MAC Architecture for Broadband Satellite Access Systems

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Abstract

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In recent years, the telecommunications industry has expanded tremendously. A tendency of integrating various business revenues with the conventional communication systems is becoming more and more popular to achieve global information services. The integration is triggered by increasing demands of costumers to access various types of broadband multimedia services. The access system can be implemented on many platforms: from line feed as cable, fiber, or copper networks to wireless as radio or satellite networks. Broadband satellite access is a leading candidate to contribute to such development due to satellites' distinctive features of global coverage over single hops and distance insensitivity. However, as satellite networks possess rather longer delays and bounded resources, a MAC layer that can efficiently share resources over a minimum possible bandwidth is mandatory to the success of satellite access. Existing MAC protocols are not able to achieve optimum performance. Hence, design of a new MAC becomes inevitable. The new MAC should introduce a novel structure with certain behavioral sequences and an efficient access technique. In this thesis, we propose a MAC architecture that aims to address such requirement. We utilize a novel access technique based on an enhanced CFDAMA protocol. We also introduce a new concept of two level differential scheduling. We present formal models based on SDL to verify the validly of the devised system. Finally, we build an OPNET simulation model to demonstrate quantitative system operation and serve as a nucleus model for possible future research involving performance optimization in satellite networks over the devised architecture.

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God has blessed me with my family. I dedicate this thesis to them. To my mother Wadouda, my father Osama, and my little sister Ethar

Contents

List of Figures

List of Acronyms and Abbreviations

ADSL	Asymmetric Digital Subscriber Line
ATM	Asynchronous Transfer Mode
BSA	Broadband Satellite Access
BTS	Base Tranceiver Station
BWA	Broadband Wireless Access
CATV	Cable TV
CDMA	Code Division Multiple Access
CFDAMA	Combined Free Demand Assignment Multiple Access
DAMA	Demand Assignment Multiple Access
DAVIC	Digital Audio-Visual Counsil
DCA	Dynamic Capacity Allocation
DHCP	Dynamic Configuration Host Protocol
DOCSIS	Data Over Cable System Interface Specifications
DS-DL	Downstream Down-Link
DS-UL	Downstream Up-Link
DSL	Digital Subscriber Line
DVB	Digital Video Broadcasting

FDMA	Frequency Division Multiple Access
FEC	Forward Error Correction
FTTC	Fiber To The Curb
FTTH	Fiber To The Home
GEO	Geo-stationary Earth Orbit
GII	Global Information Infrastructure
IDBS	Interactive Distribution Broadcast Satellite
IP	Internet Protocol
LAN	Local Area Network
LLC	Logical Link Control
LMDS	Local Multi-point Distribution System
MAC	Medium Access Control
MCS	Master Control Station
MCS-DL	Master Control Station Down-Link
MCS-UL	Master Control Station Up-Link
MF-TDMA	Multiple Frequency Time Division Multiple Access
MMDS	Multi-channel Multi-point Distribution System
MPEG-2	Moving Picture Expert Group-2

ONU	Optical Network Unit
OPNET	Optimized Network Engineering Tools
PBX	Private Branch Exchange
PSTN	Public Switched Telephone Network
QCM	Queue and Capacity Manager
QoS	Quality of Service
RSVP	Reservation Protocol
SAT-MAC	Satellite Medium Access Control
SDL	Specification and Description Language
SNMP	Simple Network Management Protocol
STS	Subscriber Tranceiver Station
TDMA	Time Division Multiple Access
TFTP	Trivial File Transfer Protocol
US-DL	Upstream Down-Link
US-UL	Upstream Up-Link
VDSL	Very high bit-rate Digital Subscriber Line
VoD	Video on Demand

Chapter 1

Introduction

The telecommunications industry is one of the most promising and anticipated global businesses towards achieving universal information services. In recent years, it has been tremendously expanded and its evolution is oriented towards integration of conventional telecommunications industry with the emerging interactive Internet industry as well as the evolving entertainment industry (e.g., Cable TV (CATV), Video on Demand (VoD), etc.). Therefore, it is foreseen as a new prominent business arena with enormous potential and business opportunities. Moreover, with the continuous advancements in network and information technologies, it is reasonable to expect that every piece of information in the real world will eventually be digitized, stored, and processed. This sets the stage for all industries and businesses to be combined together and integrated with the telecommunications industry. Such integration is evident in the case of electronic commerce (e-commerce) [1], which on the long run will grow to become one of the most important services on the networks that can create new business opportunities, new business operations and new industries [2]. This emphasizes the core role expected from the telecommunications industry to play in achieving the Global Information Infrastructure (GII) [3]. The GII is anticipated to become an infrastructure that facilitates the development, implementation, and interoperability of existing and future information services and applications within and across the telecommunications and information technologies.

1.1 Broadband Access

One of the long-term targets for telecommunications networks in the multimedia era is to support any type of telecommunications services - distribution as well as interactive services to residential subscribers or users [4]. The continuously evolving broadband access systems address all the requirements in order to achieve this objective. The term access involves a subscriber access to some other network, such as, the Internet, a private network, a telephony network or any other backbone network. Telecommunications systems in that case can be divided into three parts: access networks, core networks and subscriber networks. The access network is defined as a network entity providing access capabilities for various service applications to access various service providers located at the edges of the core network. Alone, it does not represent a complete end-to-end communication system. The core network may be the Internet, Public Switched Telephone Network (PSTN), etc. The subscriber network represents the end-user doing the access. It does not necessary constitute of a single user. Rather, an interface from some network on the subscriber side (LAN or PBX) more likely represents the standard configuration.

Figure 1.1 depicts the general configuration of a broadband access system. Various broadband access system technologies are currently under development over cable, optical fibers, wireless and satellite, etc. It is worth mentioning, as indicated in [5],

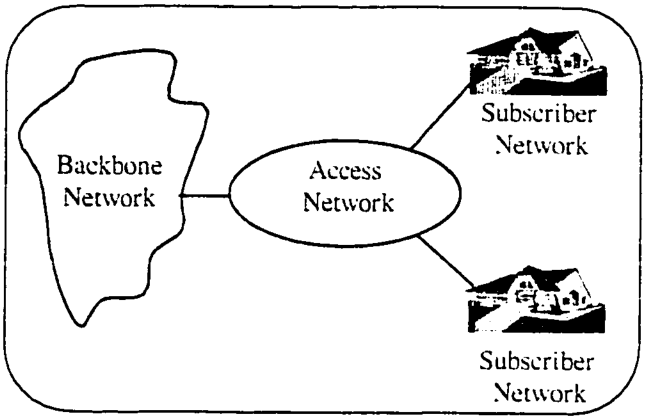

Figure 1.1: General Configuration of a Broadband Access System

that in 1996, the access network accounted for US$6 billion of telecommunications business worldwide. It is growing at an average rate of approximately 27% year. By 2000-2001 it will have a value of about US$19 billion.

1.2 Broadband Access Services

The whole telecommunications residential industry is service centered. Successful services are driven in part by advanced network and information technologies. The other part is market dependent, where the envisioned services should address consumers' perceptions, marketing sensitivity, cost profit analysis, and advanced network and information technologies [2]. The development of broadband access systems is driven by and coincides with increasing users' demand for transparent transmissions of data traffic, especially multimedia, between subscribers and backbone core networks in order to support envisioned multimedia services. A multimedia service is a service handling several types of presentation media in a synchronized way from the consumers' point of view. The media may be text, graphics, sound, image, and video, organized to provide various ways of access. Multimedia services envisioned to be deployed over the access systems may include asymmetric services, such as, Internet access, VoD (Video on Demand) and Digital Audio Video Multi-cast or symmetric services, such as, digital telephony and video conferencing. Other areas of application and investigation include electronic commerce, telemedicine, city information services, intelligent transportation systems, distance learning, electronic libraries and museums, etc.

1.3 Broadband Satellite Access

As previously mentioned, in recent years, numerous broadband multimedia services have been introduced. With MPEG-2 [6], Digital Video Broadcasting (DVB) [7], [8] is already a reality. Video-conferencing and VoD (Video on Demand) services as well as numerous multimedia applications over the Internet will not take long before they become efficiently deployed. Expected popularity of these services has led to rigorous competition between current technologies in order to serve as the underlying infrastructure. Data Over Cable System Interface Specifications (DOCSIS) [9], [10] is already implemented by the cable industry in some regions. Digital Subscribers Line (DSL) [11] technologies lately developed a Very high bit-rate DSL (VDSL) [12] to consolidate its competition chances. IEEE 802.16 Broadband Wireless Access (BWA) [13] task group was recently formed to investigate wireless access. Other technologies involving fiber networks are also under investigation such as, Fiber to the Home (FTTH) [14] and Fiber to the Curb (FTTC) [14].

Advancements in satellite technologies has encouraged satellite providers to envision themselves as strong competitors. However, the satellite competition for the backbone core network role seems questionable from both the cost and delay standpoints mainly, due to its well-known longer delay over shorter distances as well as its power and bandwidth constraints. Satellite providers seem to have a better chance with satellites as access networks to the backbone or as interconnections between remote networks. In that context, the former referred satellite drawbacks are balanced out. Global connectivity over single hops allows for wide area coverage while saving lots of switching and routing delays as well as sequencing problems that other technologies will experience over similar distances. Reachability to remote inaccessible areas proves cost-effective in low population rural areas. Satellite transmissions are broadcast in nature. This allows for cost-effective deployment of broadcast multipoint services, especially, in regions with infrastructure deficiencies. Satellite systems differ from other systems in that the network provider (satellite provider) is usually independent of the service provider (VoD server for example). This allows satellite networks to become more suited in developing services characterized by a competitive environment. Competitiveness guarantees better pricing for end-users. Such configuration will also encourage numerous service providers to join the market without worrying about transmission equipment.

1.4 Broadband Satellite Deployment

Broadband services are far more complicated than traditional baseband services. While baseband services simply usually involve only a single data type, broadband services are characterized by network integration, high bandwidth demands, multimedia services complexity, quality of service (QoS) requirements, and traffic fluctuation. The operation of future telecommunications networks therefore, is expected to be more complicated than the current situation. Taking telephone service as an example of baseband services, the service has a fixed bandwidth requirement for its connection. Although there may be many service features, such as, call forwarding and call waiting, to be added to the basic service mechanism, establishing a call remains the major task. Broadband services on the other hand, demand much more than this. A VoD service for example needs to handle not only connection establishment between a client and its server in order to carry audio, video, and possibly text streams, but also the various control messages such as forward, pause, and rewind [15]. Video signals under MPEG-2 compression are comparatively bandwidth hungry and produce bursty variable bit-rate traffic. Moreover, real-time as well as non-real-time multimedia services are usually characterized by stringent QoS requirements.

Deploying a broadband service with necessary efficient transport of data, voice and video in terms of bandwidth, reliability and delay, therefore is far more complicated and requires complex engineering efforts. A key element in satisfying such a requirement will be the development of an efficient Medium Access control (MAC) protocol technique, especially, over shared media. A MAC protocol specifies the message sequences necessary to establish and maintain connections between terminals across the satellite links involved in broadband communications. The MAC technique on the other hand, defines how users will efficiently share the capacity allocated achieving maximum subscribers under minimum bandwidth requirements.

The design of an adequate efficient MAC layer for satellite networks represents a serious challenge and is one of the hottest research areas, as satellite systems possess several characteristics that hinder decent performance of regular MAC. Development of new access techniques that efficiently utilize the limited bandwidth is required. These techniques must achieve rapid channel access by users sharing the bandwidth in order to minimize satellite long delay effects. Satellite MAC should also support flexible reconfigurable channels to face the harmful effects of non-stability and interference of the satellite medium. Moreover, as satellite systems are configured differently from regular telecommunications systems, the satellite MAC must achieve proper coordination between the various terminals involved in data communications.

1.5 Satellite Systems Implementation

The trend in implementing current telecommunications systems is oriented towards the development of networks that satisfy the requirements of an open system. An open access system has its end-user terminals independent of the employed access technology. Hence, access network providers introduced the concept of interface terminals as intermediate gateways that connect the customers with their corresponding access network. The advantage of such configuration is that it promotes mass production of end-user equipment at lower prices and renders flexibility to their producers. In satellite systems, this is evident in an air-interface terminal between users and the satellite medium. The air-interface terminal should convey the responsibility of addressing and managing all the satellite requirements. As a result, all the efforts on development of an efficient satellite MAC layer should reside at the air-interface. It is obvious that correct development of this air-interface terminal is critical to the success of satellite systems.

Satellite networks as all communication systems are complex, concurrent, safety-critical and require standardization. Descriptions given in non-formal natural language and/or diagrams are hard to avoid ambiguity and not easy to analyze or process automatically as they lack explicit technical presentations. Generally over the years, protocol implementation for telecommunications systems was done non-formally. Implementation was a direct translation from an non-formal specification. Though final products were released after numerous debugging iterations, still many faults due to design and implementation errors were experienced through practical use resulting in huge wasted investments. This would be completely unacceptable with satellite systems, where only the launching process would cost millions of dollars. Over the last two decades, a new trend has emerged for telecommunications systems development through the use of formal techniques [16]. Formal techniques (FT) are capable of defining clear, plain and unambiguous systems in order to achieve consistent standards. They have been successfully utilized for description and validation of communication protocols. While system description involves behavior and requirement specification, validation insures system correctness.

The advantage of describing systems using formal languages lies in their representation. Using formal languages for system specification can be considered as an intermediate stage before implementation that achieves precise description and specifies technical attributes. Moreover, some languages as the Specification and Description Language (SDL) [17] complement that by visuality through utilizing a graphical representation. Another interesting aspect of formal languages is their ability to employ abstractions without affecting the integrity of the description. In that scenario, description and consequent simulations are able to utilize abstracted (input output behavior) system constituents to reduce complexity while achieving clearer understanding. This can be utilized to simplify the description of interfaces to the system of interest and present mutual interactions. Again in some languages like SDL that are object oriented, abstractions allow for easier model development. Models are built

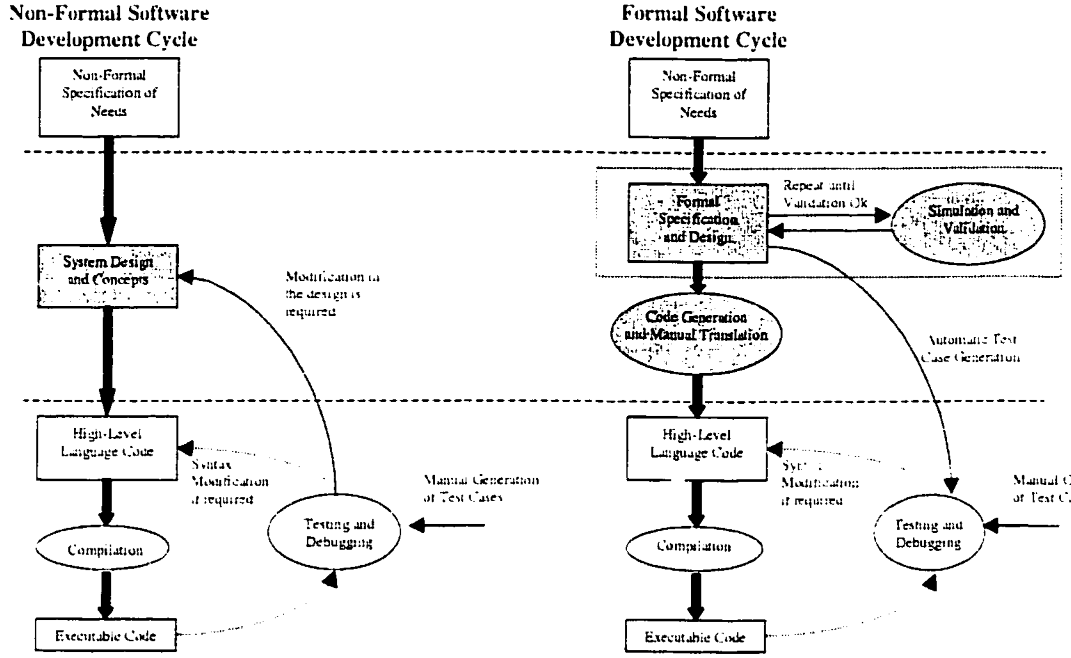

Figure 1.2: Formal and Non-Formal Development Cycles

in stages with continuous extensions in order to gradually, yet simply achieve a complete model. Moreover, as some formal languages represent a standard language (e.g., SDL), an automatic code generation is always possible, thus, relieving some of the implementation efforts.

One fundamental constituent of system development is the testing. It is usually conducted on implementations to confirm their functionality. This is a tedious procedure especially within non-formal system development due to the complexity of current communication systems. A complex communication system might require millions billions of test cases to confirm its functionality. Even with the most effective testing techniques, faults are still usually discovered. Formal techniques provide a way to minimize the required testing by employing formal validation and verification at earlier stages. With the development of formal verification techniques as reachability analysis, system verification insures the absence of deadlocks, unspecified receptions, live-locks, etc. in system operation. Validation uses the verification process to confirm different behavioral scenarios insuring that the developed system behavior coincides with the requirements. Successful verification and validation guarantee correctness of the design and the consequent testing would be simplified. A comparison between formal and non-formal system development cycles is shown in Figure 1.2. As shown in the figure, the advantage of formal techniques is evident in the independence between the design and the implementation phases, while non-formal development requires going back and forth between the two phases and it is usually difficult to distinguish between design and syntax errors in testing. Hence, once the validation of the formal specification is completed, we can expect less iterations in the implementation test phase and therefore less total development time.

Although formal methods are powerful tools for systems specification and verification, their building semantics lack the ability of providing quantitative performance analysis for the developed systems [18]. Performance measures are very important to evaluate and compare communication systems. Hence, equivalent simulation models must be built to meet common standards. One of the most popular simulation tools is the Optimized Network Engineering Tools (OPNET) [19]. Combining performance and behavior under formal methods is a very hot research issue.

1.6 Contributions and Outline of the Thesis

We can summarize the contributions of our research work in the following:

1. Constructing a flexible MAC layer architecture that can be employed in residen-

tial two-way interactive services over satellite.

2. Employing an enhanced CFDAMA access technique based on prediction for dynamic capacity allocation.

3. Employing a flexible two-level scheduling structure based on a differential services approach with minimum complexity.

4. Defining behavioral description for two modes of data transfer operation under the prediction-based CFDAMA protocol.

5. Developing a formal model for the devised MAC layer behavioral description and verification.

6. Developing a performance simulation model that demonstrates performance analysis of the utilized access technique.

The rest of the thesis is organized as follows:

In Chapter 2. we discuss issues related to the state-of-the-art of broadband access systems. We describe standards bodies and highlight various access networks technologies. We then conduct a survey of interactive broadband satellite access systems and discuss open issues in the field. Then in Chapter 3. we describe an interactive residential broadband satellite access system. We show its configuration structure. constituents and proposed protocol stacks. We emphasize the MAC layer specification as we describe dynamic capacity allocation. access techniques. scheduling structures. behavior description and data transfer operation. In Chapter 4. we develop a formal model for the devised MAC layer. We discuss model description and present verification and validation results. Then in Chapter 5. we built an OPNET simulation model for the utilized access technique and present an example for performance analysis. Finally, in Chapter 6, we summarize as we conclude our work and suggest possible further related research studies.

Chapter 2

Broadband Access Systems

The term broadband literally means large bandwidth. With inevitable increase in the customers' needs to access multimedia information. popularity of broadband systems is continuously on the rise. Successful deployment of these systems however. necessitates numerous efforts in all domains of the field in order to achieve efficient cost-effective services from the perspective of service and network providers as well as customers. In this chapter. we discuss issues related to the state-of-the-art of broadband access systems as we address the various efforts and technologies that envision broadband services and aim for systems standardization. We then shift our interest to focus on deployment of such services over satellite networks. We present examples of current efforts and highlight their drawbacks. We then discuss the open issues in satellite systems. In the end. we address one of the most important challenges of satellite access related to development of an efficient MAC layer.

2.1 DAVIC

Soon, as we approach closer towards achieving the GII [3], *digital* audio-visual services will dominate the telecommunications markets. The vision of shared audio-visual information transmitted back and forth over telecommunications networks between service providers and end-users is steadily becoming more and more evident with ceaseless efforts of development and implementation of globally agreed audio-visual standards. The Digital Audio-Visual Council (DAVIC) is a well-recognized technology standards leader in this domain and, through its specifications and cross-industry role, actively promotes the successful worldwide growth of interactive digital audio-visual applications and services [20]. In this section, we present a brief discussion of the DAVIC organization work, technology and specifications.

2.1.1 DAVIC Organization

The Digital Audio-Visual Council (DAVIC) was founded in October 1994 based in Geneva. It is a non-profit making association with a membership in more than 200 companies from over 25 countries worldwide and has taken the leadership of promoting and developing broadband digital services. The DAVIC membership is represented by all sectors of the audio-visual industry including the computer, consumer electronics and telecommunications manufacturing sectors, and the broadcasting, telecommunications and cable companies as well as some government and research organizations. DAVIC members include major industry players including Microsoft, BT, AT&T, Intel, and the BBC [21]. Moreover, DAVIC is also committed to operate with other standards organizations and is open to integration of the partial solutions provided by their standards and specifications whenever possible.

