ABSTRACT

Title of Thesis: ON-DEMAND MULTIPLE ACCESS FOR NEXT-GENERATION NASA MISSIONS

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There is considerable interest at this time in developing small satellites for quick-turnaround missions to investigate near-earth phenomena from space. The aim of the thesis is to investigate issues related to the migration from current Pre-planned Multiple Access operation mode to the next generation on-demand mode focusing on spacecraft in near earth orbits. In this thesis, an evolutionary on-demand mode network architecture is proposed. One of the most important design issues is the development of medium access control (MAC) schemes. For this new scenario, to meet the objective of the bandwidth-efficient support while guaranteed specific QoS requirements, a detailed investigation of the suitability of the MAC schemes is performed. Performance measures of interest include end-to-end delay, successful throughput and channel efficiency. The general protocol investigation framework is first given. Reservation-based Demand TDMA protocol is proposed for the dynamic

LEO scenario. Performance evaluations are performed by means of simulation. We compare the system's performance under Reservation-based demand-assigned multiple-access channel allocation schemes with that obtained under fixed-assigned scheme. Simulation results demonstrate that on-demand mode is a suitable strategy for next-generation NASA space mission with unpredictable traffic pattern, and can offer certain performance advantages.

ON-DEMAND MULTIPLE ACCESS FOR NEXT-GENERATION NASA MISSIONS

by

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DEDICATION

To my family and my husband Xin Li

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Chapter 1: Introduction

1.1 Motivation and Significance

There is considerable interest at this time in developing small satellites for quick-turnaround missions to investigate near-earth phenomena from space [1]. NASA has conducted and is developing a large number of missions of this type for Space Science and Earth.

In the current mode of operation, missions have a limited communication capability (limited bandwidth), mission operation is done using a static, pre-planned concept and mainly rely on TDRSS, the NASA relay satellites, for data relay to the ground. There is also a heavy reliance on custom-developed communication protocols and technology. However, the number of active NASA missions is increasing and communication requirements are exploding, quickly reaching a data transfer requirement in the range of Gigabits/s. Control of assets in Space will become automatic/decentralized (distributed spacecraft (constellations), addressable instruments, etc). Also, current deployment of technology and commercial Internet infrastructure on the ground vastly outpaces the NASA infrastructure.

As the NASA network evolves, it would be required to support large numbers of single or constellation spacecraft with IP-addressable instruments. Mission Operation will gradually evolve to a dynamic concept and use both NASA & commercial assets for communication support and direct-to-ground as well as GEO relay solutions. Commercial technology and standard communication protocols would also be employed (where possible).

One problem to be addressed in such Low Earth Orbit (LEO) mission planning is the development of the means of communications between the control infrastructure in the ground segment and the satellite in the space segment. A nominal small-satellite mission design often includes an omni-directional or similar wide pattern antenna on the satellite and a dedicated ground station for telemetry, tracking, and command (TT&C) support. These terminals typically provide up to 15 min of coverage during an orbit that is within the visibility of the ground station. However not all orbits will pass over the ground station so that coverage gaps will exist in the data flow [1].

1.1.1 Evolution from Pre-planned Mode to On-demand Mode

Starting from existing infrastructure it is possible to move to an IP compliant pre-planned operations mode for next-generation NASA Missions. However, in order to take full advantage of IP flexibility that would support “anytime, anywhere” access on-demand operations mode becomes necessary. As network size (number of spacecraft) grows the need for on-demand mode becomes greater. As shown in Fig.1, in next-generation NASA space network, a Principle Investigators (PI), which is connected to Core Internet via high-speed terrestrial links, can access his instrument to set control parameters or retrieve data as desired “any time any where”. If connectivity is not available, network returns “subscriber not in service” message similar to wireless services.

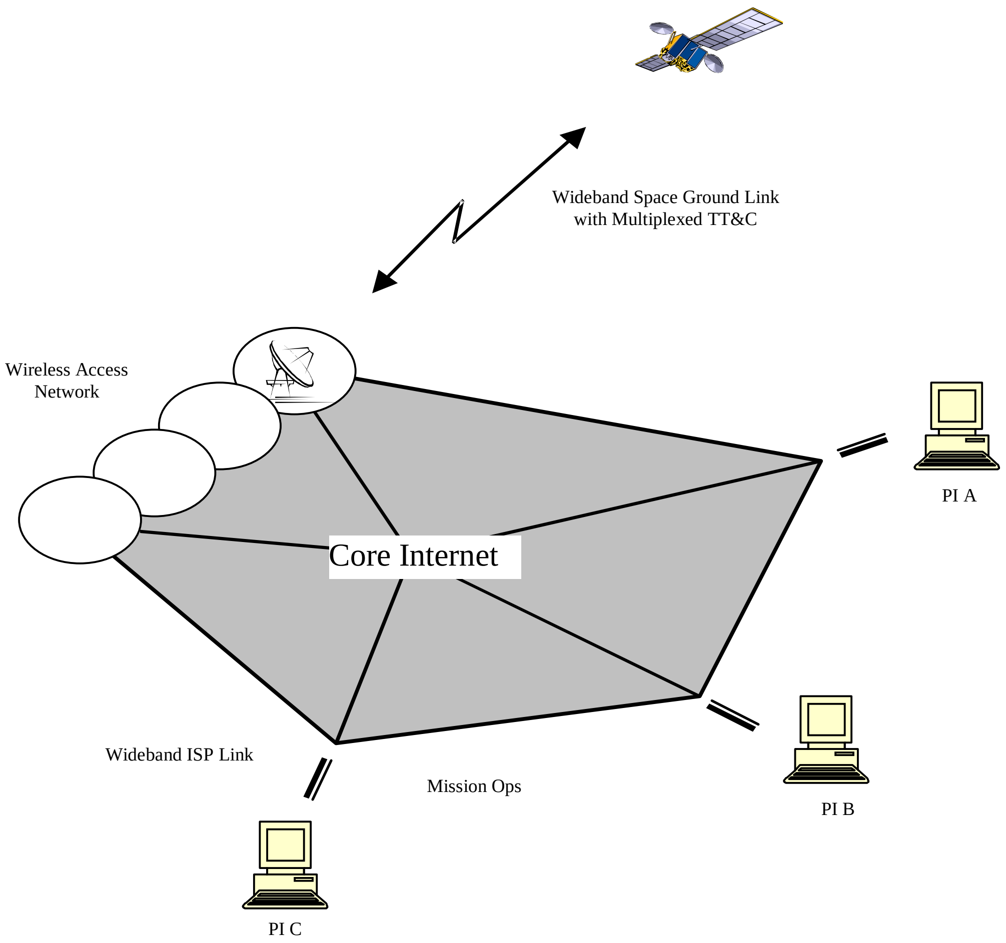


Figure 1.1: On-demand scenario for next-generation NASA Space Missions

Clearly, we need to define a new type of QoS for this unique scenario that the Multiple Access is required to address. Fig. 2 shows the concept of bandwidth allocation under time constraint. Users (spacecraft) are visible by a ground station for a limited time window. Therefore, we have another dimension added to the dynamic allocation problem: dynamic allocation of capacity under a time constraint. A user, such as Spacecraft 1, will have no use of any bandwidth allocated by the Ground Station if this happens after it has moved outside its coverage area.

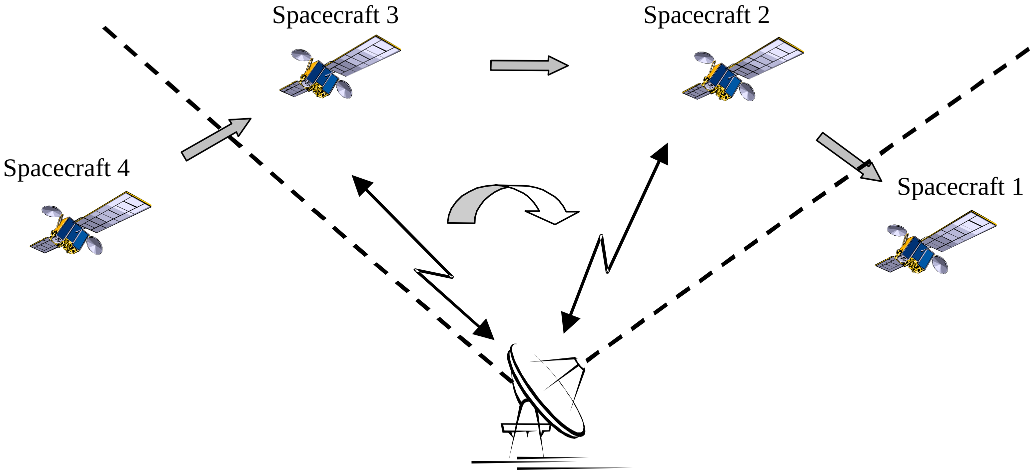


Figure 1.2: New type of QoS for Space-Ground communication scenario

In this space-ground communication scenario, an efficient, robust multiple access technique is needed, especially as number of data sources and associated data volumes increase. The aim of the project is to investigate issues related to the migration from current Pre-planned operation mode to the next generation on-demand mode focusing on spacecraft in near earth orbits. Our main objective would be to propose an evolutionary on-demand mode architecture, which means we must investigate the complexity/performance tradeoff to improve the functionality of the system, while being backwards compatible with the pre-planned mode system. The most important protocol design issue concentrates on medium access control (MAC) schemes.

Similar to pre-planned operation mode, on-demand mode requires multiple spacecraft sharing access to ground station. A priori bandwidth allocation is still based on advance requests/scheduled passes over certain position. At the same time, we can add an option for dynamically assigned additional bandwidth (either piggy-bagged to a priori reservation) or available on demand as spacecraft enters coverage of ground station. The advantages of on-demand mode lie in potential to support more efficient channel utilization, accommodated emergencies, faster access to data, larger number of users. However, it is a more complex implementation, which requires signaling channel, careful time coordination necessary and more complex hardware/software on-board. Moreover, QoS guarantee is the main concern due to the long propagation delay and satellite mobility in the dynamic satellite environment. [2]

1.1.2 Significance of Suitability Investigation of On-demand Operation

Our goal is to utilize the radio resource more efficiently by developing on-demand mode multiple access (MA) schemes. Meanwhile, for the mobile satellite network the QoS guarantees are essential. A large number of papers on MA techniques ranging from pure random access to totally coordinated dynamic assignment access have appeared in the literature [3, 4, 5, 6]. However, traditional MA schemes are not suited well to satellite channel due to the long propagation delay, which causes the user to have to wait considerable time to receive an allocation for every request. Satellite networks present a lot of challenges related to quality of service (QoS) provision. The long propagation delay may degrade the on-demand mode delay performance seriously. For this new scenario, we must investigate the suitability of on-demand operation in mobile satellite network environment before developing the MAC protocols.

Our objective is to analyze the impact of using on-demand mode for Multiple Access Problem for the LEO satellite network scenarios. Based on the examination of the performance of on-demand schemes compared with that of the pre-planed schemes, an efficient multiple access technique can be developed that can support the on-demand operational modes discussed above to address these unique network topology & QoS requirements.

1.2 Contribution of this Thesis

This thesis focuses on the framework design and MAC protocol performance investigation for next-generation of NASA Mission. Contribution of the thesis are listed as follows:

- Proposed centralized on-demand network architecture for next-generation NASA space mission in near orbit earth. (Chapter 2)
- Implemented fixed-assignment TDMA scheme for pre-planned mode in OPNET. (Chapter 4)
- Proposed and implemented Reservation-based Demand TDMA (RD-TDMA) scheme for the new scenario of next-generation NASA space mission in near orbit earth. (Chapter 4)
- Investigated the delay-throughput-utilization performance difference between pre-planned mode and on-demand mode for next-generation NASA space mission in near orbit earth. (Chapter 5)
- Verified the suitability of on-demand mode for next-generation NASA space mission in near orbit earth. (Chapter 5)

1.3 Organization of the Thesis

This thesis is organized as follows. Chapter 2 describes the characteristics and support requirements of the mobile satellite network that we are considering. The proposed on-demand mode network architecture is presented. Chapter 3 presents an overview of MAC schemes for MAC protocols with QoS for satellite network and evaluates their merits. Chapter 4 proposes an RD-TDMA protocol for on-demand mode and implements the protocol using OPNET software. Chapter 5 emphasizes the investigation of the suitability of the dynamic MAC scheme to our LEO scenario by demonstrating and comparing the performance simulation results of the two modes Finally, a summary and suggestions for future work are given in Chapter 6.

Chapter 2: Framework of On-demand Mode Investigation

2.1 On-demand Mode Behavior Analysis

Channel utilization/ Delay characteristics are the main performance measures in evaluating different MAC schemes. Before investigation the suitability of on-demand mode to our LEO scenario by simulation, we try to analyze the on-demand mode behavior by comparing with pre-planned mode from the following aspects:

- From the point of view of TDMA frame efficiency;
- From the point of view of end-to-end delay scheduling.

2.1.1 TDMA frame efficiency

A practical measure of the efficiency of the Demand TDMA system is the ratio of the time devoted to transmission of information bits in the frame to the total frame length. [1] This frame efficiency η is defined as:

$$\eta = 1 - \quad t_i \big/ T_f$$

To simplify the calculation, we assume that the guard time and preambles are neglected here. Where is the sum of all the time not used for transmission time, i.e. empty time slots. T_f is the frame period.

To improve the efficiency, one way is to enlarge the T_f ; the other way is to decrease the sum t_i . The former way requires large buffer capacity. It also increases transmission time delay, especially in satellite scenario. Details will be discussed in section 2.1.2. The latter way implies shortening the empty time slots. Note that there are two reasons for empty time slots:

- as a result of traffic unbalance, which means the traffic load is unevenly distributed among different slots;
- as a result of non optimum time slot assignment.

We will discuss the influence of the traffic load distribution among different spacecrafts to MAC scheme performance in Chapter 5. In this section, we focus on the discussion of optimum time slot assignment.

Current Operation mode for NASA Mission is done in a Pre-planned mode, i.e., a priori bandwidth allocation is based on advance requests/scheduled passes over certain position.

Similar to pre-planned operation mode, our proposed on-demand mode for this scenario requires multiple spacecraft sharing access to ground station. A priori bandwidth allocation is still based on advance requests/scheduled passes over certain position. At the same time, we can set aside an option for dynamically assigned additional bandwidth (we call it *available slot*s) for either piggy-bagged to a priori reservation or available on demand as spacecraft enters coverage of ground station or emergency request.

From the above comparison of the two different slot assignment strategies, we can see that frame structure of the preplanned mode is fixed during a period of time. That is why it may lead to low link efficiency since channel capacity can be wasted when no traffic is presented during the satellites' assigned time slot. However, on-demand mode can improve the efficiency of link utilization by utilizing the *available* *slots*. The wasted slots in the previous frame can be allocated to the other active satellites based on their dynamic requests.

By *on-demand behavior*, we mean the approaches based only on reaction to the offered traffic request (residual traffic request, emergency traffic request and network size change information). The frame structure can even be optimized on frame-by-frame basis based on the traffic reservation requests. The flexibility of on-demand mode leads to optimum time slot assignment. In the next section, we will discuss the end-to-end scheduling mechanism of on-demand mode.

2.1.2 End-to-end Scheduling

In on-demand mode, the frame structure can be optimized on a frame-by-frame basis. In addition, the spacecraft can make reservation to send traffic on the previous wasted time-slot. Thus the on-demand dynamic approach allows for flexibility, i.e., the spacecraft can send traffic by utilizing different number of time-slots and different position in each time frame. However, this solution adds complexity to the scheduling and requires additional network traffic due to the reservation phases. The distinction of the timing diagram of the two modes is shown in Figure 2.1 and Figure 2.2. The total delay T for pre-planned mode is

$$T = T_{propagation} + T_{transmission} + T_{queuing}$$

While the total delay for on-demand mode is as follows:

$$T = T_{reservation} + T_{propagation} + T_{transmission} + T_{queuing}$$

We can see that there is a unique delay component in on-demand mode, reservation delay. The reservation delay is at least twice of the RTD, since the spacecraft sends the reservation request in the first RTD and can get the reservation acknowledgement in the second RTD. Only after that can it begin to transmit data traffic. The detail analysis of the reservation delay component will be presented in Chapter 5.

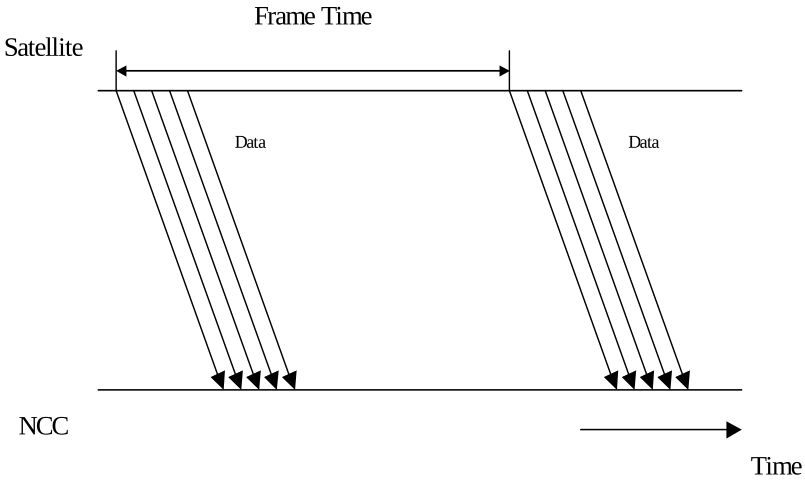


Figure 2.1: Timing diagram of Pre-planned mode

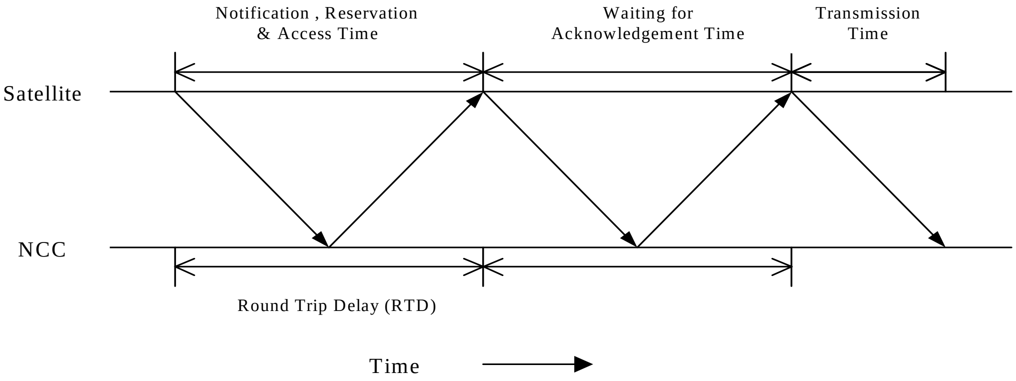


Figure 2.2: Transmission of a packet using on-demand mode

2.1.3 Design Objective

An important question arises on whether the proposed on-demand mode operation is a better solution for the unique scenario to address these unique topology & QoS requirements. A detailed examination of the suitability of on-demand mode to the scenario needs to be present at first in the following senses:

- In the sense of exploiting the utilization/delay performance tradeoff of on-demand mode
- In the sense of exploiting the tradeoff between performance/complexity of different operation modes.

Our objective is to analyze the impact of using on-demand mode for Multiple Access Problem for the LEO satellite network scenarios. Based on the examination of the performance of on-demand schemes compared with that of the pre-planed schemes, an efficient multiple access technique can be developed that can support the on-demand operational modes discussed above to address these unique topology & QoS requirements.

2.2 System Configuration

In this work, we will focus on the spacecraft topology scenarios and on providing dynamic bandwidth allocation and guaranteed QoS services. Figure 2.3 below illustrates the proposed centralized satellite network architecture.

The considered network scenario consists of several spacecraft generating different types of traffic and a Network Control Center (NCC) in the Ground Station with uplink/downlink processors that receives data traffic from downlink, collects channel reservation requests from the control links, schedule the bandwidth allocation under QoS guarantees and controls the Multiple Access operations of the satellite network.

