbitration is made to avoid a conflict. As soon as a station sees that a higher-order bit of its address is overwritten with a 1, it gives up. The channel efficiency here is $d/(d+\log N)$, which is slightly better than MLMA when there are many bursty stations, but slightly less under a full load [48].

Global Scheduling Multiple Access (GSMA) The GSMA [32] is a centralized conflict-free reservation multi-access similar to MLMA protocol. The difference is that the controller uses a separate channel to notify stations about the access sequence. GSMA is based on the time division concept for reservation. All stations listen to the same line for scheduling assignments and transmit via a slot allocation initiated by the scheduler. The channel time is divided into frames of variable lengths. A frame is divided into two subframes: a subframe in a fixed TDMA to request data slot allocation, and a subframe of data slots. By using a fixed assignment of the status slots, there is no need to transmit stations identifications, and hence the size of these slots is reduced. The user can allocate a number of slots in each frame which does not exceed the number of packets generated during the preceding frame or does not exceed a maximum number specified.

Fixed Priority Oriented Demand Assignment (FPODA) This scheme [57] is used in the Universe network. It ties together six local networks scattered around the UK with a data rate of 1 Mbps and frame length of 130 ms. Each frame begins with six minislots(100 bytes each), one per station. Minislots are used by their stations to transmit data or a reservation. A station that receives a slot allocation in a particular frame may use it to send one or more frames, which allow transmission to one or more destination stations. If a reservation is sent, it is a request for a particular service. One of the six stations acts as a master and allocates time on the channel based on reservation requests (including its own). FPODA is an effective protocol when there is a small, fixed number of stations sharing the channel.

In case where there is a large or variable number of stations, some other means of placing reservation requests is needed. One such system is the packet-demand assignment multiple access (PDAMA) protocol developed for NASA's mobile satellite systems [34, 15], discussed later in this article.

Token Passing Token passing [46] is a technique in which the stations form a logical ring. Stations are assigned positions in an ordered sequence, with the last member of the sequence followed by the first. Each station knows the identity of its preceding and following stations. A control packet known as the token provides the right of access. When a station receives the token, it has the control of the channel and can transmit for a specific time. The token is passed to the next station on the logical ring when the station finishes its transmission or its time has expired. The protocol consists of alternating data transmission and token passing phases. This protocol requires considerable maintenance. Functions such as ring initiation, addition to ring, deletion from ring, and fault management should be performed by one or more stations.

2.4 Random Access

While in contention-free protocols every scheduled transmission is guaranteed to succeed, the random access protocols do not guarantee successful transmission in advance. There is no attempt to coordinate the ready users to avoid collision entirely. Instead, each station makes its own decision regarding when to access the channel. Random access, which involves no control, is simple to implement and is adaptive to varying demand, but in some situations it can be wasteful of capacity due to collision.

An early approach for packet satellite systems was based on random access for all data and control packets. In particular, Pure Aloha with %18 channel throughput and Slotted Aloha with %37 channel throughput were used. The random access schemes suffer from relatively limited capacity, and in the presence of other bursty traffic, they can not accommodate heavy flows between two or more stations.

Further, the long round trip propagation delay aggravates the problem since each packet collision adds at least one round trip delay to packet transmission time. The maximum channel utilization of any random access scheme with infinite population has been shown to be upper bounded by 0.587 [6]. They can be classified as asynchronous and synchronous protocols.

2.4.1 Asynchronous Random Access

Pure Aloha (P-Aloha): In Pure Aloha, stations are not synchronized and stations transmit a data packet whenever one is ready. In the the event that one or more packets collide, each user realizes collision occurrence and retransmits the packet after a randomized delay. This randomized delay is crucial to the protocol stability and thus to the throughput-delay performance of all contention-based protocols. The original Aloha protocol[3, 8] led to the development of a multihop packet radio network called PRNET [21, 26] that allows direct communication among mobile users.

Selective-Reject Aloha (SR-Aloha): In asynchronous random transmission, most often collision between packets is partial. In Pure Aloha the packet is totally destroyed by a collision. The Selective-Reject Aloha protocol has been designed to avoid a total destruction of the packet. The transmission packet is divided into subpackets, each having its own header. When a collision happens, only collided subpackets will be retransmitted. The Selective-Reject Aloha protocol is well suited for variable packet lengths.

