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# CABLE MODEMS AND THE RETURN CHANNEL PATH FOR INTERACTIVE SERVICES: DOCSIS vs. DVB - A PERFORMANCE EVALUATION

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## **Abstract**

The development of a standard for interactive multimedia services over Community Antenna Television (CATV) networks is drawing interest from the data communications, telecommunications, broadcasting and the entertainment industries. Until recently, the solutions available for data transfer over Hybrid Fibre Coax (HFC) CATV networks were based on proprietary random access protocols and consequently they cannot be used in an open system and are limited when delivering digital audio and video streams. A unified standard is required, that will allow the development of interoperable hardware and drive down the cost of implementation. In Europe the Digital Video broadcasting (DVB) Cable Modem specification may be adopted. The simulated performance characteristics of this system show that bursty traffic can only be sustained by the 'reserved access mode' and constant bit rate/real-time variable bit rate services by the 'fixed-rate access mode'. In contrast the Data Over Cable Service Interface Specifications (DOCSIS), adopted in North America, uses a prioritised service mechanism which is well suited to supporting bursty traffic but which relies upon proprietary implementations of the DOCSIS features to provide constant bit rate services using a Committed Information Rate approach.

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## 1. Introduction

The potential of data delivery over Community Antenna Television (CATV) networks was realised as early as the 1960s. The first to benefit were public institutions while the technology was tested by utility companies for telemetry applications. Since then the demand for high bandwidth at the home has risen sharply and before a unified standard could be ratified. The majority of CATV networks in the USA are based on the tree and branch architecture. Alternative topologies are the tree and bush, mainly found in Europe, and the rarely used switched star architecture which uses off-premises addressable converters. Fibre has replaced coaxial feeds from the headend to the initial splitter to create the Hybrid Fibre Coax (HFC) topology. The HFC topology provides immunity from electromagnetic noise and the elements for the transmission over large distances, and the cost efficiency of coax cable for the last mile.

Cable Companies are now exploring new technologies which can be used to support digital interactive multimedia applications over their CATV infrastructures, [Azzam, 97]. Over the last few years much attention has been paid to the development of architectural options for CATV networks that will allow the immediate support of broadband services as the first step toward enhanced communication services for residential users. These technologies range from the introduction of well established Internet devices to new access mechanisms. The current CATV standards activities, [Smythe, 97], [Tzerefos, 98], are:

- IEEE 802.14 – the IEEE committee producing a broadband Metropolitan Area Network (MAN) Medium Access Control (MAC) and Physical layer protocols;
- ATM Forum Residential Broadband Working Group (RBWG) – investigating the provision of Asynchronous Transfer Mode (ATM) across different CATV network topologies and for distribution within the home itself;
- Internet Engineering Task Force (IETF) – investigating the use of the Internet Protocol (IP) Over Cable Data Networks (IPCDN). This work is based upon the use of routers to interconnect different logical internet structures;

- Multimedia Cable Networks Systems (MCNS) partners – producing the Data Over Cable Service Interface Specifications (DOCSIS) on behalf of the North American Cable industry and using cable modem technology;
- Digital Audio-Visual Council (DAVIC) – primarily a European driven group, but including many international companies, looking at the standards for complete end-to-end interactive multimedia delivery systems;
- SCTE – an accredited American standards organisation working on compatibility issues for cable telecommunications systems. The SCTE has successfully submitted the MCNS specification for acceptance by the ITU-T;
- The Digital Video Broadcasting (DVB) project – the DVB cable system (DVB-C) was completed in 1995. DVB has adopted the DAVIC recommendations with respect to CATV and has been responsible for the development of the European standard ETS 300800.

The following sections of this paper describe:

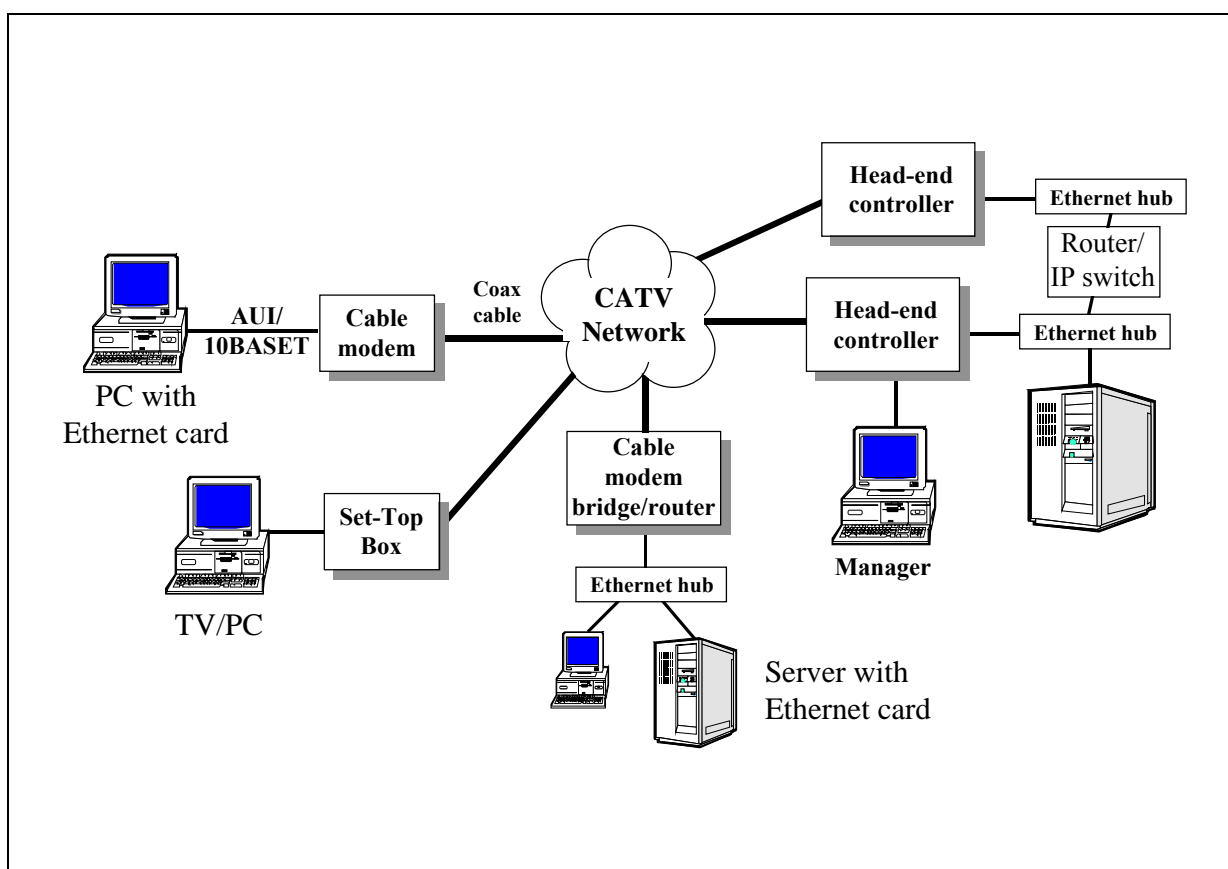
Cable Modem Architectures:	A review of pre-standardisation cable modems;
CATV Data Standardisation:	A summary of cable modem standardisation;
DVB/DAVIC Specifications:	A review of the DVB/DAVIC cable modem standard;
DOCSIS Specifications:	A review of the DOCSIS, versions 1.0 and 1.1, cable modem standard;
Performance Characterisation:	A review of the performance capabilities of the DVB/DAVIC and DOCSIS cable modems.