Since 1994, DAVIC experts have succeeded in producing five separate releases of the DAVIC specification. Each of these industry specifications is backward compatible, and specifies needed interoperability and functional capabilities of consumers, content providers, service providers, as well as delivery systems to achieve the target services. Earlier versions of DAVIC specifications only involved audio-visual services, e.g., TV, VoD as the initial purpose for DAVIC was favoring the success of emerging digital audio-visual applications and services. However, with the Internet currently being accessed worldwide by some 50 million PC owners, recent versions of DAVIC specifications specify tools for Internet services, e.g., web browsing. DAVIC's interrelation with the Internet provides an evolutionary path for the Internet towards excellent multimedia distribution with guaranteed connection as well as defined quality of service (QoS)[1] (using bandwidth reservation and differential services) in terms of bandwidth, latency, loss, and jitter [22]. Full details on the latest DAVIC specification 1.4 could be found in [23]. The next DAVIC release 1.5 is expected to investigate *TV anywhere* on the Intra-net design level. Examples of existing implementations that utilize DAVIC specifications could be found in [20].

2.1.2 DAVIC Objectives

The goals of DAVIC are declared as '... *to identify, select, augment, develop and obtain endorsement by formal standards bodies of specifications of interfaces, protocols and architectures of digital audio-visual applications and services*' [21]. The objective is to define minimum tools and core functions required by digital audio-visual systems for end-to-end interoperability across countries, applications, and services. In order

[1]The term QoS defines parameters as delay, throughput, jitter, etc. that should be sustained during the lifetime of a certain connection.

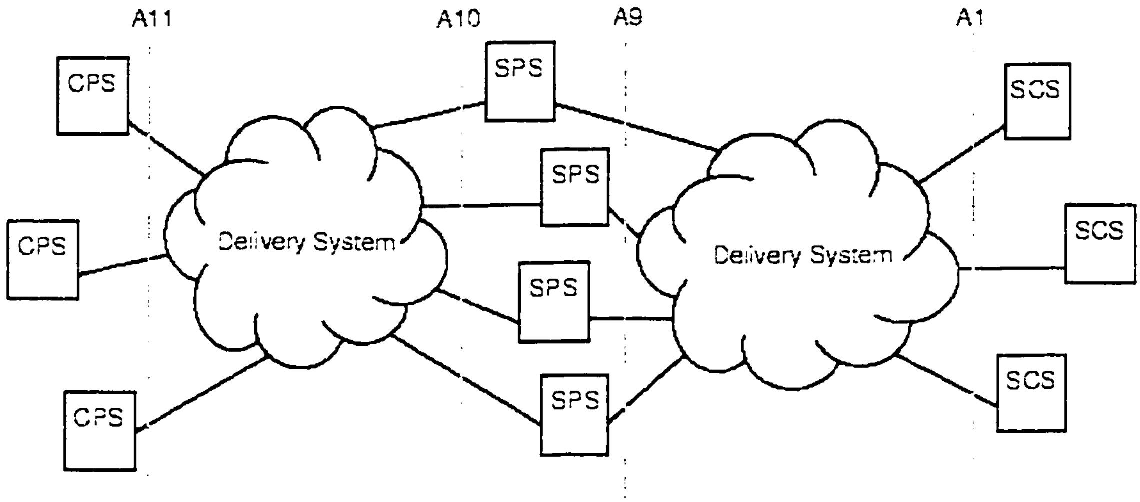

Figure 2.1: General DAVIC Configuration

to guarantee interoperability across different systems and applications. DAVIC's approach precludes the definition of a system: instead, non-system-specific components, or "tools", are defined. These tools should have the capability to be employed in a variety of different systems as well as in different parts of the same system.

2.1.3 DAVIC General System Configuration

The general DAVIC system model is shown in Figures 2.1 and 2.2 [21]. It consists of 5 entries: the content provider system (CPS), the services provider system (SPS), and the service consumer system (SCS), which are interconnected by the CPS-SPS delivery system and the SPS-SCS delivery system. As shown in the figure, the system defines five information flows [21]:

S1: Principal services layer peer flow for uni-directional transfer of encoded audio, video and data from the server to the set-top unit.

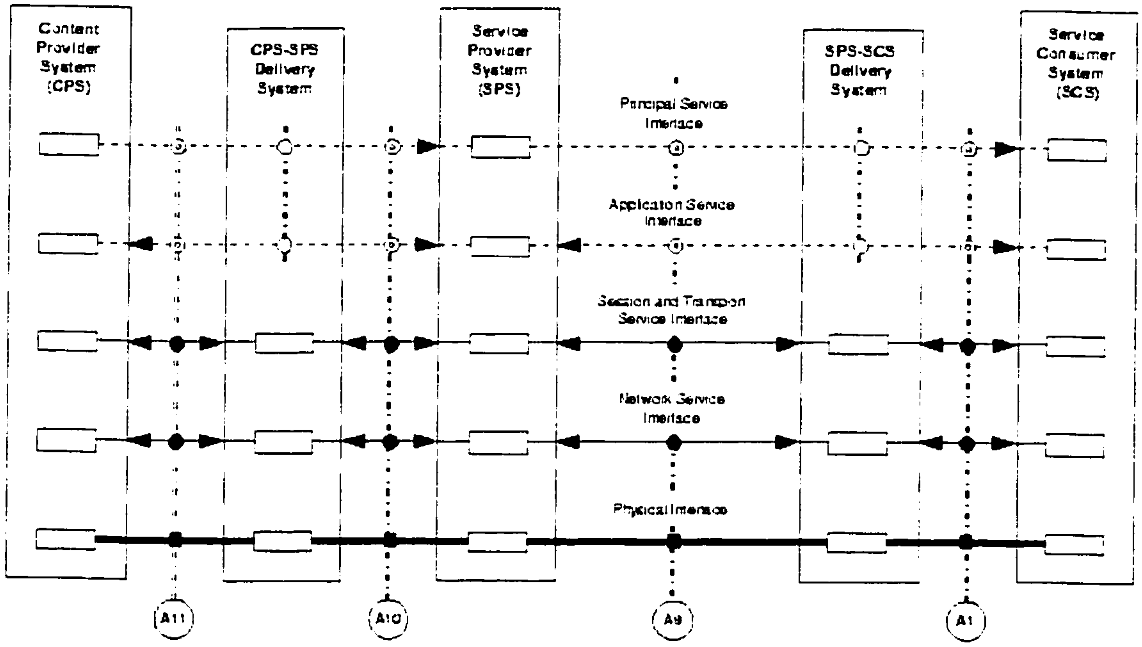

Figure 2.2: General DAVIC System

S2: Application services layer peer flow for bi-directional exchange of the control information from an application service layer source object to a peer destination object.

S3: Session Transport services layer peer flow for the connection control of a session.

S4: Network services layer peer flow for the connection of the network and routing through the network.

S5: Administration of network elements. e.g.. network management.

For these five flows. DAVIC has defined a full protocol stack based upon the appropriate and currently available protocols.

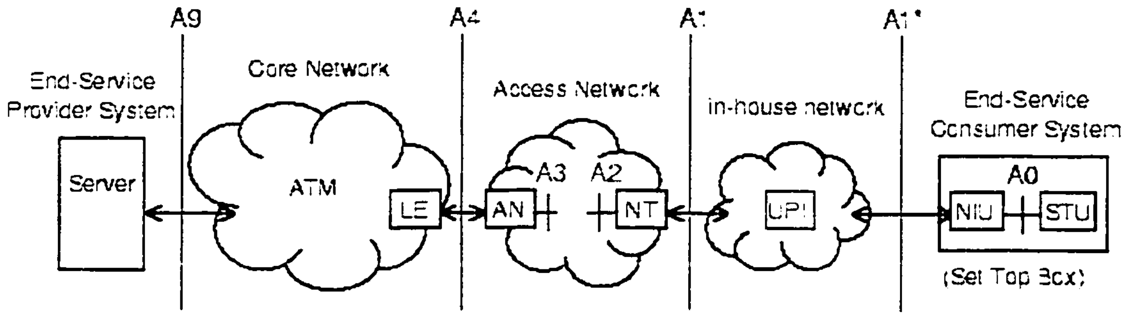

Figure 2.3: Cabled Network Architecture in DAVIC

2.1.4 DAVIC Delivery System

The term 'delivery system' involves any means of conveying information from one entity to another in order to support the services envisioned by DAVIC. Figure 2.1 shows how the various entities of the general DAVIC model are connected to the delivery system and defines the reference points through which connections pass. Delivery systems may be networked or non-networked. Non-networked systems include physical storage media, such as, CD-ROM, disc and tape. Networked delivery systems include Cabled networks, Radio networks (transport signals using electro magnetic waves and are essentially broadcast networks), such as, terrestrial and satellite, and Hybrid networks, such as, Multi-channel Multi-point Distribution System (MMDS) and Local Multi-point Distribution System (LMDS). It is worth mentioning that the scope of this thesis will focus on the access network (Satellite network) delivery system between reference points A1 and A9 (Figure 2.2) with emphasis on the upstream up-link at A1 reference point. Figures 2.3 and 2.4 [21] show general structures for Cabled and Satellite (an example for Radio) networks as described by DAVIC.

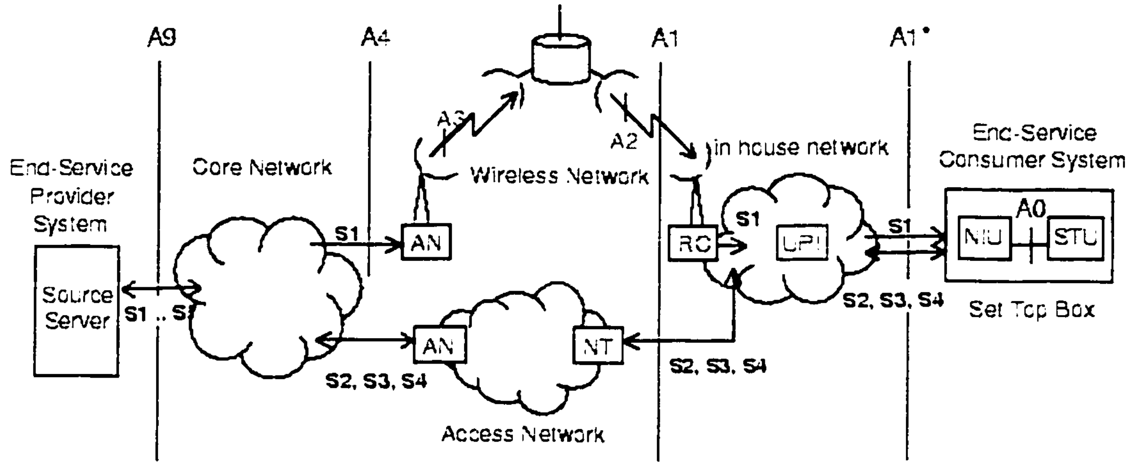

Figure 2.4: Satellite Network Architecture in DAVIC

2.2 Broadband Access Network Technologies

As indicated above, one of the areas of DAVIC's study involves delivery systems. In the access systems architecture, the key delivery component resides in the access network as it is considered the linking bridge that should efficiently support communications between consumers and the service providers. Moreover, since a concept of multi-service integration over common access networks is becoming more popular due to the economical benefits of sharing the access resources among services, the access network, especially, the MAC layer must be carefully designed to accommodate numerous possible divergent services. Various broadband access system technologies are currently under development. Figure 2.5 shows examples of access network architectures as described in [24]. It is important to note that most of these technologies may always share similar end-system participants to ensure an open system policy. Differences are usually rather evident in the access medium itself. In the following sub-sections, we provide examples of efforts conducted in the access technology field.

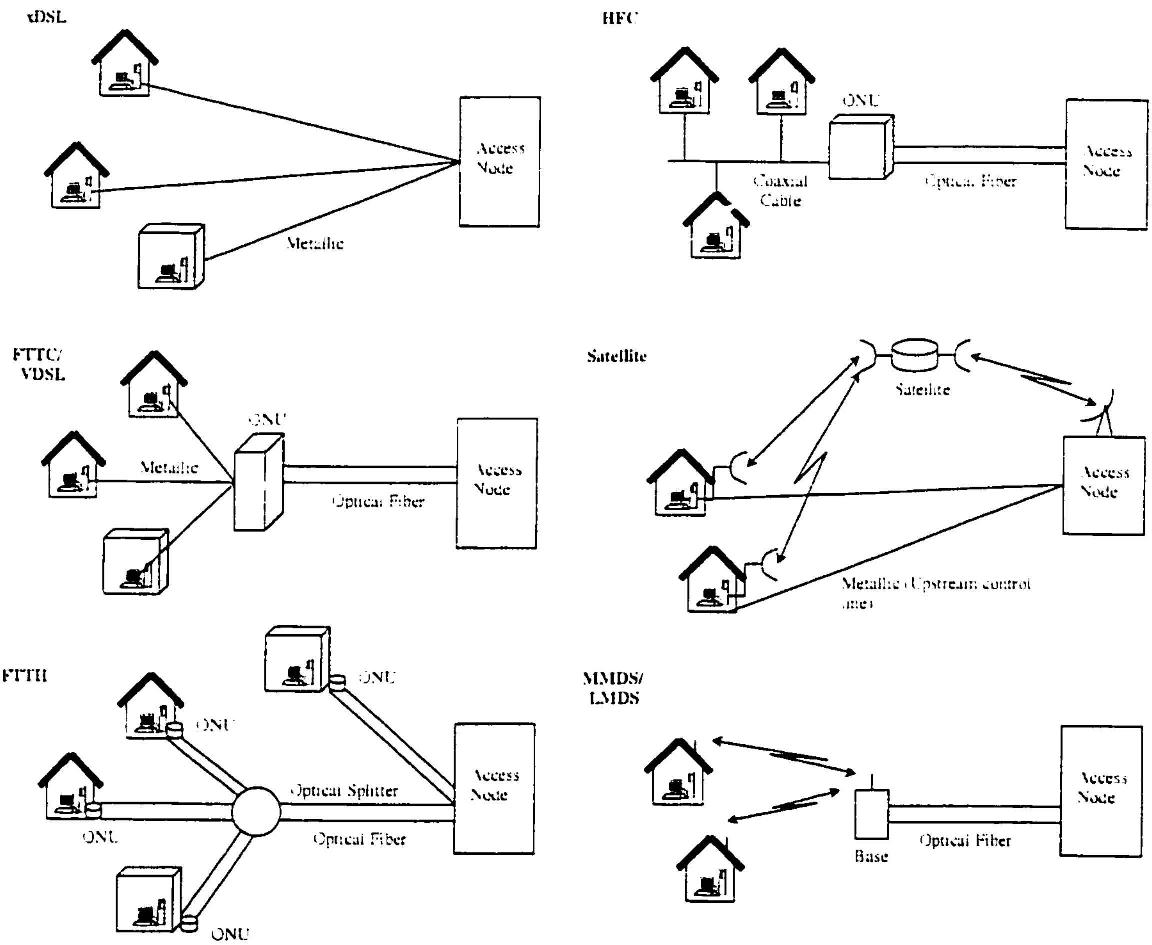

Figure 2.5: Examples of Access Network Architectures

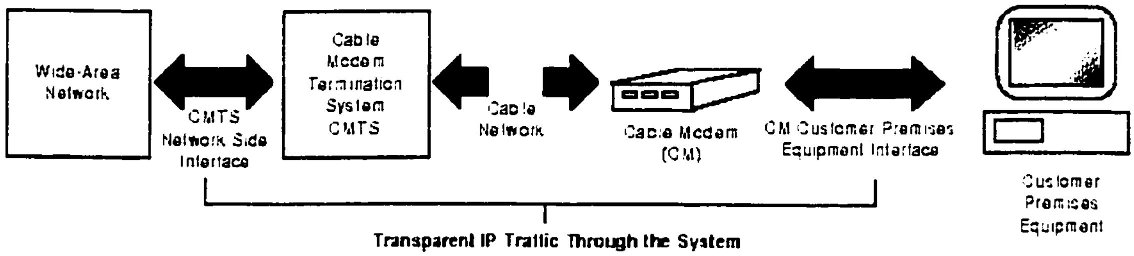

Figure 2.6: DOCSIS General Configuration

It is also worthwhile to mention that these technologies may participate in implementing a (complete or partial) DAVIC compliant system. which is not necessarily developed by the organization itself.

2.2.1 Cable Networks

The Data Over Cable System Interface Specification (DOCSIS) [9]. [10] was introduced for cable operators in deploying high-speed data communications systems on cable television. It describes terminal structures and data interfaces that will provide better performance on cable networks. Subscribers access the network through a Cable Modem (CM) and their transmissions are realized at the head-end by a Cable Modem Termination System (CMTS). A general configuration for the DOCSIS system is depicted in Figure 2.6 [10]. The envisioned services rely on efficient bi-directional transfer of data traffic over an all-coaxial or hybrid-fiber coax cable network organized in a *tree-and-branch* [9] architecture. The system uses upstream (CM to CMTS direction) frequencies between 5-30 MHz and downstream (CMTS to CM) frequencies with a lower edge between 50 and 54 MHz and an upper edge ranging from 300 to 860 MHz. Signals may be transmitted at as high as 10-15 Mb/s. DOCSIS 1.1 [10] was recently released to complement the former DOCSIS 1.0 [9]. DOCSIS 1.0 only supported static network connections initiated during subscriber registration (when users turn terminals on). DOCSIS 1.1 on the other hand, introduced a dynamic dimension to the specification by defining dynamic services. Dynamic services enable changing attributes of existing connections as well as establishing new connections during terminal operation. DOCSIS 1.1 also envisioned the use of some differentiated scheduling services. However, specific categories are not yet completely standardized. We have considered the DOCSIS as a candidate towards development of an efficient satellite MAC. Details on such procedure and on the DOCSIS MAC specification itself will be presented in the next chapter.

2.2.2 Digital Subscriber Line

Digital Subscriber Line (DSL) [11] offers broadband services over spectrum bands beyond the 4kHz voice channels of twisted pairs. In the past, bandwidth allocated by the telephone company switch to voice calls limited the bandwidth of the voice modem. DSL technology revealed the capability of phone lines of carrying very high data rates if the narrow band switches can be avoided. Asymmetric Digital Subscriber Line (ADSL) is one of the current developed DSL systems. It defines an asymmetric transmission system in which downstream signals use the bandwidth of several hundred kb/s required for Internet access or several hundred Mb/s required for video transmission, while the upstream uses bandwidth sufficient for service control signals with lower initial investment in facilities. ADSL is capable of transmission in a range of several hundred meters to several kilometers. The latest DSL system is Very high bit-rate Digital Subscriber Line (VDSL) [12]. It is a high bit-rate version of ADSL that offers downstream signals up to 30 Mb/s. However, due to the fact that its transmission is limited to less than 1.5 kilometers there is a restriction on its applications.

2.2.3 Fiber to the Home

Fiber to the Home (FTTH) [14] is a fully optical network from the service provider to the consumer. The optical multiplexed signal is brought to a splitter in the vicinity of a group of customers. There are optical splitters of different ratios, but the most typical ratio used is 1 to 16. This means that the multiplexed signal is split to 16 different households. Since the optical signal has to be converted to electrical at the customer's premises, an Optical Network Unit (ONU) has to be installed at the end of the network. Because the ONU are expensive, it has been suggested that the resources of a single ONU should be shared among several customers. Figure 2.5 suggests what the FTTH access network might look like. Applications of optical fibers result in fewer restrictions on transmission distances and bandwidths for future service provisioning. If we can achieve cost-effective optical components, it may be considered an ideal line-feed access system [24].

2.2.4 Broadband Wireless Access

Broadband Wireless Access (BWA) is a wireless system designed to deliver data, voice and video with low delay. In BWA, multimedia services are provided by base stations to business or home networks in a star topology. As larger chunks (on the order of 1 GHz) of microwave and millimeter wave spectrum are becoming available, BWA becomes more liable for deployment in several regions. Most of the BWA frequency allocations are in the 24, 28, 31 or 40 GHz bands and have the capability to deliver data rates in the tens of Mb/s range. It should be mentioned that BWA is different from the traditional cellular system in two significant aspects. Firstly, BWA assumes fixed terminals and thus does not support mobility and the associated complexity due to hand-over and fading. Secondly, BWA operates at high frequency, which limits the cell size [13]. The IEEE 802.16 task group was recently formed to develop 802 standards for BWA.

2.2.5 Multi-channel Multi-point Distribution System

A typical Multi-channel Multi-point Distribution System (MMDS) receives scrambled satellite or cable TV signals at a central location. The central station then de-scrambles, digitizes, multiplexes, and re-transmits the received signals by special transmitters (SHF). The Super High Frequency (SHF, typically in GHz) transmitters then distribute the signals throughout the coverage area. Antennas installed on subscribers' roofs then will receive these signals and distribute them within the home or building through coaxial cable into a set-top box located near the television. MMDS configuration is shown in Figure 2.5.