The Time-of-Arrival Collision Resolution Algorithm (TACRA) The TACRA protocol [11] provides an improvement to the Aloha protocol by avoiding the possibility that a packet which has already been collided encounters another packet during its retransmission. In this protocol, stations avoid transmitting new packets during time slots provided for retransmission of packets which have suffered a first collision. This protocol needs a procedure to identify and retransmit packets which suffered a collision. This protocol tends to be complex to implement.

2.4.2 Synchronous Random Access

Slotted Aloha (S-Aloha): In Slotted Aloha Protocol [37, 1, 23], stations are required to synchronize their packet transmissions into fixed-length channel time slots. The maximum channel throughput is 0.368. Numerous variation of Aloha protocols have been addressed in the literature. It has been shown in [5] that constant length packets yield the maximum throughput over all packet length distributions.

2.4.3 Sensing Protocols

Carrier Sense Multiple Access, (CSMA): CSMA Protocols [51, 24, 33, 17, 28, 53, 29] are among the most popular protocols for LANs. In a broadcast channel with short propagation delay, collision in the channel can be significantly reduced by requiring each station to sense the channel for the presence of any ongoing transmission before accessing it. Following a successful transmission, each ready station transmits with probability 1 into the next time slot. Upon detection of a collision, each ready station executes an adaptive algorithm for selecting its transmission probability in the next time slot. The process of sensing (listening) to a channel is not demanding. Every station is equipped with a receiver. However, career sensing does not relieve us from collision. Variations of this protocol include 1-persistence, 0-persistence, and p-persistence CSMA [48].

Carrier Sense Multiple Access with Collision Detection (CSMA/CD): Persistent and nonpersistent CSMA protocols are an improvement over Aloha protocol. In CSMA, no station begins transmission when the channel is sensed busy. In CSMA with collision detection (CSMA/CD), stations abort transmission when they detect a collision. This could happen when two stations sense the channel to be idle and begin transmitting simultaneously.

2.5 Contention-Oriented Reservation

The objective of the reservation protocols is to avoid collision entirely. Since users are distributed, a reservation subchannel is necessary for users to communicate with each other such that only one station can access the channel at a time. Most reservation protocols adopt either a fixed assigned TDMA protocol or some variation of the S-Aloha protocol. There is a trade-off between the channel stability and the channel control mechanism. A TDMA protocol performs poorly for large number of users with bursty traffic. On the other hand, the S-Aloha protocol is independent of the number of users, but it needs to be adaptively controlled for stable operation. Part of the price that one pays for the gain in the channel throughput by using contention-oriented reservation protocols is the increase in message delay. The minimum delay incurred by a message, excluding message transmission time, is more than twice the channel propagation time. This is an important consideration for satellite channels. VSATs (very small aperture terminals) network is an example of a digital satellite network composed of thousands of small earth stations transmitting data in bursts using random access protocols [2].

Reservation Aloha (R-Aloha): The R-Aloha Protocol [14, 27, 30] is a distributed contention protocol with implicit reservation, and it is the simple form of reservation protocols. Reservations are implicit in the sense that successful transmission in a slot serves as a reservation for the corresponding slot in the next frame. Initial access is random and S-Aloha is used during the contention period. Once the transmission is started, the same slot within succeeding time frames is reserved for the same station as long as it has data to send. Ready stations monitor the slots in the current frame. R-Aloha is basically a Slotted Aloha in which slots are organized into frames of equal sizes. There are fewer slots per frame than there are stations. For satellite environment, the duration of a frame must be grater than the satellite propagation delay. R-Aloha allows a dynamic mixture of stream and bursty traffic. If the average message length is long, the protocol performs as fixed-assignment TDMA scheme. If the traffic is bursty, the protocol performs as S-Aloha. The performance is less than S-Aloha if most messages are one slot in length. This is because the slot remains empty for one round.

Priority-Oriented Demand Assignments (PODA): In PODA [20], the time frame consists of a control part and a data part. The boundary is adapted to the current load. Access to the control part can be deterministic or by Aloha contention. All stations track the control part and maintain a queue to determine their proper access instances. In PODA, two distinct reservation mechanisms; datagrams and streams, are used to satisfy the requirements for both voice and data. For stream traffic such as voice and video, a reservation is made only once, and is retained by every station in a separate queue. Datagram reservations are made on a per-burst basis.