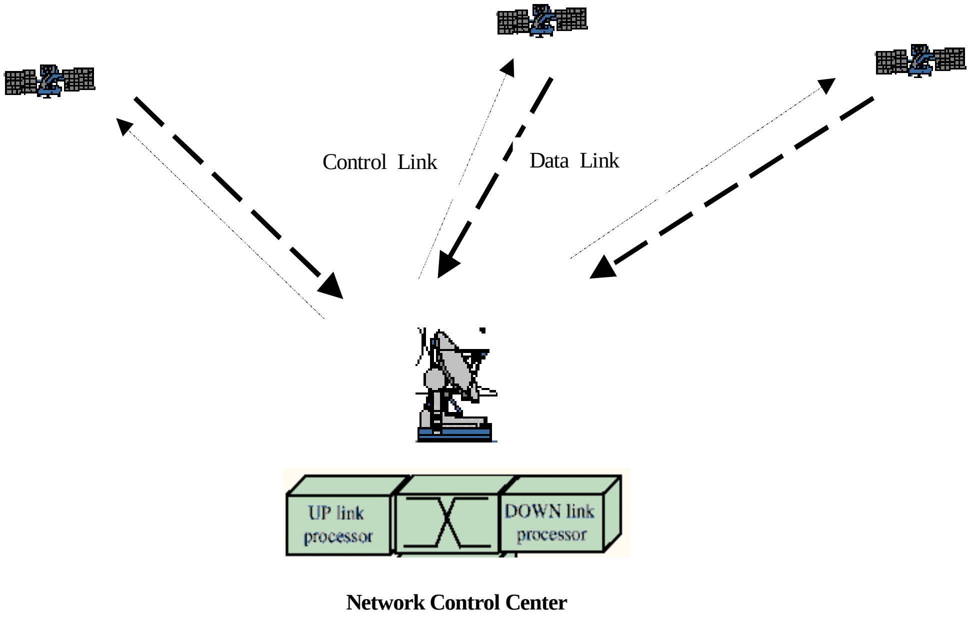


Figure 2.3: Centralized satellite network architecture

2.2.1 Network Support Services

In this space-ground communication scenario, an efficient, robust multiple access technique is needed especially as number of data sources and associated data volumes increase. The following requirements for Multiple Access protocol must be satisfied. It must

- Enable multiple spacecraft to share common link to same Ground Station;
- Provide required QoS/availability guarantees for different classes of traffic (TT&C, Scientific Data Request, other priorities);

- Handle mobility of spacecraft (“mobile platform”);
- Take advantage of special architecture (limited number of users, predictable mobility).

2.2.2 Uplink and Downlink

Uplink is the control link, which is operated in TDM broadcasting mode. The channel assignment information and reservation attempt results information (reservation being accepted or denied). The downlink is the data transmission link, which is much larger than the uplink. The design of multiple access for the downlink is the focus of the thesis.

2.2.3 Traffic

The traffic considered in this thesis is mostly non-real-time traffic, consisting of short file (instrument status data or temperature readings, etc.) and long file (large images, etc.). Details of traffic modeling will be discussed in Chapter 5.1.3.

2.3 Framework of On-demand Multiple Access Schemes over Satellite Link

We list four considerations for the mobile satellite network architecture design and protocol selection.

- NASA space mission network service support requirements
- Cost/complexity/performance tradeoff
- Coordination between satellite and terrestrial infrastructure
- Reusability of pre-planned mode network facilities and current MAC schemes

2.3.1 *Hierarchical Design Phases*

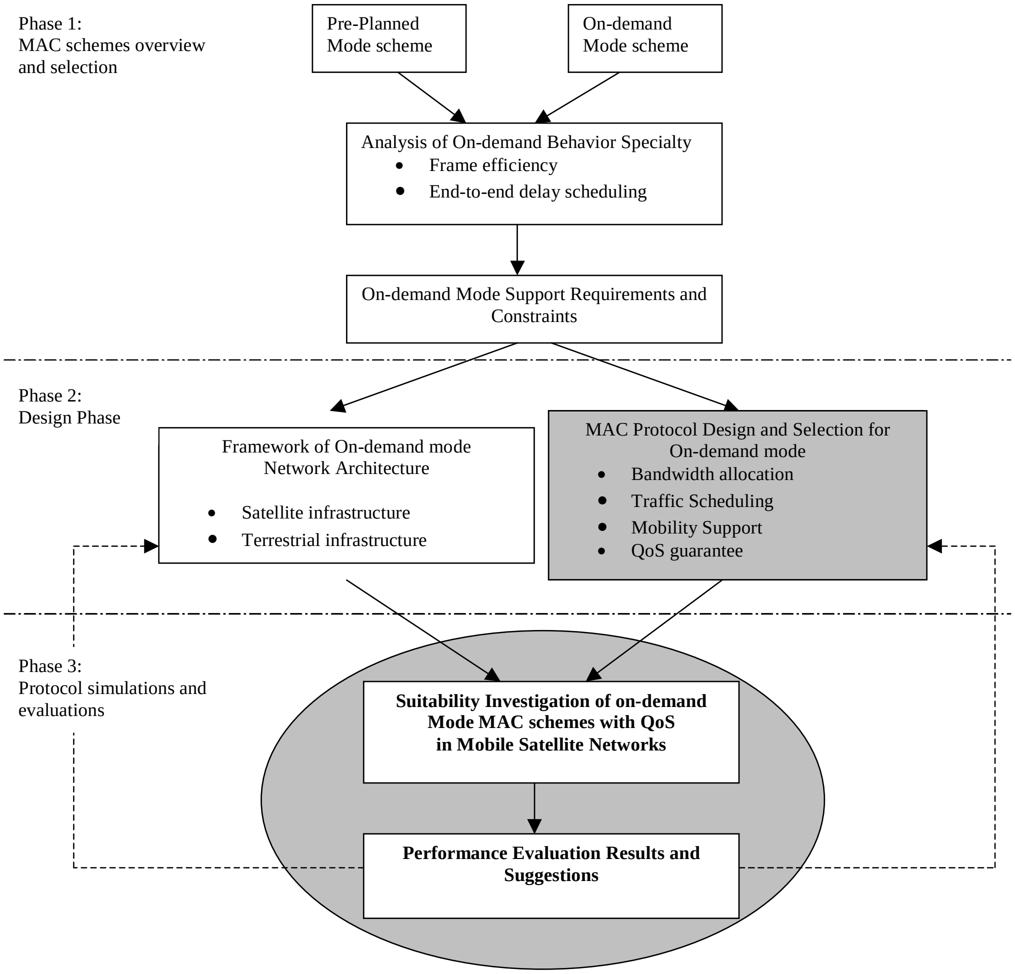


Figure 2.4: Framework of hierarchical design phase

As shown in Figure 2.4, the on-demand mode study is divided to three phases, in which the shaded areas are the focus and contribution of this thesis:

- MAC schemes overview and selection phase
- Design phase
- Protocol simulation and evaluation phase.

2.3.2 On-demand Mode Protocol Design Framework

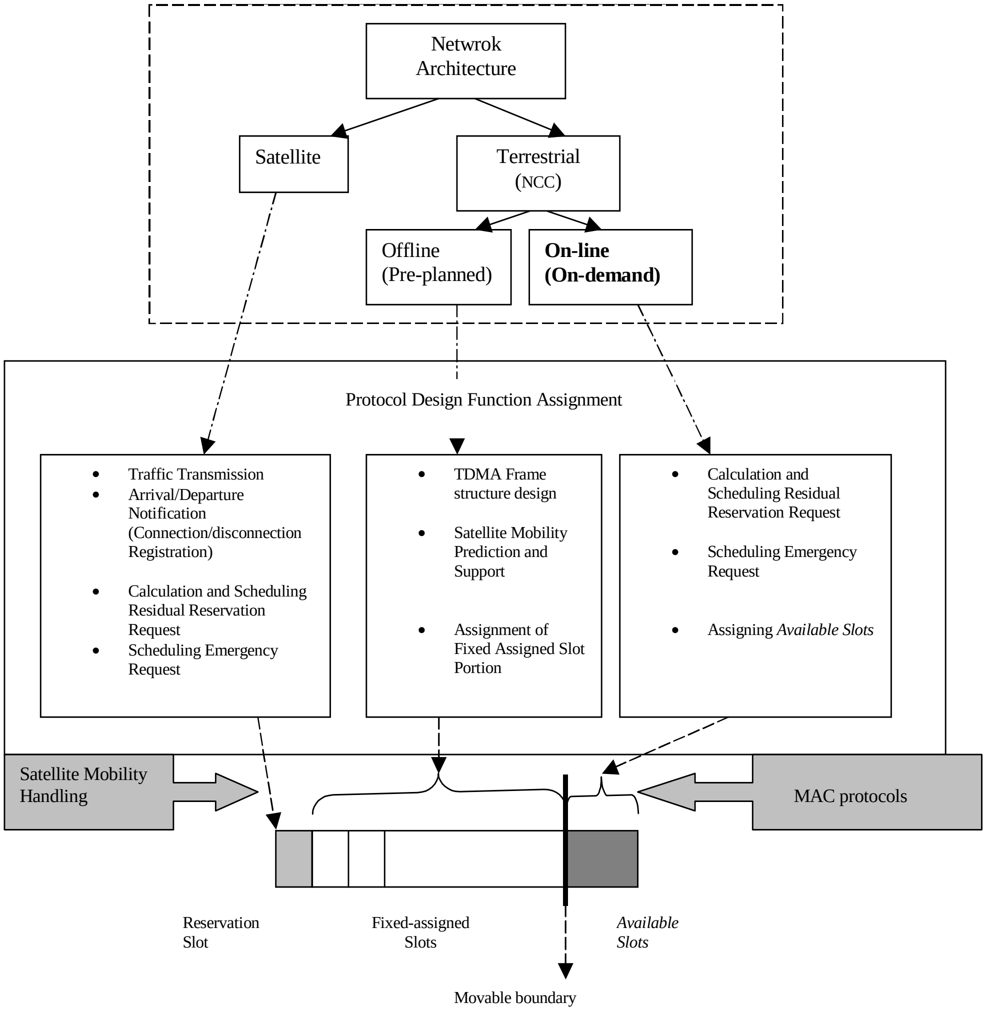


Figure 2.5: On-demand mode protocol design framework

As shown above, the protocol functions have been assigned to different network entities. The shaded arrows represent two focuses of on-demand mode design: (i) Satellite mobility handling is implemented by satellite, which means the satellite should be responsible for connection/disconnection establishment when arrival/departure of the ground station's coverage; (ii) MAC protocol is developed to efficiently utilize the satellite channel meanwhile to guarantee the QoS requirement.

2.3.3 Suitability Investigation Framework

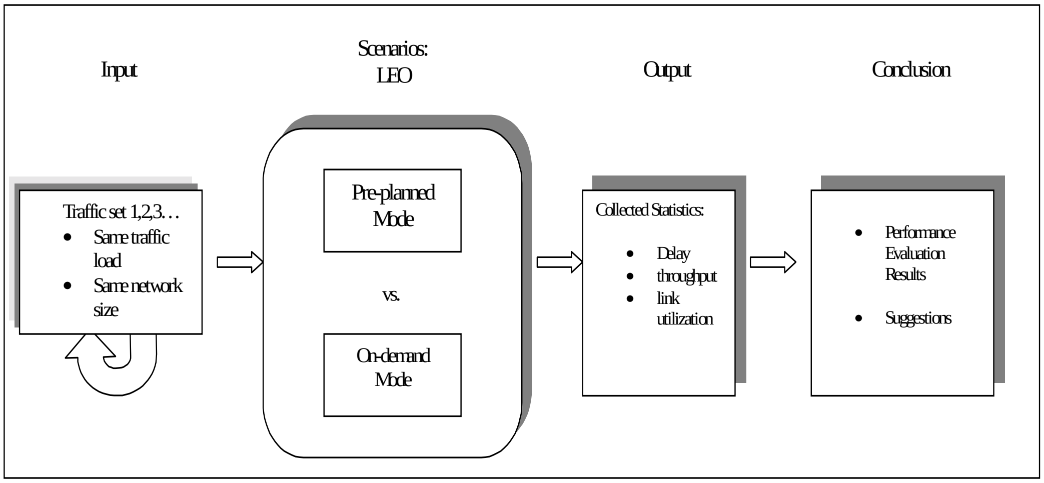


Figure 2.6: Suitability investigation framework

As shown in Figure 2.6, by changing different traffic sets, we compare the performance of pre-planned mode and on-demand mode in different scenarios. Based on the simulation results and analysis, performance evaluation results and recommendations are given.

Chapter 3: Overview of Multiple Access with QoS for Space Missions

The space segment of most near earth NASA Space Mission communication systems consists of non-GEO satellites; in particular Low Earth Orbit (LEO) spacecraft, which are characterized by relatively low propagation delays and low propagation attenuation [2]. The main problem in using MAC schemes in a LEO satellite system is the inherent Round Trip Delay (RTD) that typically varies from 5 to 30 ms, depending on the satellite constellation altitude and the minimum elevation angle acceptable by ground stations for reliable communications. It is obvious that in this environment, with the non-negligible delay and extremely limited bandwidth, the MAC schemes will considerably affect the performance of the system.

In this chapter, we will present an overview of the existent MAC protocols and evaluate their merits. Our objective is to propose a suitable MAC scheme for our unique LEO network scenario based on the evaluations.

3.1 Multiple Access and Multiplexing

Our LEO satellite network scenario is reverse to the traditional space-ground communication scenario, such as Internet access using VSAT [9, 10]. In the direction from the Ground Station (GS) to the spacecraft users, the communication channel is one to many, or a broadcast channel. In the direction from the spacecraft users to the GS, the communication channel is many to one, or a multiple access channel. Transmitting data from a single hub station to a large number of remote terminals (the broadcast channel) is a relatively simple problem. This channel architecture is almost always configured in a simple time-division multiplexed (TDM) mode. Transmitting data from large numbers of remote terminals to single hub (the multiple access channel) is a much more challenging problem. The choice of the multiple access schemes has a great impact on the performance of the LEO satellite network. It should match the traffic load of the network and be able to satisfy the users' quality-of-service (QoS) requirements.

While FDMA, TDMA, and CDMA are the three "classical" multiple access techniques, two others should be mentioned. Space-division multiple access is one of them; it is based on a simple idea: by using separate beams, a single frequency can be used simultaneously by several users [11]. Since the thesis focuses on TDMA schemes, we will introduce TDMA schemes in detail.

In time-division multiple access (TDMA), users are assigned positions in a quickly-repeating schedule for transmitting on a common frequency to the satellite. The abilities of buffering digital data and maintaining tight synchronism have rendered TDMA a practical access technique. TDMA requires synchronization among all LEO spacecrafts so that their downlink signals all arrive at the ground station at the correct instants. In a TDMA system, the time slot plan can be changed dynamically to accommodate varying demands.

3.2 Different Choices of MAC Schemes for Space Missions

Satellite communications have evolved with respect to the use of limited satellite channel capacity. There are a number ways the satellite bandwidth can be allocated, and the service the network must provide determines which is the best choice. There are also other factors that affect the choice of allocation scheme, such as the complexity of implementation and the network architecture. The most important evaluation criteria of MAC protocols are efficiency in space capacity utilization, delay/throughput characteristics and cost/complexity for implementation.

For the mobile satellite networks we consider here, the network topology changes frequently, so the MAC techniques must be more flexible for efficient shared radio resource utilization. Especially when there are a large number of bursty stations in the system, traffic tends to be unpredictable and conventional fixed assignment results in low link utilization and a larger packet delay. In order to propose a suitable MAC scheme for our on-demand mode network architecture, we first introduce the important MAC protocols and then evaluate them in terms of above evaluation criteria.

In this chapter, the “connection” means the stream of data packets of a particular traffic connection in application level. The “lifetime” means the duration for a particular satellite from its arrival to its departure in the coverage of the ground station.

The access techniques to the shared radio medium can be classified in various ways according to their characteristics. According to the way they are used to set up connections they could be classified in four types:

- Random Access or Contention;
- Fixed Assignment;
- Demand Assigned Multiple Access (DAMA)[7, 8];
- and Free Assignment.

By “*on-demand*” mode, we mean the latter three schemes or the combination of fixed assignment and the latter three schemes in which reservation is involved, while the first fixed-assignment scheme with no reservation is implemented by the current pre-planned operation. Therefore, we will introduce the MAC schemes with the respective characteristics, i.e., with or without reservation.

3.2.1 Fixed Slot Assignment Strategy

Downlink access can be performed by fixed assignment techniques. Users are assigned a priori a constant number of slots, codes or frequencies. Static TDMA, FDMA and CDMA belong to this category. With fixed assignment, a satellite’s connection is permanently assigned a constant number of slots per frame (or some multiple number of frames) for the lifetime of the satellite. This means that when the connection is idle, the slots are not utilized (wasted). The fixed slot assignment strategy is very suitable for cases where traffic flow are predictable and demand remains unchanged. However it has two obvious disadvantages: (i) it is inefficient if there is no constant traffic flow, as slots are wasted when user has no traffic to send; (ii) As number of supported spacecraft increases it will be difficult to support them with limited bandwidth.

3.2.2 Reservation-based slot assignment strategies

In order to utilize the wireless channel capacity more efficiently, random access protocols and reservation protocols have appeared in the literature. [12, 13] Random access or contention techniques such as Aloha and its variations [14] (e.g. Slotted Aloha) have been used for networks of large numbers of users carrying narrowband bursty traffic. Users transmit without checking the channel's status and simultaneous transmissions result in "collisions" and retransmissions. However, contention techniques have reasonable throughputs only at low traffic. Drawback of random access is low utilization. It cannot provide any bandwidth guarantee required to ensure acceptable QoS.

In reservation schemes such as Robert’s reservation ALOHA [15], a fraction of the channel capacity is allocated for the transmission of reservation packets. Although reservation schemes waste certain channel capacity in the transmission of reservation information, they are more efficient than fixed assignment and random access schemes, at least at medium and high throughput ranges [12]. A disadvantage of all reservation schemes is the necessity to transmit reservation packets, which tends to increase the total delay. This increase in packet delay is particularly significant in a satellite channel where the ratio between propagation delay and packet transmission time is large.

Conceptually, a strategy that combines random access and reservation access would offer an improved delay-throughput performance. Many MAC access schemes and their variations have been proposed for better utilization of a wireless link, such as CRRMA [12], D-TDMA (dynamic time division multiple access)[16], PRMA (packet reservation multiple access)[17, 18, 19, 20, 21, 22], RAMA (resource auction multiple access)[23, 24], and DRMA (dynamic reservation multiple access)[25]. In all of these schemes, a certain amount of bandwidth is reserved for sending reservation packets or detecting collisions. They mainly differ in the manner by which the bandwidth is allocated for reservation or collision packets. Most of the above MAC schemes were initially proposed for terrestrial micro cellular networks or packet switch broadband satellite networks where they exhibited very interesting features such as high efficiency, dynamic bandwidth allocation and transparent behavior with respect to user mobility [9, 26,27, 28, 29, 30, 31, 32]. These protocols are flexible and efficient in bandwidth utilization. They are possible for QoS guarantee. However, they are complex in implementation.

Demand assignment (DA) allocates slots on an as-needed basis. There are two types of DA: fixed-rate and variable rate DA. With fixed-rate variety, a connection is assigned a fixed number of slots per frame (or some multiple number of frames) for the duration of the connection. Like the fixed assignment scheme, if the source is idle, the slots will be wasted. So, the fixed-rate DA and fixed assignment schemes are the same except that one is for the duration of a connection while the other is for the lifetime of the satellite. This is more flexible than fixed assignment as just described but might still result in wasted bandwidth.