One major limiting characteristic of wireless cable systems is the requirement of line-of-sight (LOS) transmission. Such constraint induces a crucial decision on the locations of the tranceivers. A preferable location would be a mountain peak, with a high angle of elevation and few obstacles that block the signal [25]. MMDS typically operates in frequency bands of less than 10 GHz, whereas Point-to-Multi-point wireless communications systems for multimedia broadband access services called Local (L)MDS operate in millimeter-wave frequency bands over 10GHz.

2.2.6 Satellite Access

Satellite communication systems can offer two-way interactive broadband multimedia services over wider regions than all previously described technologies due to the natural broadcast capability. They have the advantage of possible quicker deployment in comparison to line-feed systems, especially, in regions with minimum infrastructures. They also provide line-of-sight advantages over mobile networks, especially, in crowded regions where signal blocking of wireless transmissions is inevitable. More details about satellite systems will be presented in the next section.

2.3 Broadband Satellite Systems

In this section, we focus on presenting various systems deployed for interactive services over satellite networks and highlight their drawbacks. We then revert to discuss the open issues in the field with emphasis on the development of an efficient MAC layer.

2.3.1 Brief History

Satellite technology dates back to as early as 1947 when Arthur C Clarke proposed Geo-stationary Earth Orbit (GEO) Satellites. The first satellite launched though was a low earth orbit known as Sputnik developed by the Russians in 1957. The success of Sputnik signaled the beginning of a new era in telecommunications characterized by global worldwide coverage. In 1965, Early Bird (aka Intelsat I) began the era of commercial GEO satellite communications. Afterwards, GEO satellite services started to spread rapidly to provide International as well as Regional telephone services over wide areas. Currently, GEO satellite applications are very popular in the TV broadcasting industry, e.g., Directv, PrimeStar, etc. Low Earth Orbit (LEO) satellite systems are also becoming more popular with Orbcomm (1998), GlobalStar (2000), and ICO-Global (2002).

On the course of satellite development, complexity of equipment has changed drastically from 34 kg, 240 telephone circuits in the 1965 Early Bird to 3000 kg, 8 - 15 kW power, 1,200 kg payload in a year 2000 large GEO indicating the huge investments dedicated for the satellite industry. It is reported that expected revenues from all satellite communications services should reach $75 billion by 2005 [26].

2.3.2 Interactive Broadband Satellite Systems

Satellites are currently mainly used for TV and voice communications worldwide. As the most attracting feature of satellite is its natural broadcasting, video services by satellite earned $17 Billion in 1998. Hence, Wall Street Journal called Direct Broadcast Satellite TV the Greatest Technology Development of the Century [27]. However as users' demands for multimedia Internet-based services increase, satellite technology is challenged to enhance its capabilities by introducing a user interaction dimension to its structure. Satellite networks operation will no longer be confined to a video provider broadcasting its data to customers. Users will have to be able to transmit data themselves for satellite operators to have any chance to survive in a highly competitive telecommunications market. As a matter of fact, communications satellites have been used in the Internet from the beginning, where one of the first global networks using the Internet protocols was the Atlantic SAT-NET interconnecting the ARPANET with research networks in Europe in the years 1979-1985. However, the scope of future satellite networks in order to sustain its established success must sur-

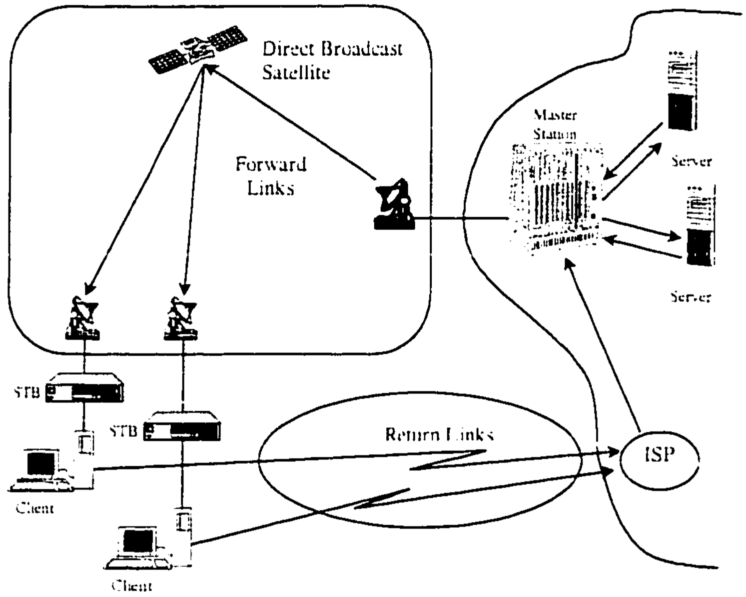

Figure 2.7: An IDBS Satellite Network Configuration

pass just interconnecting purposes. In the following sub-sections, we present examples of different efforts to construct an interactive satellite system. We also point out the drawbacks of each system and how they are avoided under the scope of our work.

2.3.2.1 Interactive Direct Broadcast Satellite

A network configuration described in [27] proposes a forward channel supplied by Direct Broadcast Satellite (DBS). The return link to a server is provided by some other network (telephone, separate satellite channel, etc.) in order to achieve interactive data devices. These systems are termed Interactive (I) DBS. Figure 2.7 [27] shows an IDBS configuration. The IDBS as described in [27] may use different data link protocols depending on the satellite channel used. IDBS-A uses the Wegener system for digital sub-carriers where data packets for IDBS are multiplexed over up to eight digital audio channels onto one analog TV channel for a net data rate of 192 kb/s (still limited in transmission capacity). IDBS-V uses Very Small Aperture Terminals (VSAT) modems with integrated FEC codes for data rates of 384 kb/s to 2 Mb/s. IDBS-D relies on the popular MPEG-2/DVB standards and represents the most advanced solution, as multimedia applications require the higher data rates. The MPEG-2 standards define how compressed video and audio are encoded as Packetized Elementary Streams (PES) and transported. This asynchronous Time-Division Multiplex (TDM) system utilizes a packet transmission system with fixed length cells of 188 bytes to attain data rates of 4 or 8 Mb/s being common for television quality. The MPEG-2/DVB protocol architecture can be broken down into three levels: Physical layer defined by EBU-DVB documents [28]. The data link provides transport over 188 bytes long packets. Level three provides adaptation layers. More details on MPEG-2 and DVB may be found in [6], and [7], [8] respectively.

It is noted that IDBS assumes an asymmetrical network access configuration that envisions a separate network for the return link: usually is a terrestrial network. Rates attained on this return link are much lower than the forward link. Such a configuration might appear relevant for web browsing like applications: especially that measurements of typical web sessions and user behavior show a ratio of about 10:1 to 20:1 between incoming and outgoing data streams. However, under the pressure of users' demands for service integration, the allocated bandwidth will never be sufficient to deploy some key services such as IP telephony or video conferencing, etc. Moreover, using terrestrial networks with its equipment and facilities for return links, yet adds a new player to a satellite access system. This will result in higher costs if compared to systems that integrate the forward and return paths over a shared medium under the same provider. It is also worth mentioning that recently IDBS has tried to use separate satellite channels for the return link. However, such efforts are not yet standardized.

2.3.2.2 TR34.1 SATATM

Based on demand from the industry, the Communications and Interoperability Section (CIS) of the Telecommunications Industry Association (TIA) satellite communications division has started this standardization process. TR34.1, the standards committee for CIS, has defined a set of satellite based ATM [29] network architectures for future physical layer specification. The architectures defined by TR34.1 are presented in [30] and can be broadly grouped into two categories: satellite ATM (SATATM) architectures for transparent satellites, and SATATM architectures for satellites with on-board switches. In order to provide ATM and Internet services at required Quality of Service (QoS) levels in a very bandwidth efficient manner, the TR34.1 considers a Demand Assigned Multiple Access (DAMA) satellite network as an ideal platform to respond to expected variable bandwidth demands. One such network is the COMSAT Linkway 2000 wide area networking and switching system that provides access and transport for packet switched services (ATM, IP LAN, and Frame relay), and circuit switched services (ISDN and Signaling system No. 7) [30]. It provides a full-mesh multi-service satellite network with a multi-frequency Time Division Multiple Access (TDMA) [31] satellite air-interface and unified frame, cell, and circuit mode transport services.

ATM packet size of 48 bytes was primarily chosen to specifically carry voice packets ranging between 32 and 64 kb/s with required quality of service. However, with the invasion of multimedia services, especially, video with variable length packets, ATM packets will not necessarily remain the most efficient transport system from the utilization point of view. Since higher switching speeds are feasible due to faster processing capabilities, systems with rather longer yet still fixed size packets will achieve the required quality of service with minimum overhead. Moreover, ATM is currently even being challenged by non-fixed packets systems such as integrated and differential services of the Internet Engineering Task Force (IETF). As a result, we find that newly deployed systems should be reluctant to commit to a specific technology. To succeed in achieving an open system, the design of a flexible system with an independent protocol (SAT-MAC) that allows convergence for ATM or any other upper layer protocol whenever needed is preferred.

2.3.3 Satellite Challenges

While satellite networks indeed promise to become widely deployed as access networks for interactive residential broadband services, yet a lot of open issues must still be addressed before satellite achieves the anticipated success. One of the most common research issues focuses on developing extensions to TCP in order to overcome the slow start problem under the long delay encountered by satellite systems. Antenna technology is also experiencing continuous developments in order to produce robust cost-effective terminals. Moreover, in order to respond to the effects of interference and fading of the satellite medium, powerful FEC coding algorithms are desirable. Other open issues include on-board processing, beam switching, protocol suites, etc.

One of the most important studies involves development of an efficient air-interface MAC layer in terms of utilization as well as complexity. It should be noted that most satellite studies conducted in this domain up to this point usually involved the downstream (from providers to customers) and how to encode data over the broadcast channel. This issue is nearly settled with advancements in MPEG-2 technologies. However, with the increasing users' demands for interactive services, the challenge switches towards the capability of multiplexing the maximum number of users efficiently over smaller bandwidths without affecting the Quality of Service (QoS). The traffic pattern over downstream satellite channels can always be assumed to achieve a rather high utilization as a result of consistent broadcast transmission of data from a central base station to various customers. On the other hand, upstream transmissions represent a distributed system. With customers' behavior being less consistent as well, the burden on the return link capabilities increases and requires standardization. This triggered the necessity of developing an efficient MAC layer at the air-interface terminal in the upstream direction in order to respond to the challenge.

In this thesis, we propose a MAC architecture that aims to answer the above requirements. The scope of the developed MAC emphasizes on introducing a new access technique with minimum delay and high utilization as well as a novel distributed scheduling architecture to minimize system complexity. The integral functionality of both constituents will employ a Dynamic Capacity allocation (DCA) approach to dynamically assign resources. Complete system description will be presented in the next chapter. In the following sub-sections, we will present a brief survey on both the MAC access techniques and different scheduling structures in satellite systems. We should also point out that other issues related to the MAC layer such as scheduling algorithms, admission control and user parameters control are out of the scope of this thesis.

2.4 MAC Access Techniques

MAC protocols are designed to enable communicating stations at diverse locations to regulate transmissions of their packets and manage network bandwidth in order to utilize the network resources as efficiently as possible. If the individual traffic load per connection was high and the interconnection patterns were static, a fixed capacity allocation would have been applicable. Unfortunately, traffic in residential service applications supporting multimedia is rather bursty and users' behavior is non-consistent. Hence, capacity allocation has to be more dynamic to cope with the real-time traffic demands so that satellite resources may efficiently be shared by a large population of earth-terminals. Many access techniques have contended to lead that role [32], [33]. In this section, we describe some of these techniques and discuss their suitability in satellite access networks.

2.4.1 Fixed Assignment

In the fixed-assignment multiple access technique, the allocation of channel bandwidth to a station is a static assignment and independent of other stations' activities (i.e., circuit switching). Examples of fixed assignment techniques are Frequency, Time or Code Division Multiple Access (FDMA, TDMA or CDMA) [31]. Fixed assignment has the advantage of being simple and with minimum delay. However, with bursty traffic, fixed assignment results in a huge waste in bandwidth resources rendering very low utilization. Moreover, with channels being completely devoted to single users over extended time periods, fixed assignment allows limited number of users that can simultaneously access the medium with the required quality of service.

2.4.2 Random Access

Random access allows terminals to instantly transmit their data packets as soon as they arrive, independent of other stations. As it represents a distributed system, data packets of various terminals are destroyed from time to time due to possible collisions. Examples of random access techniques include pure ALOHA and slotted ALOHA [29] proposed for earlier stages of satellite communications. Random access has the advantage of being simple. It also requires no set up phase, which other schemes, such as, reservation might use. At low load, retransmission (due to possible collisions) is negligible, which offers terminals instant channel access. However, with increasing loads, collision rates grow exponentially and consequent packet retransmission becomes non-acceptable, especially, in real-time applications and quality of service cannot be guaranteed. It is worthwhile to mention that the most innovative random access schemes can only provide an upper bound of achievable utility in the region of 0.4-0.5

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2.4.3 Demand Assignment

Demand assignment allows dynamic allocation of capacity on demand in response to station requests. The algorithm reserves bandwidth based on terminal demands and therefore renders high utility. The reservation scheme itself might be fixed or random. Examples of demand assignment techniques include Priority Oriented Demand Assignment (PODA) and FIFO Oriented Demand Assignment (FODA) [32]. Demand assignment is best suited for jitter-tolerant queueable traffic. In spite of its high utility, demand assignment in satellite environment experiences inevitable set up (reservation) delays of two round trips (around 500 ms) added to another round trip delay of data transmission for a total of three round trip delays. This is rather unacceptable for interactive asymmetric real-time applications, where users continuously produce short control commands, especially, given that random access can avoid such delays under low loads.

2.4.4 Combined Techniques

Multimedia traffic contains both real-time (e.g., voice and video) and jitter-tolerant (e.g., data and graphics) and requires a combined technique to be efficiently transported. Combined techniques aim to provide fast access for low load conditions and short messages, such as, inquiry messages in interactive data sessions, and to attain high utility of satellite resources at high traffic load. In the following sub-sections, we provide examples for combined techniques.

2.4.4.1 Combined Random/Reservation

A random reservation scheme achieves low delay at low loads with high utility of reservation schemes. Bandwidth may be categorized into reserved and unreserved slots. Jitter-tolerant traffic may be conveyed over both types of slots. Real-time traffic on the other hand, only uses reserved slots. Since satellite providers use spot beams to achieve channel reuse, the scheduler at the master control is required to monitor unreserved channels and reliably detect collisions as terminals will not be able to detect collisions with simultaneous transmissions on other beams. This will lead to very long collision resolution periods; i.e., a terminal will not be able to detect a collision before two roundtrip delays and is forced to remain idle within that period. In case of a single beam, terminals could be able to detect collisions instantaneously and therefore might attempt retransmission in the next unreserved slot.

2.4.4.2 Combined Free/Demand Assignment Multiple Access

Contention free protocols can control the worst delay in case of real time applications. In combined demand assignment with fixed assignment or with free assignment, unreserved slots are either fixed or freely assigned. The Combined Free Demand Assignment Multiple Access (CFDAMA) provides better performance due to its dynamic feature. By combining free assignment with demand assignment, CFDAMA protocol offers much shorter delays at low and medium traffic loads, while maintaining the high channel utility of DAMA techniques. Reservation in these schemes may be pre-assigned request slots, piggybacking or any other special algorithm. A study in [33], [34] shows superiority of CFDAMA over other access techniques in satellite environments. CFDAMA might be even enhanced by allowing terminals to reserve ahead of time based on a prediction. If the prediction algorithm has acceptable accuracy, the new enhanced CFDAMA will even provide better performance with lower delays. Details on that scheme and the devised protocol behavior are presented in the next chapter.

2.5 Scheduling Structures

Scheduling is mandatory to complement an efficient access technique to achieve high performance. It determines how the master control station distributes available capacity on different terminals based on a special algorithm. The simplest scheduling algorithms are first come first served and round robin. However, scheduling algorithms are out of the scope of this thesis. In Dynamic Capacity Allocation (DCA), the scheduler must dynamically assign slots to various terminals each time frame (24 ms) . Hence, it requires a lot of computing and data processing. Accordingly, scheduling structures with less complexity are always desirable. This section describes two possible scheduling structures.

2.5.1 Centralized Scheduling

In centralized scheduling, the scheduler supervises each and every connection within the network. As a result of service integration, each terminal is expected to continuously produce numerous simultaneous connections. This will overload the scheduler with long look-up tables and will lead to long processing delays.

2.5.2 Centralized/Distributed Scheduling

As mentioned above, the scheduler is obliged to control a large number of connections over a huge population. In order to reduce the complexity, schedulers may be structured into two levels of scheduling: a macro level responsible for handling the aggregate requests of each terminal and a micro level, where each terminal distributes granted capacity over local connections. While the master control station performs macro level scheduling, it is the terminals themselves that handle micro scheduling. As the master control station then deals only with total terminal demands and not single connections, the scheduling processing duty becomes distributed rendering lower complexity and minimum processing delays. However, the overall bandwidth control still resides at the master control station in a centralized manner. Full details on that scheduling structure will be discussed in the next chapter.

2.6 Summary

In this chapter. we have indicated the importance of broadband access in future telecommunications systems. Accordingly. we highlighted the structure. objectives and achievements of DAVIC as one of the most active standards bodies in the field. We have also discussed various competing technologies contending for the access network role and hence pointed out the essence of development of efficient satellite networks to achieve simple and cost-effective global coverage. Consequently. we presented the bounding factors that limit direct successful deployment of broadband interactive satellite access and focused our interest on development of an efficient MAC layer at the air-interface terminals to achieve maximum utilization and minimum delay.

In the next chapter. we will discuss throughly a proposed MAC architecture to address the above requirements. We show system structures. behavior sequences. access techniques and scheduling architectures.

Chapter 3

Broadband Satellite Access

Broadband satellite access is an access system with a satellite segment representing its access network. It addresses the same markets and services as other access technologies such as, wireless, copper, cable, etc. As indicated in Chapter 2, most services deployed over current conventional satellite systems are only one-way and usually rely on a phone line for the return path (upstream) to provide interactive features. Any failures in the public network will directly terminate any communication possibility. In broadband satellite access, two-way interactive multimedia services are supported over shared bandwidth. In this chapter, we describe a proposed broadband satellite access system. We show its configuration structure, constituents and proposed protocol stacks. We emphasize on the MAC layer specification due to its critical role in system implementation. The main scope of the developed MAC includes dynamic capacity allocation under a novel access technique based on an enhanced CFDAMA and simple scheduling structures as well as the protocol behavior specification.

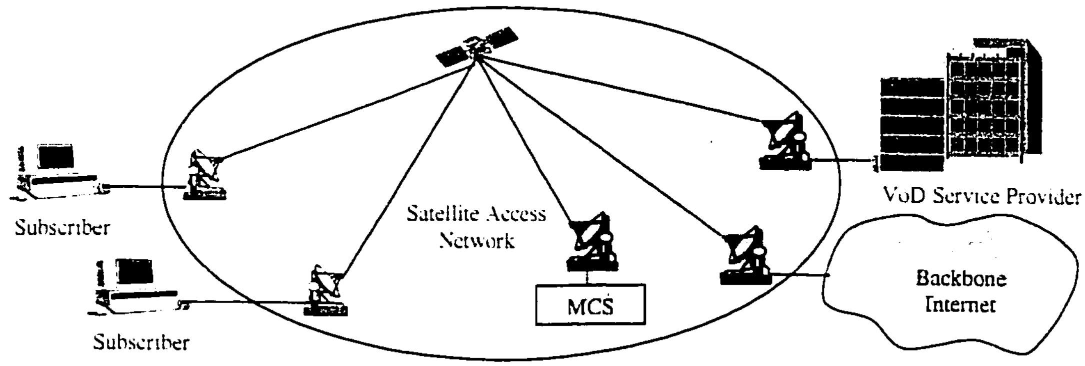


Figure 3.1: General Configuration of a Broadband Satellite Access System

3.1 Broadband Satellite Access Configuration

Figure 3.1 shows the general configuration of a broadband satellite access system. The figure indicates that via the satellite, subscribers may access a VoD service or an Internet backbone forming two access domains. Within each access domain, a service provider renders its application services to a group of subscribers. A Master Control Station (MCS) supervised by the satellite provider is necessary in order to regulate medium access among subscribers within the same domain as well as across different domains. This is one of the main differences that distinguish satellite access from other technologies. In these technologies, the service and network providers are commonly supervised and usually physically located at the same station. On the other hand in satellite systems, the service provider and the network provider (satellite) are separate. Proper coordination and signaling between both providers is therefore essential to guarantee successful access. This can be achieved by implementing a carefully designed MAC layer. The MAC layer architecture must be configured to dynamically multiplex the maximum number of terminals with highest possible utilization and optimum use of satellite resources over the satellite network.