Split-Channel Reservation Multiple Access (SCRMA) The SCRMA [54] is a centralized and explicit reservation protocol in which FDMA is used. The available bandwidth is divided into two channels: one to transmit control information, and the other is used for data messages. There are many operational modes for this schemes [55]. In the request/answer to request message scheme (RAM), the control bandwidth is further divided into the request channel and the answer-to-request channel. The request channel is operated in random access such as Aloha or CSMA. When a request for transmission is received by the scheduling station, it computes the time at which the message channel will be empty and transmits an answer. The answer contains the address of the station and the time at which it can start transmission back to the requesting station using the answer-to request channel.

Assigned Slot Listen Before Transmission(ASLBT): In ASLBT[18], time is divided into frames, each containing an equal number of L minislots. Stations are ordered from 1 to N and a given subset of N/L stations is assigned to each minislot of a frame. A ready station can sense the channel only on its assigned minislot. The ASLBT scheme has been proposed to improve on MSAP protocol. There is a trade-off between the time wasted in collisions and the time wasted in control overhead [55]. The parameter N/L is adjusted according to the load placed on the channel. $N/L = 1$, is optimal for high throughput, and the scheme becomes a conflict-free one which approaches MSAP. $L = 1$ is optimal for very light throughput, and the scheme becomes CSMA. In between the two extreme cases intermediate values of N/L are optimum.

2.6 Hybrid of Random Access and Reservation

Reservation schemes are designed to have the advantages of both random access and the TDMA. An immediate extension is to use a reservation scheme with contention. The stations content during a reservation period and those who succeed in making reservation transmit without contention. Hybrid protocols derive their efficiency from the fact that Reservation periods are shorter than transmission periods by several orders of magnitude. In recent years, attempts have been made to find minimum delay protocols under certain stochastic conditions such as Poisson packet arrival patterns and combined Poisson arrival of new and retransmitted packets [59].

Aloha Reservation: Aloha-R [38] is a distributed contention-oriented reservation protocol. It explicitly makes exclusive reservation. A frame is divided into equal-length slots, one of which is further divided into minislots. The minislots, acquired via S-Aloha, function as a common queue for all users. The data slots are used on a reservation basis and they are free of conflict. The number of slots is adapted to the current load. A station wishing to transmit sends a request packet in a minislot specifying the number of slots desired (less than a max). If the reservation is successful, the station then determines which future slots it has acquired and transmits in them. To execute the reservation mechanism properly, each station maintains a queue that holds information on the number of outstanding reservations (the queue), and the slots at which its own reservation begins. Thus a station knows when to transmit. This is determined by the FIFO discipline based on the successful reservation received. Another variation of this reservation protocol has been described by [39]. In this protocol the idle slots are also available to be reserved by others. If there is a collision in the reservation minislots all users except the owner of the minislot will abstain from reservation.

Round-Robin Reservation(RRR): Round-Robin protocol [7] is a distributed contention-oriented reservation. The basis for this scheme is a fixed TDMA assignment. It requires a fixed number of stations less than or equal to the number of slots in a frame. Each station has a dedicated slot. If there are extra slots, they can be used by all stations using S-Aloha. If a slot is not being used by its owner, it is available to be used by other stations. The station can reclaim the slot (possibly via collision) by using the slot in the next time frame. In a variation of this scheme [7], each station keeps track of the global queue by including the length of its queue in the header of the packet. A round-robin algorithm is used to allocate available slots (excess slots and unused slots) to the queued packets. Each station is required to transmit information regarding its own queue of packets piggybacked in the data packet header (transmitted in the previous frame). A zero count indicates that the corresponding slot is free. A station recovers its slot by deliberately causing a conflict in that slot which other users detect. This allows other stations to know the current state of its own slot. This approach is superior to R-Aloha for stream-dominated traffic since each station is guaranteed one slot of bandwidth. For a large number of stations, this algorithm can lead to a large delay.

Interleaved Frame Flush-Out (IFFO): In IFFO [58], a time frame consists of a control slot, reserved slots and contention slots. The boundary between the later two depends on the number of reservations made in the previous frame. The control slot is subdivided into minislots, one for each station, and is used to make reservations. All packets that become ready during the time interval of the reserved slots must make a reservation in the next time frame. The same holds for last contention slots. If a collision occurs, the packets are retransmitted in reserved slots of the next time frame. *Flush-Out* means packets are guaranteed to be successfully transmitted in the second time frame after they became ready for transmission. *Interleaved* means that reservations in the odd-numbered time frames are independent of those in the even-numbered ones. Frame length is variable but must be at least one round-trip propagation delay.