With the variable-rate DA schemes, slots are only assigned when it is known that there are packets awaiting service at the connection’s terminal queue in the particular satellite. This works as follows. When a packet arrives at the terminal queue, signaling messages are sent to the NCC notifying it of the arrival. When the NCC receives this information, it dynamically assigns slot(s) to the connection. Variable-rate DA is a guaranteed assignment scheme in the slots are assigned based on previously allocated bandwidth, which is available for use whenever it is needed. It avoids collisions and efficiently uses the downlink capacity because the NCC is aware of the needs of the source and it responds to the need by assigning slots on a frame-by-frame basis. If the connection does not need a slot, which has been allocated to it during connection establishment, the NCC may assign the slots to others. The drawback of this scheme is the long one-way propagation delay from when the signaling information diagram showing the delays associated with variable-rate DA is given in Figure 2.1 assuming that the processing and queuing delays are small. As can be seen from the figure, the end-to-end delay is always at least Round Trip Delay (RTD). Part of the bandwidth is needed for transmitting the requests to the Network Controller on the ground). Variable Rate Demand Assignment allows dynamic allocation of satellite power and bandwidth based on the changing traffic load of the users [8,12]. It is suitable in bursty traffic, where a significant capacity is required but not for the duration of the connection, and using Single Channel Per Carrier (SCPC) would thus waste valuable bandwidth. Of course using such a scheme implies a system that is more complex and expensive and there are always a number of tradeoffs between improvements in the efficiency of the bandwidth use and the system implementation complexity.

Free assignment is concerned with the remaining slots in a frame, which have not been assigned by the fixed or demand schemes. These remaining slots are the spare downlink capacity that the network can freely assign to connections in order to increase the overall throughput, to relieve congestion at the satellite terminal queues, or to reduce the end-to-end delay.

3.3 Conclusions of MAC protocols Evaluation

Considering the uniqueness of our LEO NASA mission scenario, i.e., the traffic is bursty and unpredictable and the network size fluctuates due to the mobility of LEO spacecraft, we should develop a flexible MAC scheme to be able to adaptive to the unpredictable pattern of networking condition and traffic condition. Under the assumption of unpredictable demands on channel capacity, considerable delay-throughput performance improvements are possible if demand assignment of channel capacity is used [12]. The drawback of the demand schemes, as with all the reservation schemes, is that the additional delay incurred by the request of channel assignment transmissions constitutes a large portion of the overall delay when the propagation delay is large compared to the packet transmission time. In satellite network environment, the propagation delay is in the order of ms and it is not negligible. Therefore, the choice of the "*on-demand*" mode MAC scheme has a great impact on the performance of the mobile satellite network.

Our primary goal in the assignment access is to maximize the utilization of the downlink at the same time to satisfy satellite users' QoS requirements. Conceptually, we need to combine the static-TDMA (S-TDMA) and slotted-ALOHA to meet our design objective. The developed protocol should be reservation-based demand TDMA. It uses slotted-ALOHA for reservation, which can make up with the shortcoming of inflexibility of slot assignment of S-TDMA. At the same time, once the spacecrafts make successful reservations, the system can perform like S-TDMA, which is possible to guarantee QoS requirements. In addition, the proposed MAC scheme should be simple to implement and be able to lower the reservation overhead as much as possible in the satellite environment. We will describe the proposed MAC protocol for on-demand mode in the next chapter.

Chapter 4: Evaluating MAC Protocols for NASA Missions

In this chapter, we first propose Reservation-based Demand-assigned-TDMA (RD-TDMA) protocol for on-demand mode. Then we introduce the detail implementation of the protocol using OPNET software.

4.1 Multiple Access Protocols

Current Preplanned Mode uses Static TDMA (S-TDMA) as MAC access scheme. It is described as fixed-assignment scheme in section 3.2. It is a simple MAC scheme, however it is inefficient in bandwidth utilization under the bursty traffic condition. To meet the design objective of our non-real-time, bursty traffic environment, we proposed Reservation-based Demand-TDMA (RD-TDMA) Protocol based on the combined Reservation/Demand MAC protocols discussed in Chapter 3 as our on-demand baseline MAC scheme for next-generation NASA Space Mission. The disadvantage is that the reservation delay overhead is relatively large under a satellite network environment with long distance propagation delay. However, this scheme has two obvious advantages: (i) efficient in bandwidth utilization under bursty traffic environment; (ii) able to accommodate larger number of spacecrafts. These advantages are very important for satellite network due to the fact of the limited and expensive satellite channel bandwidth and the mobility of LEO spacecrafts.

4.1.1 RD-TDMA protocol for on-demand mode

The RD-TDMA protocol can have several channel allocation options as listed below, in an order of increasing complexity: i) The bandwidth is divided into identical sub-channels, and a fixed number of these is allocated for random access and reservation requests while the remaining sub-channels are available for stream traffic connections. The partitions are determined by the expected traffic load.

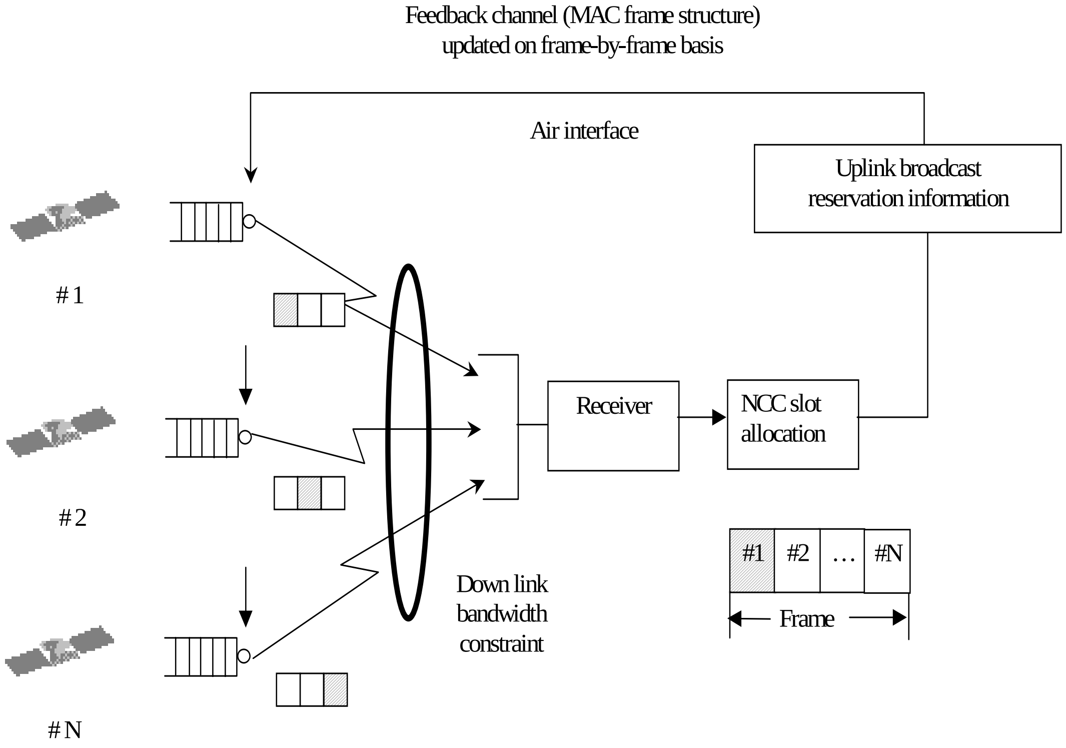


Figure 4.1: Protocol operation diagram of RD-TDMA in satellite network

A special case of this would be to define a single random access channel for reservations and make the rest available for connections. ii) There are no predetermined reservation or data message channels. Reservations take place over multiple channels, and the partition between the channels is dynamically determined according to changes in the traffic load. All channels are identical. iii) Same as before, but message channels are not identical and do not have a predetermined bandwidth. The required bandwidth is reserved for each transmission.

This dynamic access is a reservation scheme that dynamically re-assigns reservation channels for optimum performance. The protocol operation is split in two parts:

- Channel Reservation: Users with long data messages transmit their requests in this part of the protocol. A random access protocol operates and a collision resolution scheme is used to resolve possible collisions of the request packets. The choice of the access scheme could be an important factor in the protocol's overall performance.
- Data Message Transmission: Successful requests enter a global queue (operating in a FCFS mode) for message channels, and when a suitable channel becomes available it is allocated for the duration of the transmission.

4.1.2 RD-TDMA Protocol Operation

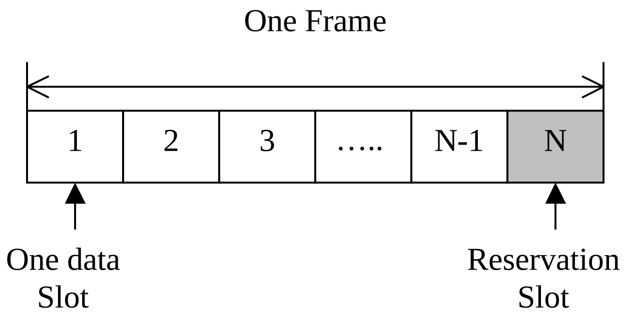


Figure 4.2: Frame structure of RD-TDMA

Due to the consideration of protocol operation performance/complexity tradeoff, we select and implement the simplest version of RD-TDMA protocol as described in the section 4.1.1. This simplified version RD-TDMA protocol utilizes a Slotted-ALOHA (S-ALOHA) access[15, 33] and a Time Division Multiple Access (TDMA) transmission mode on a reservation basis.

The satellite channel of capacity B is subdivided into N equal size channels, each having a capacity B/N. Note that the terms "channel" and "sub-channel" do not necessarily represent frequency allocation. Channel division may take place in either the time or frequency domain, or even using Spread Spectrum techniques. Here, we focus on TDMA scheme. The TDMA frame structure is shown in Fig. 4.2. Note that in contrast to the terrestrial micro-cellular systems where the RTD value is in the order of few ms (hence, we may assume that a terminal immediately knows the outcome of its transmission attempt), in the LEO scenario the RTD is in the order of ms and it is not negligible. For RD-TDMA in LEO, we have considered RTD always equal to its maximum value for a given satellite constellation, RTD_{max} (conservative assumption). Moreover, we have assumed $RTD_{max} = T_f$. Hence, when a user makes a successful transmission attempt on an idle slot it knows the outcome of its transmission before the beginning of the same slot in the next frame.

Downlink channel is divided into N channel, in which the final channel is reservation channel while the other N-1 channel is for data transmission. As we focus on the MAC layer, a message reservation request contains information about the message's origin ID (MAC address) and type (Short Data Message/ long File Transfer). Figure 4.3 shows the logical events interfacing with the RD-TDMA protocol from upper layer and physical layer.

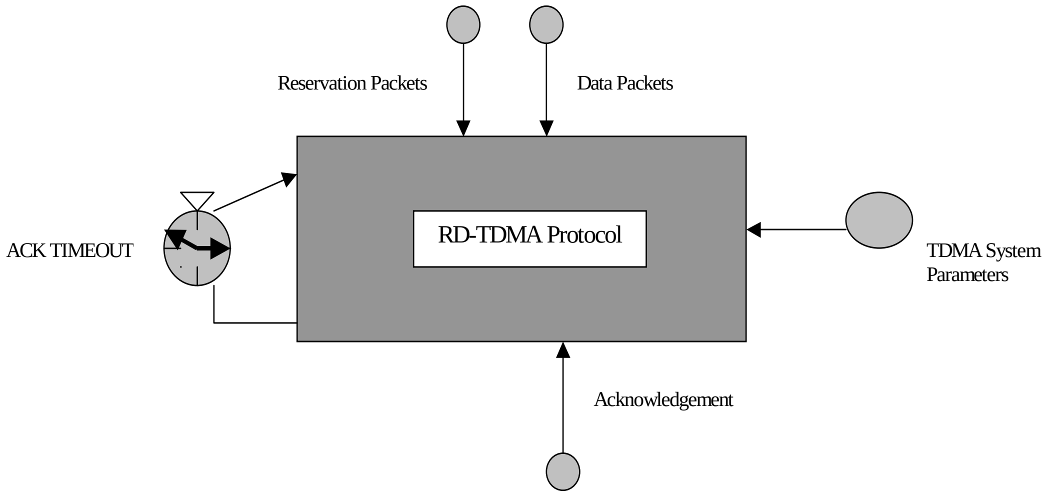


Figure 4.3: Logical events interfacing with RD-TDMA protocol

Table 4.1: Reservation-related logical events in RD-TDMA protocol design

Reservation type		Slot grant request	Slot release request
ACK Response type	Granted	×	×
	Rejected	×	
ACK TIMEOUT		×	×

As shown in Table 4.1, when we design the MAC protocol, we assume that there are two kinds of slot requests: *Slot-grant Request* or *Slot-release Request* and two kinds of ACK response: Granted or Rejected. We also assume all the release requests are not rejected.

The efficiency of the RD-TDMA approach in managing resources relies (i.e., slots of the TDMA frame) on the utilization of silent periods within a connection. During a connection, a satellite transmits one packet (or several packets) per frame on a given slot (or slots), only during an active period. When there is a silent pause, this slot can be destined to another active traffic source (satellite). Therefore, the assignment of time slots to spacecrafts is not fixed, but it is dynamically handled on the basis of the presently active satellites. When a time slot has been assigned to a satellite, it is marked as *unavailable*; otherwise it is *available*. A feedback channel as shown in Figure 4.1 broadcast by the NCC informs the satellites about the state of each slot and about the results of their transmission attempts (if any, *Allocation-Request Granted*, *Allocation-Request Rejected or Deallocation Granted*). Different slot assignment schemes are

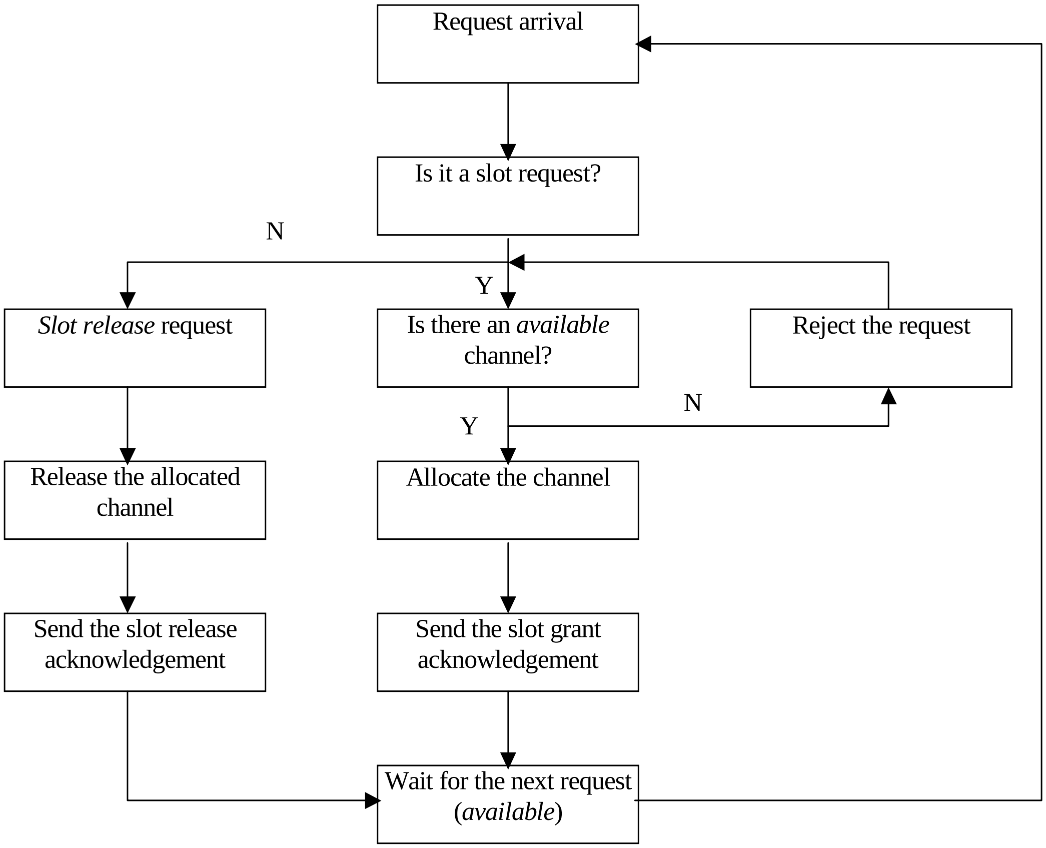


Figure 4.4: Channel assignment scheme in network control center (NCC)

performed in NCC node and spacecrafts. Their slot assignment scheme operations are described as follows:

Slot assignment scheme operation in NCC node:

The NCC assigns the N_d data channels to the user whose reservation request was successful. Its slot assignment algorithm is shown in Figure 4.4.

The NCC identifies the reservation type via the last reservation slot.

1. If it is a slot grant request, it will assign the available slot to the user if there is no reservation collision among different satellites; otherwise it will reject the request.
2. If it is a slot release request, it will grant the slot release request immediately.

Slot assignment scheme operation in satellite node:

Two different activities of satellite node are implemented in different period. Here *active* period stands for a satellite has traffic file to send. *Silent* period means that the satellite has no traffic to send in this period.

- Operation before entering *active* period:

When a satellite has a data message to transmit, it sends a reservation request over the last channel (Reservation Slot) without knowing whether another satellite has sent a *slot grant request* to the Reservation Slot. It then has three options based on the different feedback information from the NCC listed as follows:

1. if slot request is granted, it begins to send data packets in the assigned slot(s);

2. if slot request is rejected, it resends the reservation request after a random period of time;
3. if it has not received any feedback information, with the predetermined *Allocation-Timeout* period, it resends the reservation request after a random period of time.

- Operation before entering Silent period:

Once the satellite has no traffic file to send, it sends a *slot release request* to NCC. If it does not receive *deallocation-granted* request within the predetermined *Deallocation-Timeout* period, it resends the *deallocation-granted* request after a random period of time.

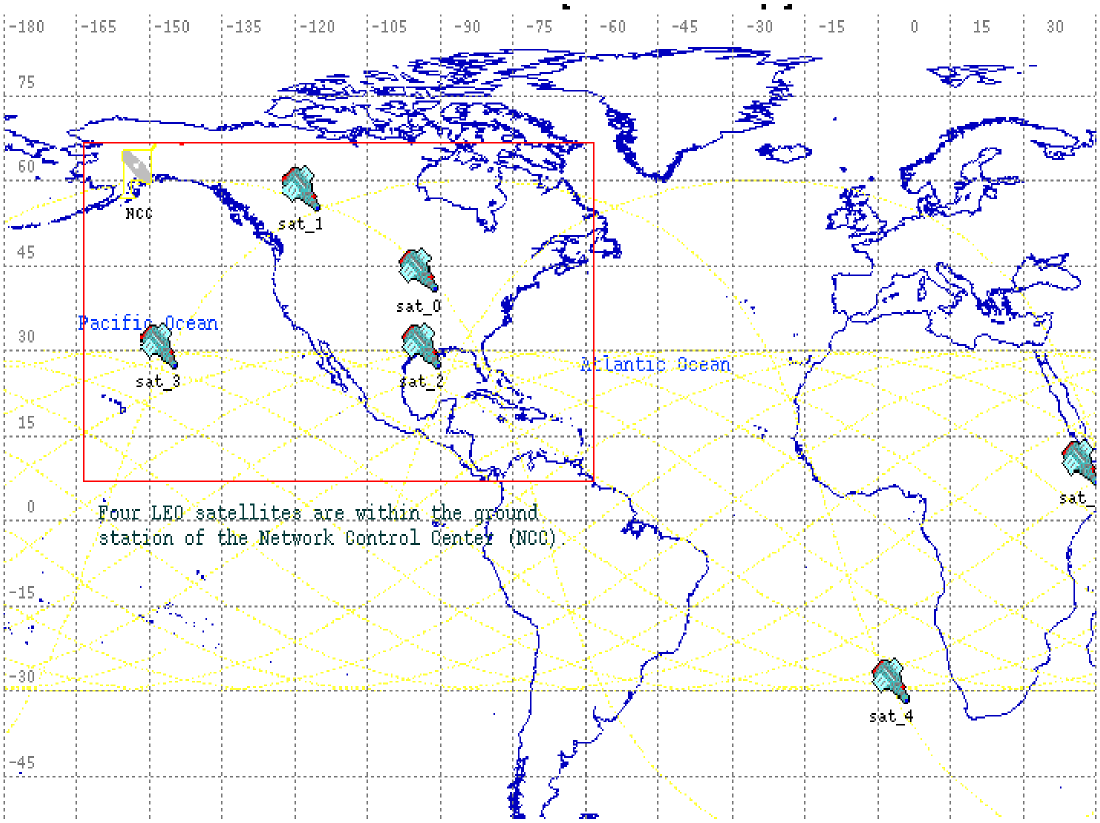
4.2 MAC protocol Implementation using OPNET

Simulation is a very useful tool for performance evaluation of protocols or schemes in network systems. When the system to be characterized is still at the design stage, simulation provides an easy and quick way to predict a new scheme's performance or compare performances of several alternative schemes.