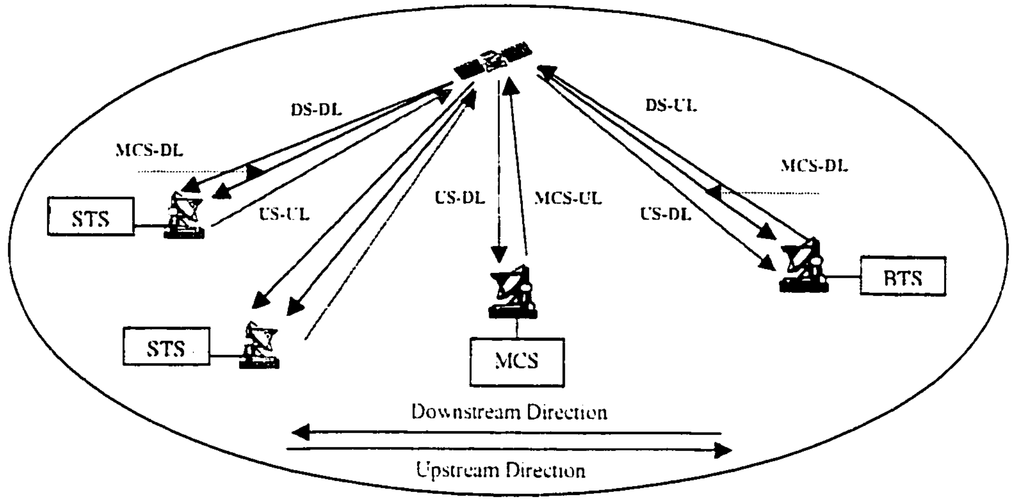


Figure 3.2: BSA Single Domain Block Model

In general, satellite communications is one type of BWA (Broadband Wireless Access). However, the IEEE BWA group excludes satellite from their specifications. Our proposed system is part of a general Broadband Satellite Access (BSA). However, from this point and throughout the rest of this thesis, we will use the term BSA to specifically refer to our proposed broadband satellite access system.

3.2 BSA System

Figure 3.2 depicts the proposed block model for the BSA system. The system consists of three main stations:

- Base Transceiver Station (BTS): It represents the gateway to the backbone network. Subscribers' information and registration files to be downloaded during STS initialization are located there.
- Subscriber Transceiver Station (STS): It is connected to the user premises equip-

ment. It represents the air-interface terminal. The interface to the user equipment is standardized to satisfy requirements of an open system.

- Master Control Station (MCS): Regulates the access to the satellite medium.

It is worthwhile to mention that we adopt similar terminology, as BWA, IEEE 802.16 for BTS and STS, however we must again highlight that the MCS is unique to satellite systems. The configuration shown is based on a Point-to-Multi-Point structure to form a star topology for only one access domain. Multiple domains however, may coexist in the access network. Upstream direction involves data transmissions from STS to the BTS. Downstream direction involves data transmissions from the BTS to STS. The satellite can have non-regenerative transponders and acts as a bent pipe where up-link transmitted signals are amplified, retransmitted and switched at RF onto the corresponding down-link beams. As indicated in the figure, traffic and control information may be transmitted over three different possible paths:

1. STS control and traffic information transmitted over the US-UL (Upstream Up-link) are amplified and regenerated by the satellite over the US-DL (Upstream Down-link) where they can be received by the BTS and MCS.

2. BTS traffic information transmitted over the DS-UL (Downstream Up-Link) is amplified, regenerated and broadcast by the satellite over DS-DL (Downstream Down-link) to be received by different STS

3. MCS control information transmitted over the MCS-UL (MCS Up-link) is amplified and regenerated by the satellite over MCS-DL (MCS Down-link), where it can be received by the BTS and STS.

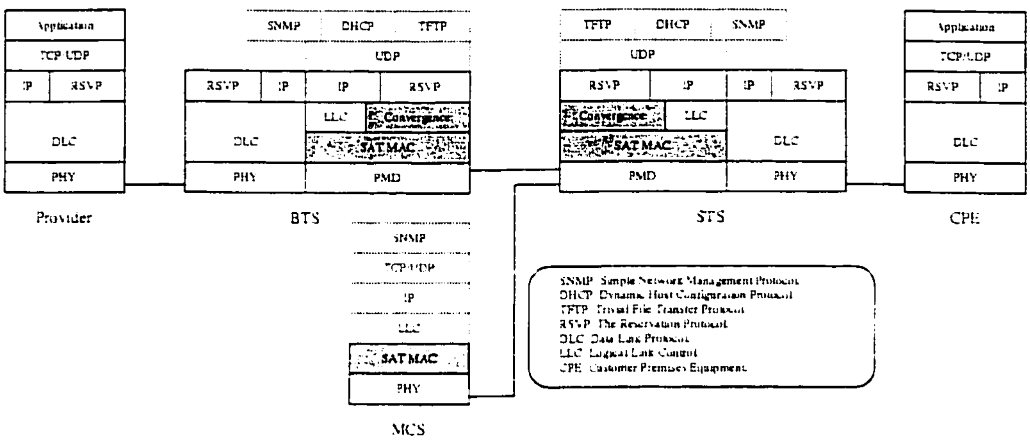


Figure 3.3: Overall BSA Stack Structure

3.3 BSA Protocol Stacks

Figure 3.3 depicts the overall stack structure for a BSA system. The main focus of our study involves the interfaces to the satellite medium at the air-interface terminal. Design of interfaces towards the service provider and user equipment should use standardized protocols and are assumed to satisfy the requirements of an open system. An open system facilitates mass production of customer equipment independent of the access technology used (cable. wireless. satellite. etc.). As shown in the figure. the BTS and STS may operate as forwarding agents (bridging or at the network level as in Figure 3.3) and also as end-systems (hosts). As hosts. the application layer supports a number of protocols. SNMP (Simple Network and Management Protocol) is responsible for network management. DHCP (Dynamic Host Configuration Protocol) and TFTP (Trivial File Transfer Protocol) are used during STS initialization procedures. Figure 3.4 shows a three dimensional model for the BTS and STS acting as forwarders at the network layer. The stack is divided into two planes. In the data plane. the following layers may be defined:

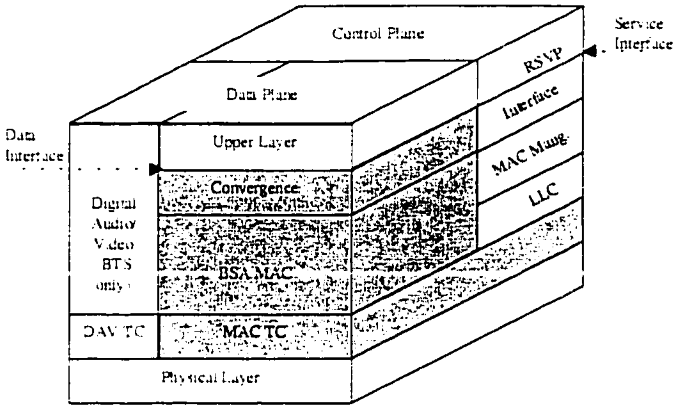


Figure 3.4: 3-Dimensional BSA Stack Model with BTS and STS acting as Forwarders at the Network Layer

- Upper layers: The proposed MAC is flexible and may independently support Internet protocol or ATM services. We assume that real-time traffic over these layers may bypass the LLC and directly access the MAC as supporting services may accept slightly erroneous packets rather than afford delays resulting from retransmissions.

- Convergence Layer: It encapsulates Protocol Data Units (PDU) framing of upper layers into the native BSA MAC PHY PDU and translates upper layer QoS parameters into BSA MAC constructs. It also maps upper layer's addresses into corresponding BSA addresses.

- BSA MAC Layer: This is the main focus of our study. It guarantees efficient data transmission over the satellite medium. Details on the MAC layer are presented in the next sections.

- Segmentation and Re-assembly: This process at the MAC Transmission Convergence (TC) sub-layer is responsible for segmenting variable length MAC frames into equal length packets to be reassembled once again at the other side. It is essential in MF-TDMA as capacity allocations by the scheduler at the MCS may be distributed over a range of carrier frequencies. Transmission of MAC frames over fixed size packets is essential to satisfy QoS [35].

Note that in the BTS only, broadcast MPEG-2 encoded digital audio video may bypass the MAC protocol layer and directly access the physical layer in the downstream as it usually conveys distribution traffic and does not need the MAC access functionality used with upstream transmissions[1]. In the control plane, the general structure can be summarized into the following layers:

- A Control Protocol: As an illustrative example, we assume the IETF Reservation Protocol RSVP [36]. It is the control protocol used for resources reservation in IPv6 (IP the next generation) [37]. In RSVP, data is forwarded to the destination across the path determined during the resources reservation phase.
- Interface Layer: It translates RSVP commands into local messages that will be used for the resource reservation over the satellite link. It contains the dynamic services process as well as admission and policy functionalities.
- MAC Management Layer: It is responsible for overall MAC layer management. Typical functions include system management and STS registration.
- LLC Packaging: We encapsulate MAC management messages in LLC packaging in consistency with the DOCSIS specifications [9], [10].

[1]MPEG-2 transmissions over the upstream must utilize the MAC access functionality. All upstream connections define point-to-point links between an STS and the corresponding BTS.

3.4 BSA MAC Layer

As indicated earlier, a key element to the successful deployment of a BSA system is the development of a suitable MAC protocol technique to efficiently share the satellite resources. The MAC Layer should address the following challenges:

1. Satellite medium long delay and its resource constraint.

2. Expected bursty Internet and multimedia traffic of envisioned services.

3. QoS requirements for real-time and non-real-time data expected to be conveyed by the BSA system.

Capacity of the downstream links may be assumed to be fixed, as the aggregate broadcast transmission is considered to have high load and is rather smooth (i.e., the peak-to-average ratio is close to unity). Transmission over the upstream and MCS links is bursty with high peak-to-average ratio and necessitates an efficient MAC. The MAC must satisfy certain delay bounds and attain maximum utilization at the same time. As an illustrative example, in the following discussions we focus on one access domain. We assume that in a BSA system, the STS can only communicate with each other via the BTS. We should also mention that we consider Internet-based upper layers specifically, IPv6 and RSVP for integrated services. However, we must again emphasize that our developed architecture is completely consistent with other upper layers dependent on differential services.

3.4.1 BSA MAC Architecture

We have chosen the DOCSIS 1.1 RF-interface [10] specification as our building block due its popularity in addressing the same range of services anticipated over satellite networks and we also adopt their message terminology. However, as cable and satellite media render diverse characteristics as well as different configurations (with satellite systems employing a MCS), large modifications to the DOCSIS 1.1 infrastructure should be introduced to achieve optimum performance over satellite. In the following sub-sections, we present various features of our BSA MAC layer. We also highlight as well as justify the differences with the DOCSIS 1.1 specification.

3.4.1.1 BSA Medium Access Scheme

Terminals are assumed to deploy a Multiple Frequency Time Division Multiple Access (MF-TDMA) [33] access scheme widely used in satellite communications. It offers simple connectivity, great flexibility and compatibility with digital transmission. Superiority of MF-TDMA over FDMA TDMA employed by DOCSIS is attributed to a better trunking efficiency due to a larger pool of available physical channels. In MF-TDMA, the bandwidth is first divided into a number of frequency bands. A stream of time slots is recognized over each frequency band. A channel in MF-TDMA is defined by a time-frequency slot in a two-dimensional frame as shown in Figure 3.5. All STS may access these time-frequency slots in a shared manner. Capacity allocation in MF-TDMA can be represented by a time-frequency map indicating the time-frequency slots assigned to each terminal. Note also as shown in the figure, that mini-slots in the time-frame map might vary in the time-slot sizes or the transmission bandwidth. Since each time-slot must have a segmentation and re-assembly (SAR) header, variation in slot sizes supports the capability of decreasing the resulting overhead when smaller pools of physical channels are allowed under low loads. Variation in transmission bandwidth on the other hand, gives the BSA system the flexibility of supporting

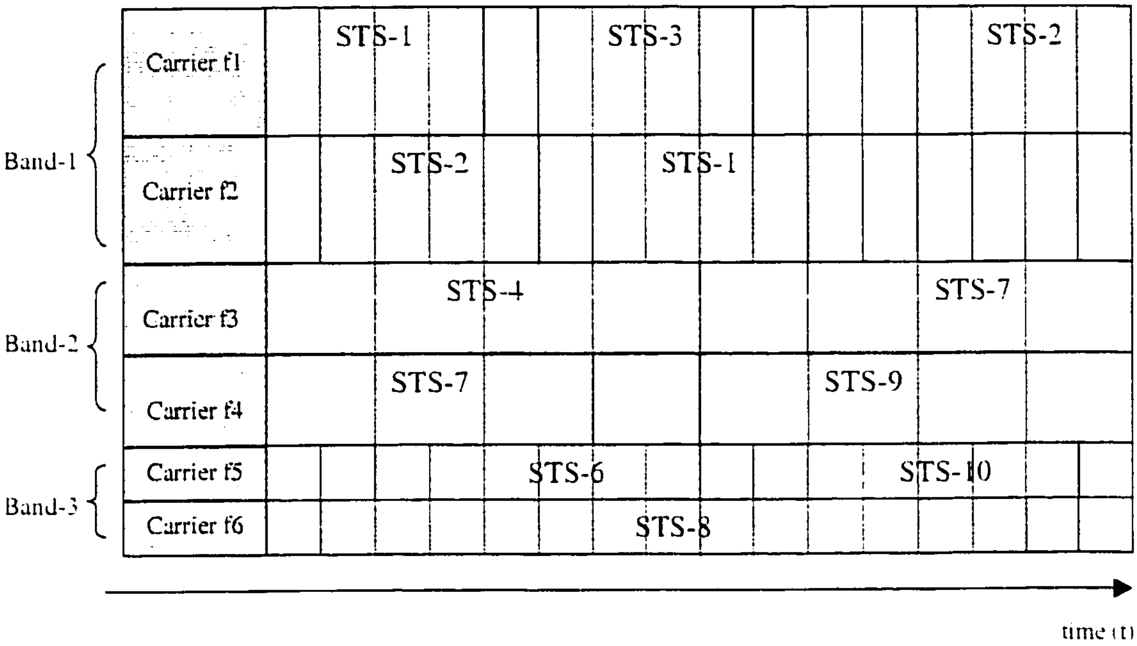


Figure 3.5: MF-TDMA Structure in BSA

terminals with various modem transmission rate capabilities.

3.4.1.2 Dynamic Capacity Allocation

Traffic in residential applications supporting multimedia services has different types with diverse characteristics and is rather bursty in nature. Hence, the capacity allocation scheme has to be carefully chosen to attain better performance. Terminals with real-time traffic request satellite resources infrequently but with relatively high capacity and a stringent timing requirement. Accordingly, in BSA, we employ Dynamic Capacity Allocation (DCA) for assigning data traffic. In DCA, satellite resources are dynamically allocated to registered terminals depending on the request, scheduler's status, priority, etc. Dynamic Capacity Allocation (DCA) will therefore give enough flexibility to guarantee that satellite resources can be efficiently shared by the largest possible population under minimum possible bandwidth requirements. Successful DCA necessitates the following two complementary functions:

Access Technique Random access techniques based on ALOHA [29] were initially proposed for satellite systems. ALOHA is contention based with low utility and envisioned services will not tolerate delays accompanied with retransmissions due to collisions. In BSA, we propose to use a CFDAMA-based MAC access technique for dynamic capacity allocation. CFDAMA [33] is a hybrid access technique where unrequested bandwidth is freely allocated to users according to a pre-determined algorithm. DOCSIS 1.1 employs a hybrid reservation contention based access technique. As discussed in Section 2.4, contention degrades utilization and delay performance in satellite systems. We have also discussed CFDAMA superiority in satellite networks over traditional techniques in that section.

Furthermore, in BSA we propose an enhanced CFDAMA access technique. By combining prediction with CFDAMA, better access delay performance may be achieved. In that scheme, STS utilize a prediction function in their demands. STS requests to the MCS will not reflect their instantaneous needs. Rather, anticipated bandwidth after two round trip delays will be demanded. Moreover, free assignment by the MCS can be based on a prediction of terminals' demands and activity. While the first approach promises faster access for demand assignment traffic, the second approach would promote better utilization of freely assigned traffic. It is worthwhile to mention that we only allow contention in the beginning initialization procedures as users signal to the MCS when turning on their terminals.

MCS Scheduling MCS are obliged to control a large number of connections over a huge population. In order to reduce the MCS complexity, we have structured two levels of scheduling in our system: a macro level responsible for handling the aggregate requests of each STS terminal and a micro level where each terminal distributes granted requests over local connections. While macro level scheduling is done at the MCS, the terminals themselves (STS) handle micro scheduling. As the MCS deals now only with total terminal demands and not single connections, the scheduling processing duty becomes distributed. Distributed scheduling achieves an MCS with lower complexity and minimum processing delays. However, overall bandwidth control still resides at the MCS in a centralized manner. To further decrease variables processed by the MCS, connections between an STS and the MCS on the upstream up-link may simply be defined by only a limited number of standard service categories (real-time and non-real-time for example) with minimum parameters per category (required average bandwidth for example). This means that the maximum number of logical connections with an STS that the MCS has to handle is always bounded by the number of categories able to support all upper layer connections within that STS. This relieves the MCS from the burden of managing numerous connections per STS with minimum information to be processed.

3.4.1.3 Dynamic Services

In BSA, we adopt the DOCSIS 1.1 concept of dynamic services to support QoS. QoS defines parameters as delay, throughput, jitter, etc. that should be sustained during the lifetime of a connection. Dynamic services allow terminals to dynamically add, modify or delete connections based on upper layer requests. Each connection corresponds to a single differentiated service category. Based on their QoS parameters, upper layer connections will be categorized into local service categories with specific equivalent parameters via a translator. Requests with the resulting parameters and consequent negotiations will then be conveyed through dynamic service procedures. Service categories are also proposed by DOCSIS 1.1, however, they are not yet well-standardized. The current DOCSIS 1.1 specification rather relies on single connections between the subscribers and the equivalent MCS.

3.4.2 MAC Protocol

The MAC protocol specifies the MAC layer behavior and defines message sequences across the system. A MAC Frame defines the unit of information exchanged between MAC entities. MAC frames may be one of the following types:

- Data Frames: Data frames may carry an IP packet or a variable number of ATM cells.
- MAC Specific Frames: Specific frames may be Request frames used for reservation requests or MAC management frames, which carry the MAC management messages.

MAC management plays a key role in the MAC protocol operation as it controls and manages all the protocol main functions. Management messages are encapsulated in LLC information frames, which in turn are encapsulated within MAC framing in consistency with the DOCSIS specifications.

3.4.2.1 MAC Management Messages

The different management messages chosen coincide with DOCSIS 1.1 terminology and are described as follows:

- SYNC (Synchronization): A SYNC message is transmitted periodically by the MCS. STS use it to establish MAC sub-layer timing. The MCS broadcasts inside this message the current state at transmission of a clock inside the MCS to offer timing reference.

- UCD (Up-link Channel Descriptor): A UCD message is transmitted periodically by the MCS. It defines the characteristics of possible STS up-link channel bands with similar characteristics. Typical descriptors would include mini-slot size, symbol rate, modulation type and other physical parameters.

- MAP (Allocation Map): A MAP message is regularly sent by the MCS in order to organize and regulate bandwidth allocations on upstream up-links. Based on scheduling decisions, it describes time as a variable number of variable-length transmit opportunities over a band of frequencies. Opportunities include request, data, initial maintenance (ranging), station maintenance (ranging), and registration.

- RNG_REQ (Ranging Request): RNG_REQ messages are transmitted by an STS at initialization and periodically on request from MCS to determine network delay and request for time, power and frequency adjustments over a certain band of frequencies described by a certain UCD.

- RNG_RSP (Ranging Response): A RNG_RSP message must be transmitted by the MCS in response to a received RNG_REQ. Typical carried parameters will include timing and power adjustment as well as frequency fine tuning.

- REG_REQ (Registration Request): A REG_REQ message is transmitted by an STS during the initialization phase. It carries STS configuration parameters as downloaded from the BTS. These parameters are used by the MCS in registering the STS with the satellite network.

- REG_RSP (Registration Response): A REG_RSP must be transmitted by the MCS in response to REG_REQ. The MCS may modify some of the REG_REQ parameters in the response.

- REG_ACK (Registration Acknowledgment): A REG_ACK message is transmitted by the STS in response to a REG_RSP from the MCS. It confirms the reception and acceptance of the STS to the QoS and other registration parameters as reported by the MCS in the REG_RSP.