Reservation Upon Collision (RUC): In RUC [9, 56], slots are subdivided into a control part and a data part. The data sub-slot can be in a random or a reserved mode. The basic mode is random access via a Slotted Aloha. When collision is detected, the data sub-slot becomes reserved. It returns back to the random mode when all collided packets have been transmitted successfully. The control sub-slot provides information about stations involved in a collision. Access to control slots is collision free.

Split-channel Reservation Upon Collision (SRUC): In SRUC [10, 56], the previously contended stations do not mix with new ones. SRUC is an adaptive protocol which combines S-Aloha and reservation protocols. It switches from one to the other according to the state of the channel. SRUC divides the stations into a number of groups. The same number of slots are then combined into a time frame so that all stations have an information entry after a corresponding number of time frames. The size of the control sub-slot becomes smaller because each of them serves only some of the stations. The SRUC protocol is alway stable since all colliding packets are retransmitted in the reserved state.

Announced Retransmission Random Access (ARRA): The ARRA [35] protocol provides a mechanism to avoid collisions between new messages, and retransmission packets. Each packet incorporates additional information indicating the slots number reserved for retransmission in case of collision. It uses a low-rate subchannel to announce the retransmission time so that conflicts between new and retransmitted packets are prevented. The throughput is 50% - 60%. This protocol provides significant throughput improvement over conventional contention protocols, without additional complexity.

Scheduled-Retransmission Multiple Access (SRMA): SRMA [61] is somewhat similar to ARRA. In addition to avoiding the collision between new and retransmitted packets, SRMA also eliminates the reservation collisions. The common pool of minislots at the beginning of each frame is not needed for SRMA. Two versions of SRMA are described in [61]: the fixed-frame version (SRMA/FF), and the dynamic frame version (SRMA/DF). With 3% retransmission reservation overhead, SRMA/FF gives a maximum throughput of 65%, and SRMA/DF gives 89% throughput. SRMA behaves like Aloha protocol under light load, and like a reservation protocol under heavy load.

Packet-Demand Assignment Multiple Access (PDAMA): In PDAMA [34, 15, 46], a frame consists of a leader control slot, a guard slot, reservation minislots, and information slots. The leader slot contains acknowledgment of received reservations and allocations of frame times for other stations. The contents of the leader slot is transmitted by the master station. The guard slot assures that each station hears the leader slot before attempting further reservation. When a station first comes on line it listens for the next leader subframe. It then transmits a short identification message which includes the time of transmission, during the guard subframe. If there is no collision, the station will hear its own identification message and can determine its round trip time. If there is a collision, the station tries again during subsequent guard subframes, using a random back-off algorithm [48]. Stations contend for the reservation using S-Aloha. Three sorts of reservations can be made: 1) Urgent messages can be sent as a unit in a single information subframe. A station may request an ongoing allocation for a digitized voice exchange. The information subframe is of variable length. 2) A station may request that the system be placed in long message mode. 3) Digitized mode allows digitized voice. Sufficient capacity is allocated to support full-duplex voice transmission.

A Satellite-Controlled Scheme This protocol [47] employs the satellite rather than an earth station to make reservations. It is designed to deal with a mixture of stream and bursty traffic. It is a dual-mode protocol for packet and circuit switched traffic. The channel frame is divided into two subframes: one for bursty stations, and the other for heavily loaded stations. The subframe for heavily loaded stations is further divided into two subchannels, a reservation subchannel consists of minislots and a message subchannel. The bursty stations use S-Aloha in their dedicated subframe for packet transmission. The heavy loaded stations use reservation minislots randomly to reserve slots in the coming message subchannel for their circuit switched traffic. Each frame consists of three subframes. The reservation subframe contains a set of reservation minislots. The unreserved subframe contains data slots that stations contend for using S-Aloha and is intended for bursty traffic. The reserved subframe contains data slots that may be reserved for stream traffic.