## **2. Cable Modem Architectures**

Cable modems available for immediate deployment do not comply to a specific standard. They are based on proprietary interfaces for the modem to headend communications, and are not interoperable. The most common interface between the modem and the subscriber device is a 10BASET Ethernet connection. Current cable

modem implementations operate similarly to a Local Area Network (LAN) bridge or repeater. They relay traffic, destined for nodes not within the home network or broadcast/multicast traffic, to the CATV network. However devices in the home/business LAN network and cable modem have to be attached to an Ethernet hub as the modems feature a single port. Less sophisticated modems do not support multiple devices. In such cases the workstation attached to the cable modem can act as a proxy server for the rest of the devices in the subscriber's LAN (Figure 1).

Although manufacturers are not releasing detailed information about their MAC protocol, most of them are based on random access methods and variations of the broadband Carrier Sense Multiple Access with Collision Detection (CSMA/CD) protocol. Com21 has implemented UPSTREAMS in their range of cable modems [COM21, 97] which features an RJ-45 Ethernet interface to the subscriber end, and an Asynchronous Transfer Mode (ATM) over HFC MAC protocol at the modem-to-head-end interface. UPSTREAMS can support different classes of traffic, i.e. Constant Bit Rate (CBR), Variable Bit Rate (VBR) and Available Bit Rate (ABR).



**Figure 1** Cable modem data connectivity.

In terms of modulation schemes, most manufacturers have implemented 64 Quadrature Amplitude Modulation (QAM) for the downstream and Quadrature Phase Shift Keying (QPSK) for the upstream channels. Terayon is the first to have introduced spread spectrum transmission techniques using Synchronous-CDMA on both the upstream and downstream channels. The benefits from using S-CDMA are high noise immunity and increased security since signals are hard to detect and demodulate due to their resemblance to noise. S-CDMA has now been adopted by the IEEE 802.14 as one of the key components for its new Advanced Physical Layer Specification. A small number of manufacturers have introduced modems which use telephone lines and standard analogue modems for the upstream path (Telco return modems). This solution, primarily targeting residential Internet access applications, is not widely accepted due to the limited upstream channel capacity and the increased running costs of the additional phone line.