In this work, the OPNET simulator is selected to build the network simulation models. OPNET simulator is event-driven and operates at three hierarchical levels to describe and control the network to be analyzed. These are the network level, the node level and the process level. The network level consists of network nodes connecting each other by links. The node level comprises different function modules inside each network node, for example, traffic generator, packet queue and processor. The actual operations, algorithms or schemes are implemented in the process level.

4.2.1 Network model

Figure 4.5 shows the network level OPNET model used to simulate the satellite network and MAC schemes discussed in previous sections.



Four LEO satellites are within the ground station of the Network Control Center (NCC)

Figure 4.5: OPNET simulation network model

As shown in Figure 4.5, the leftmost *Satellite* nodes within the square are within the coverage of the ground station of NCC. They are responsible for generating downlink traffic, making slot reservation and transmission of packets to downlinks. The *ground station* node does the slot assignment, collecting data packets and simulation results. The node modules for *satellite* node and *ground station* node will be presented in section 4.2.2.

4.2.2 Implementation of MAC schemes

In this section, at first we will introduce the implementation of MAC schemes in OPNET simulation according to the hierarchical levels: the node module level→the dynamic process relationship tree level→ specific key process level. The RD-TDMA slot assignment scheme is implemented in the **sl_alloc** process model which lies in the **TDMA_MAC** module.

OPNET node modules

Our network model in OPNET consists of LEO satellites and a ground station. MAC schemes are implemented in **TDMA_MAC** modules within the *satellite* nodes and *NCC* node. The *satellite* node module is shown in the top part of the Figure 4.6 and their correspondent dynamic process relationship tree for the **TDMA_MAC** module is presented in the bottom part of the figure. In the top part, the upper-level four modules are the composite traffic generator explained in section 5.1.3, which consists of **short_file**, **long_file**, **queue** and **tdma_intf** modules. The bottom level modules are **TDMA_MAC** module, **TDMA_RX** module, **TDMA_TX** module and **ant** module, which are responsible for satellite's MAC protocol operation, data transmission and receiving respectively.

The NCC node module consists of **sink** module, **tdma_intf** module, **TDMA_MAC** module, **TDMA_rx** module and **TDMA_tx** module. They are responsible for NCC's MAC protocol operation, interfacing upper layer with MAC layer, data transmission and receiving respectively.

OPNET Dynamic Process

The RD-TDMA protocol is accomplished by dynamic process capability in OPNET. The dynamic process relationship trees in both *satellite* node module and *NCC* node module consist of the following paths:

- Path 1: **root** →**parent** → **sl_alloc** → **tx_chan_final** process;
- Path 2: **root** → **tx_parent** → **tx_chan** process;
- Path 3: **root** → **rx_parent** → **rx_chan** process.

At the beginning of the simulation, a **root** process is entered, and it will invoke the **parent** process each time when a packet arriving from upper layer of satellites (or NCC). As shown in Figure 4.3, there are two kinds of packets: reservation packets and data packets. If the packet is a data packet, it will follow Path 2 or Path 3 to invoke the next level child process; otherwise, if the packet is a slot reservation packet, it will follow the Path 1 to invoke the **sl_alloc** process to generate slot reservation request (in *satellite* node module) or slot reservation response (in *NCC* node module).and then invoke **tx_chan_final** process to transmit the reservation request/response.

Figure 4.8 presents the cooperation of the two node modules and the direction of slot request/response signal in the satellite RD-TDMA system. There are four kinds of information flow in the whole TDMA system.

- the data transmission signal;
- the downlink reservation signal from satellite;
- the uplink slot response signal;
- and the invocation of child process from parent process in OPNET.

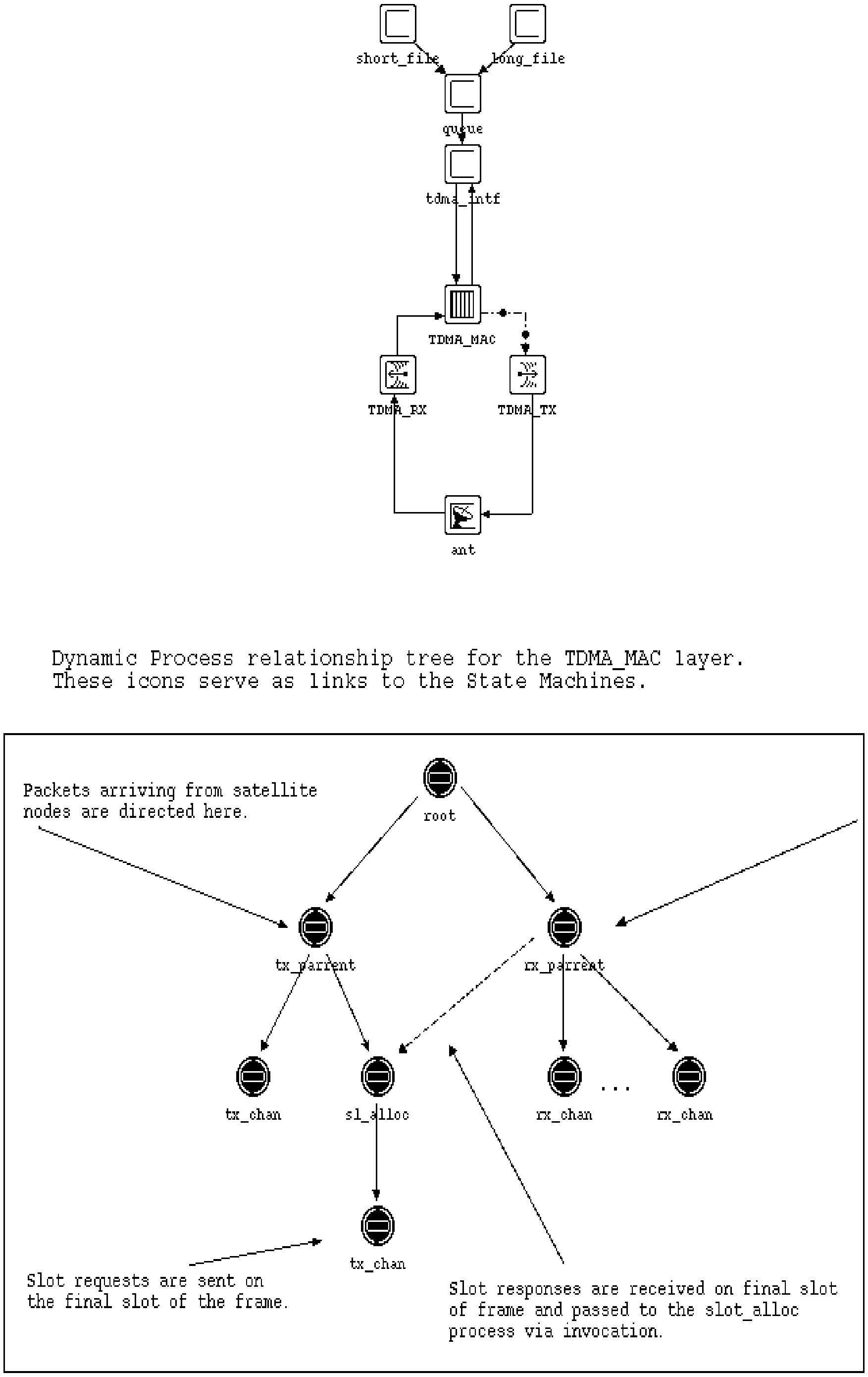
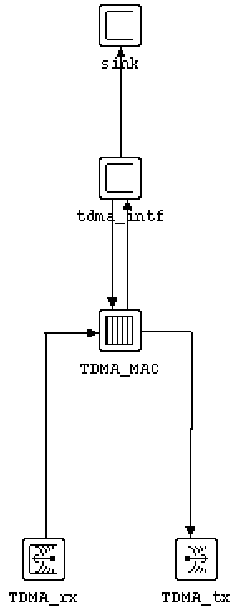
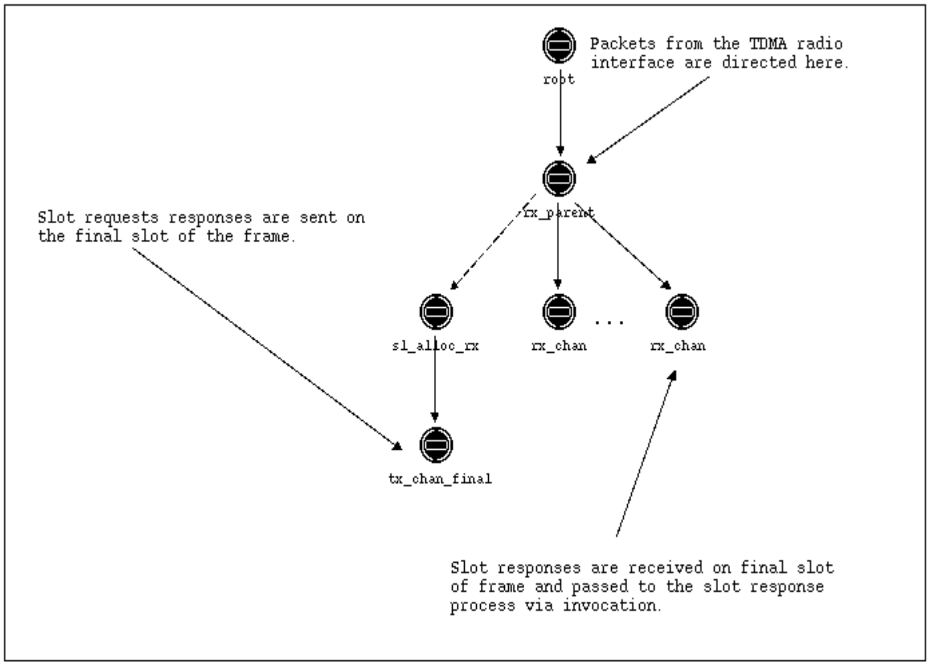


Figure 4.6: Satellite node module and corresponding process models in OPNET



Dynamic Process relationship tree for the TDMA_MAC layer.
These icons serve as links to the State Machines.



Packets from the TDMA radio interface are directed here.

Slot requests responses are sent on the final slot of the frame.

Slot responses are received on final slot of frame and passed to the slot response process via invocation.

Figure 4.7: NCC node module and correspondent process models in OPNET

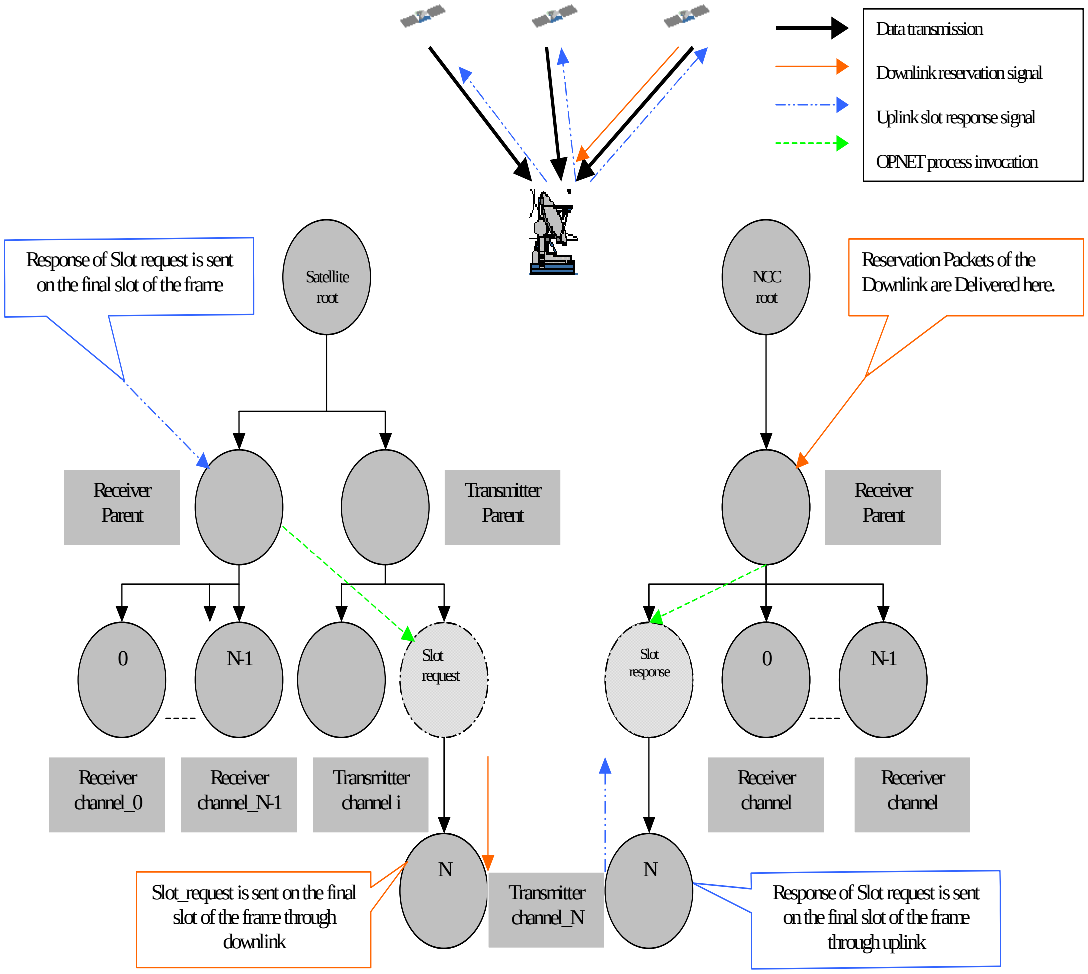


Figure 4.8: Dynamic process parent-children relationship tree for RD-TDMA system

In the four level dynamic process relationship tree for the **TDMA_MAC** module of *satellite* node module, the RD-TDMA slot allocation/deallocation algorithm is implemented in **sl-alloc** process model. Figure 4.9 and Figure 4.10 show the **sl-alloc** process model state machine diagram in *satellite* node module and *NCC* node module respectively.

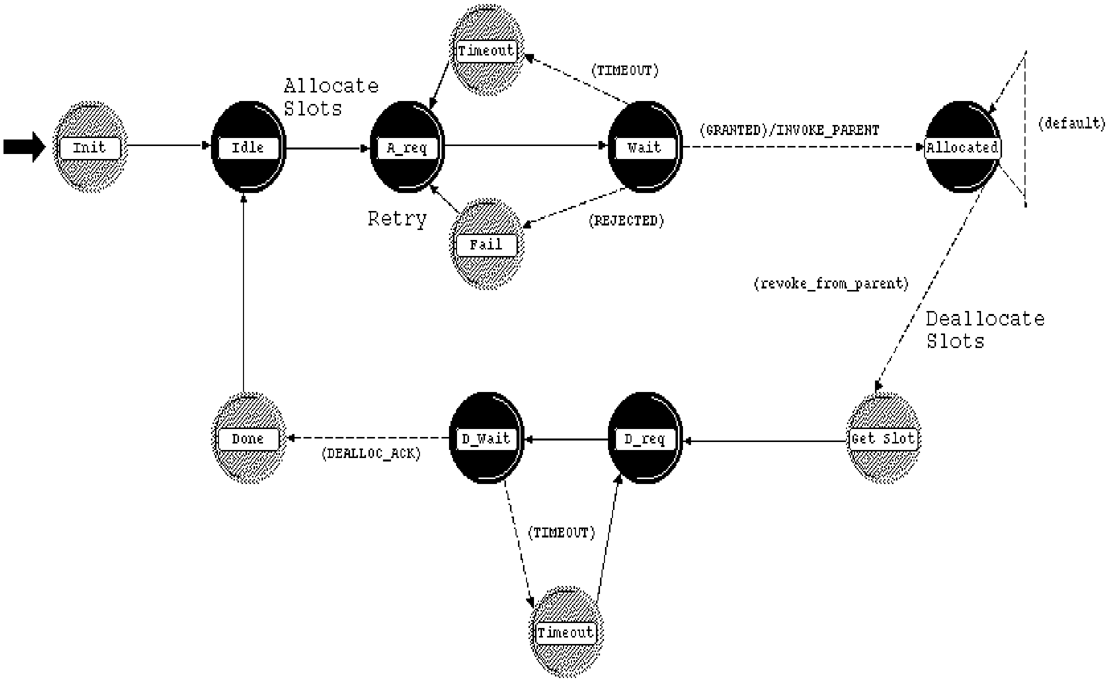


Figure 4.9: State Machine diagram of sl_alloc process model in satellite node-TDMA_MAC module

Figure 4.9 shows the RD-TDMA slot allocation scheme implemented in **sl-alloc** process model in satellite node. It consists of twelve states: **init**, which initialize the system and statistic vectors ; idle, where the system waits for an event to occur; **A_req**, which invoke a **tx_chan** child process to send a *slot grant request;* **Wait**, which wait for a slot response; **Fai**l, which get the slot request rejected reponse; **Timeout**, which has not receive any response from NCC during the predetermined time limit; Allocated, which represents receiving a *slot granted response;* **Get_Slot**, which get the assigned slot to send data packets; **D_req**, which sends a *slot release request* to release the slots; **D_Wait**, which wait for the response of *slot release request;* Done, which represents the slot has been released. The transitions between the states are: **REJECTED**, which indicates the arrival of a *slot request rejection* acknowledgement**; TIMEOUT**, which indicates satellite receive no response within the predetermined time limit; **(GRANTED)/INVOKE_PARENT**, which indicates the arrival of a *slot granted response;* **DEALLOC_ACK**, which indicates the arrival of a acknowledgement of *slot release response;* and default, which indicates that no event took place.

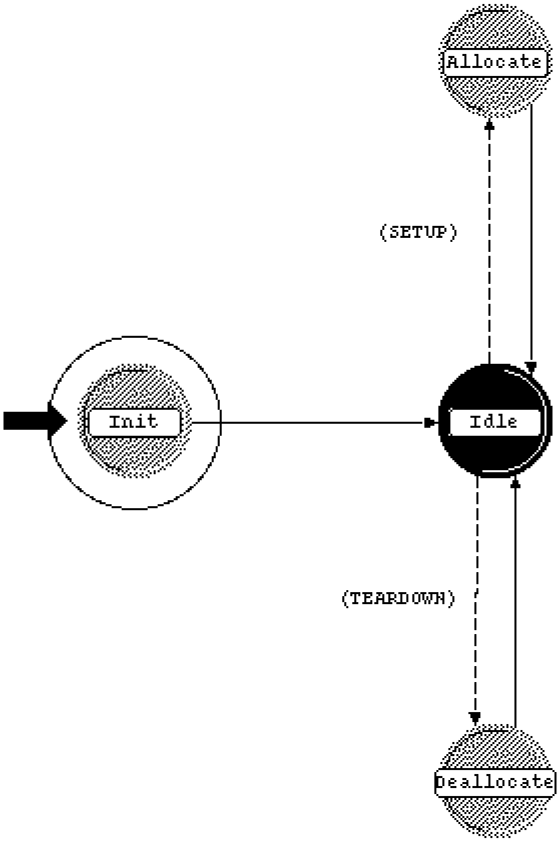


Figure 4.10: Slot allocation process model of NCC

Our state diagram of slot assignment algorithm in NCC node is implemented in OPNET as shown in Figure 4.10. It consists of four states: init, which initialize the system and statistic vectors: Allocate, which allocates slots to the arriving *slot grant request*; idle, where the system waits for an event to occur; Deallocate, which deallocates the slots to the arriving *slot release request*. The arrows in the diagram define the transition relation between the states. The transitions are: SETUP, which indicates the arrival of a *slot granted request;* TEARDOWN, which indicates the arrival of a *slot release request.*

Chapter 5 Simulation Results and Discussions

5.1 Simulation assumptions and parameters

In order to investigate the suitability of on-demand mode to next-generation LEO NASA mission, we need to understand the changing behavior of satellite network size, the availability and access time of the mobile spacecrafts to the ground station. To obtain the above information, we build a baseline LEO NASA mission satellite network model using Satellite Tool Kit (STK) software (section 5.1.1). The obtained information is applied for OPNET simulation, which is discussed in this chapter. We highlight the simulation assumptions and parameters in detail in section 5.1.2.