To acquire slots in the reserved frame, a station contends for a minislot using S-Aloha to transmit a reservation. A reservation consists of the earth station identifier. If a reservation is successfully received at the satellite, and if at least one unreserved slot is available in the reserved subframe, the satellite immediately sends a confirmation in the same minislot. The confirmation consists of a slot position within the reserved subframe. Upon receipt of the confirmation, the earth station can then use the reserved slot in each succeeding frame until it transmits an end-of-message flag. This informs the satellite to release the slot for future use.

2.7 Limited Contention and Adaptive Protocols

The two channel acquisition methods, namely contention-free and contention-oriented reservation protocols described earlier have their advantages and disadvantages. Each scheme can be rated as to how well it does with respect to the two important performance measures; delay at low load and channel efficiency at high load. For asymmetric traffic the overall performance of the protocol can be improved by allowing stations with higher traffic load to have more opportunity to transmit. In limited contention protocols, stations are divided into (not necessarily disjoint) groups. Only members of a group are permitted to compete for their assigned slot. If one succeeds, it acquires the channel and starts transmitting its frame. If there is a collision, the members of another group contend for their slot. By making appropriate division, the amount of contention can be reduced. In this section we describe limited contention protocols including adaptive strategies and mixed modes.

Adaptive Probing: Adaptive polling is a centralized access scheme that adapts the size of the polling group to the current traffic load. The group becomes smaller as network loading increases. For heavy load, all stations are individually polled.

Adaptive Tree Protocol: The adaptive tree walk protocol [12, 11] is a distributed protocol in which stations are organized as leaves of a binary tree. Following a successful transmission on slot 0, all stations are allowed to attempt on slot 1. If there is a collision during this time slot, only stations belonging to left sub-tree are allowed to compete for next time slot. In general the tree is searched in depth first fashion, to locate all ready stations. The search can begin farther when the number of ready stations increases. If q ready stations are uniformly distributed, then r, the optimal level to begin searching is $\log_2 q$.

Urn Protocols: This is a distributed scheme in which groups of stations sequentially receive permission to transmit via S-Aloha. The size of the group depends on the number of active stations. The Urn protocol [25, 60] is designed to operate as the Aloha protocol in light load and as TDMA in heavy load. This is an alternative strategy for ready stations to determine whether or not to transmit in the next time slot. Thus the probability of transmission is either 0 or 1. Some stations have full channel-access rights, whereas others have none. For a lightly loaded network, a large number of users get channel access rights. As the network load increases, the number of stations getting access rights is reduced.

A Minimum Delay Multi Access Protocol (MDMA): Wong and Yum [59] have developed a model based on Poisson arrival/retransmitted packets. MDMA uses a single slotted uplink channel and a control channel for transmitting reservation information. In this model a packet that hits an Aloha channel, will either make a reservation with probability of f_1, on the control channel, or with the probability $1 - f_1$ transmits the packet in the current Aloha slot and makes a spare reservation with probability a. In case of a collision in the Aloha slot, the spare reservation, if successful, allows the packet to be transmitted in a reserved slot after a round trip propagation delay. If transmission on the Aloha slot is successful, the spare reservation is ignored by the satellite. If the arrival packet hits a reserved slot, it will either make a reservation with probability f_2, or transmits the packet randomly with probability $1 - f_2$, and makes a spare reservation on the control channel with probability a. For each successful reservation, a reserved slot on the channel is assigned. The protocol can take the optimal setting of f_1, f_2, and a in different traffic conditions. These values can be measured or precomputed off-line and used in the protocol. The protocol stability is inherent by selecting f_1 and f_2 to be 1 for heavy load. This means all packets make reservations before transmission. When the traffic is very light, by selecting f_1 and f_2 be 0 the protocol becomes S-Aloha.

Group Random Access Protocol (GRA): The GRA [42] protocol grants random access to some stations only during certain periods. Other times, other groups can access the channel, or other access schemes such as reservation and fixed assignment are operated.

3 The Mars Regional Network Model

The Mars Regional Network [49, 50] consists of six nodes as shown in Figure 5. The network consists of two geostationary satellites that provide multiple access and broadcast capabilities to all Mars stations within the coverage area. A Mars station can send packets to the satellites in multiple access mode. This provides a fully connected network topology with direct logical connections and distributed coordination among all Mars stations. The nodes are numbered as Mars Communication Hub (1), Primary Relay Satellite (2), Instrument Lab (3), Rover (4), Remote lab(5), and Mars Secondary Relay Satellite (6). The traffic generated by stations are asymmetric and therefore, different distributions have applied to the station. Table 1 shows the traffic matrix used to simulate a group of hybrid MAC protocols for this network.