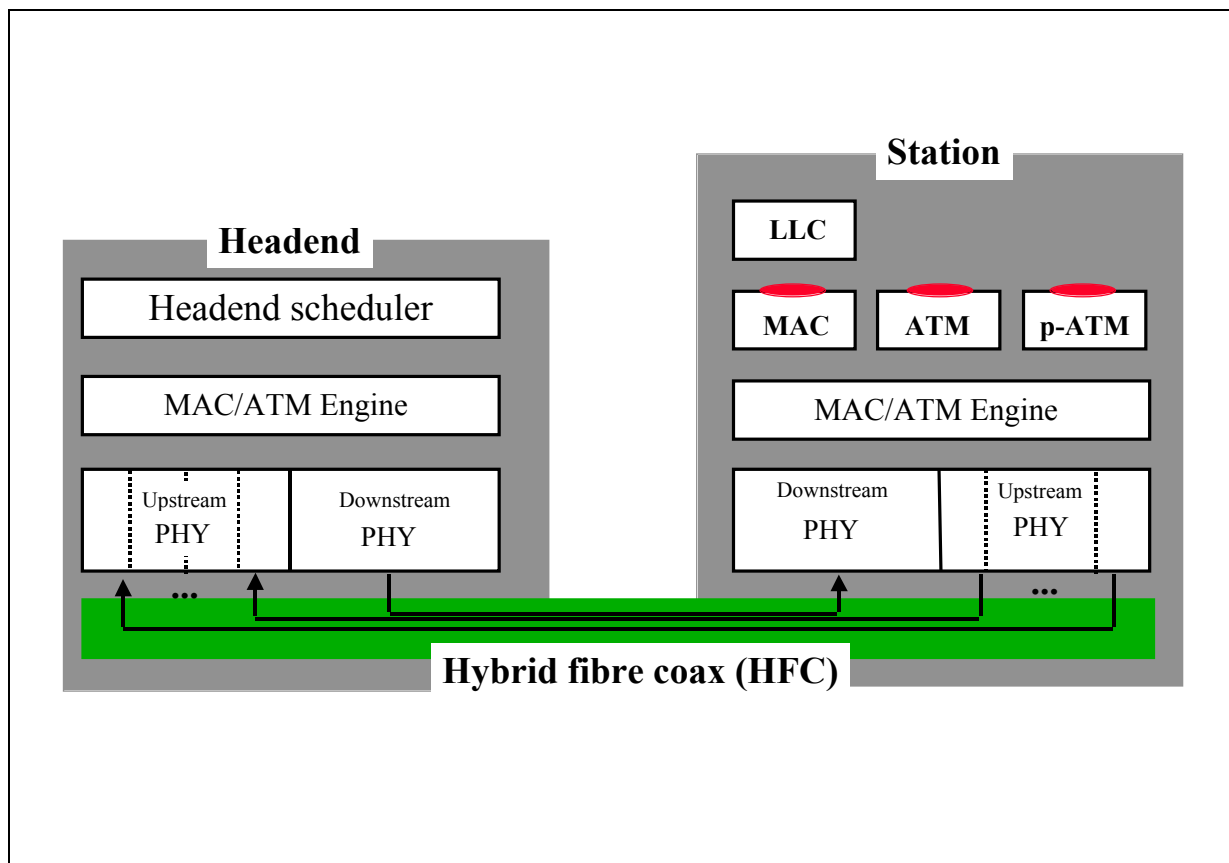
### **3. CATV Data Standardisation**

#### **3.1 IEEE 802.14**

The architecture of the IEEE 802.14, [IEEE, 98], solution is shown in Figure 2. Two key services are to be supported: the IEEE 802.2 Logical Link Control (LLC) – to support frame data transfer (mandatory for all IEEE 802 standards); an ATM service which fully conforms to the corresponding ITU-T recommendations. A HFC cable infrastructure is assumed upon which a single downstream channel is used with multiple aggregated upstream channels. The scheduling algorithms in the head-end are NOT a part of the standard (these are left to individual implementations).

The MAC sublayer is itself composed of the MAC Convergence Subprocess (MACCS), the ATM and the MAC Access Arbitration (MAA) sublayers. The aim of this sublayering is to multiplex the LLC and ATM traffic streams as effectively as possible so that the appropriate QoS are supplied. All data is encapsulated within ATM Adaptation Layer 5 (AAL5) Protocol Data Units (PDUs). A sophisticated security system is supported for user registration and encryption. As per the DOCSIS specification, data transmission is based on a grant/request scheme. The head-end allocates transmission resources in the upstream channel to users for contention-based reservation and information transfer. A user wishing to transmit

data waits for a request minislot which it uses to compete for later minislot allocations. The contention resolution algorithm is a tree-search based group splitting algorithm capable of resolving collisions in multiple request minislots simultaneously. Successful users are informed by the head-end which allocates the start and number of minislots for data transmission.



**Figure 2** The IEEE 802.14 protocol architecture.

The IEEE have specified three physical layer specifications to reflect the US, European and Japanese requirements. These are known as Types A, B and C which reflect the ITU J.83 Annex A, B and C recommendations [ITU, 97]. Types A and C differ with respect to the upstream channel bandwidth (Type A is 6MHz and Type C is 8MHz). The PHY consists of the Transmission Convergence (TC) and Physical Medium Dependent (PMD) sublayers. The modulation schemes for the Type A, B and C downstream is 64 and 256 QAM and an MPEG-TS is used to carry the information frames. Reed Solomon coding, scrambling and interleaving is also employed to provide a bit error rate of  $10^{-8}$ , after Forward Error Correction (FEC). In the upstream, supplied as a 'sea of minislots' QPSK or 16-QAM is employed. The downstream data rate is either 30 (64-QAM) or 40Mbps (256 QAM), and for the

upstream each channel will support either 320, 640, 1280, 2560, 5120, 10240 or 20480Kbps (inclusive of all FEC, etc).

The latest work by the IEEE 802.14 is the development of a new high speed Advanced Physical Layer. This is based upon a combination of:

- Frequency Agile Time Division Multiple Access (FA-TDMA);
- Synchronous Code Division Multiple Access (S-CDMA).

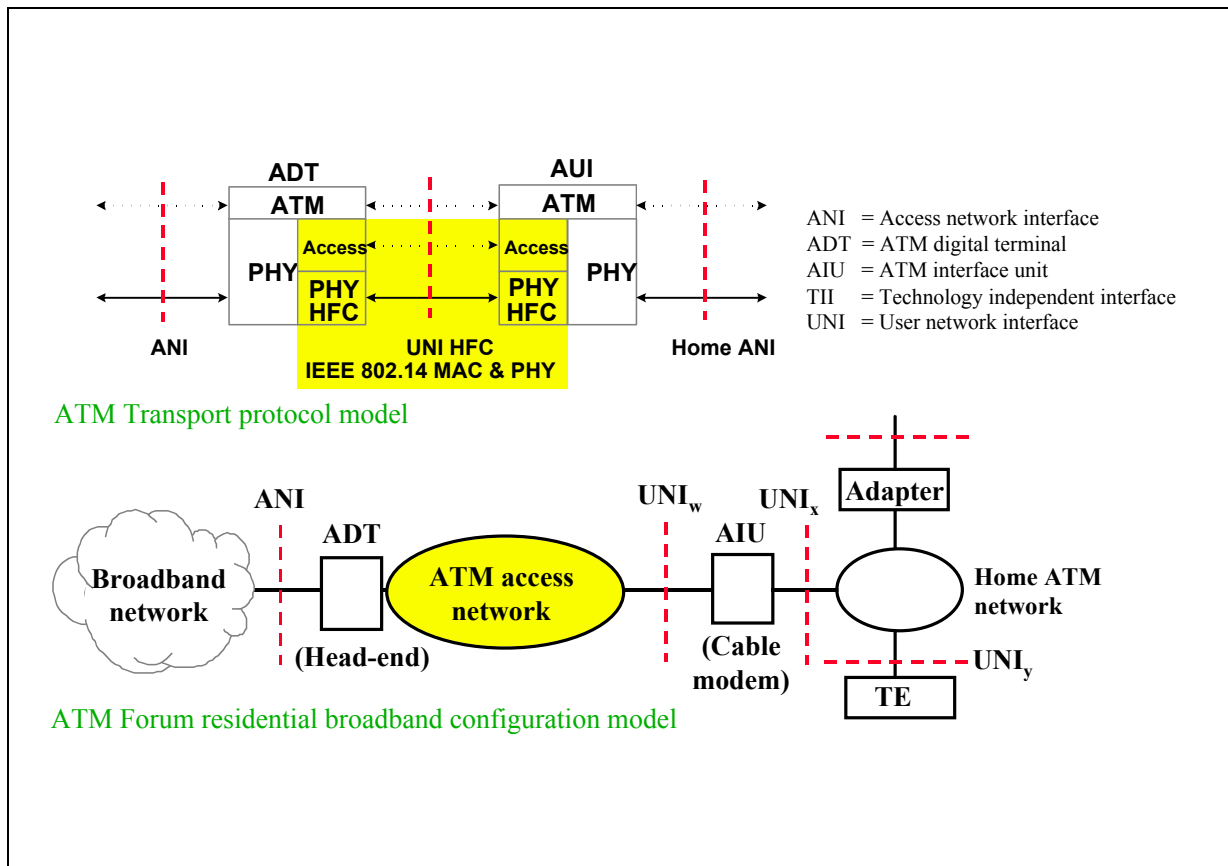
The standardisation of this layer will take another 12 months. The advanced physical layer has also been adopted by DOCSIS and will form part of DOCSISv1.2.