5.1.1 Satellite network model

For the purposes of investigation of changing behavior of satellite network size availability and access time of spacecraft to the ground station, we assume that the Satellite Network (SN) is composed of eleven active LEO spacecrafts. These are NASA missions LANDSAT_04, LANDSAT_05, LANDSAT_07, QUIKSCAT, TERRA, DMSP_5D_3_F15, EO-1, EOS_AM-1, NOAA_15 and NOAA_16. As shown in Figure 5.1, the ground station is located in Fairbanks with latitude of 64 degree and longitude of –147 degree. The availability service depends on the relative satellite positions, the availability of communications links, and the requested service duration. The data link between the SN and the ground communications networks is run through the NCC facility which interfaces with the LEO satellite's control center utilizing NASA’s communications links. This investigation looks at the possible SN access modes, i.e. a single LEO satellite is available during the coverage time of the ground station.

In this study, we use the commercially available simulation package Satellite Tool Kit to simulate the orbits of 11 LEO spacecrafts over a 24-hour period to determine their access potential. The description of these NASA missions is listed in Table 5.1.

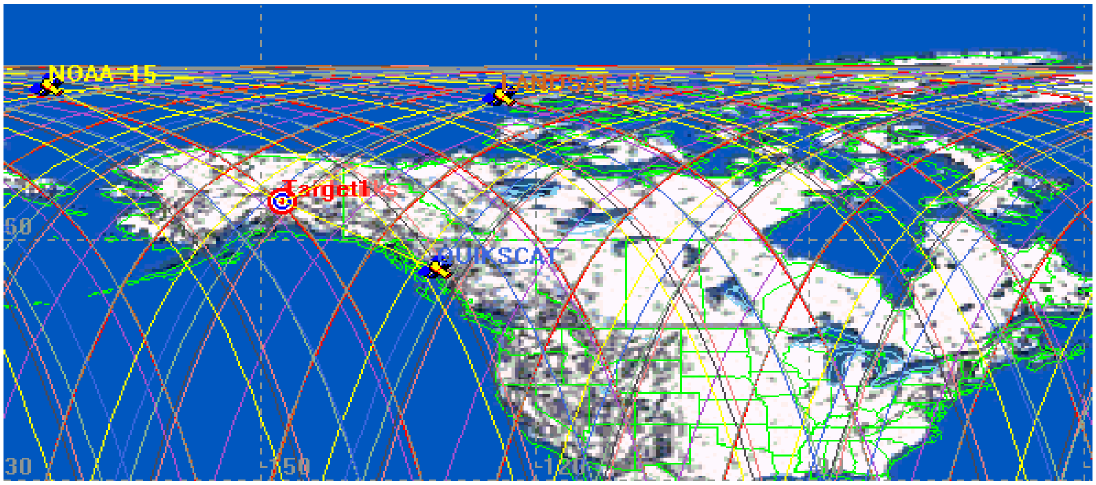


Figure 5.1: STK network model - LEO case

Table 5.1: Description of different LEO NASA Missions

Satellite	Apogee	Perigee	Total Access Period	Inclination
DMSP_5D_3_F15	851 km	837 km	101.8 min	98.9 deg
EO_1	716 km	703 km	98.9 min	98.2 deg
EOS_AM_1	703 km	701 km	98.8 min	98.2 deg
LANDSAT_04	705 km	699 km	98.8 min	98.3 deg
LANDSAT_05	703 km	701 km	98.8 min	98.2 deg
LANDSAT_07	703 km	701 km	98.8 min	98.2 deg
NOAA_15	821 km	805 km	101.1 min	98.6 deg
NOAA_16	864 km	847 km	102.0 min	98.8 deg
QUIKSCAT	805 km	804 km	100.9 min	98.6 deg
TERRA	703 km	701 km	98.8 min	98.2 deg

A set of simulations was run in which the satellite was given orbital elements corresponding to an orbital altitude between 699 km and 864 km. The correspondent Round Trip Delay (RTD) is between 4.7 and 5.7 ms. The orbital inclination angle for the set of simulations was varied around 98 degrees. Before presenting the simulation results using STK, we introduce several terminologies in STK as follows:

- *Strand access time*, which means the time period that each individual spacecraft is in the view of ground station.
- *Complete Chain Access time*, which means the time period that there is one or more spacecrafts in the view of the ground station.
- *Number of accesses*, which means the number of spacecrafts that can be accessed by the ground station simultaneously.

As shown in Figure 5.2, each individual spacecraft accesses the ground station in different time period. There are gaps among the access times. There are also gaps among the complete chain access time as shown in Figure 5.3. More importantly, Figure 5.4 shows that the number of accesses varies from 0 to 5. The access time is in the order of minutes. Therefore, when using OPNET we assume the network size *n* is less or equal to 5 for this scenario. Each simulation run is set for several minutes. Here by network size *n* we mean the number of spacecrafts in the view of the ground station during a period of time.

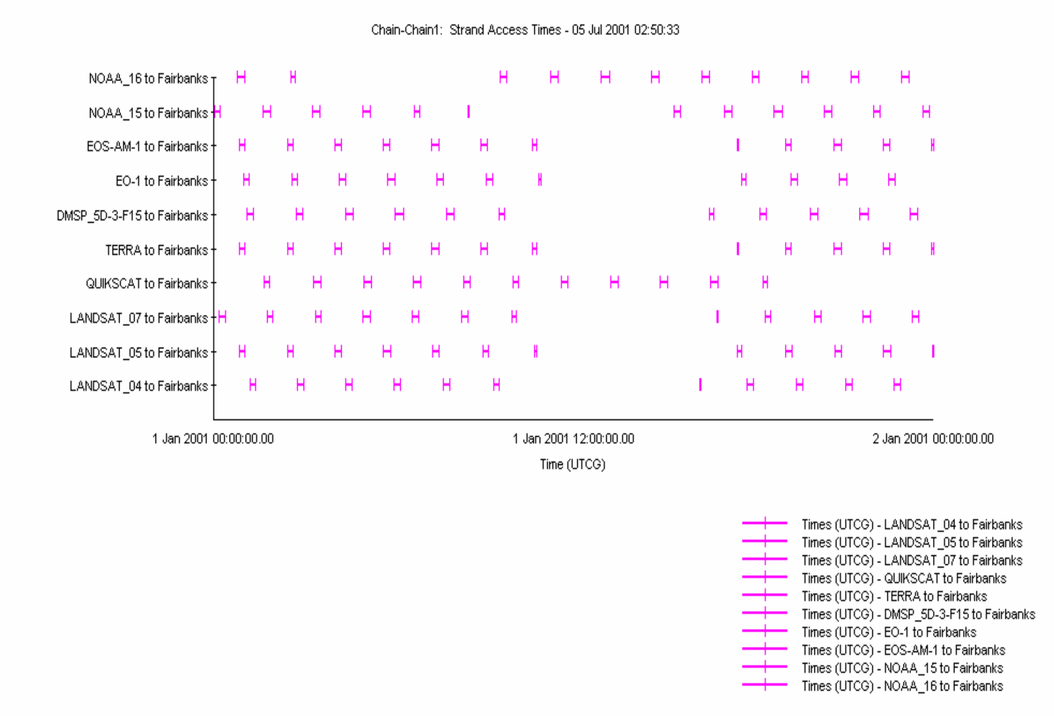


Figure 5.2: Analysis of strand access time using STK

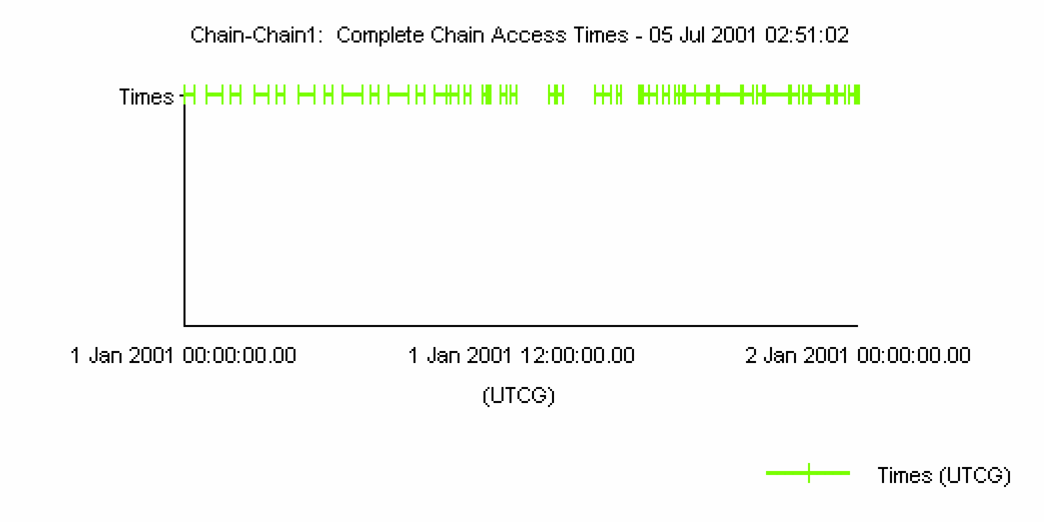


Figure 5.3: Analysis of complete chain access time using STK

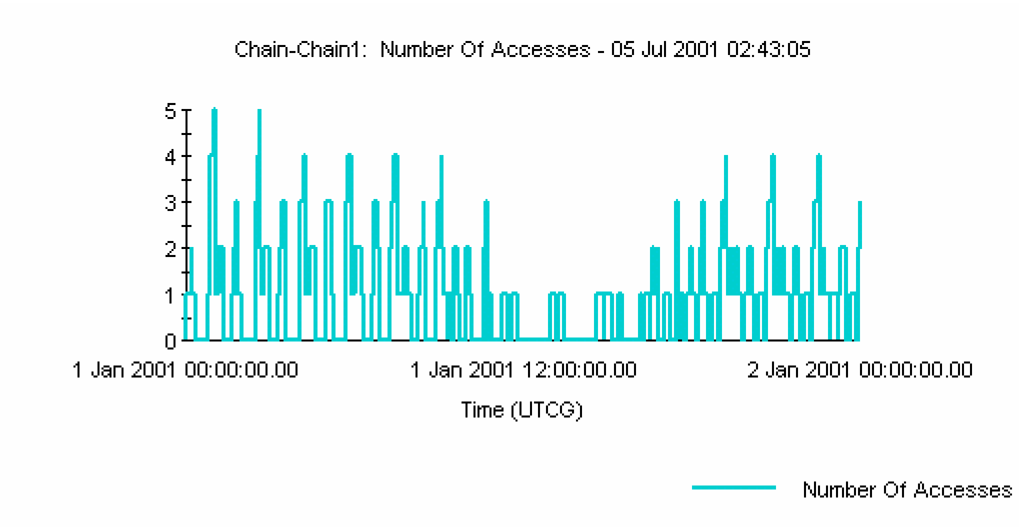


Figure 5.4: Analysis of number of accesses using STK

5.1.2 Simulation assumptions and parameters

At this stage, we are interested in the scenario that the traffic is generated in the spacecraft and then is downloaded to the ground. Therefore, we model the space-to-ground scenario as follows:

1. The downlink channel is considered as error-free using a TDMA scheme to share the channel among different LEO satellites.
2. Only those LEO spacecrafts in the coverage of the ground station acting as Network Control Center (NCC) are considered. Handover is not considered in this preliminary investigation stage.
3. The TDMA frame time and slot time is determined in advance since the number of LEO spacecraft in the view of the Ground Station is predictable during different period of time of a day.
4. We assume a fixed network size *n* for each simulation run. Here by network size we mean the number of spacecrafts in the view of the ground station

during a period of time. We try to investigate the relative performance of the two main scenarios (the pre-planned mode and on-demand mode).

5. Performance measures of interested in the simulation are End-to-end (ETE) delay and successful throughput. By ETE delay, we mean the time that each file experienced from its generation in the spacecraft to the time it is received by the ground station receiver, which is the sum of the propagation delay, the transmission delay and queuing delay. Note that, the ETE delay in on-demand mode also includes the reservation delay. By successful throughput, we mean how much traffic is successfully received at the ground station in a unit of time (a second).
6. A net information bandwidth of 1 M bits/s is assumed for the two modes. (This could be adjusted in future simulation runs)
7. We assume both the two modes support constant size packet transmission, which means the long file must be segmented into small packet before being transmitted and the short file is 1024 bits per file.
8. We set TDMA frame time as 6.2ms, which is about the maximum RTD delay among the NASA mission spacecrafts as discussed in section 5.1.1. In order to support the data rate of 1M bits/sec in each slot, we set the slot number as six slots for on-demand mode. As for the pre-planned mode, the setting of slot number depends on the network size n, where n is less or equal to 5. Thus, each slot can contain one packet, since each slot time is greater than 1.024ms, which is the packet transmission time.

All the relevant network configuration parameters and TDMA frame parameters are tunable.

5.1.3 Traffic model

Traffic modeling plays an important role in the design and simulation of communication networks [34]. In order to resemble the traffic pattern for the next generation of NASA mission, let's look at the typical mission examples.

There are different kinds of NASA mission. The missions we are interested includes Earth Science and Space Science missions to LEO [35]. File Management In Space architecture has been proposed, in which LEO spacecrafts can be considered as an Internet file server. Spacecrafts can uniquely name the results from specific science activities as files and deliver the files from space to the ground [36].

To configure the traffic profiles, we need to model the traffic behavior in two levels:

- High level: modeling the LEO network TDMA system's traffic, which means how is the traffic load distributed among different spacecrafts. In other word, how is the traffic distributed in different TDMA slots.
- Lower level: modeling an individual spacecraft's traffic, which means how much traffic each spacecraft is loaded, i.e., how much traffic is loaded in each TDMA slot.

In consideration of the TDMA system's traffic conditions, we discuss two cases, namely *evenly distributed traffic load condition* and *unevenly distributed* *traffic load condition respectively*. Before the discussion of the two definitions, we introduce two states of spacecraft in the view of ground station: *high activity* and *low activity*.

- *High activity*

  By *high activity*, we mean that the spacecraft sends traffic load profile very frequently.

- *Low activity*

  By *low activity*, we mean the spacecraft seldom sends traffic.

- *evenly distributed traffic load condition*

  evenly distributed traffic condition means that each spacecraft is *active* during the coverage time of ground station. By *active*, we mean the spacecraft is with *high activity*.

- *unevenly distributed traffic load condition*

  unevenly distributed traffic load condition means that not all the spacecraft are *active* during the coverage time of ground station.

We choose to concentrate on *unevenly distributed traffic load condition* the so as to match the unpredictable traffic pattern for next-generation NASA space mission. In addition, the advantage of on-demand mode over pre-planned mode lies in the optimum utilization of potentially wasted frame slots under *unevenly distributed traffic load condition* by using slot reservation scheme.

As for the lower level of traffic model, for simplification, the traffic for each individual spacecraft considered in the simulation is mostly non-real-time traffic consisting of short file (status data or temperature information) and long file (large images, etc.). We can add more variations and add more complexity to the traffic model later on. The long file transfer traffic constitutes the majority of the current traffic volume. This type of bulk data traffic can be modeled at the connection level by fitting statistical distributions to two key traffic variables: file interarrival times and file transmission (“download”) sizes.

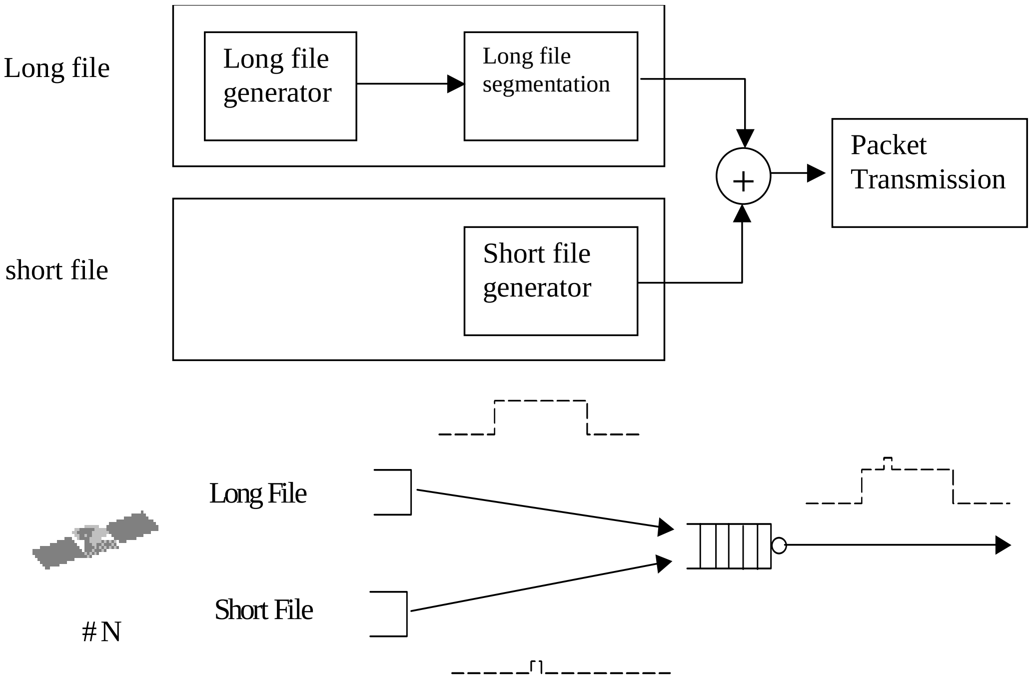


Figure 5.5: Composite traffic generator generating non-real-time traffic in OPNET satellite node

As shown in Figure 5.5, the simulation of traffic was done in OPNET as follows: the traffic source incorporates a long file traffic generator and a short file traffic generator. The long file traffic generator in Figure 5.5 delivers files with a constant file size k_l and an exponential interarrival distribution with mean λ_l. k_l and

λ_l are chosen for each simulation run, in order to get the desired mean long file traffic load. The long file size is the multiple of 1024 bits. The Long file segmentation process (Fig. 5.5) formats the file into 1024 bits packets. The short file traffic generator in Figure 5.5 delivers packets with an exponential inter-arrival distribution, with a mean λ_s chosen for desired mean short file traffic load. The short file length is 1024 bits. The total size of the traffic S_{total} is as follows:

$$S_{total} = \sum_{i=1}^{N} s(i)$$

where $s(i)$ is size of the i_{th} 's traffic file; N is the total number of the traffic file. Thus the ratio of percentage of long file in total traffic load P_l to the percentage of short file P_s in total traffic load is

$$\frac{P_l}{P_s} = \frac{\dfrac{k_l}{\lambda_l}}{\dfrac{k_s}{\lambda_s}}$$

where k_l is the size of the long traffic file and k_s is the size of the short traffic file. Here we introduce an important evaluating factor for MAC protocol, the normalized traffic load S, which is defined as

$$S = \frac{A}{C}$$

where A is the average throughput and C is the channel capacity in bits/s.