Table 1. Traffic Matrix (Mbps)

Source	1	2	3	4	5	6
Rate	0.116	90.0	166.3	106.3	4.1	0.116

To compare the performance of different protocols under a uniform condition it is necessary to define the network parameters in a unified environment.

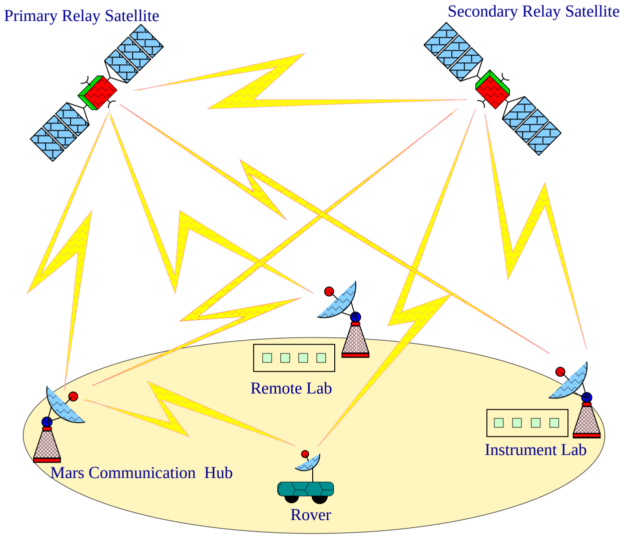

Figure 5. MaRNet Configuration

Frame size In reservation or demand-assignment protocols, each station should be aware of the usage status of slots one frame ago. Therefore, M, the number of slots in a frame is chosen to be larger than R, the propagation delay in slots. Different values for M and B result in different throughput versus delay performance. Given the packet size B, a frame should be long enough to span the transmission delay, and should be small enough to support the traffic efficiently. Therefore, the following relation must be satisfied when choosing the frame size, M.

$$\left\lceil \frac{C_T}{B} \right\rceil \le M \le \sum_{i=1}^{N} \left\lceil \frac{\lambda_i T_f}{B} \right\rceil, \qquad (3)$$

where N is the number of stations.

Slot and Packet Size Selections Packet size and slot size directly influence the performance of a MAC protocol. In theory, a packet can span multiple contiguous slots. However, in practice, a packet fits into one slot. A slot must be large enough to carry a packet plus the guard bits. The selection of packet size involves the following trade-offs [16]. First, For voice application, the packet cannot be played back until the last bit of the packet has been received. The total delay cannot exceed 500 ms. For a geostationary satellite on Earth's orbit with 278 ms propagation delay, this delay implies that the packet duration must be at most 222 ms. For telephone transmissions, CCITT G-114 recommendation stipulates that the propagation time between subscribers must not exceed 400 ms [31]. If we allow 30 ms for the sum of the propagation delays in the end networks, for Earth applications

$$T_f \le \frac{1}{2}(400 - 278 - 30) = 46 \ \text{ms}.$$

In practice, $0.750 \le T_f \le 20$ ms. Second, retransmissions of lost packets are impractical for interactive voice. Third, smaller packets reduce the throughput due to constant overheads for small and large packets. Many Hybrid protocols with movable boundary between voice and data handle single-slot transmission and longer transmissions differently. Therefore, it is advisable to make the slots as long as possible, provided that there are not many short messages. However, if a large number of messages are short, short packets make the the common case fast. Although the throughput versus delay characteristics of some MAC protocols can be performed analytically, the selection of the optimal packet size typically requires a simulation.

Selecting different values for M from Equation **??** result in throughput and delay performance as shown in Figure 6. Clearly, smaller frames have better transmission delay than large frames. On the other hand the throughput increases as M increases, but with a smaller slope. Therefore, we have chosen $M = 47$, for $B = 1$ Mb in the simulation model. Figure 6 illustrates the impact of the frame size and the packet size on the transmission delay for the MaRNet with a 400 Mbps channel and 0.113 propagation delay.