### **3.2 ATM Forum RBWG**

The RBWG was formed by the ATM Forum in order to promote the deployment of ATM over emerging residential network infrastructures [ATMF, 98]. The efforts of the RBWB focus on the delivery of ATM the home and ATM within the home. ATM-To-The-Home (ATTH) is proposed for the support of new generation of interactive services over CATV networks. ATM is a broadband network technology which features high bandwidth and guaranteed quality of service and the ATM Forum has recently established a group that is standardising the interfaces for the deployment of ATTH over the different network architectures. There are numerous advantages from the adoption of ATM as a standard protocol. A key advantage of ATM is the support for guaranteed end-to-end quality of service and bandwidth. Hardware devices for ATM networks are widely available and can be used on CATV networks [Kwok, 95]. ATM switches running in the multi-gigabit range are already commercially available with switching capacity continually growing. Also, since the next generation of CATV networks will need efficient management, CATV networks could benefit from the existing management capabilities of ATM protocols. The proposed ATMF RBWG architecture is shown in Figure 3.

The major concern when implementing ATM over CATV networks is the definition of the protocols that would allow the deployment of ATM over the different cabling plants (HFC, FTTH, FTTC and ADSL) already in operation i.e. a legacy systems problem. For some cabling structures, the usage of ATM is not straightforward

[Kwok, 95]. The ATM protocols must be extended to support the shared downstream and upstream channels for FTTC and HFC networks.



**Figure 3** The ATM Forum’s residential broadband architecture.

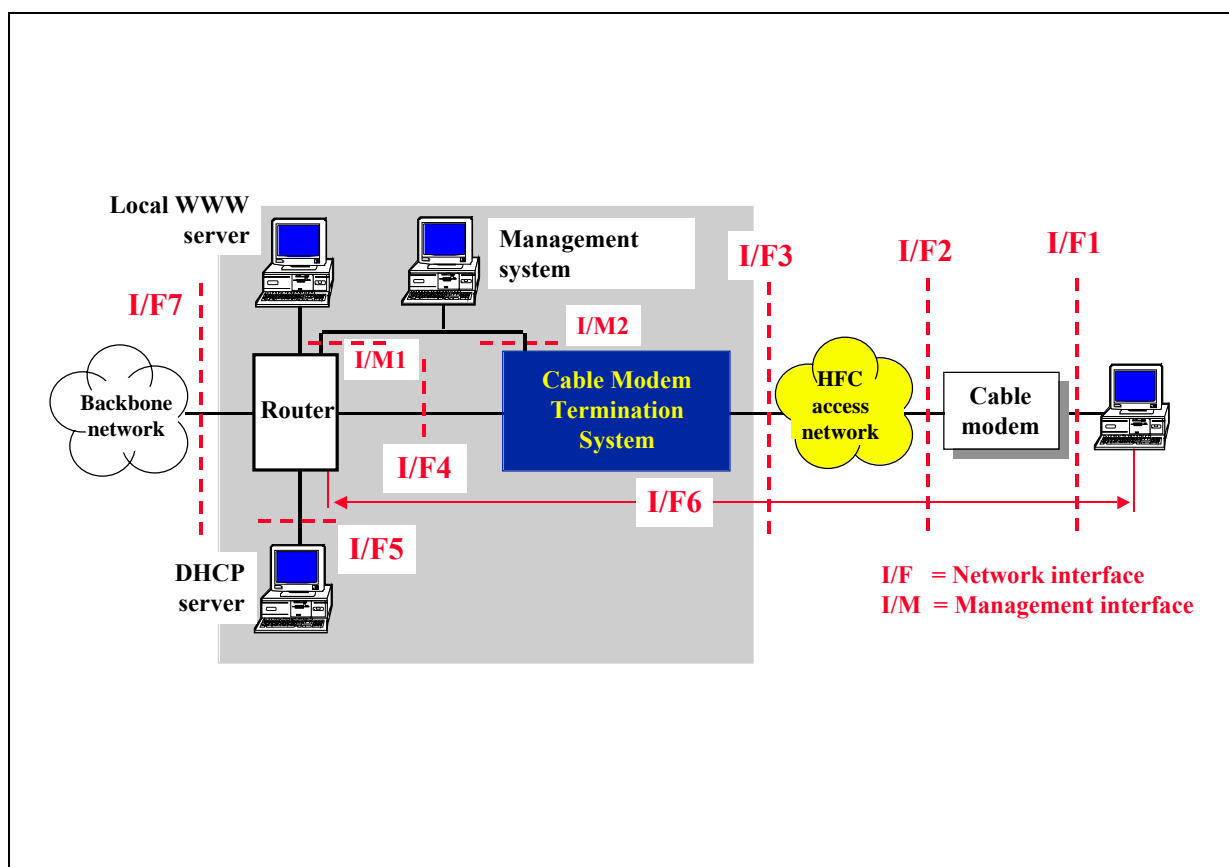
ATM can be implemented over HFC networks by placing an ATM switch within the head-end to interconnect the server with the rest of the cable plant. In turn each port of the ATM switch must be logically connected to each 6/8MHz downstream channel. At the subscriber’s end the receiver must be tuned to the right frequency before decoding ATM cells. For FTTC networks, in which no PON is used, the implementation with ATM is trivial since the FTTC architecture becomes a switched point-to-point network. When using a Passive Optical network (PON) to support the HFC or FTTC infrastructure, then a new MAC protocol has to be defined to manage the shared upstream bandwidth. Equally trivial is the implementation of ATM on FTTH and ADSL architectures since these are point-to-point network infrastructures; a different physical layer has to be defined for the ADSL architecture that supports the non-standard ATM data rates.