5.2 Simulation results and discussions

To make sure that we collect accurate statistics, we ignore the “warm-up” period and the transient period and wait until the simulation has reached steady state when the effects of initial conditions have become insignificant.[27] All simulation runs in OPNET have been performed for steady-state periods of several minutes. Moreover, the movement of satellites and the mobility of users has been neglected during the OPNET simulation run. Since the altitude of NASA mission spacecrafts we are considering ranges from 699km to 864km, the typical range of propagation delays is from 2.33 ms to 2.83 ms, The propagation delay variance is 0.5ms, which is orders of magnitude smaller than the mean End-to-End (ETE) packet delay. Therefore for simplicity, we assume a constant propagation delay for all simulations.

We have first verified the function of the protocol models as can be seen in the results in this section. We compare the performance of pre-planned mode and on-demand mode in term of throughput and ETE delay. Section 5.2.1 highlights the general performance comparison of the two modes under similar conditions of traffic and networking conditions. After that, we give a detail throughput/delay performance analysis by presenting specific examples from section 5.2.2 to 5.2.5. In section 5.2.6, we will highlight the unique characteristics of on-demand mode by analyzing the reservation delay component.

5.2.1 General analysis of delay-throughput performance

Figure 5.6 and 5.7 show the comparison of ETE delay under different *unevenly distributed traffic load condition* with network size *n* is five. The delay of short file and long file are plotted separately. We can see that, given the percentage of active spacecraft, with the increase of the normalized channel traffic load, the ETE delay is increased; given the normalized traffic load, the ETE delay is also increased with the increase of percentage of active spacecraft. The on-demand mode performs well under light traffic load in all of the five different scenarios. By scenarios, we mean the different network topologies with different percentage of *active* spacecrafts. However, a different situation occurs under heavy traffic load. The scenarios with 20%, 40% and 60% of *active* spacecrafts perform well. When the percentage of *active* spacecraft increases to 80%, the delay increase from 310ms to 650ms, which is still acceptable. Whereas when the percentage of active spacecraft increases to 100%, the delay increases suddenly. This is because, that with the increase of the number of active spacecraft, the number of *available slots* is decreased. By *available slots,* we mean the remaining unassigned slot in a frame after assigning one slot to each *active* spacecraft. When percentage of active spacecraft increases to 100%, each spacecraft can only utilized one slot. With the limited channel bandwidth of 1M bits/sec, each slot can only handle 20% of data traffic load. Beyond this limit, the data traffic is queued in the spacecraft. With the arrival of heavy load in each slot, the queue length in each slot becomes longer. The delay becomes larger. In the graph, the prompt increase is a little behind 20% normalized channel traffic load. This is because, actual data traffic is smaller than the normalized traffic load since the normalized traffic load includes the data traffic and control data traffic of downlink. Therefore, the delay increases promptly after 20% of normalized channel load. Thus, we can make the following conclusions:

- With the increase of traffic load, the delay is increased in on-demand mode.

- With the increase of percentage of active spacecraft, the delay is increased in on-demand mode. The on-demand mode performs better in *unevenly distributed traffic load condition* than *evenly distributed traffic load traffic condition*.
- Under heavily *unevenly distributed traffic load condition*, in which the percentage of *active* spacecraft is less or equal to 60%, on-demand mode can fully utilize the unused slots in transmitting the traffic load. Thus, it has a good delay-performance in light and heavy traffic load conditions. Under lightly *unevenly distributed traffic load condition*, in which the percentage of active spacecraft is 80%, on-demand mode has an acceptable delay-performance in light and heavy traffic load conditions.
- Under *evenly distributed traffic load condition*, in which the percentage of active spacecraft is 100%, on-demand mode can only work well in light traffic load condition.

From the above analysis, we can see, under *unevenly distributed traffic load condition*, on-demand mode performs well under different traffic load condition (light/heavy traffic load conditions). Therefore, we will focus on the investigation of delay-throughput performance of two modes under *unevenly distributed traffic load condition.* We will see that on-demand mode outperform pre-planned mode in most cases.

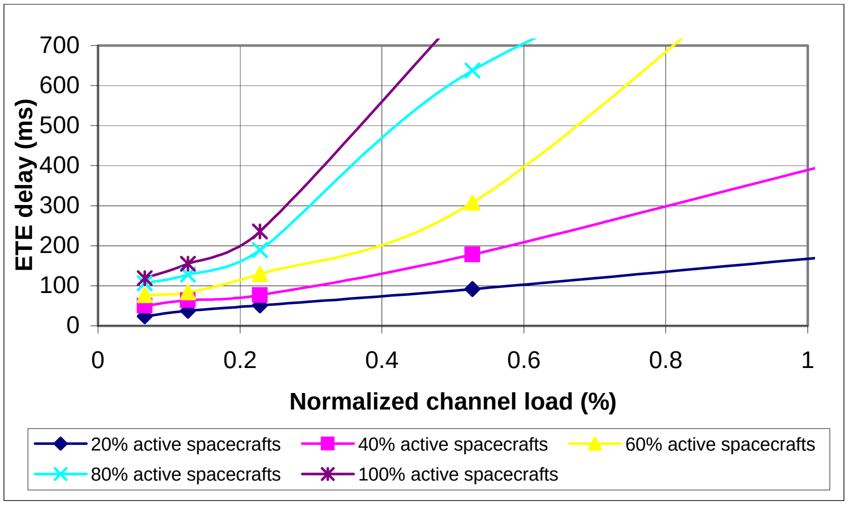


Figure 5.6: Comparison of ETE delay of long file in on-demand mode

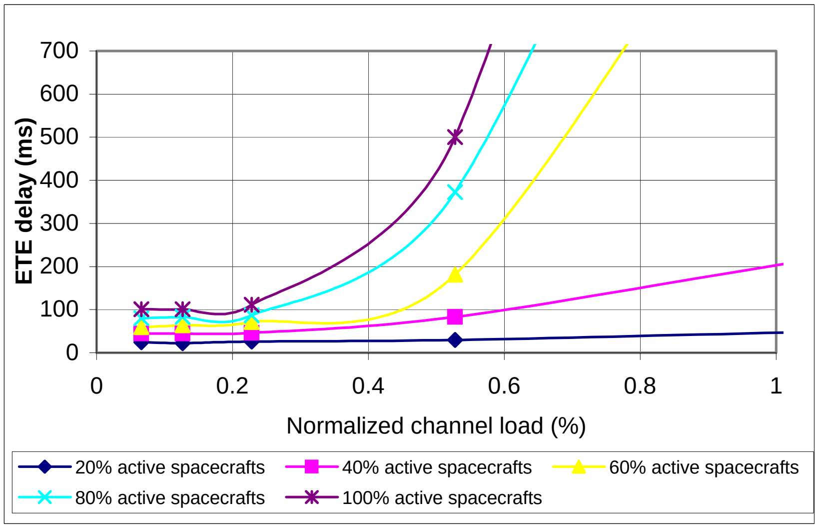


Figure 5.7: Comparison of ETE delay of short file in on-demand mode

As shown in Figure 5.8 to Figure 5.15, on-demand mode has significant advantage in delay performance under heavy unbalanced traffic condition with 20%, 40% and 60% percentage of active spacecraft in most cases. Pre-planned mode only performs a little better in low throughput condition. Only when the percentage of active spacecraft increases to 80%, on-demand mode begins to perform worse than pre-planned mode. The more unevenly distributed traffic load among different spacecrafts, the better performance on-demand mode presents.

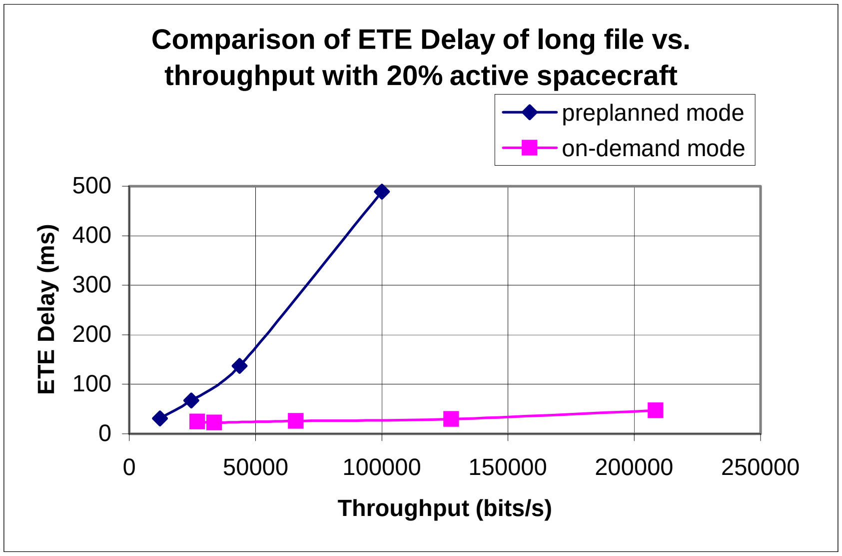


Figure 5.8: Comparison of ETE delay of long file vs. throughput with 20% spacecraft

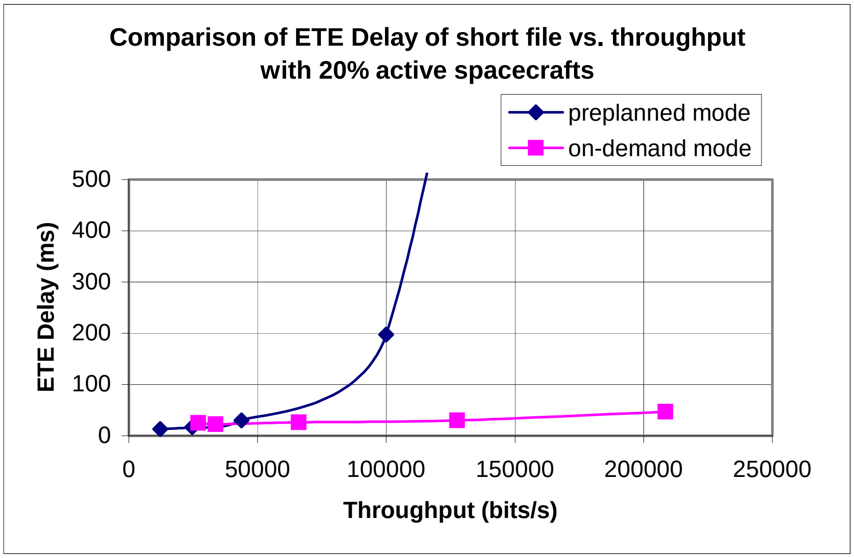


Figure 5.9: Comparison of ETE delay of short file vs. throughput with 20% active spacecraft

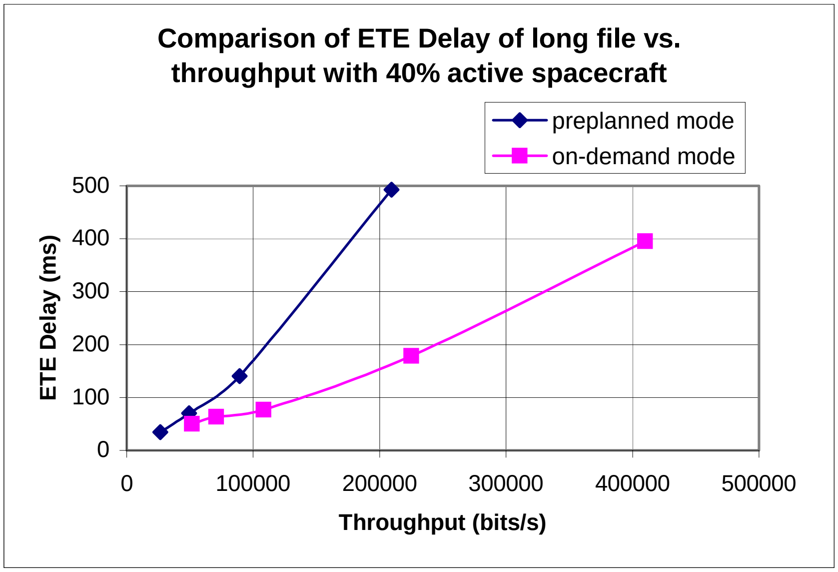


Figure 5.10: Comparison of ETE delay of long file vs. throughput with 40% active spacecraft

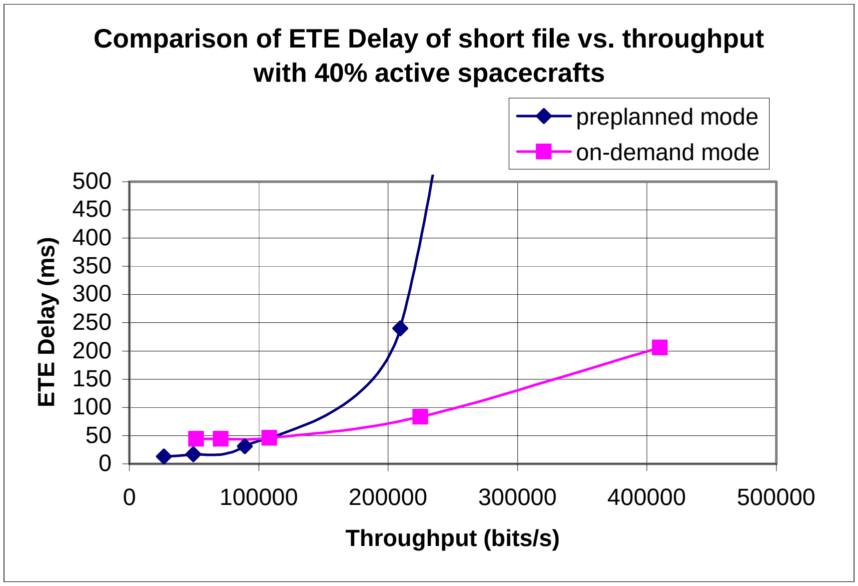


Figure 5.11: Comparison of ETE delay of short file vs. throughput with 40% active spacecraft

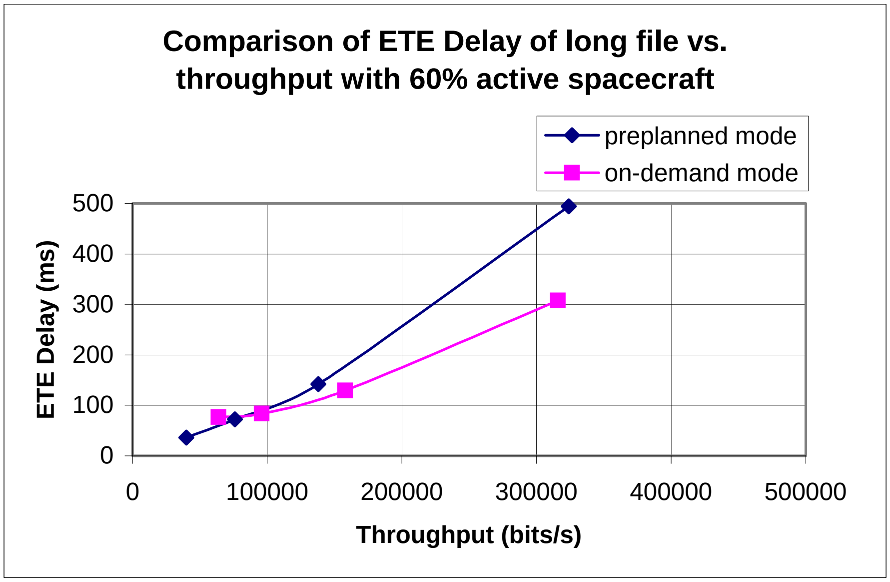


Figure 5.12: Comparison of ETE delay of long file vs. throughput with 60% active spacecraft

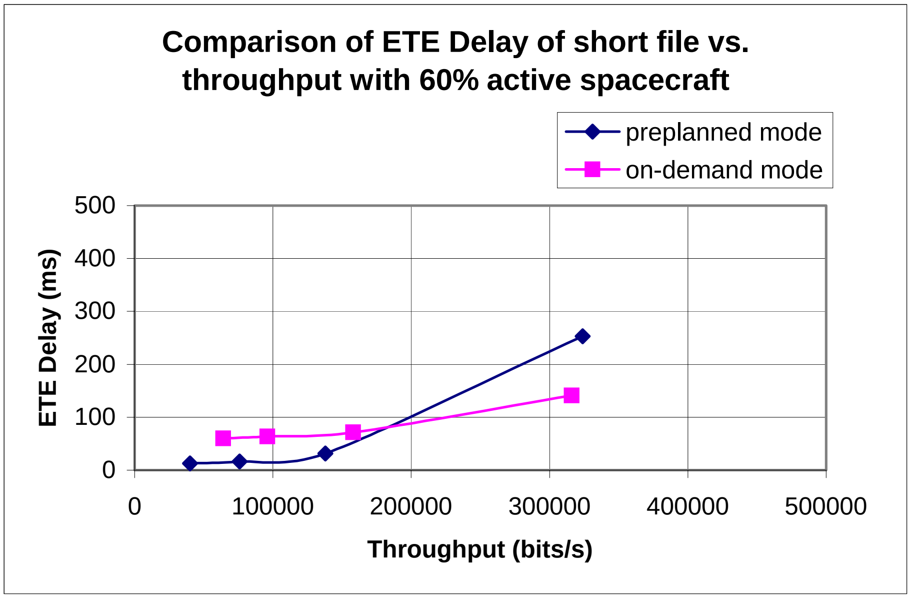


Figure 5.13: Comparison of ETE delay of short file vs. throughput with 60% active spacecraft

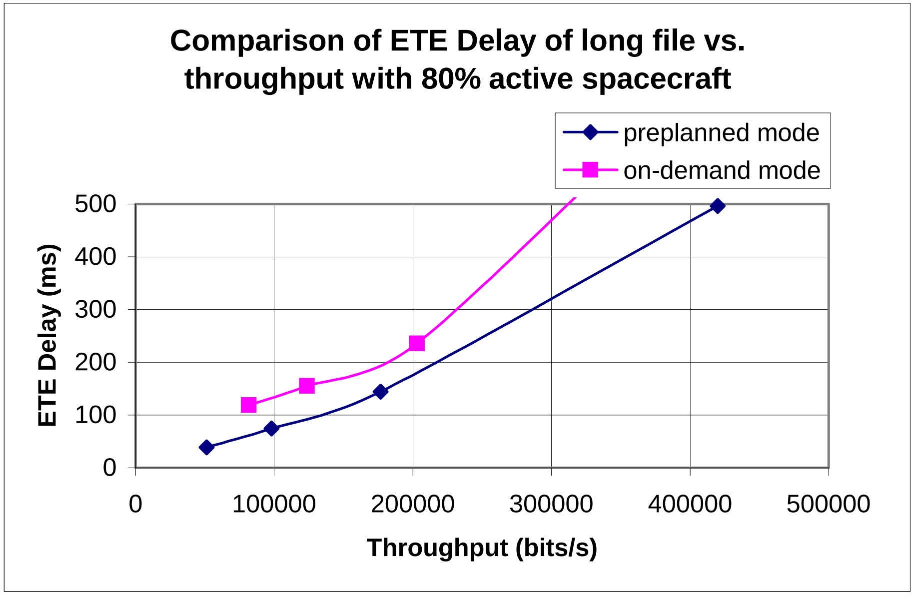


Figure 5.14: Comparison of ETE delay of long file vs. throughput with 80% active spacecraft

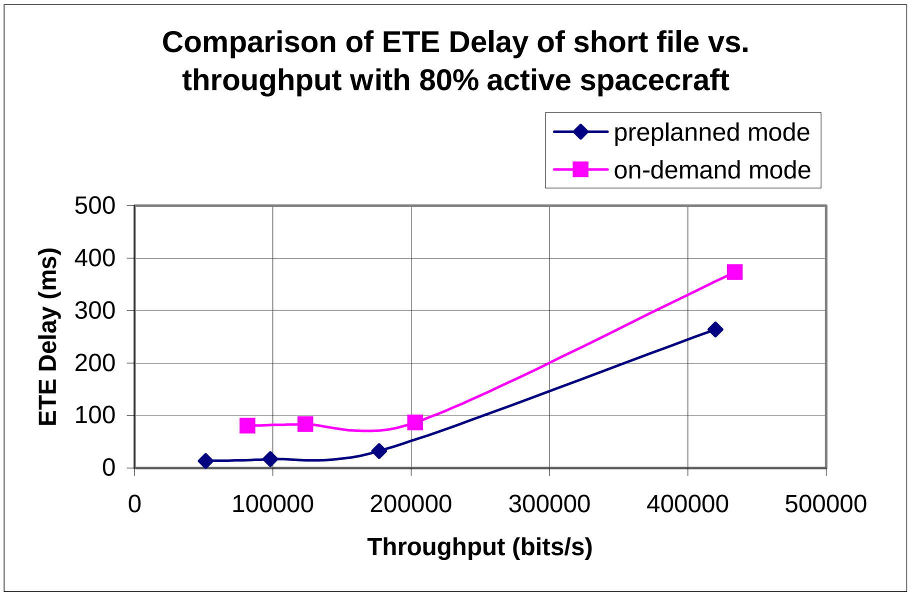


Figure 5.15: Comparison of ETE delay of short file vs. throughput with 80% active spacecraft

We highlight the comparison of delay performance of the two modes under different *unevenly distributed traffic load condition* in Table 5.2 and Table 5.3. We use “×” to represent the situation that one mode outperforms the other. We use A to represent the average throughput in bits/sec as described in section 5.1.