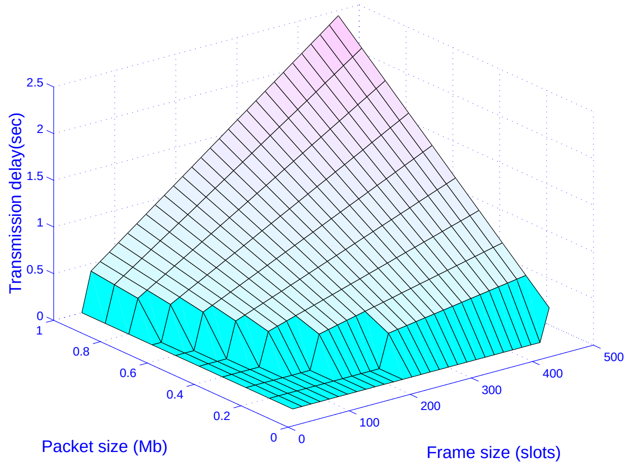

Figure 6. Delay vs frame size and packet size

4 Performance Measures and Evaluations

There are several performance measures used in evaluation of MAC protocols including throughput versus delay characteristic, fairness, robustness to channel noise, reliability, and adaptability to various traffic. The most important performance measure is the throughput versus average message delay trade-off characteristic that are often used as a performance measure in analytical studies of MAC protocols. For the MaRNet, the other important performance measure is the buffer requirement for each protocol. In most studies, it is assumed that stations have infinite buffers. This is not the case for the MaRNet. Therefore, in our study, we evaluated the performance of the MAC protocols with respect to their buffer performance as well. scalability, stability and reconfigurability of the protocols have also been taken into consideration.

4.1 Performance Comparisons

A group of hybrid and adaptive protocols: including R-Aloha, Aloha-R, RRR SRUC, and MDMA have been simulated and evaluated for the MaRNet. The performance of these protocols have been compared with the performance of other well known and implemented protocols such as Basic TDMA, Generalized TDMA and S-Aloha. In G-TDMA, each station can receive more than one slot per frame. The number of slots assigned to a station during a frame is proportional to its traffic load. In B-TDMA, all stations are treated the same regardless of their traffic load. Figure 7 illustrates the throughput versus delay performance of these protocols when the average message length taken to be 10 Mb. The maximum and the average buffer sizes are shown in Figures 8 and 9, respectively. Similar results were obtained when messages other than 10 Mb had been chosen.

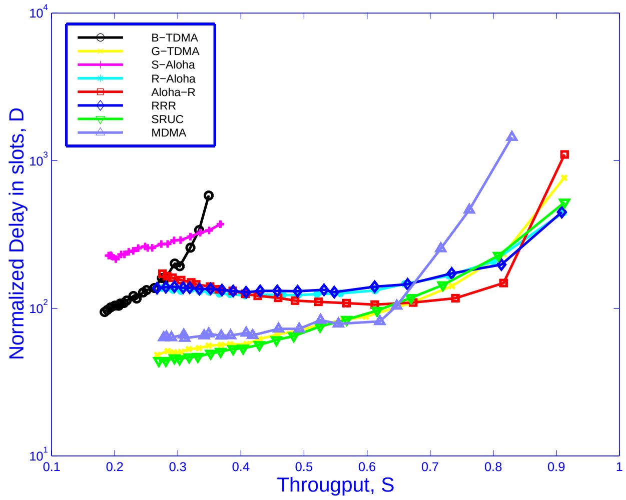

Figure 7. Throughput vs delay performance

For different message sizes, G-TDMA performs better than others, but at some cost. The protocol is simple algorithmically, however, it requires customized synchronization at each station. The B-TDMA not only depends upon the station population, it suffers from poor utilization for the MaRNet traffic. S-Aloha has the advantage of simplicity, but the maximum throughput is 0.38.