The RBWB is working closely with the IEEE 802.14 for the development of standards for ATM over HFC. The two basic interfaces under development are the ATM Digital Terminal (ADT) at the head-end and the ATM Interface Unit (AIU) at the subscriber. The first adopted specification should be ratified by the end of 1998.

#### 4.4 IP over Cable Data Network (IPCDN) Charter

The IETF has formed a working group that will produce a framework and requirements document for IP over a CATV infrastructure. Issues to be addressed by the IPCDN WG are the service interface between IP and CATV network, multicast, broadcast, address mapping and resolution (for IPv4), neighbour discovery (for IPv6) and network management. The IPCDN architecture is shown in Figure 4 [Ahmed, 96].



**Figure 4** IETF IPCDN architecture.

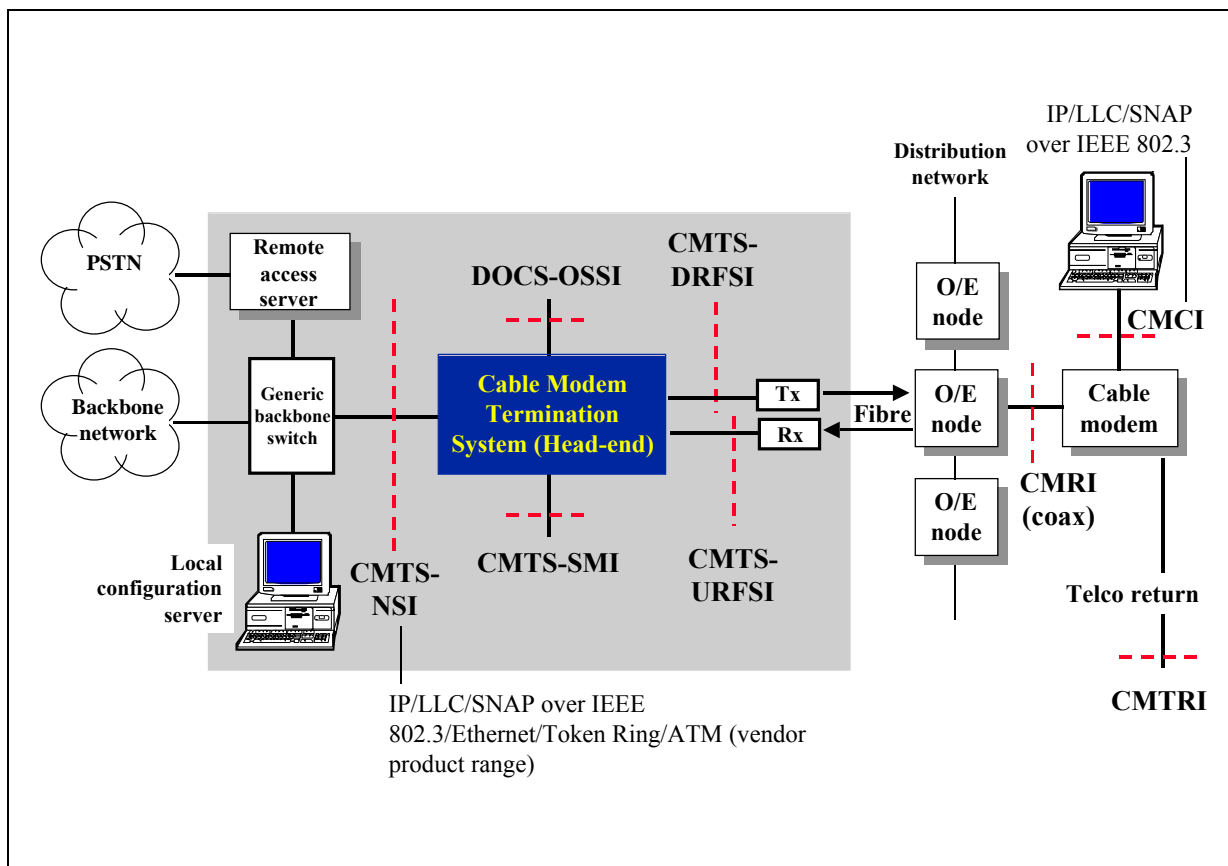
The deliverables from the WG are:

- RFCs covering the framework architecture, requirements and terms of reference for Cable Data Networks;
- IPv4-over-HFC access network document covering the mapping of IP over RF channels, encapsulation and framing of IPv4 packets, IP to modem and/or PC address resolution, multicast and broadcast;
- IPv6-over-HFC access network document covering the mapping of IP over RF channels, encapsulation and framing of IPV6, IP to modem and/or PC address resolution, neighbour discovery, multicast and broadcast;
- A media specific Management Information Base (MIB) for managing the HFC spectrum;
- A MIB for managing the cable data network services including the management of IP over the CATV network itself.

The IPCDN has already released an Internet Draft document presented for discussion purposes only and not for setting any standards. Issues covered are IP service features, IP address assignment using the Dynamic Host Configuration Protocol (DHCP), Address Resolution Protocol (ARP) and other service specific issues relating to IP over CATV. At present the primary focus of the IETF's work is on the adoption and extension of the MCNS's DOCSIS MIB.