Table 5.2: Comparison matrix of long file delay performance

Percentage of active spacecrafts		20%	40%	60%	80%
Pre-Planned Mode	$0<A\leq 100000$			×	×
	$A\geq 100000$				×
On-demand Mode	$0<A\leq 100000$	×	×		
	$A\geq 100000$	×	×	×	

From Table 5.2, Figure 5.8, 5.10, 5.12 and 5.14, we can see that on-demand mode absolutely outperforms pre-planned mode in terms of long file ETE delay in most cases. Only when the traffic load is lightly unevenly distributed among different active spacecrafts (80% of *active* spacecrafts), preplanned mode is better than on-demand mode. The reason is that each *active* spacecraft only need one successful reservation for its long file transmission. The more continuous traffic each spacecraft needs to send, the less the reservation overhead is. In addition, on-demand mode can utilize more slots in transmitting the long file in each frame, the delay becomes smaller than that of pre-planned mode. However, when there are more active spacecrafts, most of the slots have been utilized. As for on-demand mode, there is a small fraction *available slots* can be reassigned to the spacecraft with reservation. The contention of reservation increases with the increase of the number of *active* spacecrafts. The reservation overhead dominates the ETE delay. Therefore, when there is 80% of *active* spacecrafts, preplanned mode is better than on-demand mode.

Table 5.3: Comparison matrix of short file delay performance

Percentage of *active* spacecrafts		20%	40%	60%	80%
Pre-Planned Mode	$0<A\leq50000$		×	×	×
	$50000<A\leq100000$		×	×	×
	$100000<A\leq180000$			×	×
	$\mathrm{A}\geq180000$				×
On-demand Mode	$0<A\leq50000$				
	$50000<A\leq100000$	×			
	$100000<A\leq180000$	×	×		
	$A\geq180000$	×	×	×	

From Table 5.3, Figure 5.9, 5.11, 5.13 and 5.15, we can see that pre-planned mode absolutely outperforms on-demand mode when there are 80% of *active* spacecrafts. On-demand mode outperforms pre-planned mode when there are 20% of active spacecrafts except in the situation when average throughput *A* is less than 500000 bits/sec. The two modes have similar performance in the other cases. Even if when there are 80% of *active* spacecrafts, the delay difference between the two modes is less than 100ms. Compared with the ETE delay performance of long file delay in on-demand mode, the short file performance is worse. This is because each spacecraft still needs reservation for sending short file. Thus the reservation overhead is relatively larger in the total ETE delay since the short file delay is shorter than long file delay.

Summing up the above results, on-demand mode's delay performance outperforms pre-planned mode in most situations, especially the long file delay performance. This is because, under *unevenly distributed traffic load condition,* *inactive* spacecrafts waste their slots due to the fixed slot assignment in pre-planned mode. Whereas the on-demand mode can utilize the wasted slots by assigning them to the *active* spacecraft whose reservation has been granted. Therefore, the on-demand mode can utilize more slots per frame to send the same amount of traffic load, which leads to a shorter delay. Given the burstiness of traffic, the longer the file, the smaller the overhead is in the total ETE delay, the larger the delay difference between to the two modes is. The more *available slots* lie in pre-planned mode, the more on-demand mode outperforms the pre-planned mode in delay performance.

5.2.2 Comparison of throughput

Figure 5.16 to Figure 5.18 show the throughput performance comparison between two modes with 20%, 40% and 60% of *active* spacecraft in total of *network size* of five respectively. The average throughput performance is improved under both light traffic condition and heavy traffic load condition in all these three scenarios. With the increase of active spacecraft, the throughput under two modes is increased due to increased generated traffic load by more active spacecraft. However, on-demand mode has better average throughput than pre-planned mode. This is because part of the bandwidth is wasted in pre-planned mode by the *inactive* spacecraft due to the fixed slot assignment. For example, with 20% active spacecraft in total network size of five, the active spacecraft can only utilize one time slot to send the traffic while the active spacecraft can utilize five time slots to send the same amount of traffic. This maximum utilization of frame slots in on-demand mode leads to its improved throughput performance compared with pre-planned mode.

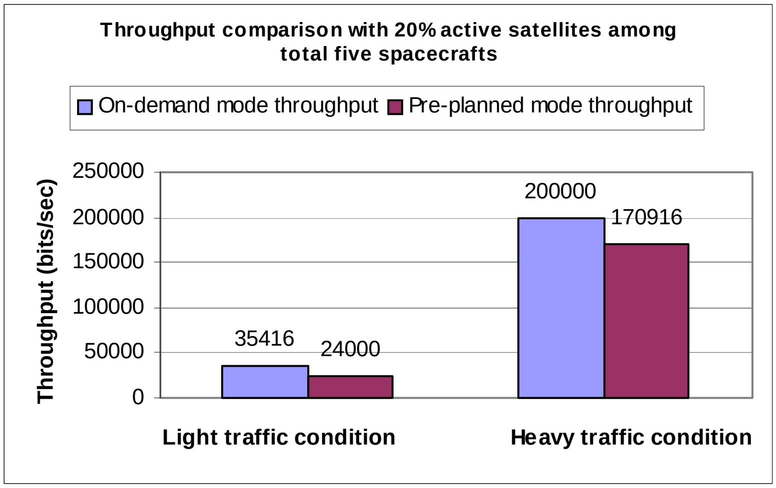


Figure 5.16: Throughput comparison with 20% active spacecraft

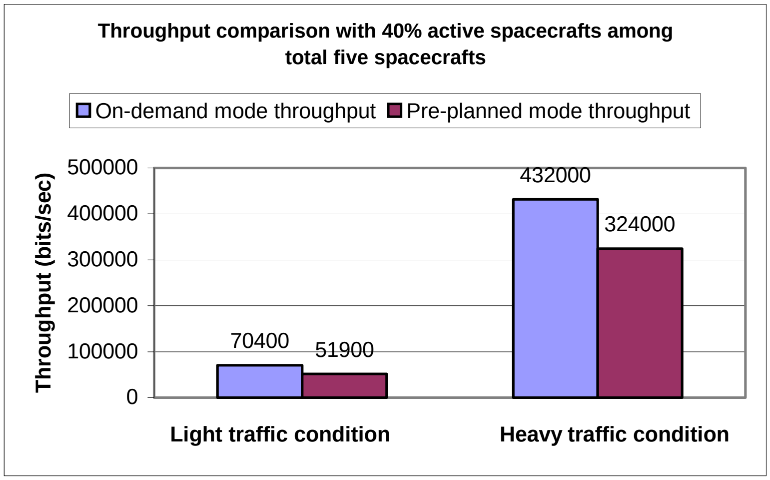


Figure 5.17: Throughput comparison with 40% active spacecraft

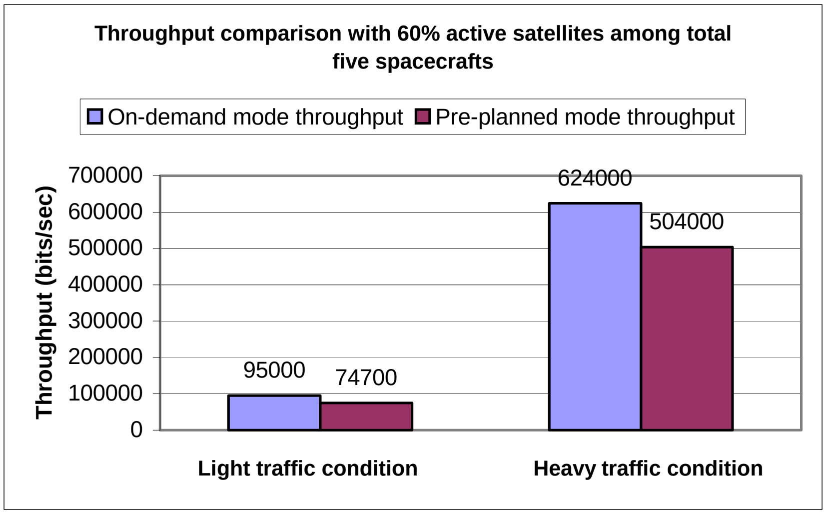


Figure 5.18: Throughput comparison with 40% active spacecraft

5.2.3 Comparison of delay performance

Figure 5.19 and Figure 5.20 show the mean ETE delay of packets when *active* spacecraft are loaded with light traffic load profile. The on-demand mode has a better delay performance than pre-planned mode in above *unbalanced traffic* condition. Given the number of *active* spacecraft and the same traffic load intensity, the delay variation between the two modes is increased with the increase of the *network size*. This is because, in the preplanned mode, each *active* spacecraft has been assigned a shorter slot time whereas in the on-demand mode the *active* spacecraft can demand the whole frame slots to transmit the traffic. For example, as shown in Figure 5.19, the *active* spacecraft has been assigned 2ms, 1.5ms and 1.2ms to transmit its traffic in each frame when the network size is three, four and five respectively. While in the on-demand mode, the one *active* spacecraft always has five slots (5ms) available to transmit the same amount of traffic in each frame.

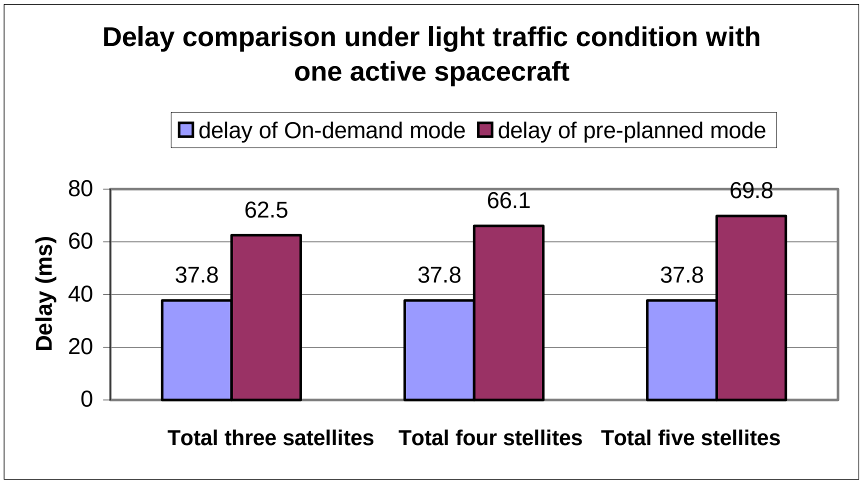


Figure 5.19: Delay comparison under light traffic condition with one active spacecraft

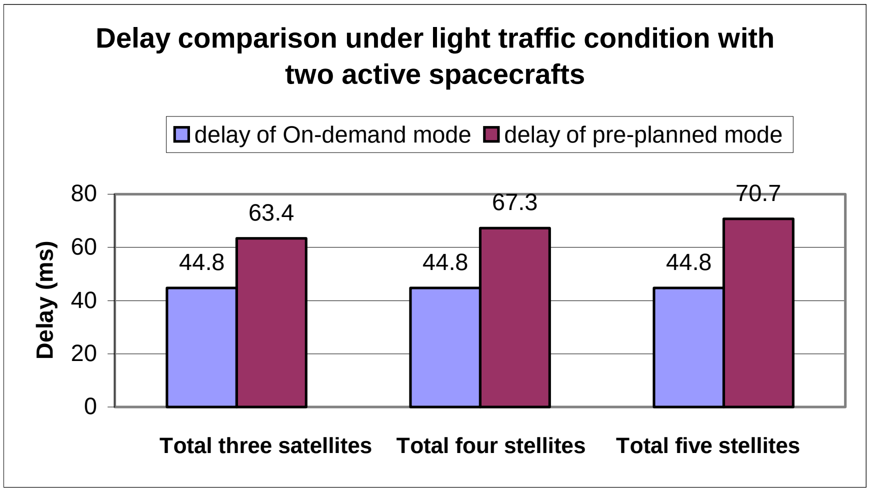


Figure 5.20: Delay comparison under light traffic condition with two active spacecrafts

5.2.4 Evaluation of delay performance over light and heavy traffic load

As shown in Table 5.4, two kinds of mixes will be considered in this section: 1) Light Traffic (LT) load profile. 2) Heavy Traffic (HT) load profile.

Table 5.4: Traffic profiles description

Traffic profile type	Normalized traffic load (S)	Percentage of long file in total traffic load (P_l)	Percentage of short file in total traffic load (P_s)	Size of the long traffic file (k_l) (in bits)
Light traffic	5.85%	80%	20%	10240
Heavy traffic	85.5%	95%	5%	102400

Figure 5.21and Figure 5.22 show the mean ETE delay of packets when *active* spacecraft are loaded with heavy traffic load profile. The on-demand mode also has a better delay performance than pre-planned mode in heavy loaded *unbalanced traffic* condition. Table 5.5 shows the delay difference between two modes. Note that on-demand mode has a significant delay improvement under heavy load traffic condition compared with that under light traffic load condition. The delay in on-demand can even be decreased 92.1% of the delay in preplanned mode under HT condition, while the delay in on-demand can be decreased at most 45.8% of the delay in preplanned mode under LT condition. This is because preplanned mode has worse delay performance under HT load condition due to the slot capacity limitation. While on-demand mode can utilize more bandwidth to transmit heavy traffic by demanding more unused slots. Under the extreme situation, one active spacecraft can even utilize the whole frame to transmit the traffic. Therefore, on-demand mode has good delay performance under both LT and HT load condition, while pre-planned mode has good

delay performance under LT condition but performs badly under HT load condition especially when the HT load is closed to the slot capacity limitation. Thus the difference between their delay becomes larger with the increase of traffic load intensity.

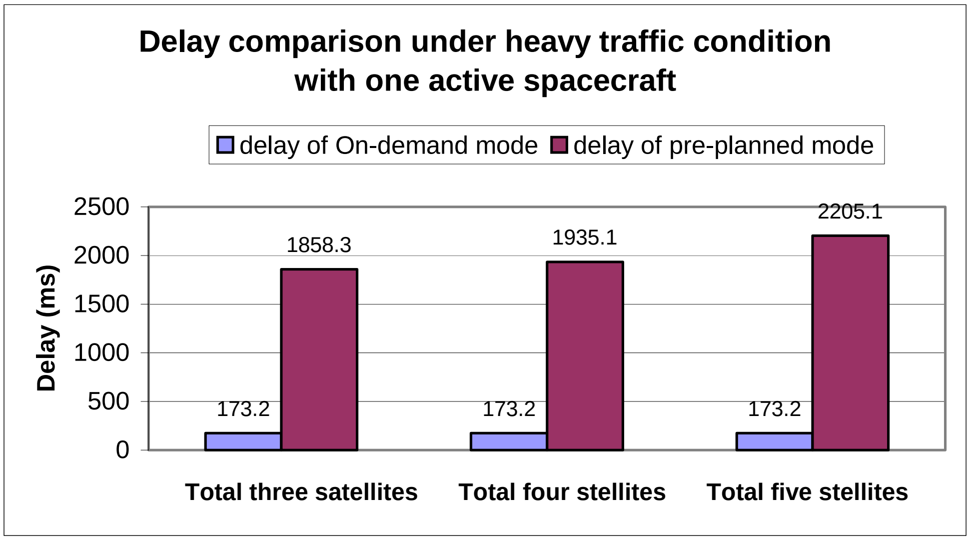


Figure 5.21: Delay comparison under heavy traffic condition with one active spacecraft

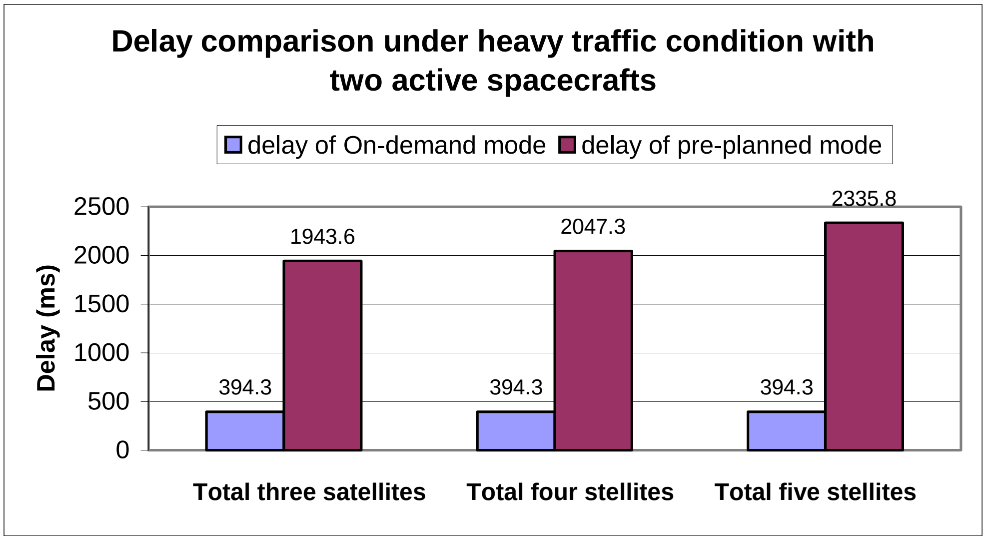


Figure 5.22: Delay comparison under heavy traffic condition with two active spacecrafts

Table 5.5: Delay variance between LT/HT scenarios

	n = 3				n = 4				n = 5			
*NAS	LT		HT		LT		HT		LT		HT	
	(ms)	(%)	(ms)	(%)	(ms)	(%)	(ms)	(%)	(ms)	(%)	(ms)	(%)
1	24.7	39.5	1685.1	90.7	28.3	40.5	1761.9	91.4	32	45.8	2031.9	92.1
2	18.6	29.3	1549.3	79.7	22.5	33.4	1653.0	80.7	25.9	36.6	1941.5	83.1

*NAS: number of active spacecrafts

5.2.5 *Evaluation of network size in on-demand mode*

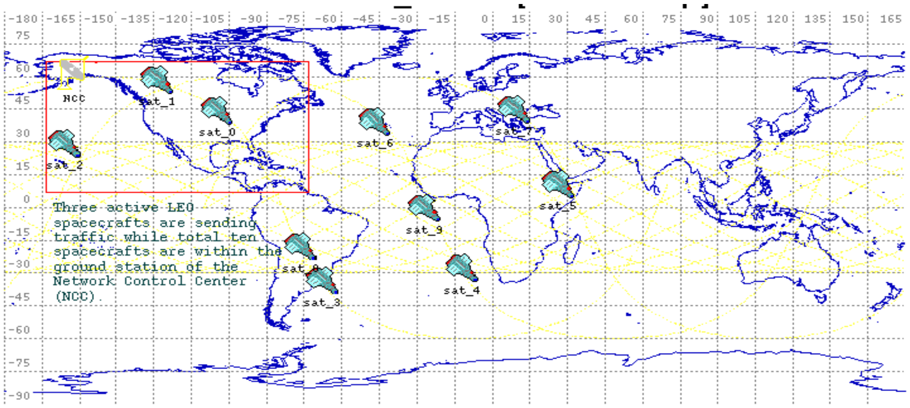


Figure 5.23: Network model in OPNET of three active spacecrafts when *n* =10 under HT condition

Figure 5.23 to Figure 5.26 show one example of how on-demand mode can accommodate a larger network size. The network model this example is shown in Figure 5.23. There are ten spacecrafts in the view of the ground station. Only three *active* spacecrafts are busy in sending traffic at the same time. Note that the three *active* spacecrafts refer to any three spacecrafts of the total of ten. Figure 5.24 to Figure 5.26 show the delay, average slot in use and average throughput of this scenario. On-demand mode has this advantage in accommodating larger network size than the number of slot in a frame. This is because the on-demand mode performance is affected by the number of *active* spacecraft transmitting traffic instead of the total number of spacecraft in the view of the ground station. The *inactive* spacecrafts do not utilize any slot in each frame.