R-Aloha and Round Robin Reservation protocols both have the same performance, however, R-Aloha excels in robustness. While Aloha-R adds complexity, it has better throughput versus delay characteristic for bursty traffic. It

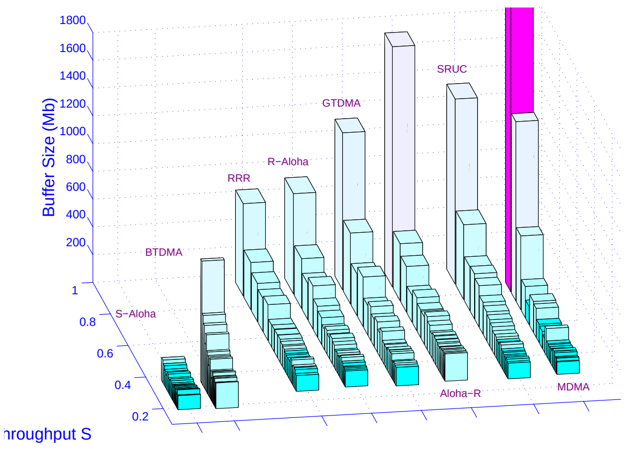

Figure 8. Maximum buffer performance

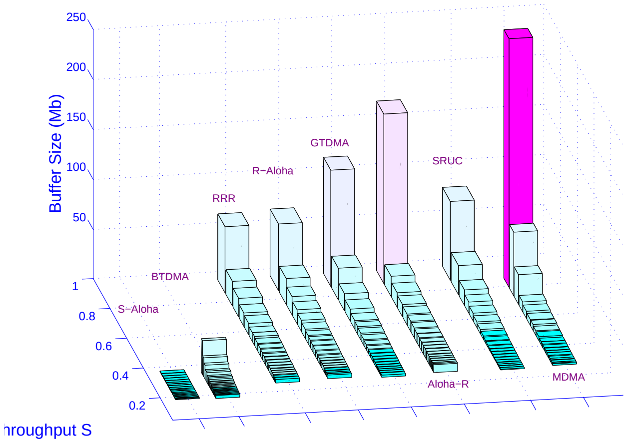

Figure 9. Average buffer performance

Table 2. Relation between traffic models and MAC choices

Traffic Model	MAC class choice
Nonbursty users	Fixed assignment
Bursty users, short messages	Pure Contention
Bursty users, long messages, and large number of users	Reservation protocols with contention
Bursty users, long messages, and small number of users	Reservation protocols with fixed TDMA reservation channel

is also adaptable to changes in number of stations and traffic patterns.

Among the adaptive protocols, the SRUC protocol gives a very good throughput versus delay characteristic with relatively good buffer performance. It is alway stable since all colliding packets are retransmitted in the reserved state. It is also adaptable to traffic load and topological changes. For higher burst factors the SRUC is superior to all other protocols investigated in this report. The complexity of the control algorithm is similar to the complexity of Aloha-R protocol.

The MDMA protocol, that is proven theoretically to provide minimal delay [59], generally does not perform better than the SRUC protocol. The reason is that the MaRNet traffic is neither Poisson nor symmetric, while this protocol has been designed for Poisson traffic. Although it is adaptive, the control mechanism of the MDMA protocol is very complex, and it requires a significant amount of processing capability at each node. The parameters f_1, f_2, and a have to be calculated before each transmission.

5 conclusions

Despite the fact that there is no protocol that performs better than the others for different traffic scenarios and different applications, some protocols have certain characteristics that make them more suitable for satellite communications. In general, hybrid protocols that take advantages of both random access and reservation protocols have better throughput versus delay characteristics. They can also adapt to the network dynamics such as scalability and reconfigurability. For the protocols studied for the MaRNet, G-TDMA protocol would perform better than the others in a highly static environment. This is due to the fact that the assignment of the shared bandwidth can be tailored to the traffic load for each station. However, G-TDMA is not suitable for unpredictable traffic. For asymmetric traffic SRUC would be superior. Both G-TDMA and SRUC protocols are highly stable. However, G-TDMA has low degree of scalability where SRUC protocol is scalable and adaptive to traffic patterns and topological changes. The relation between traffic models and MAC choices are summarized in Table 5. The performance of these protocols are summarized in Table 3. This table is based on the assumption that the traffic is bursty and asymmetric.

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Table 3. Performance Comparison

Protocol	Ave. Throughput	Mean Delay	Stability	Scalability	Reconfigurability	Cost/ Complexity
B-TDMA	low	low	high	No	No	med
G-TDMA	high	low	high	No	low	med
S-Aloha	low	very low	low	Yes	high	low
R-Aloha	high	very low	med	Yes	high	low
Aloha-R	high	med-high	med	Yes	high	med
RRR	high	very low	med	Limited	high	med
SRUC	high	very low	high	Yes	high	high
MDMA	high	high	low	Yes	high	high

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