3.4.2.2 Illustrative Example for Protocol Operation

To illustrate the functionality of the MAC management. we present the following example shown in Figure 3.6 to describe an STS initialization procedure:

As soon as an STS powers on. it scans for an appropriate down-link channel and will acquire synchronization with the MCS by receiving two consecutive SYNC messages. On the same down-link channel. the STS must then receive an appropriate UCD transmitted by the MCS. An appropriate UCD defines a band of channels with similar physical attributes that coincide with the STS capabilities. Following that. a ranging process is then necessary for the STS to perform timing, power and frequency

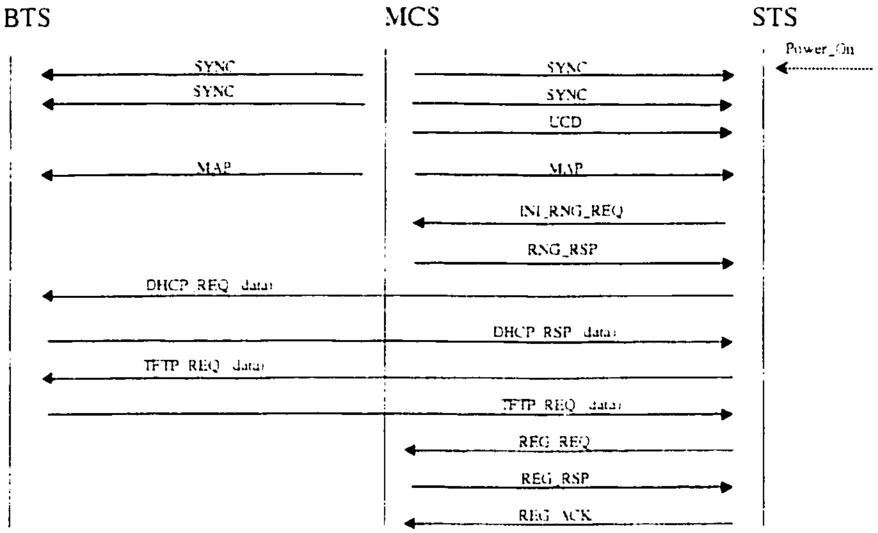


Figure 3.6: An Example for STS Initialization

adjustments. The STS should use the first initial ranging opportunity over the first received MAP message. A random back-off algorithm is used to resolve collisions[2]. Once the INI_RNG_REQ (Initial Ranging Request) transmission is successful the STS is assigned a temporary ID in the RNG_RSP and any further ranging instructions will be recognized as opportunities assigned to the temporary ID or the station ID acquired after registration. To obtain its IP address as well as the IP address of the configuration file from the BTS (service provider), the STS must establish IP connectivity via DHCP. Using this information the STS can download the required parameter file via TFTP. DHCP and TFTP commands are carried as data frames using MCS allocations to the temporary ID. In case any of these two processes is delayed or non-successful both the MCS and STS timeout and the temporary ID will be lost.

[2] Note that contention-based allocations are allowed only when terminals log on to the satellite network. The MCS cannot recognize inactive terminals and allows them to join the network over regularly transmitted initial maintenance opportunities. Probability of collisions is low because users are less likely to log on at exactly the same moment.

Re-initialization of the STS is required in that case. Successful DHCP and TFTP render the STS implicit registration to the server network. STS must also perform a registration procedure with the MCS to gain access to the satellite network. The registration should be based on the parameters of the downloaded file, which defines STS modem capabilities, allowed bandwidth, the corresponding access domain, policy data, etc. Upon registration success, STS is given a station ID identified by the BTS and is given authority to exchange data traffic with the service provider.

It is worth mentioning that the MCS always monitors registered STS data transmissions and takes necessary proceedings (station maintenance) to maintain acceptable STS ranging parameters.

3.4.3 Bandwidth Allocation and Scheduling

Allocations and transmission opportunities over future time frames rely on dynamic capacity allocation (DCA) assuming the enhanced CFDAMA technique and are defined by the MAP management messages regularly transmitted by the MCS. In this sub-section, we present the different allocation opportunities in BSA and show the STS and MCS block structures for DCA.

3.4.3.1 Transmission Opportunities

A MAP message conveying allocation description is constituted of a group of consecutive MAP elements. A MAP element is composed of a MAP opportunity, address and allocated slots. MAP opportunities are categorized as follows:

- Initial Maintenance: This defines a contention interval where new stations may join the satellite network through initial ranging.

- Station Maintenance: This defines intervals assigned by the MCS for STS to perform routine station ranging to maintain timing, power and frequency settings.

- Request: In this interval the MCS provides opportunities for STS to report their instantaneous bandwidth demands.

- Data grants: The MCS in this interval allocates grants to STS for data transmission.

- Registration: This defines intervals where STS may transmit their registration requests and acknowledgments.

- NULL: This is used to indicate the end of a time frame's allocations.

3.4.3.2 STS Structure for Dynamic Capacity Allocation

Figure 3.7 depicts a block structure that highlights the required components for the proposed dynamic capacity allocation and scheduling in the STS. It also specifies where these components fit within the overall MAC layer and how will they interact with the MAC management as well as with upper layers. The figure defines the following blocks:

- Upper Layer Control: We assume RSVP. Requests for new connections are initiated there and forwarded towards the dynamic service process.

- Translator: It has the responsibility of translating requested upper layer QoS parameters into local parameters recognized by local admission. For example, RSVP defines QoS in terms of a token bucket model. The translator will convert the corresponding bucket attributes into local parameters as delay, jitter, cell loss, etc.

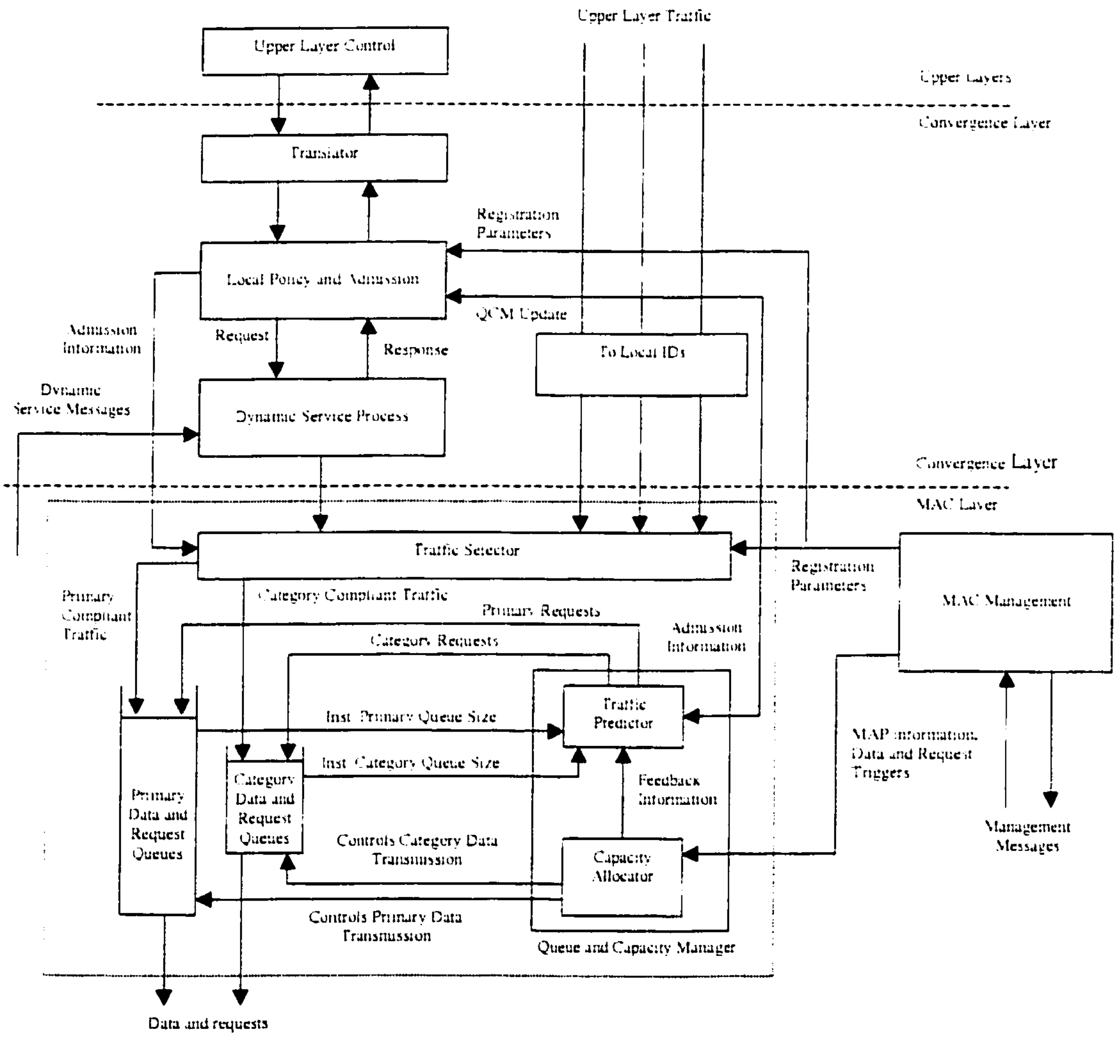


Figure 3.7: STS DCA Block Structure

- Local Policy and Admission: It defines the STS policy. It also handles admission of all connection requests from upper layer control. Translated upper layer requests from single connections are categorized according to internal criteria into certain service categories (real-time and non-real-time for example). Admission might immediately refuse a connection request locally: in case local resources are completely exhausted or if the connection violates the terminal's capabilities. Admission mechanisms might also decide to multiplex requests over an existing contract in case it is under-utilized. Otherwise, the admission must consult the MCS and connection-related requests for the corresponding category are issued. These requests accompanied by traffic parameters related to that specific category will be transmitted over the MAC as dynamic service commands. Registration information and periodic Queue and Capacity Manager (QCM) updates help in admission decisions. The admission must also update the QCM with the current admitted resource status to be utilized in the prediction process. It will also feed information about the various connections to the traffic selector to help it monitor complying traffic.

- Dynamic Service Process: The dynamic service process is the means by which the STS conveys its request to the MCS and defines the behavior of mutual negotiations.

- Traffic Selector: The traffic selector has the responsibility of forwarding compliant user traffic into data queues of the corresponding category. It also interleaves over each time frame, traffic from different local connections before forwarding them into the queues to avoid monopolizing of the queues by a single connection.

- Data Queues: Data from all connections of the same category enter the corresponding data queue. Instantaneous queue status updates are reported to help in the prediction process. The primary queue is utilized by control messages and is used as an escape mechanism for non-categorized data packets.

- Queue and Capacity Manager: It has the responsibility of managing and distributing granted resources from the MCS. Based on queue status and admission information the QCM will predict and request the required bandwidth and allocate granted allocations. The queue and capacity manager is composed of:

  1. Traffic Predictor: The traffic predictor has the responsibility of requesting the necessary capacity from the MCS to serve the packets in the data queues. The traffic predictor periodically receives updates from the data queues on their current status and records instantaneous data requests. The predictor also maintains a record and receives regular updates from admission on the traffic parameters of currently accepted connections. All provided information will be used in predicting the anticipated number of data packets after two round trips (requests from STS to MCS and back). Fine-tuning is achieved by comparing predicted requests with actual queue size at reception of allocated grants.

  2. Capacity Allocator: It receives description of the grants from MAC management and updates the predictor by the allocated grants to modify its prediction if necessary. It also manages the queues and their timing. In case of multiple queues. the allocator may decide to move allocations from one category to another (real-time over non-real-time for example). Excess bandwidth if any will also be shuffled based on local algorithms

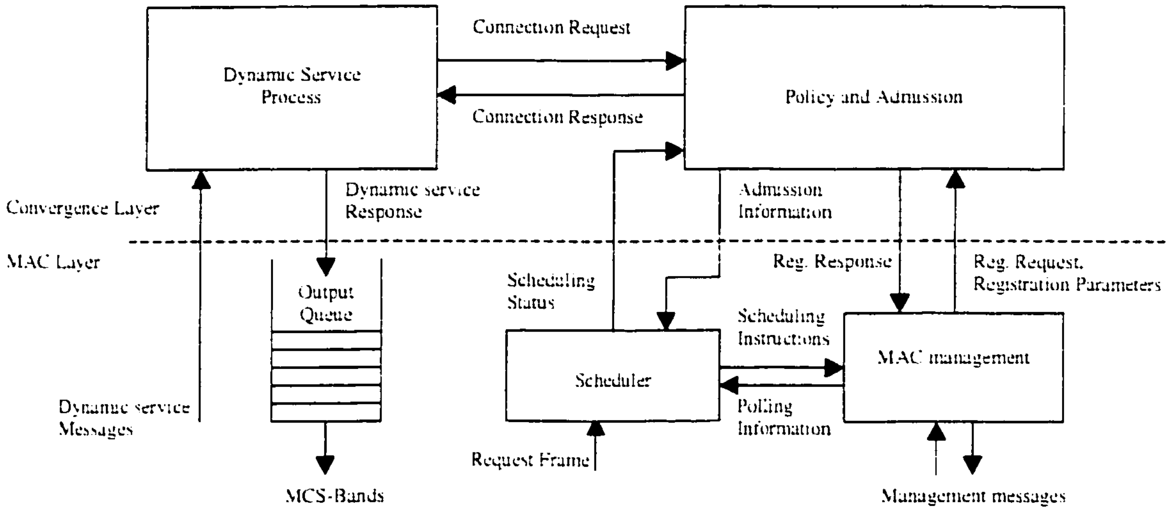


Figure 3.8: MCS DCA Block Structure

as well as instantaneous sizes of the different queues.

3.4.3.3 MCS Structure for Dynamic Capacity Allocation

Figure 3.8 depicts a block structure that highlights the required components for the proposed dynamic capacity allocation and scheduling at the MCS. It also specifies where will these components fit within the overall MAC structure and how they will interact with the MAC management as well as with upper layers. The figure defines the following blocks:

- Policy and Admission: It carries policy information acquired during registration. Admission decisions depend on the current network status and regular updates received for the current scheduler status. The policy and admission block will also always regularly update the scheduler with latest admission information.

- Scheduler: It has the responsibility of allocating capacity grants to all requesting

STS. STS requests represent their overall requirements per category. The scheduler regularly receives admission information and uses it to monitor complying stations. It is also frequently polled from MAC management to allocate management opportunities (Ranging and Registration) to specific stations. Scheduling instructions are forwarded to the MAC management to be transmitted as MAP messages.

3.4.3.4 Example for Admission Procedure over the Proposed Structure

The following example will give a scenario to illustrate admission procedure and help understand interactions between the system components: Assuming an STS registered to a contract that specifies an average of 3 slots per time frame with a maximum of 5 for the real-time service category. If a user is trying to run a multimedia application which requires more capacity than is currently available (an average of 8 slots and a maximum of 10 slots for example). local admission will need consultation from the MCS before it can accept the connection. The admission will request the dynamic service process to handle the modification. In that particular scenario. the dynamic service process will send a request to the MCS for an increase of 5 slots in the average grants and an increase of 5 slots in the maximum allowable grants per one time frame in the real-time connection. Upon reception by the MCS dynamic service process. the request is forwarded to the policing and admission process. The policing is performed according to registration parameters received during initialization. Admission decision is based on the availability of the requested resources after consulting scheduler updates. If the modification is accepted the response will be forwarded back to the STS and modifications will take place in future frames reported by broadcasting MAP messages[3].

3.5 Data Transmission Protocol under the Enhanced CFDAMA Scheme

Subscribers in residential applications services are expected to produce real-time as well as non-real-time traffic. Non-real-time traffic involves bulk services as ftp, http, etc. It has the least priority and can tolerate certain periods of delay. Real-time traffic may involve two categories of service: *Short Impulse* services are asymmetric in their nature and are characterized by much more traffic on the downstream than the upstream. Example of short impulse services is VoD. *Continuous Burst* services on the other hand, are rather symmetric with much longer packets but the application may tolerate single packet losses every once and a while. Examples of these services are IP telephony and video conferencing. An intermediate category might also be defined, where rather short but continuous commands must be transmitted on the upstream. These commands are very sensitive to loss and error. Examples of such a category include Internet gaming and virtual shopping. In this section, we focus on real-time traffic and propose two modes of data transmission operation under the enhanced prediction based CFDAMA protocol.

3.5.1 General Assumptions

1. Satellite propagation round trip delay is 480 ms, while the satellite MAP time frame describes a period of 24 ms . This means that the propagation delay is 20

[3]Note that MAP messages are usually monitored by the BTS on a regular basis. The BTS may use the message information to anticipate possible transmissions from its various subscribers.

times the MAP time frame period.

2. Usually per time frame, a single application will generate a maximum of one data packet[4].

3. In residential services, more than one application may be in use at the same time. However, the number of simultaneous applications is bounded. Hence, it is legitimate to assume that the aggregate number of packets (variable in size each) generated per time frame is also constrained by an upper bound. This provides an estimate on the upper bound for maximum number of slots that may be requested by a single terminal per time frame.

4. The prediction algorithm predicts the number of slots needed to convey the packets generated by active services after a round trip delay.

5. Requests issued by the terminal describe their aggregate requirement within a certain category.

6. In case the allocation is not enough to empty the queue, fragmentation will be allowed. The user terminal will continue to attempt to send the deferred packets over N time frames and will then drop them from its queue.

7. A request might be transmitted either explicitly over a request opportunity or piggybacked if the user terminal receives a grant at the time of the prediction.

[4]This a is legitimate assumption, as we assume a MAP frame every 24 ms. The expected services are not expected to generate traffic at a higher rate, as all of them are controlled by humain behavior.

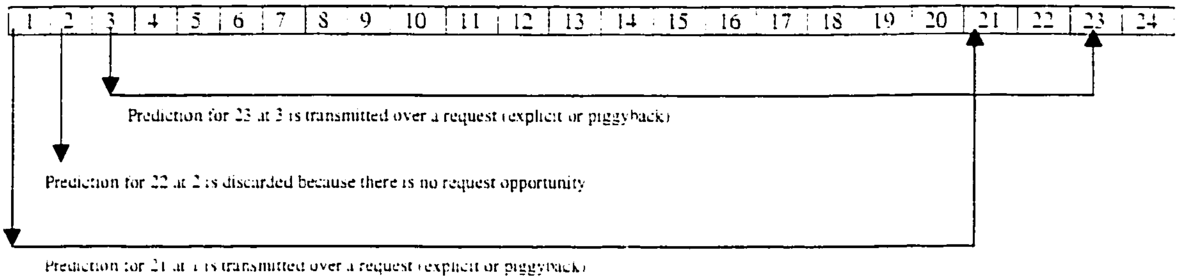


Figure 3.9: Data Transfer under Normal Mode Operation

3.5.1.1 Traffic Transmission Modes

Normal mode In this mode, the STS predicts mini-slots demands needed after an exact round trip (20) frames into the future, neglecting offsets due to processing delays, packets transmission time, etc). However if the terminal is not able to convey its prediction to the MCS (no request opportunity explicit or piggybacked), it will discard this request and process the prediction of the next frame. Normal mode operation is shown in Figure 3.9. The normal mode will be more efficient for services that continuously generate packets over bursts. In this case, all requests can be conveyed over data packets as piggybacking.

Accumulative Mode In this mode, the STS predicts mini-slots demands needed after a roundtrip delay plus some tolerance (25 frames into the future for example). Since the STS may not necessarily get a request opportunity each frame and the prediction is performed earlier by 5 frames, the STS might convey its un-transmitted request within the 5-frame tolerance zone. However, in this case when the STS is able to send a request, the request should address the aggregate predicted demands from the first un-transmitted request till the request transmission time. Since these de-

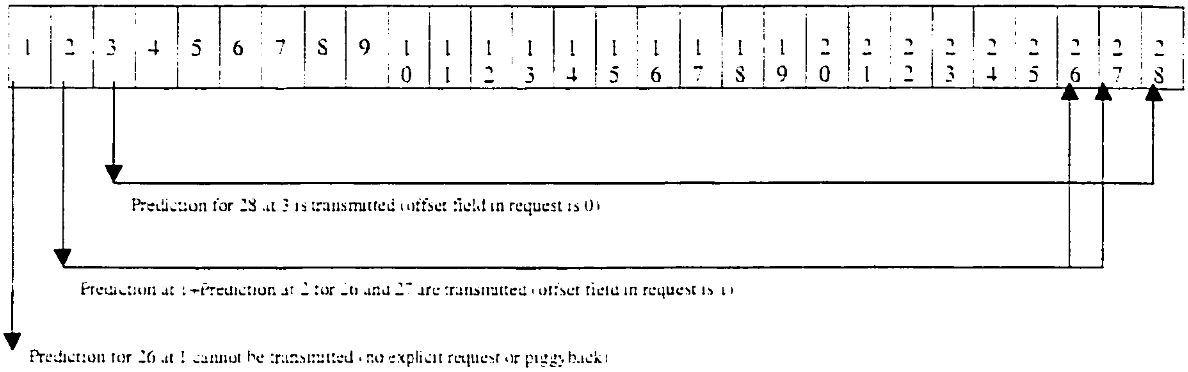


Figure 3.10: Data Transfer under Accumulative Mode Operation

mands represent consecutive frames, they can be assumed highly correlated with close demands. Based on local criteria in the MCS and its scheduling status, it decides to distribute the aggregate demands on the corresponding frames (equally for example). Aggregate mode operation is shown in Figure 3.10. The aggregate mode will be more efficient for applications that produce short random traffic bursts.