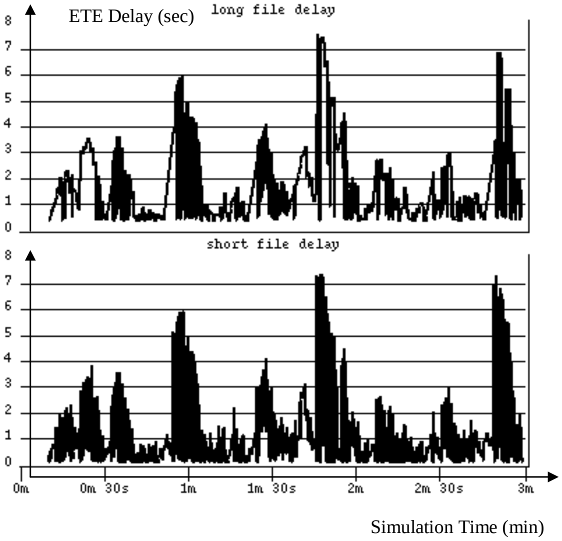


Figure 5.24: Delay of three active spacecrafts when *n*=10 under HT condition

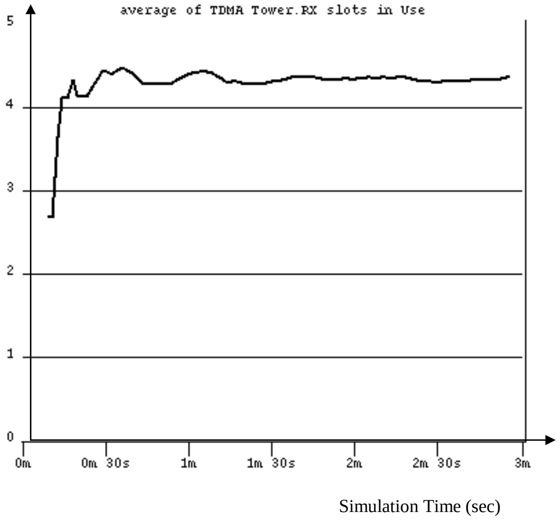


Figure 5.25: Average slot in use when n=10 under HT condition

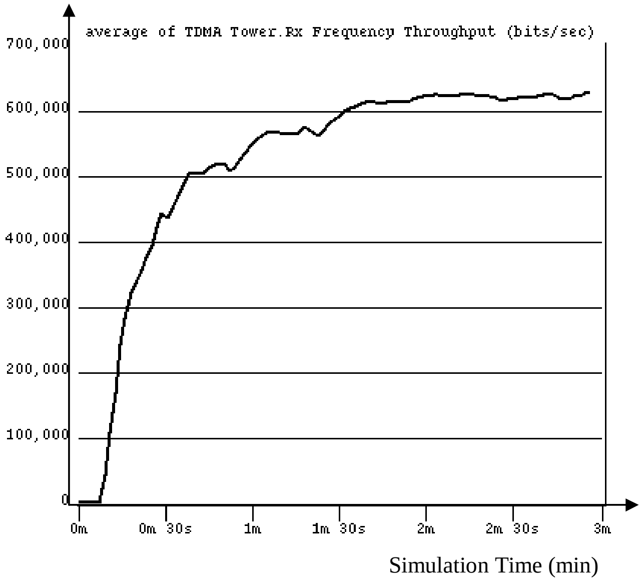


Figure 5.26: Average throughput of three active spacecrafts when n=10 under HT condition

5.2.6 Evaluation of channel bandwidth utilization

Due to the fixed slot assignment, even if the slots are wasted by the *inactive* spacecrafts, they cannot be assigned to *active* spacecraft. This is why preplanned mode is less efficient than on-demand mode in channel bandwidth utilization. Figure 5.27 to Figure 5.30 show such an example. The normalized traffic load for this example is about 65%. As shown in Figure 5.27, the average delay of preplanned mode cannot converge to a stable value. The average received traffic is 510000 bits/s as shown in Figure 5.28. While in on-demand mode, the average delay of can converge to a stable value (2560ms) under the same traffic condition as shown in Figure 5.29. The average traffic throughput is 641666bits/s, which is about 64.1% of the channel capacity. Thus, we can see that the received traffic in preplanned mode is less than 60% of the channel capacity (600000bits/sec) though the traffic load (65%) is more than that. This is because the three active spacecraft can only utilize three slots in transmitting data traffic files. In addition, this is a slotted TDMA system. Some bandwidth is wasted when the arrival of traffic is not synchronized with the beginning of the slot. Therefore, when the channel received traffic is larger than 510000 bits/sec, there are more and more traffic files queued in the spacecrafts and cannot be transmitted immediately. Thus the ETE delay always increases. The average cannot converge to a stable value. However, in the on-demand mode, each *active* spacecraft can access one more slot to transmit the traffic. Therefore, spacecraft in on-demand mode utilizes the channel bandwidth more efficiently.

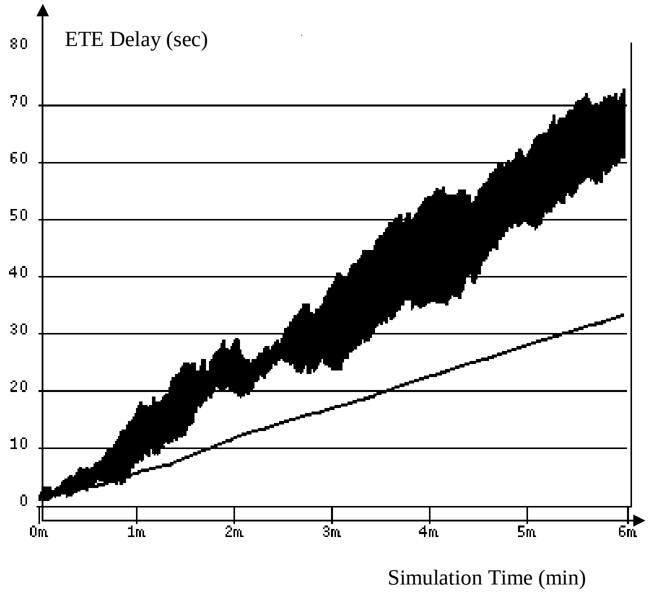


Figure 5.27: Delay in pre-planned mode with three active spacecrafts when n=5 under HT condition

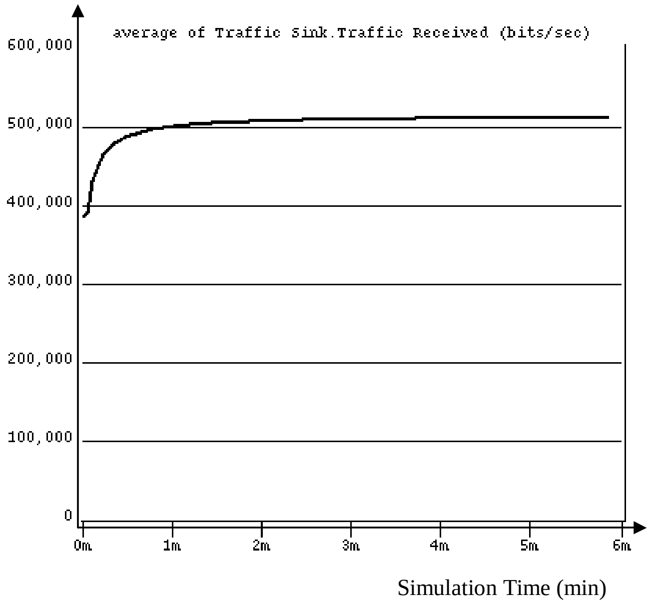


Figure 5.28: Average throughput in pre-planned mode with three active spacecrafts when n = 5 under HT condition

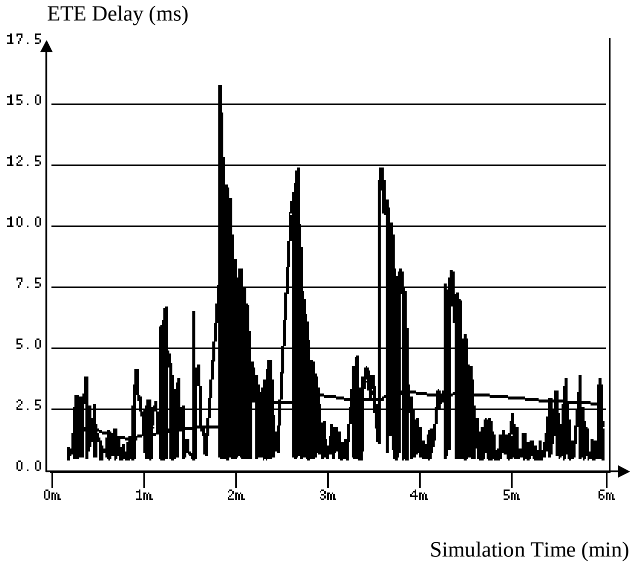


Figure 5.29: Delay in on-demand mode with three active spacecrafts when n=5 under HT condition

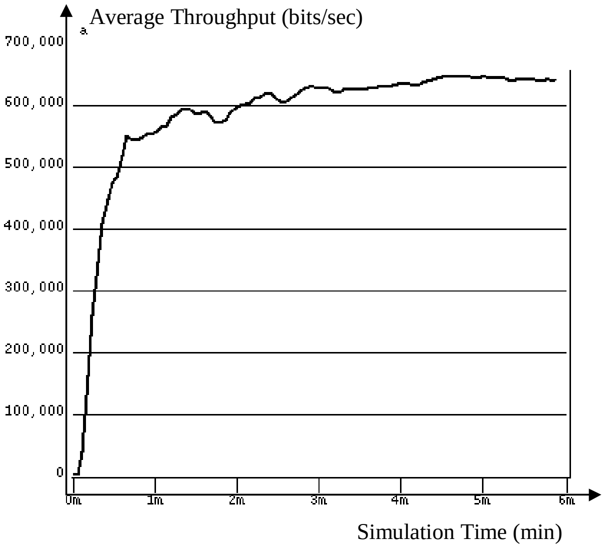


Figure 5.30: Average throughput in on-demand mode with three active spacecrafts when n=5 under HT condition

5.2.6 *Evaluation of reservation overhead of RD-TDMA scheme*

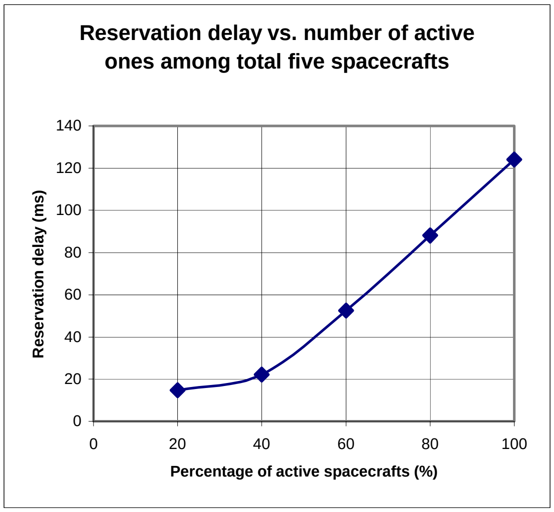


Figure 5.31: Reservation delay vs. number of active spacecrafts when *n*=5

Compared with pre-planned mode, the on-demand mode has reservation delay overhead. This reservation delay overhead consists of two delay components:

Non-contention request reservation delay (NCRR) delay and Contention request reservation (CRR) delay. As shown in Figure 5.31, the shape of the curve can be divided into two phases:

- Phase 1:

  The delay variance between the first two scenarios (with 20% and 40% percentage of *active* spacecrafts) is small. This is because, when number of active spacecraft is one, the reservation delay is equal to NCRR delay since there is no contention between different spacecrafts. The NCRR delay is about 13ms, which is about twice of frame time to set up the connection for data transmission. (Please refer to the detail explanation in Chapter 2). When there are 40% of active spacecrafts, i.e. two active spacecrafts, there is reservation contention between different *active* spacecrafts. Under the contention situation, the *active* spacecraft has to resend the reservation request until it is assigned a slot. This behavior adds CRR delay overhead to the ETE delay. For the scenario with 40% of *active* spacecraft, the CRR delay is equal to a TDMA frame time. Thus, the reservation delay is about 20ms. In this phase, the NCRR dominates the ETE delay, which is twice of the frame time.

- Phase 2:

  When the when percentage of *active* spacecraft is more than 40%, the reservation delay increases promptly with the increase of the number of active spacecraft since all the active spacecrafts content for the same reservation slot. The increase of the number of active spacecrafts increases the collision probability and the CRR delay overhead. The more the active spacecrafts, the larger the CRR delay overhead is. The CRR delay dominates the ETE delay.

Therefore, we can get the following conclusion from the above analysis about the reservation delay in on-demand mode:

- The reservation delay increases with number of active spacecraft in the network.
- The reservation delay consists of two components: CRR and NCRR.
- When there is small number of active spacecraft (two active spacecrafts in this example), NCRR dominates the ETE delay. Reservation delay is relatively small.
- With the increase of the number of active spacecrafts, the reservation delay increases promptly due to the fact that the contention between different active spacecrafts becomes more severely. The CRR delay begins to dominate the ETE delay.

This analysis gives us insight that in order to improve performance of RD-TDMA scheme, efforts should be given to decreasing the CRR to a minimum extent while the NCRR is unavoidable.

5.3 Conclusions

From the simulation results analysis in section 5.2, we can see that the delay-throughput-utilization performance of the MAC protocols depends on the networking condition, the individual traffic load condition, network traffic load distributed condition and slot assignment strategy. We summarize the important conclusions as follows:

Conclusion 1: Compared with *evenly distributed traffic load condition*, on-demand mode performs better under *unevenly distributed traffic load condition.* (Section 5.2.1)

Conclusion 2: on-demand mode has significant advantage in delay performance with 20%, 40% and 60% percentage of active spacecraft in most cases. Only when the percentage of active spacecraft increases to 80%, on-demand mode begins to perform worse than pre-planned mode. The more unevenly distributed traffic load among different spacecrafts, the better performance on-demand mode presents. (Section 5.2.1)

Conclusion 3: On-demand mode has better channel throughput performance than pre-planned mode under *unevenly distributed traffic load condition*. (Section 5.2.2)

Conclusion 4: Under *unevenly distributed traffic load condition*, on-demand mode has significant delay performance improvements under both heavy traffic load condition and under light traffic load condition. When the traffic load increases, on-demand mode has an increasing advantage over pre-planned mode in delay performance. (Section 5.2.3)

Conclusion 5: Pre-planned mode can only accommodate at most the same number of spacecraft as the number of slots in a TDMA frame. On-demand mode accommodates larger network size. Its performance is affected by the number of *active* spacecraft transmitting traffic instead of the total number of spacecraft in the view of the ground station. (Section 5.2.4)

Conclusion 6: On-demand mode has larger bandwidth utilization than pre-planned mode under *unevenly distributed traffic load condition*. (Section 5.2.5)

Conclusion 7: In order to improve performance of RD-TDMA scheme, efforts should be given to decreasing the CRR to a minimum extent while the NCRR is unavoidable. (Section 5.2.6)

In summary, the simulation results prove that on-demand mode has significant advantage over pre-planned mode under *unevenly distributed traffic load condition* in terms of delay-throughput-utilization performance and accommodating larger network size. In other word, on-demand mode has significant advantage in efficiently utilizing the satellite channel bandwidth and accommodating larger network size. Meanwhile it can guarantee the comparable delay performance with that of the pre-planned mode in most cases. This makes on-demand mode a promising strategy for next-generation LEO scenario NASA space missions with unpredictable traffic pattern.

Chapter 6 Summary and Future work

6.1 Summary

Large number of small spacecrafts in LEO will play an important role in the next-generation NASA space missions. We are interested in the space-to-ground scenario which the data file is downloaded from LEO spacecrafts to the ground station acting as NCC. Currently, a pre-planned operation is used, which is simple to implement but inefficient in satellite bandwidth utilization. In order to maximize the utilization of the expensive and limited satellite bandwidth, we proposed an evolutionary on-demand mode for next-generation NASA mission.

We first discussed a centralized on-demand mode network architecture. After that, a detailed overview of MAC protocols was presented. Although a lot of demand TDMA protocols were proposed in the literature, they addressed the MAC issues for cellular network and packet-switched radio satellite network architecture. Here we have proposed RD-TDMA protocol for our unique LEO network scenario with the novel on-demand mode network architecture. The RD-TDMA protocol is a reservation based demand TDMA protocol. It uses slotted-ALOHA for reservation. Our objective is to evaluate its suitability for LEO network scenario.

We compared the two modes (pre-planned mode and on-demand mode) by means of simulation. Performance measures are ETE delay, throughput and utilization. We used OPNET to implement the MAC protocols and demonstrate the performance comparison analysis. We applied similar networking conditions and traffic load conditions to the two modes. We found that the delay-throughput-utilization performance of MAC protocols in our LEO scenario heavily depends on the network traffic load distribution among different spacecrafts. We divided the network traffic load distribution into two cases: *evenly distributed traffic load condition* and *unevenly distributed traffic load condition.* Comparisons of the simulation results have shown that on-demand mode outperforms pre-planned mode in most cases under *unevenly distributed traffic load condition* in terms of ETE delay, throughput, utilization and accommodated network size. Therefore, on-demand was proved to be a promising strategy for next-generation NASA mission with unpredictable traffic pattern.

6.2 Future Work

Future work in this area includes the development of advanced MAC schemes of on-demand mode for next-generation NASA mission. Also, more specific traffic models for the NASA mission can be used in further optimizing the MAC schemes.

On-demand mode and pre-planned mode can be combined to obtain more efficient bandwidth utilization and better delay performance by developing intelligent hybrid MAC schemes which can identify and predict the traffic load condition and perform different schemes adaptive to different traffic and networking condition.

In order to improve the delay performance of on-demand mode for QoS guarantee requirements, efforts should focus on minimizing the reservation overhead that might involve:

- Special random access slot can be added to the TDMA frame, which is used for short file transmission without reservation.

- Adaptive collision algorithms can be developed to minimize the number of contentions.
- A priority-based solution to serve the reservation requests with priorities first, etc.

Satellite orbit and mobility simulations can be used to investigate the changing behavior of LEO network size and coverage time of ground station and access time of LEO spacecraft. These simulation results can be integrated with OPNET to further investigate the study for the LEO scenario, especially for mobility handling.

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