### **3.4 MCNS DOCSIS**

The MCNS partners consist of Comcast, CableLabs, TCI, Cox Communications, Time Warner, Continental Cablevision, Rogers Cablesystems, CableLabs and Arthur D. Little. The task of the DOCIS project is to define on behalf of the North American cable industry, the required communications and operations support interfaces for cable modems. Originally the CableLabs were producing their own standards but these now appear to have been superseded by the MCNS activities. In the MCNS system [DOCSIS, 96a] the transmission path over the cable network is performed by the Cable Modem Termination System (CMTS) at the HE and the Cable Modem (CM) at the customer premises. The reference architecture shown in Figure 5 contains three interface categories:



**Figure 5** The MCNS DOCSIS reference architecture.

- Data interfaces which include the CMTS Network Side Interface (CMTS-NSI) between the CMTS and the data network, specified in [DOCSIS, 96b] and the CM to Customer premises equipment Interface (CMCI) between the customer's computer and the CM, specified in [DOCSIS, 97a];
- Operations support systems and telephone return path interfaces which correspond respectively to network element management layer interfaces between the network elements and the high level Operations Support Systems (OSSs), defined in [DOCSIS, 97b], and the interface between the CM and the telephone return path for the cases where the return path is not available or provided from the cable network, specified in [DOCSIS, 97c];
- RF interfaces, defined in [DOCSIS, 96b], that includes interfaces between the CM and the cable network, the CMTS and the cable network (in both the upstream and downstream paths).

The principle function of the MCNS protocol specification is the transparent transfer of Internet Protocol (IP) messages across the cable system without Quality of Service (QoS); IPv4 support is mandated but migration to IPv6 will be considered in later versions. However, since the protocol operates on bandwidth reservation from the CMs to the CMTS, QoS can be provided by extending the protocol and using a scheduling algorithm in the HE. DOCSISv1.1 introduces a full QoS provision [DOCSIS, 98]. Comparisons between the MCNS DOCSIS and the IEEE 802.14 standards are now available [Smythe, 98] and Lin [98].

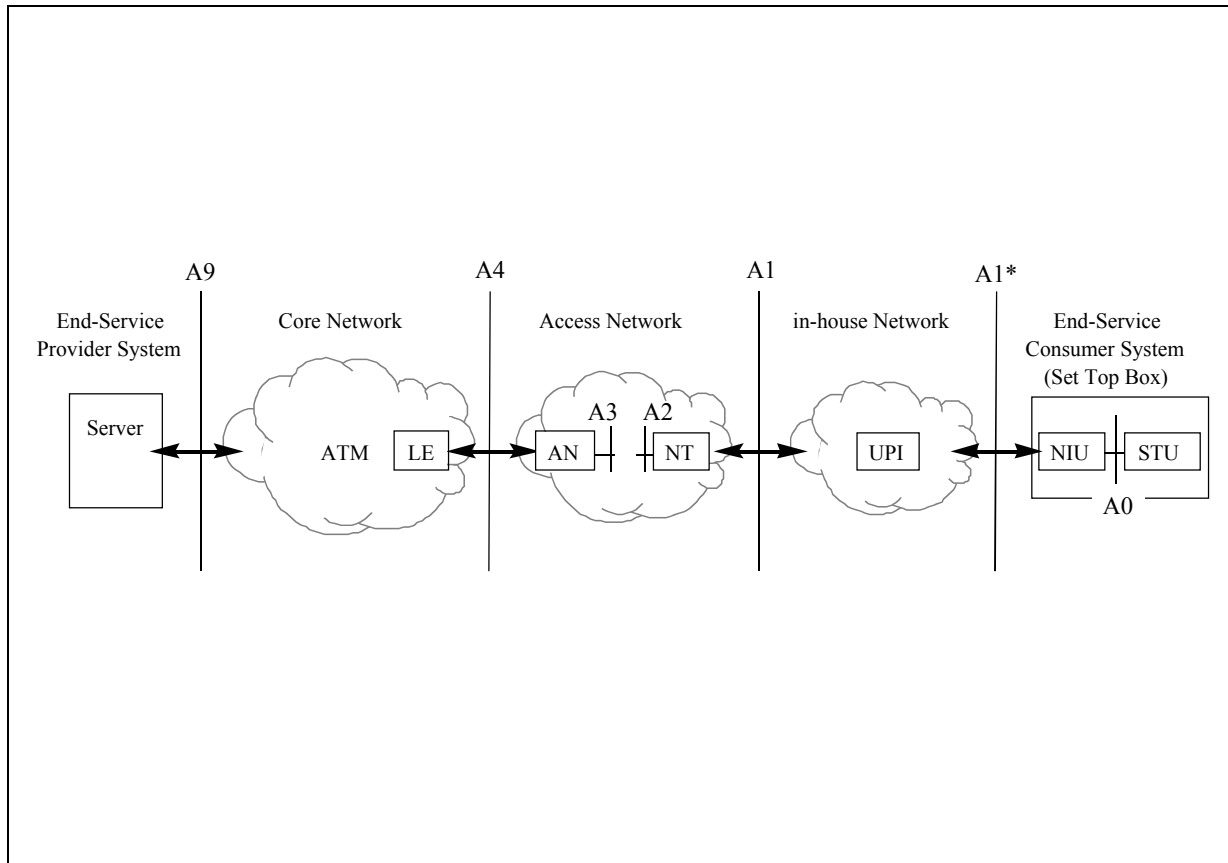
### 3.5 DAVIC

The Digital Audio-Visual Council (DAVIC), founded in October 1994 and based in Geneva, is a non-profit making Association which has charged itself with the task of promoting broadband digital services. The goals of DAVIC are declared as “... to identify, select, augment, develop and obtain the endorsement by formal standards bodies of specifications of interfaces, protocols and architectures of digital audio-visual applications and services”. The applications of particular interest are Video-On-Demand (VOD) and Near VOD (NVOD).

DAVIC is producing a series of specifications, version 1.2 was available in December 1996, version 1.3 was released in 1997 and version 1.4 in 1998. DAVIC 1.0 defined the initial set of tools to support the deployment of systems supporting applications such as TV distribution, NVOD, VOD and some basic forms of teleshopping. The later DAVIC specifications define different grades of existing tools or additional tools which provide compatibility with the full range of new Internet facilities e.g. web browsers and Java, [Donnelly, 97]. DAVIC have adopted the following philosophy:

- Tools and not systems. DAVIC’s goal of interoperability across applications requires the definition of non-system specific ‘tools’ or components which ensure interoperability;
- Relocation of tools. Tools should be useable in a variety of different systems and also in different parts of the same system;
- One functionality—one tool. Wherever possible tools are defined to be unique;

- Specify the minimum. DAVIC has to satisfy a multi-industry constituency and so only the very minimum that is required for interoperability is specified e.g. DAVIC have agreed to adopt the IEEE 802.14 recommendations for upstream data transfer.