3.6 Summary

In this chapter, we have presented a proposed MAC layer architecture at the air-interface terminals to deploy interactive residential two-way broadband services over satellite access networks. We have described the system configuration and corresponding protocol stacks. We also have shown behavioral sequences and introduced a new technique based on an enhanced CFDAMA protocol. Furthermore, we have proposed a novel scheduling structure that can reduce system complexity. We have also shown examples of data exchange operation over two modes of data transfer.

In the next chapter, we develop an SDL model to formally describe the devised system. We will then verify and validate the resulting model, to ensure system correctness, using the ObjectGEODE tools. Finally, we will reflect on our experience by providing an evaluation on the use of formal techniques, especially SDL, to describe validate real telecommunications systems.

Chapter 4

BSA Formal Description and Validation

In the last chapter, we have described the proposed MAC structure at the air-interface terminals for BSA systems. As presented, the implementation of such system will necessitate complex engineering efforts due to the ambiguity of a plain English description. Different programmers might understand the specification differently, which sets a boundary on achieving the necessary real standardization. The non-formal specification is very far from implementation technicalities and system validity cannot be guaranteed. During the last two decades, formal techniques have been used successfully for the description and validation of communication systems. A system is correct if it satisfies general as well as specific protocol properties. General properties of a protocol include the non-existence of deadlocks, unspecified receptions, live-locks and unreachable states. Specific properties on the other hand are derived from the non-formal specification to guarantee a proper system behavior. We have developed a formal model using the Specification and Description Language (SDL) [17] for the proposed BSA MAC with necessary abstractions to test its validity. In this chapter, we present the constructed SDL model and show validation procedures and results. In the end, we comment on the utilization of formal methods, especially SDL for description and validation of real complex systems.

4.1 SDL Model

We have chosen SDL as the formal language to model the MAC layer and system structure. SDL is an ITU standard formal description language that is used to describe systems using graphical representations as well as textual representations. SDL describes a system as a set of processes. Transitions in SDL from one state to another are triggered by the reception of signaling messages. For each process, SDL describes the actions it is allowed to take and which events are expected to happen. In SDL, a system is divided into building blocks that communicate using channels. Blocks are composed of processes. Processes (within a block) are connected using signal routes. Each process is an extended finite state machine, which has its own infinite queue and is assumed to operate independently from all other processes. Figure 4.1 depicts the different constructs of an SDL process.

4.1.1 BSA System Model

Figure 4.2 shows the devised BSA system model. It is composed of a BTS, a MCS and two STS of an access domain communicating through a satellite bent pipe. The MCS is given MAC address 2, the BTS is MAC address 3, while the STS are represented by MAC addresses 4 and 5. The two STS are instances of a common block type:

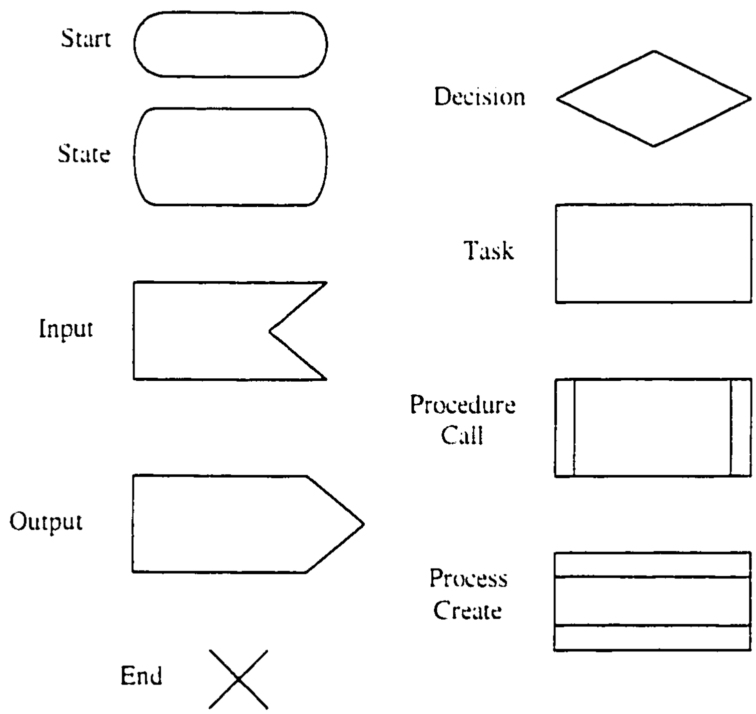


Figure 4.1: SDL Process Constructs Notation

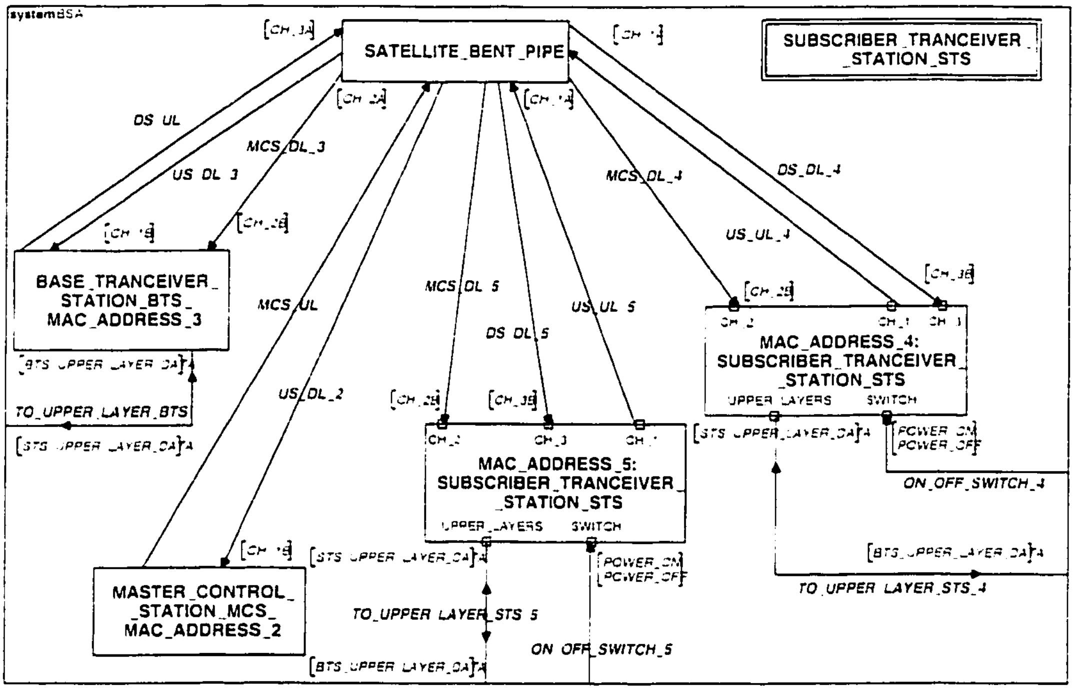


Figure 4.2: BSA Structure Model

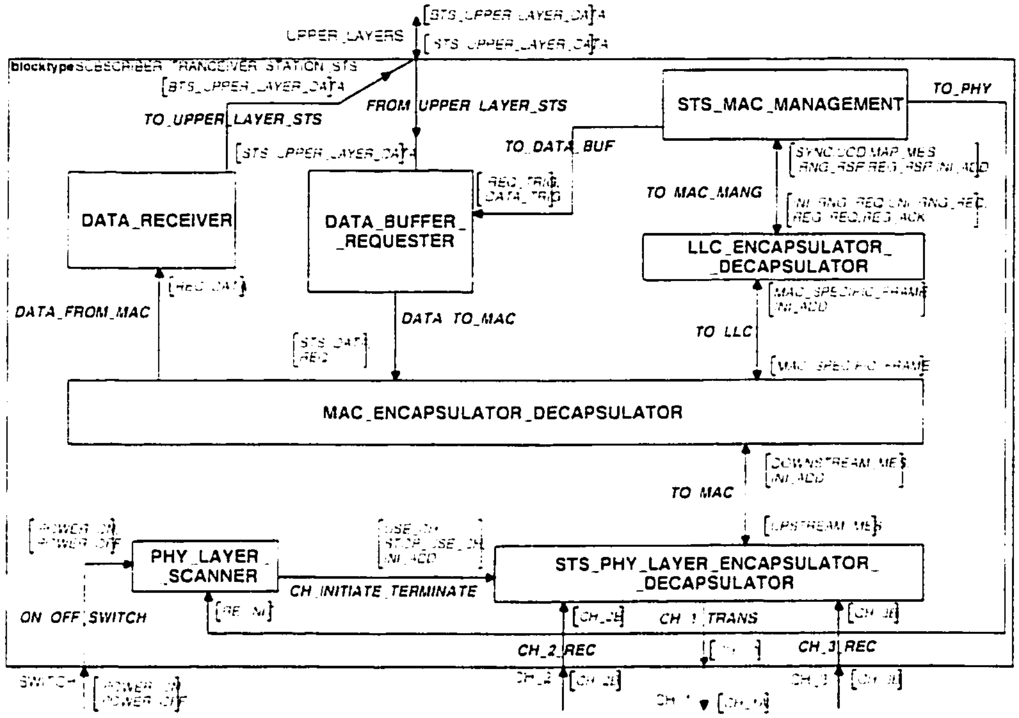


Figure 4.3: STS Block Type Structure

SUBSCRIBER_TRANCEIVER_STATION_STS and are initialized by feeding their corresponding MAC addresses as an attribute of the POWER_ON signals. We have modeled an MF-TDMA system over a single band of frequencies with similar characteristics to reduce model complexity. The model therefore depicts only three channel bands: CH_1 carries all STS (stations 4 and 5) transmissions, CH_2 conveys MCS control commands, while CH_3 bears BTS data packets. It is worth mentioning that MCS and BTS are always logged to the network, while STS are turned on and off by feeding POWER_ON and POWER_OFF signals via the ON_OFF_SWITCH.

4.1.2 STS Block Type

Figure 4.3 depicts the SUBSCRIBER_TRANCEIVER_STATION_STS block type. As indicated by the figure, its structure coincides with the proposed protocol layers. The block type is further decomposed into the following building blocks:

- PHY_LAYER_SCANNER: We use the block to simulate a channel scanning process. On reception of a POWER_ON trigger from the environment, the scanner will activate the STS_PHY_LAYER_ ENCAPSULATOR_ DECAPSULATOR functionality by sending a USE_CH signal. A POWER_OFF signal will result in deactivation of that encapsulator decapsulator block through a STOP_USE_CH instruction. If the MAC Management procedures dictate a re-initialization process, the RE_INIT signal will trigger a STOP_USE_CH followed by a USE_CH to simulate system rebooting.

- STS_PHY_LAYER_ENCAPSULATOR_DECAPSULATOR: The block simulates physical layer framing composition and extraction. When the STS is powered off the block is in a dormant state. Activity of this encapsulator decapsulator block is controlled by the scanner via the USE_CH and STOP_USE_CH signals.

- STS_MAC_ENCAPSULATOR_DECAPSULATOR: It decapsulates received signals and categorizes them as data or MAC Specific Frame messages. Signals flowing in the other direction (data, request and management) are encapsulated and forwarded to the physical layer. Modeling of erroneous packets is done by dropping one out of every 100 received signals for an error rate of 0.01[1].

[1]This value does not represent a realistic satellite medium performance. We only introduce it to be able to describe system behavior in case of corrupted packets.

- LLC_ENCAPSULATOR_DECAPSULATOR: It converts MAC management messages to MAC_SPECIFIC_FRAME signals and vice versa.

- DATA RECEIVER: This block simply receives data frames from the BTS and forwards them to upper layers.

- DATA_BUFFER_REQUESTER: This block simulates the Queue and Capacity Manager (QCM) process as well as traffic queues. It is made simple assuming a single queue to reduce model complexity. We assume data transmission operation under the normal mode. Existence of a prediction is randomly determined every time frame. If a prediction is detected, the STS may convey its request to the MCS only when a request opportunity is sensed via an explicit REQ_TRIG or implicitly by receiving a DATA_TRIG (Piggybacking). The queue status (empty or non-empty) each time frame is also randomly determined unless fragmented packets are outstanding from the previous frame. Note that we are only interested in describing all the possible scenarios per time frame, i.e., in a certain time frame a received grant might satisfy one of two possibilities: either it is sufficient to empty the data queue or outstanding packets will remain to be served in future frames. The queue behavior in between each time frame is out of the scope of the specification (i.e. we assume that prioritization, queue dropping, queue management, etc., are done externally).

- STS_MAC_MANAGEMENT: This block is responsible for STS MAC management. Figure 4.4 describes its components. It is consists of:

    1. STS_MANAGEMENT_MESSAGES_DISTRIBUTER: It receives all management messages and correctly distributes them to various pro-

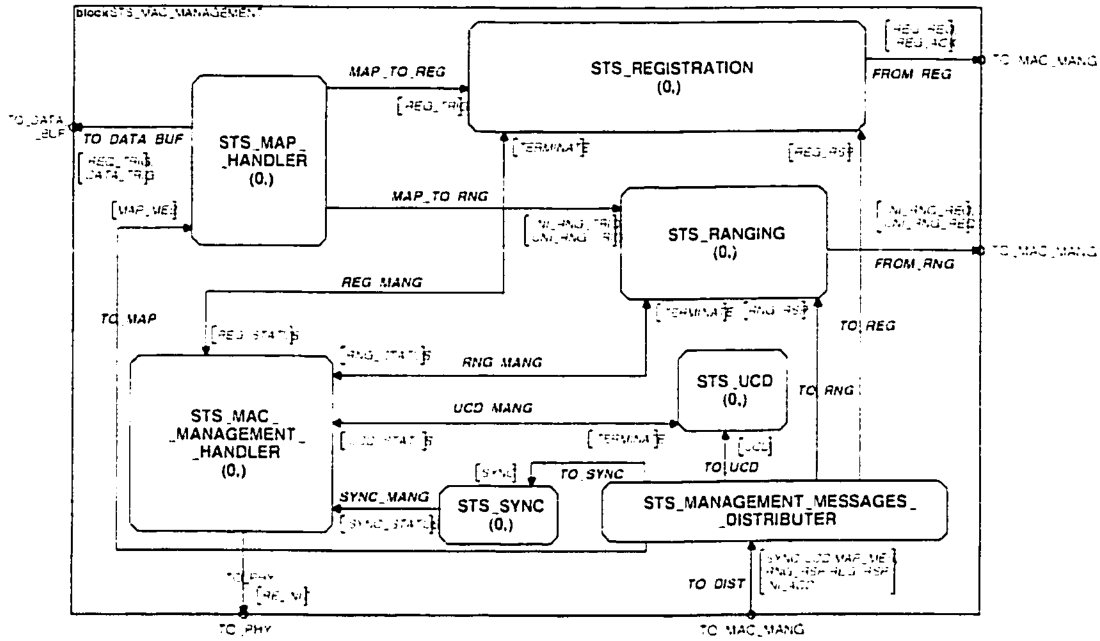


Figure 4.4: STS MAC Management

cesses of the Management block.

2. STS_MAC_MANAGEMENT_HANDLER: It manages the overall STS_MAC_MANAGEMENT block. An STS is either in an initialization phase or a data transfer mode as determined by the Handler. It receives SYNC, UCD, Ranging and Registration status updates and enforces re-initialization in case of any failures. It will terminate UCD, ranging or registration processes whenever re-initialization is in effect.

3. STS_SYNC: It is responsible for handling synchronization procedures. Failure to receive a SYNC message within a certain timeout period forces re-initialization.

4. STS_UCD: It receives UCD messages. The suitability of the band's parameters is randomly determined using an ANY construct. A re-

initialization procedure is triggered if the process fails to receive a UCD message within a certain timeout period or if a received UCD message indicates a non-compatible change in the band's parameters.

5. STS_RANGING: It handles initial and periodic ranging procedures. It forces re-initialization in case of failures in ranging procedures.

6. STS_REGISTRATION: It is responsible for exchanging registration information with the MCS. Registration failure forces a terminal re-initialization.

7. STS_MAP_HANDLER: It receives and translates the MAP_MES signal. It then issues triggers to the various corresponding processes in the same sequence as that indicated in the MAP.

4.1.3 MCS Block

Figure 4.5 depicts the MASTER_CONTROL_STATION_MCS block. Its structure also coincides with the proposed protocol layers. The block is further decomposed into the following building blocks:

- MCS_PHY_LAYER_ENCAPSULATOR_DECAPSULATOR: As in the STS, the block simulates physical layer framing.

- MCS_MAC_ENCAPSULATOR_DECAPSULATOR: It decapsulates received signals and categorizes them as request frames or MAC Specific Frame messages. Specific Frame signals flowing in the other direction are encapsulated by this block to be sent over the MCS_UL.

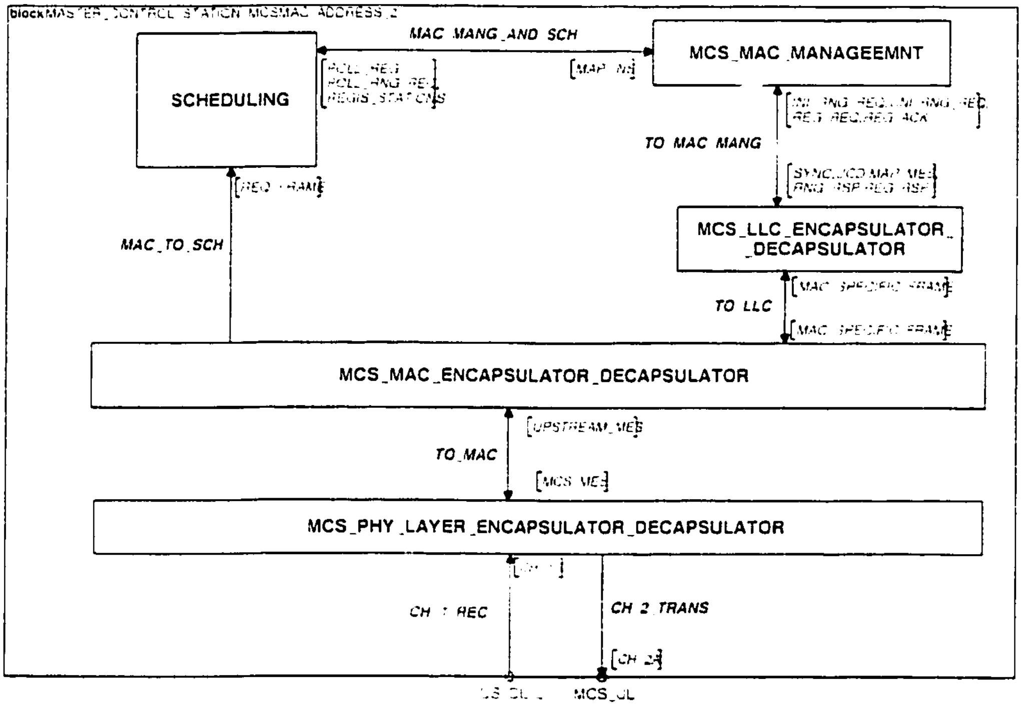


Figure 4.5: MCS Block Structure

- MCS_LLC_ENCAPSULATOR_DECAPSULATOR: It converts MAC management messages to MAC_SPECIFIC_FRAME signals and vice versa.

- SCHEDULING: The scheduler may receive request frames from STS or is locally polled for management opportunities (e.g., maintenance or registration). The scheduler randomly (with ANY construct) responds to requests or polled messages each time frame (to simulate possible behavior scenarios dependent on capacity availability or system policy). After each time frame the scheduler sends a MAP_INS to MAC management describing contents of future MAP messages. A Request opportunity for each registered terminal is randomly determined each time frame. Free data is also randomly granted per registered terminal each time frame. The algorithm by which requests and free data allocation are determined is out of the scope of the model.

- MCS_MAC_MANAGEMENT: This block is responsible for MCS MAC management. Figure 4.6 describes components of the STS_MAC_MANAGEMENT. It is constituted of:

    1. MCS_MANAGEMENT_MESSAGES_DISTRIBUTER: It receives all management messages and correctly distributes them to various processes of the Management block. It also instantiates a new Handler process for every new STS logging in to the network.

    2. MCS_MAC_MANAGEMENT_HANDLER: Each instance of this process manages a single STS. It receives Ranging and Registration status updates of the corresponding STS. Successful registration would add the corresponding terminal to the registered terminals list, while a ranging

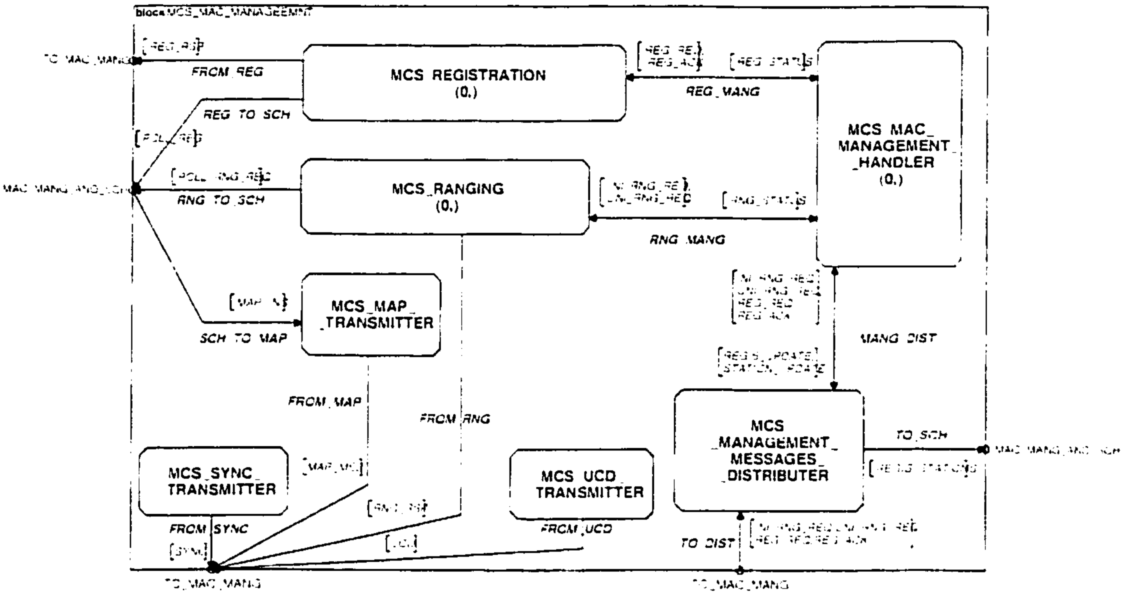


Figure 4.6: MCS MAC Management

failure of a registered terminal would remove it from that list.

3. MCS_SYNC_TRANSMITTER: It periodically transmits SYNC messages.

4. MCS_UCD: It periodically transmits UCD messages. We assume only a single band of frequencies with similar characteristics. However, the band's attributes might change as reported by the UCD every now and then due to variation of the medium conditions for example.

5. MCS_RANGING: Each instance of this process handles initial and periodic ranging procedures of a single STS.

6. MCS_REGISTRATION: Each instance of this process handles registration procedures of a single STS.

7. MCS_MAP TRANSMITTER: It receives MAP_INS messages from the

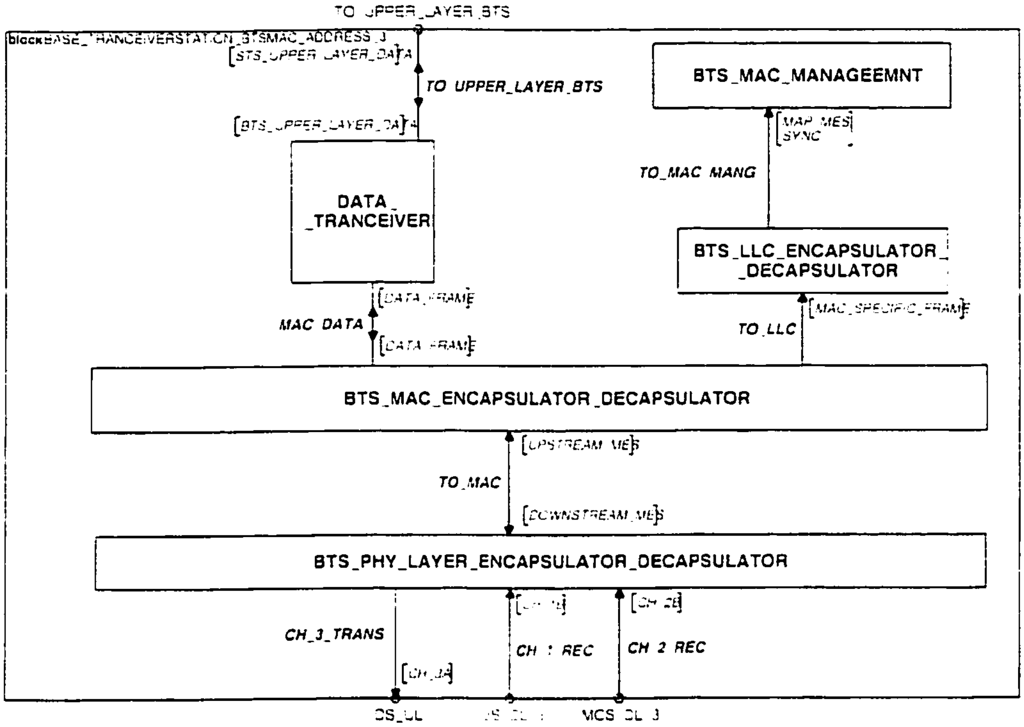


Figure 4.7: BTS Block Structure

scheduler and formats them into corresponding MAP messages.

4.1.4 BTS Block

Figure 4.7 depicts the BASE_TRANCEIVER_STATION_BTS block. Its structure also coincides with the proposed protocol layers. The block is further decomposed into the following building blocks:

- BTS_PHY_LAYER_ENCAPSULATOR_DECAPSULATOR: As in STS, the block simulates physical layer framing.
- BTS_MAC_ENCAPSULATOR_DECAPSULATOR: It decapsulates received signals and categorizes them as data frames or MAC Specific Frame messages.

Data packets flowing in the other direction are encapsulated by this block to be transmitted on the downstream.

- BTS_LLC_ENCAPSULATOR_DECAPSULATOR: It converts received MAC-_SPECIFIC_FRAME signals into SYNC and MAP_MES management messages. Other management messages are dropped by the BTS as they are irrelevant to its functionality.

- DATA_TRANCEIVER: It sends and receives data frames over the satellite system.

- BTS_MAC_MANAGEMENT: As previously mentioned, the BTS might elect to monitor the MAP messages to anticipate its subscribers' transmissions. Moreover, in order to adjust its timing, it periodically receives the broadcast SYNC messages.

4.1.5 Satellite Bent Pipe

The bent pipe structure is shown in Figure 4.8. It consists of three processes responsible for introducing satellite delay and broadcasting frames on the corresponding satellite bands involved in the communication process.

4.2 System Validation

For the verification process, we have utilized a subset of the model shown in Figure 4.2 by removing one of the STS terminals as verification is usually interested in independent peer to peer operation. The relevance of such procedure will be thoroughly

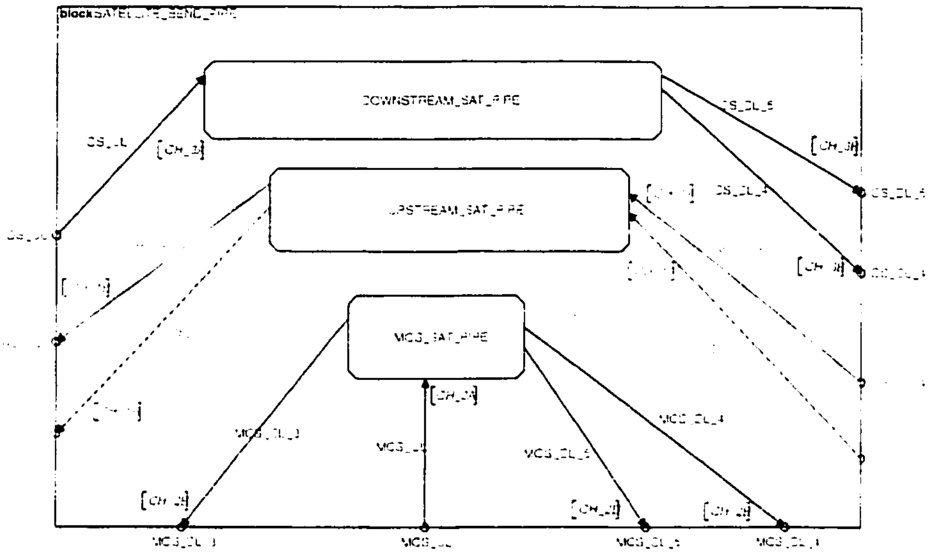


Figure 4.8: Satellite Bent Pipe

discussed in the next section. Using the aforementioned postulate, we have verified the correctness of the protocol's general properties by running the verification process in ObjectGEODE [38]. Results proved the protocol free from deadlocks, unspecified receptions and live-locks. We have also derived the most critical specific properties that we consider should cover the validation of the largest portion of the system behavior. Illustrative properties are:

- Failures in MAC management procedures (SYNC, UCD, Ranging and Registration) at the STS will always stimulate re-initialization and instances of all these processes (except for SYNC process) are terminated.

- Failures in MAC management procedures (Ranging and Registration) at the MCS will always terminate these processes as well as their Handlers.

- An STS issuing INI_RNG_REQ during initialization eventually expects a response from the MCS or else the process must be terminated if retries are exceeded (due to collisions for example).

- A change in UCD description parameters by the MCS is either accepted or refused by the STS.

- A station maintenance opportunity sensed by an STS will trigger a ranging procedure and the terminal remains registered only with successful ranging.

- Registration procedure at the STS is only complete after receiving the first data allocation from the MCS.

- Registration procedure at the MCS is complete by receiving the last registration MAC management message from the STS (REG_ACK).

- The sequence for STS registration is always synchronization, acceptable UCD parameters, successful ranging and registration procedures.

- STS are not allowed to transmit data packets on the satellite network before they are successfully registered with the MCS.

- Piggybacked requests are utilized to implicitly convey terminals' predictions to the MCS.

- Non sufficient grants will trigger a fragmentation procedure if remaining capacity is enough to convey at least one fragment of the outstanding packet.

- The scheduler MAP allocations are always regularly broadcast to the network in management messages.

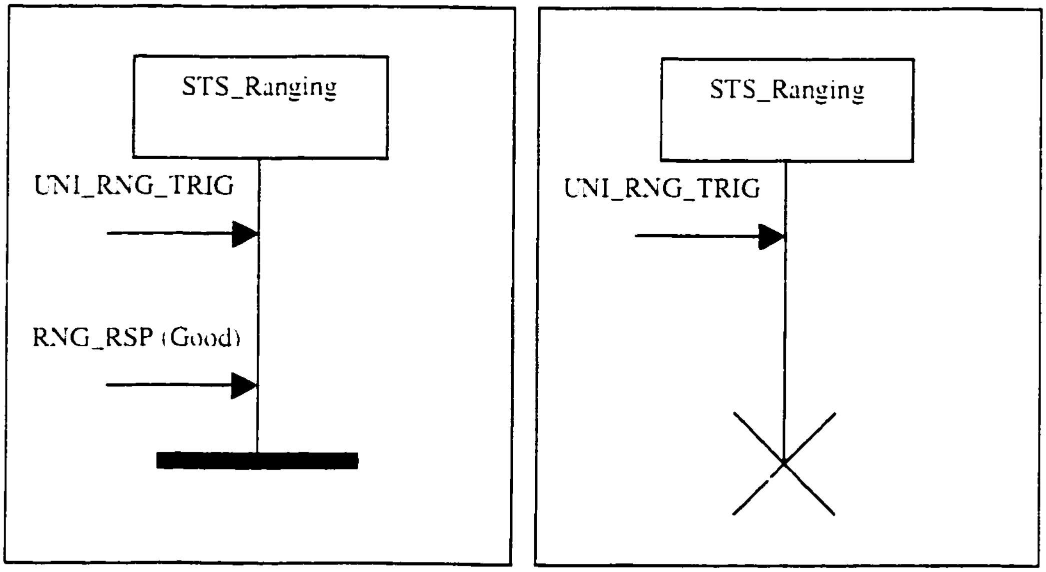


Figure 4.9: An Example for MSC Observers of Specific Properties

- Unallocated capacity by the scheduler every time frame period will be freely assigned to various terminals as described by CFDAMA.

To validate most of the above properties in ObjectGEODE. they must be translated into equivalent Message Sequence Chart (MSC) [39] observers. An MSC observer is composed of one or many MSC leaves linked by high-level MSC operator(s). e.g.. AND. OR. REPEAT. etc. Formal validation is achieved by running the verification process against these MSC observers. For illustration purposes. an example for the translation process is presented by deriving the observer for the following property: "A station maintenance opportunity sensed by an STS will trigger a ranging procedure and the terminal remains registered only with successful ranging". This may be represented by two MSC scenarios that are linked together by an OR parameter as shown in Figure 4.9. As indicated in the figure. a station maintenance opportunity at a registered STS is represented by a UNI_RNG_TRIG sent by the MAP Handler. The two possible scenarios that the property states involve either the reception of a successful RNG_RSP from the MCS or terminating the ranging process as a result of ranging failure (i.e., terminal will no longer be registered). The verification procedure is done by simulating the BSA system to the point that the scheduler includes a UNI_RNG opportunity in its MAP frame. The following step is to run a verification process against the specified observer.

Similar translations were done for other derived properties and validation was achieved by running the verification process against each of the equivalent observers. We have found that none of the properties were violated.

It is worthwhile to mention that we were not able to formally validate properties that involve variable decisions and depend on non-message (event) criteria, as non-sufficient or unallocated grants for example. It is even harder with the random behavior assumption (using ANY) due to the lack of quantitative attributes. However, due to the importance of these properties, we have chosen to try to validate them via inspection by running numerous guided simulations and studying all possible scenarios[2]. Nevertheless, none of the indicated properties were ever violated over the chosen scenarios.

4.3 Description and Verification Models

When we developed the model shown in Figure 4.2, we have set in mind two goals: system description and verification. These represent two diverse objectives. While description becomes more robust by including more details to contribute to easier

[2]This approach does not offer a true 100% validation. Simulation is a partial technique and possibly some scenarios are not studied.

implementation. the verification process is more interested in abstracted (i.e.. less complex) peer to peer operation independent of other system components. To respond to such diversity. we have developed our SDL with flexibility by merging description and verification-oriented constituents under one model. The only significant difference between the description and verification models. as indicated earlier is evident by removing one of the two STS terminals to simplify the verification process and satisfy the peer to peer requirement.

4.3.1 Description Constituents

Most of the description constituents reside on the block (i.e.. configuration) level. It is very evident that even though our larger interest is in the MAC operation. we have chosen to specify lower layer blocks. such as. the scanner and framing blocks at the STS. The reason is that we will be able to observe a clearer description of MAC operation and its interactions at the interface with the physical layer by running simulations under such circumstances. Moreover. in a BSA implementation. numerous scenarios would always include various STS joining and leaving the network. Hence. in our description model. we have introduced two STS terminals to view the implications of that on the MCS management operation. This helped us introduce crucial functional processes that are out of the scope of the MAC operation. but are essential for proper functionality. such as. the Distributor and the Management Handler processes. These processes allow the devised MCS system to simultaneously control various STS. In that case. a clearer multi-terminal behavior could be recognized as well through simulation.

4.3.2 Verification Constituents

Most of the verification constituents reside on the process (i.e., functional) level. Such an approach gives less complex processes, which is very important as the verification process consumes a lot of memory resources; i.e., a simpler model offers an easier verification procedure. Moreover, description of simultaneous events that require precise timing (as collision) is not part of the standard SDL constructs. It is even harder to describe their behavior in a distributed system such as the BSA. Even though describing such behaviors is still possible, it will expand model complexity drastically. To clarify that issue we present our approach in designing the scheduler. In our scheduler process we assume it randomly reacts to capacity demands using an ANY construct. If the grant branch is taken, this signifies available capacity. If the simulation chooses the other branch, we assume non-available capacity or a policy violation. For verification purposes, we are only interested in describing all the possible behavior scenarios and if we deploy a scheduler that counts, adds and subtracts, we can expect a large and complex process. Moreover, we will be forced to utilize a specific scheduling algorithm, which is out of the scope of the devised model and deprives it from its flexibility.

4.4 Evaluation of SDL Formal Specification for BSA

Based on our efforts in developing an SDL model for the described BSA system, we were able to evaluate the utilization of formal methods (advantages and limitations), especially SDL, in the development of telecommunications systems in the following:

- Easier System Implementation: System description in SDL should provide significant decrease in implementation effort as it should reduce the rather large jump from an English language specification to a C program (usually used in software implementation) implementation through an intermediate (semi-technical) model. Moreover, the possibility of using simulation will allow implementers to attain a clearer understanding of the required system.

- Graphical Hierarchal Representation: One of the most attractive features of SDL lies in its graphical representation. The graphical representation permits descriptions that are user friendly, easy to understand and modify. Another interesting feature of SDL is its hierarchal structure of defining systems, blocks and processes for building models. This allows for a clear, representative model description. It also offers an easy procedure for model development. Our BSA model, initially, only involved a single STS and a MCS at the MAC Management level. Further developments included data transfer operation, lower layers specification, BTS description and multiple STS introduction. Moreover, SDL is object-oriented. A station (STS) description was defined once as a block type. Multiple instances of that block type will allow for description of multiple stations. Hence, expanding the scalability of the model is simple as more STS might be simply introduced by adding new instances of the STS block type

- System Abstraction: As mentioned earlier, abstraction of various operations achieves simpler, more general and flexible models. We only care about possible scenarios rather than specific algorithms. However, due to attained model flexibility, whenever specific algorithms are needed they can be easily integrated with the developed models.

- Use of MSC observers for validation of specific properties: MSC observers have several attractive features. MSC is a graphical interface used to trace a number of events within a process. This allows for a clear description of the specific properties when defined as MSC observers compared to algebraic formulas.

- SDL Timing: SDL does not have standard timing constructs in its semantics [18]. This hindered the possibility of attaining a complete simple system specification. For example, the MAC protocol necessitates preservation of transmission sequence as defined in MAP frames. Due to the difficulty of specifying the complete SYNC operation, satisfying such a requirement over the distributed system is neglected per time frame in our model. We can only guarantee that a terminal will transmit within a certain time period. However, we are not able to identify the exact transmission instant.

- Broadcasting: The SDL version (SDL 96) utilized in this model does not define a broadcasting or multi-casting function. Therefore, to simulate a broadcasting function a data packet is transmitted on all channels in the receiving domain. However, under such an assumption, packets are sequentially transmitted rather than simultaneously as normal broadcasting regularly does.

- Delay: In order to specify the satellite round trip delay, we had to introduce the satellite bent pipe block, as SDL can only specify instantaneous transmission or a completely random delay. The bent pipe receives packets, delays them for a certain period and then broadcasts them on the down-links. This adds to the complexity of the devised model without significant benefits in the required MAC specification.

- Validation of Properties that involve Variables: We have already discussed the difficulties we experienced in verifying properties that rely on non-message criteria (mainly variables). The involved properties are critical to prove the protocol correctness and we had to try to validate them through inspection as previously discussed.

- Behavior vs. Performance: SDL is only concerned with system behavior. However, any telecommunications system must define both behavior and performance requirements. System behavior involves the various scenarios conducted through system operation. System performance defines quantitative attributes that evaluate system efficiency. It is a fundamental criteria in order to be able to compare between the performance of various protocols and identify the one with the best performance measures results suitable for optimum operation. Typical performance measures for any telecommunications system include bandwidth utilization, minimum delay, cell loss rate and time jitter, etc. As SDL lacks timing and probability constructs, it cannot be used to verify or even evaluate system performance. In Chapter 5, we introduce a simplified performance model for the prediction-based CFDAMA protocol to demonstrate quantitative operation of the utilized access technique. Numerous research efforts are currently being conducted in order to integrate performance and behavior within SDL [18].

Based on the above, as an overall evaluation, we can declare that SDL is a simple and very efficient method to describe and validate telecommunications systems behavior despite the existence of some limitations. In the next chapter, we complement those results by introducing an OPNET simulation model for a simplified prediction-based CFDAMA protocol. We will use the developed model to study the effects of buffer size on the performance in terms of total delay and cell loss rate.

Chapter 5

Effects of Buffer Size on Performance of Prediction-Based CFDAMA

In Chapter 3, we have described the structure and system behavior for the proposed MAC layer at the air-interface terminals in our BSA system. We proposed employing a prediction-based CFDAMA technique to improve the access over the satellite medium. It is obvious by intuition that the use of prediction will improve the delay performance of a DAMA technique as the requests (demands) always report future needs. This means that the roundtrip delay of the reservation period should not contribute to the total delay experienced by the data traffic. However, the level of improvement depends on the utilized prediction algorithm: its accuracy and processing speed, which is out of the scope of our thesis.

In non-prediction CFDAMA, the buffer size must be at least equivalent to the round trip delay (20 time frames) because data traffic will usually be queued for around that period before they can utilize the assignments responding to their demands. One of the interesting aspects that we would like to study about the prediction-based CFDAMA is the effect of buffer size on the total delay and the cell loss rate. However, as we have already discussed in the last chapter, SDL cannot be used to satisfy such an objective. In this chapter, we aim to provide a simplified prediction-based CFDAMA performance model to demonstrate the effect of buffer size on the total delay and cell loss rate of the system. We use the Optimized Network Engineering Tools (OPNET) [19], which is widely used in simulation and evaluation of telecommunications systems. Results obtained only serve for demonstration purposes. We also consider the devised performance model as a nucleus for possible future research interested in designing optimum prediction and scheduling algorithms to be utilized in the BSA system.