**Figure 6** DAVIC cabled network architecture with reference points.

Figure 6 illustrates the general structure of a cabled network. The delivery system is divided into a core network, an access network and an in-house network. The separation between the core and access network is formed between the Local Exchange (LE) and the Access Node (AN). The separation between the access node and the in-house network is formed by the Network Termination (NT).

In the majority of cases the end-service consumer system will contain a Set Top Box (STB) which can be divided into a network dependant part called the Network Interface Unit (NIU) and the network independent part called the STU (A0). One key point to note is that DAVIC assumes that the A4 reference point (the interface between the core network and the access network) will be fully digital and ATM based. The access node beyond the A4 reference point can be either ATM or MPEG

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Transport Stream (MPEG2-TS) based, although in the case of the latter a mapping function is needed to specify the relationship between it and ATM.

### **3.6 Digital Video Broadcasting (DVB)**

The DVB Project emerged from a group, called the Launching Group, of European broadcasters, consumer electronics manufacturers and radio regulatory bodies in September 1993. It expanded to include public and private interest groups and currently comprises more than 220 members from 30 countries. The main focus of DVB is the delivery of digital TV over satellite, terrestrial and cable links. The interest on digital TV was stimulated after experimental projects like SPECTRE demonstrated that techniques such as the “Motion Compensated Hybrid Discrete Cosine Transform Coding” were quite efficient in reducing the bandwidth required for the delivery of digital TV.

The DVB-S is satellite specification designed to operate within a range of transponder bandwidths (26MHz to 72MHz, -1dB). The cable network, DVB-C system has the same core as the satellite system, but the modulation system is based on QAM rather than QPSK, and no forward error-correction is needed. Initially DVB recommendations did not cater for bi-directional communications. However the implementation of interactive TV will require data on the reverse direction. Therefore the DVB group is turning to other standardising bodies in order to produce a specification with a wider range of applications which will span beyond digital TV broadcast such as Internet access, videoconferencing etc. At the initial stages DVB was evaluating which standard would be the most suitable for the delivery of MPEG-2 audio/video streams over CATV networks. At its meeting in July 1997 DVB announced it would adopt the DAVIC 1.2 specification. Both the UK and European Cable Communication Associations announced that they were going to support the DAVIC/DVB standard which has become a European norm. In order to accomplish compatibility with the other standards under development, DVB requested from the IEEE 802.14 group to optionally include DAVIC 1.2 part 8, sections 7.7 and 7.8: passband unidirectional and bi-directional PHY on coax, including the MAC functionality, in its specification. The ETS 300800 standard has now been produced as the specification of the interaction channel for CATV distribution systems [ETS, 1998].

### **3.7 Society of Cable Telecommunications Engineers (SCTE)**

The SCTE is a non-profit organisation formed in 1969 in order to promote the sharing of technical and operational knowledge for cable TV and broadband communications. As of August 1995 the SCTE became an accredited Standard Developing Organisation of ANSI. The Data Standards Subcommittee role is to promote data delivery in the cable industry and define standards for hardware interoperability. In its charter it is mentioned that the subcommittee will co-ordinate its efforts with the IEEE 802.14, DAVIC and CableLabs.

On August 13 1997, the SCTE submitted the MCNS specification for the transmission of data over cable to the International Telecommunications Union (ITU). The MCNS specification, has always been a compromise between the best technological solution and the standard that will allow modem manufacturers to produce interoperable hardware to satisfy the increasing demand for data over cable. To approve the specification known as DSS-97-2, the ITU will need to overlook the arguments for ATM. The MCNS specification has already been reviewed by the US State Department. The ITU have now accepted the SCTE proposal for MCNS.