5.1 CFDAMA Protocol

For simplicity, we have developed a primitive CFDAMA protocol. As previously described, in CFDAMA, the scheduler responds to demands from different terminals dynamically each time frame. The extra capacity is distributed over terminals according to a special algorithm. For scheduling, we have utilized a first come first serve policy. For the free data allocation scheme, we have assumed a fair distribution, where unallocated capacity will be distributed one by one over registered terminals in a rotating Round Robin manner (i.e., a typical free allocation sequence to registered terminals would be 2,6,10,7,5,2,6,etc.). For request opportunities, we have utilized the following algorithm based on the activity of terminals: Each registered terminal has an information row in a lookup table inside the scheduler. The scheduler uses the table to identify the periodicity of request opportunities as well as number of time frames left (using a time stamp) before the next request opportunity. Whenever the scheduler receives a request for bandwidth (indicating terminal activity) from a terminal, it resets the periodicity of requests back to one (i.e., allocates a request in the next frame). On the other hand, each time frame with no requests received from a certain terminal, the scheduler will decrease its stamp by one. If the request period expires (stamp becomes zero) with still no requests received, the scheduler would increase the request periodicity by one. This process would continue as long as the terminal remains dormant (no requests are received by the scheduler) until a certain periodicity is reached after which it becomes constant. As specified in previous chapters, a request might be explicit (request opportunities) or implicit (piggybacking). Whenever the scheduler grants capacity for a terminal, it expects that terminal will report any demands through piggybacking and removes that terminal from the request opportunity list (if it is scheduled for a request opportunity next frame).

5.2 CFDAMA Protocol OPNET Model

We initially extracted a subset of the SDL model described in Chapter 4. The model specifies a prediction-based CFDAMA protocol operating under the normal transfer mode. Next, we manually translated the SDL model into an equivalent OPNET performance model with the necessary modifications to introduce the described scheduling and free assignment algorithms[1]. The translation process was a simple direct syntax translation. Figures 5.1 and 5.2 depict the structure of the data managing process in the SDL and OPNET models respectively.

[1]As discussed in Chapter 4, the SDL model defines simplified scheduling and free assignment behavior through employing random decisions.

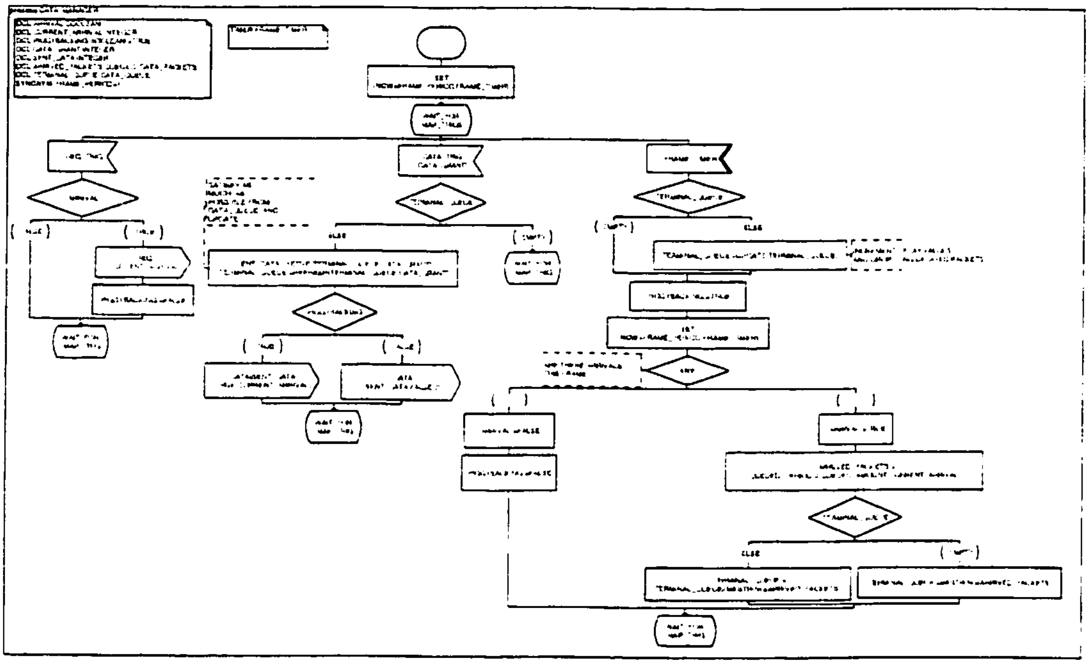


Figure 5.1: CFDAMA Data Manager for Terminals in the SDL Model

5.2.1 Model Assumptions

The developed OPNET model is shown in Figure 5.3. In model operation, we assume the following:

1. Successful registration for a population of five terminals. We conduct the study on the initial population without any terminals joining or leaving the network.

2. Round trip propagation delay over the satellite network is constant and is equal to twenty times the frame period.

3. The total bandwidth capacity per time frame is equal to 50 slots.

4. Input traffic is distributed according to a Poisson distribution[2] .

[2]The choice of Poisson is due to its simplicity and is only used for the demonstration purposes.

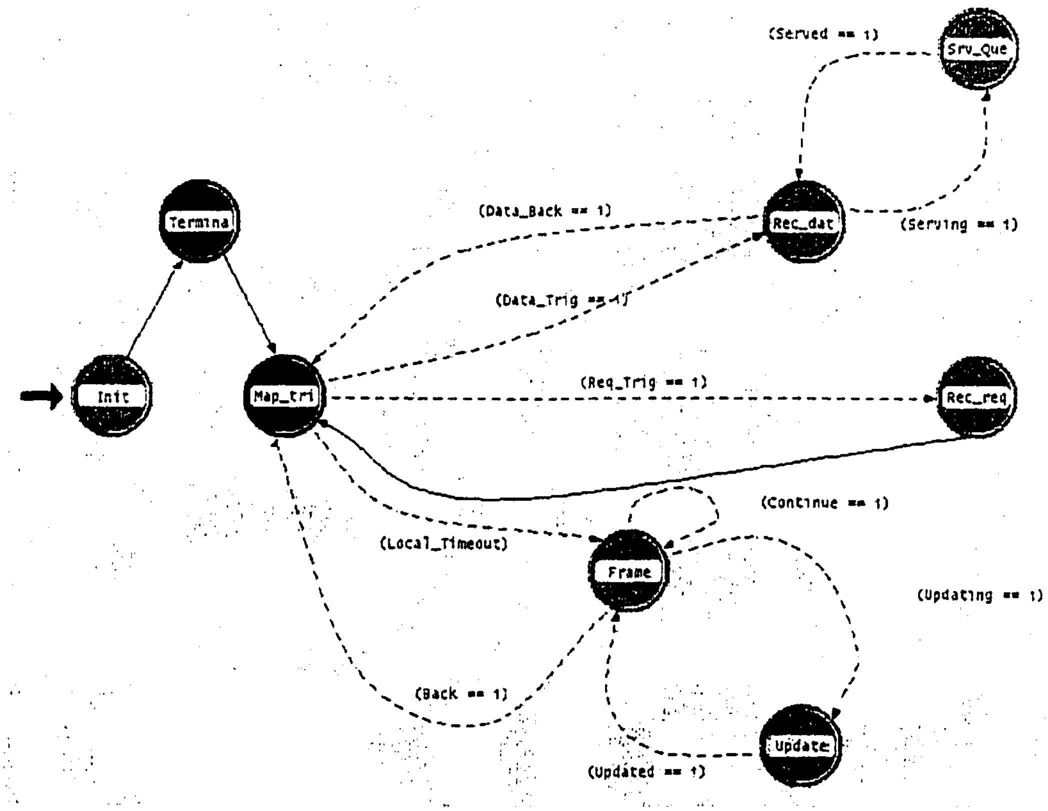


Figure 5.2: CFDAMA Data Manager for Terminals in the OPNET Model

5. More than one request message can fit into a singular data time slot. We assume that each data time slot can fit four request messages.

6. Terminals can only queue data packets for N time frames after which they are dropped.

5.2.2 Model Operation

As shown in Figure 5.3. the system consists of a central scheduler connected to five terminals in a star configuration. Each terminal is represented by instances of a Map Analyzer and a Data Manager. In order to initialize the system. we have implemented a New Terminal process that feeds the scheduler with addresses of registered terminals and consequently. the scheduler would initialize each terminal with its corresponding address. The scheduler represents the MCS functionality and regularly broadcasts MAP frames each time frame. Each terminal analyzes the MAP and accordingly. transmits their requests and grants wherever possible.

For demonstration purposes. we assume an input traffic according to a Poisson distribution. We have abstracted the prediction behavior as prediction algorithms are out of the scope of this thesis. In order to simulate prediction behavior. we generate the expected traffic arrivals early by taking a sample of the distribution. Following that. we introduce a noise (also for simplicity based on a noise function distributed according to a Poisson distribution) to the sample value with the result being the prediction. The resulting prediction value is transmitted as a request whenever possible according to normal mode operation. The distribution sample on the other hand. is delayed and is actually added into the data queues after 20 frames (one round trip propagation delay) to simulate traffic arrival. If we assume that the traffic distribution has an

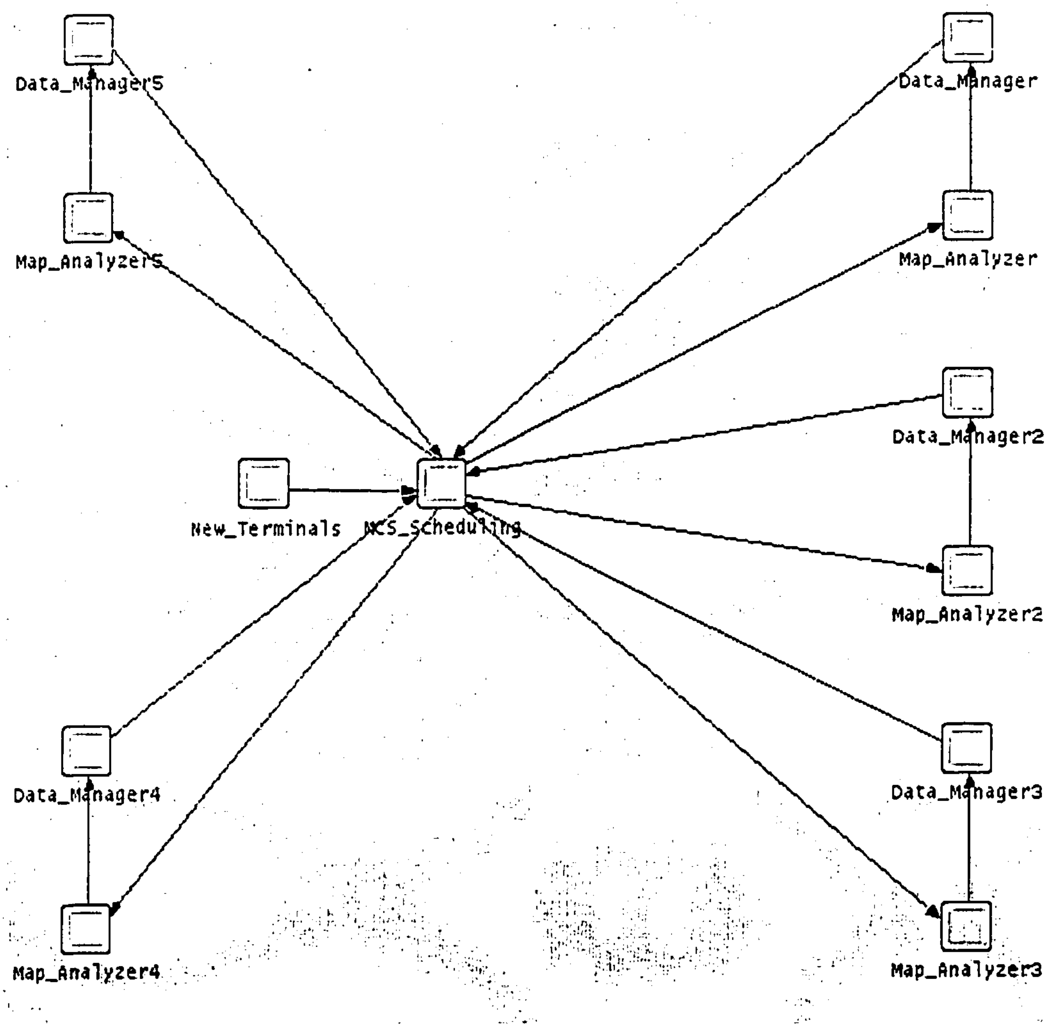
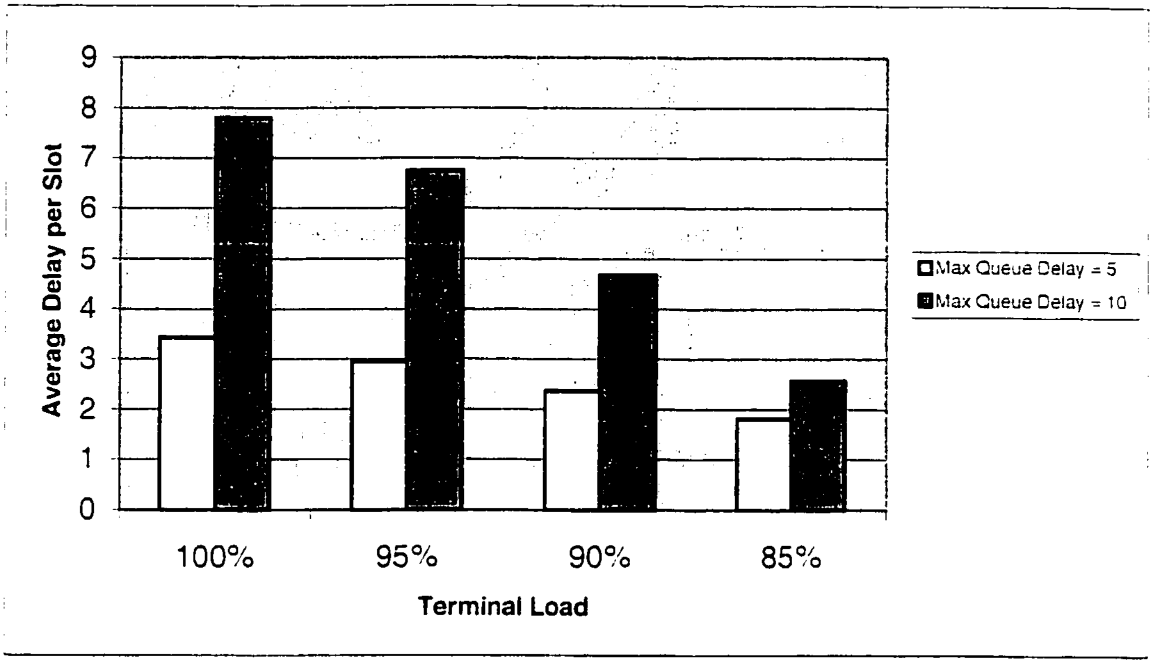


Figure 5.3: CFDAMA System Configuration in OPNET Model

instantaneous value X with a mean $\overline{X}$ and that the noise function (used to generate the sample noise value) has an instantaneous value Y with a mean $\overline{Y}$, therefore the instantaneous noise value will be $\Delta X = Y - \overline{Y}$ and the predicted value will be $P = X + \Delta X$.

5.2.3 Performance Measurements

We have described a system where five subscribers share a total capacity of 50 slots. This implies a maximum load per user of 10 slots (i.e., the maximum average traffic a subscriber can generate per time frame is 10). Numerous important performance measures can be attained using this model, such as, queuing delay, cell loss rate, bandwidth utilization, etc. However, as our aim here is to study the effect of buffer size on the average queuing delay per slot and consequent cell loss rates at variable loads of a single terminal. We have considered two queue dropping scenarios, where terminals can possibly queue packets for up to 5 and 10 time frames. Simulation was run for a total period of 40,000 time frames. Results are presented in Figure 5.4. As indicated in the figure, increasing the drop period, decreases the delay significantly. However, even though the loss rate is higher, differences between the two scenarios is minimum. Hence, an important objective on the design level would be to choose an optimum drop period to achieve minimum possible delay with least possible deterioration in the cell loss performance. This result and consequent optimization procedures cannot be realized using the behavioral model. It is therefore obviously essential to develop a performance model to attain robust specifications. As we have pointed out in previous chapters, a lot of research is currently being conducted in order to integrate behavior and performance, especially, for real-time telecommunications systems.



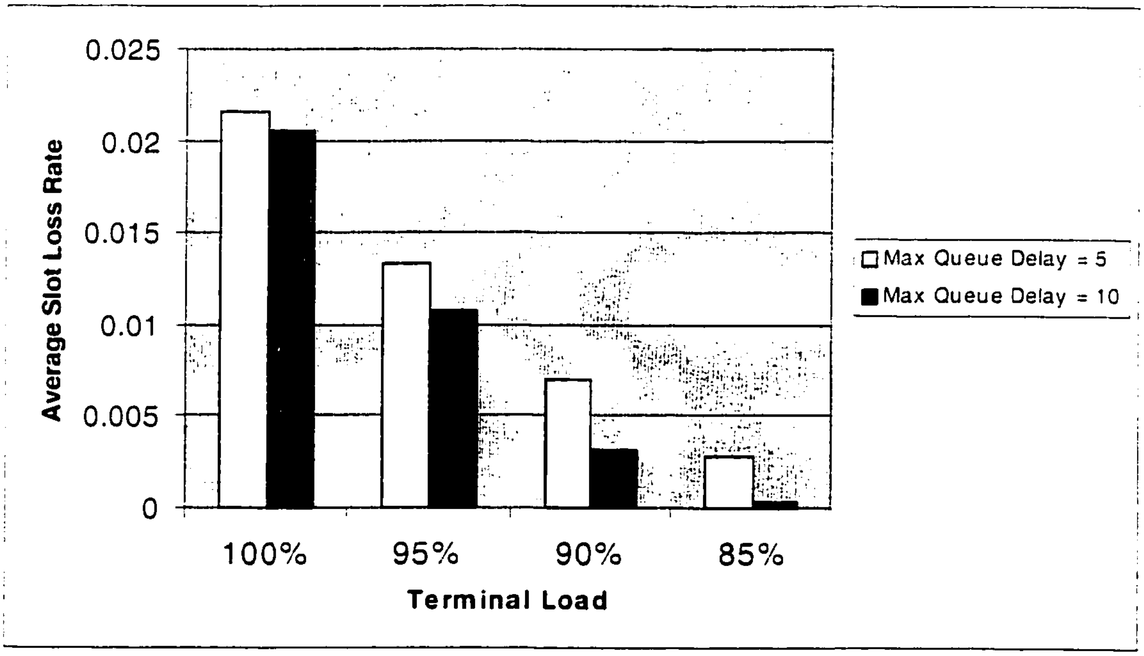


Figure 5.4: Average Delay per Slot and Average Cell Loss Rate for One Terminal under Different Loads

Chapter 6

Conclusion

In this thesis, we have suggested the expected popularity of future residential multimedia services over access networks. We have highlighted the essence of developing a new efficient MAC layer to contribute to successful deployment of these residential applications over a satellite access network. Accordingly, we have constructed a system architecture to satisfy such a requirement. We have presented protocol stacks and described protocol behavior. The system architecture dictates a simple distributed scheduling scheme. It also supports dynamic capacity allocation (DCA) over differential service categories. We have also justified the use of a CFDAMA-based access technique and proposed possible further enhancement by employing prediction. Furthermore, we have also developed a formal model that can render fast implementation. Verification and validation of the model were successful in confirming system correctness. However, the formal model lacked any capability of measuring performance attributes. Hence, we have presented an OPNET performance model for a simplified prediction-based CFDAMA protocol and demonstrated the effects of buffer size on the performance. The OPNET model can serve as a platform for future studies involving specific prediction algorithms.

The field of research involving satellite access is very broad and our work can only fit as a single part of the complete picture. The research issues are vast and range from physical layer transmission techniques to upper layer TCP extensions. Research on the MAC layer level also still requires further engineering studies. In order to effectively utilize the proposed devised system, accurate yet optimum prediction algorithms must be developed. An optimum prediction algorithm will achieve best accuracy in minimum processing time. Another field of possible research involves standardization of the differential service categories. Minimum differential categories that can convey all possible upper layers connections are desired. The number of differential categories represents the maximum number of connections with the scheduler per terminal. The smaller the number of categories defined (while maintaining the required QoS of all upper layers' connections), the easier and faster scheduler processing will be. Finally, we can identify traffic admission and policy control algorithms as possible candidates for research that can also contribute to enhance system operation and efficiently utilize resources.

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