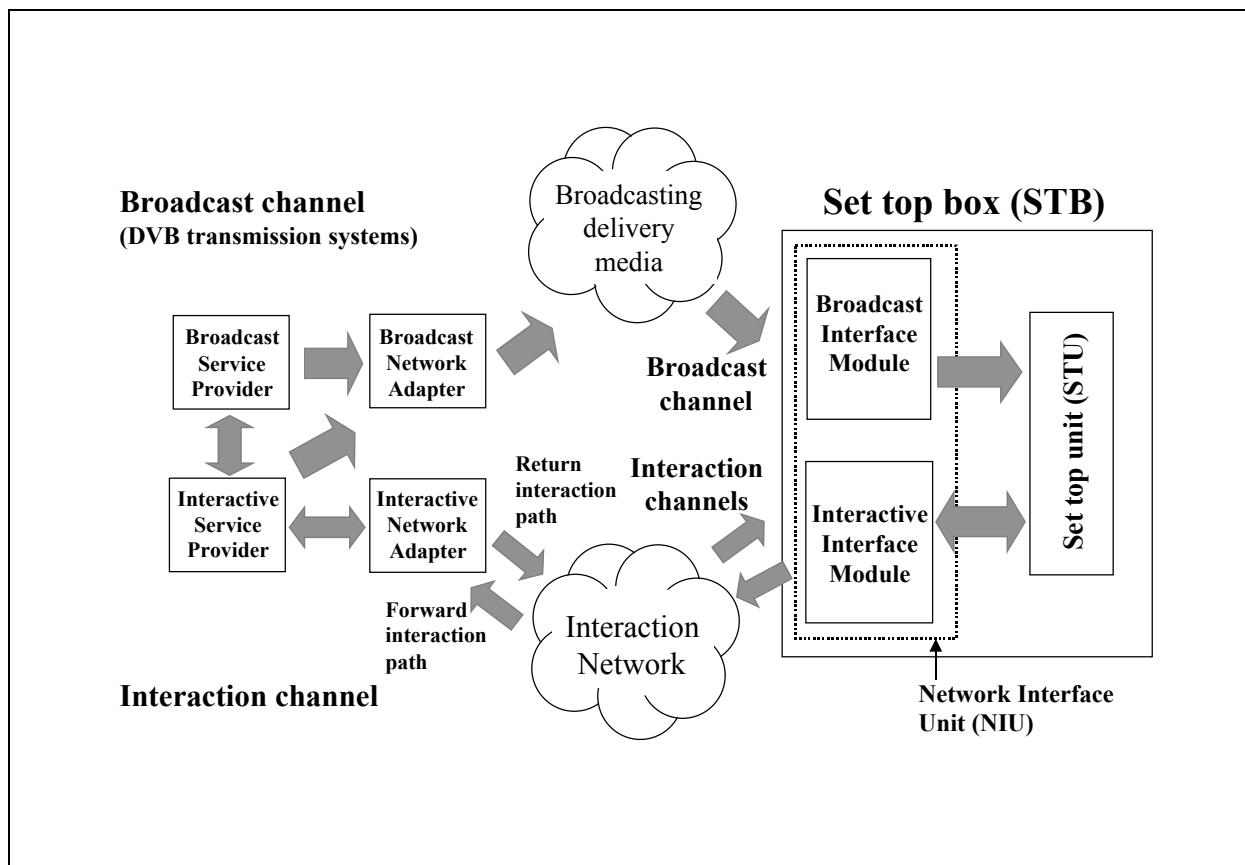
## **4. DVB/DAVIC Specifications**

Figure 7 shows the system model used within DVB for interactive services [ETS, 98]. In the system model there are two channels established between the service provider and the user:

- Broadcast Channel (BC) – a unidirectional broadband broadcast channel including video, audio and data. The BC is established from the service provider to the users. It may include the Forward Interaction path;
- Interaction Channel (IC) – a bi-directional interaction channel is established between the service provider and the user for interaction purposes. It is formed by:
  - (a) Return interaction path – from the user to the service provider. It is used to make requests to the services provider or to answer questions. It is a narrowband channel, also commonly known as the return channel

(b) Forward interaction path –from the service provider to the user. It is used to provide some sort of information by the service provider to the user and any other required communication for the interaction service provision. It may be embedded into the broadcast channel. It is possible that this channel is not required in some simple implementations which make use of the BC for the transmission of data to user.

The user terminal is formed by the Network Interface Unit (NIU) and the Set Top Unit (STU). The NIU consists of the Broadcast Interface Module (BIM) and the Interactive Interface Module (IIM). The user terminal provides interface for both broadcast and interaction channels. The interface between the user terminal and the interaction network is via the IIM.



**Figure 7** The generic system reference model for DVB interactive systems.

The key features of the DVB system are (no cable modem architecture implementation currently exists):



- The interactive system consists of the forward interaction path and the return interaction path;
- Upstream transmission is based upon TDMA of slots. One downstream channel is used to synchronise up to eight upstream channels, which are all divided into time slots;
- Three major access modes are provided, namely: contention access and two contentionless access schemes;
- Out-of-band (OOB) and in-band (IB) signalling is supported. For OOB a forward interaction path is added. For IB the forward information path is embedded into the MPEG2-TS of a DVB cable channel;
- The possible spectrum allocation is based upon 70-130MHz and/or 300-862MHz for the forward interaction path (downstream OOB), and 5-65MHz for the return interaction path (upstream);
- Upstream and OOB downstream channels are divided into separate channels of 1 or 2MHz for downstream and 1MHz or 2MHz or 200kHz for upstream;
- For the interactive downstream OOB channel a rate of 1.544Mbps or 3.088Mbps may be used. For downstream IB channels no other constraints than those specified by ETS 300 429 exist but it is expected that multiples of 8kbps will be used;
- For upstream transmission, user have three rates namely 3.088Mbps, 1.544Mbps or 256kbps;
- Upstream frames consists of packets of 512 bits (256 symbols) which are sent in a bursty mode. The upstream slot rates are 6000 (3Mbps), 3000 (1.5Mbps) and 500 (256kbps) slots per second.

## 5. DOCSIS Specifications

The principle function of the DOCSIS v1.0 protocol specification is the transparent transfer of Internet Protocol (IP) messages across the cable system (CMCI to CMTS-NSI) without Quality of Service (QoS); IPv4 support is mandated but migration to

IPv6 will be considered in later versions. However, since the protocol operates on bandwidth reservation from the CMs to the CMTS, QoS can be provided by extending the protocol and using a scheduling algorithm in the HE. The protocol layers are: the network layer (IP), the data link layer and the physical layer. Specifically, the data link layer is comprised of three sublayers: Logical Link Control (LLC) which conforms to the IEEE 802.2 standard, link-security sublayer that supports the basic needs of privacy, authorisation and authentication and the MAC which supports variable-length Protocol Data Units (PDUs). The physical layer is comprised of the upstream/downstream transmission convergence (U/D TC) and the physical media dependent (PMD) sublayers. The main features of the MAC protocol are: CMTS-controlled mix of contention and reservation transmission opportunities, a stream of minislots (units for upstream transmission opportunities and an integer multiple of 6.25 $\mu$ s increments) in the upstream, bandwidth efficiency through support of variable-length packets, extensions provided for the future support of ATM or other PDUs, support for multiple grades of service, support for a wide range of data rates.

The CMTS allocates bandwidth via MAC management messages (MAP) which describe the uses to which the upstream mini-slots must be put. Since the upstream channel is modelled as a stream of minislots the CMTS must generate the time reference for each MAP as a varying message. This consists of a fixed header followed by a variable number of Information Elements (IEs), each of which defines the slots as grants for specific stations to transmit data, indicating to a CM that its request has been received. At minimum, a MAP may describe a single mini-slot and contain two IEs: one for the data/contention requests and a null IE to terminate the list. On the other hand, at maximum, it must not describe more than 4096 mini slots (in our model of DOCSIS this value is set at 2048 to ensure the system is suitably responsive) and must be bounded by a limit of 240 IEs. The basic elements of the bandwidth allocation scheme are:

- Each CM has one or more Service IDentifications (SIDs), 14 bits, and a 48-bit address;
- Upstream bandwidth is divided into a stream of minislots, each one of which is numbered relative to a master reference maintained by the CMTS;

- CMs may issue requests to the CMTS for upstream bandwidth any time that either a request or a data PDU is allowed from a particular station.

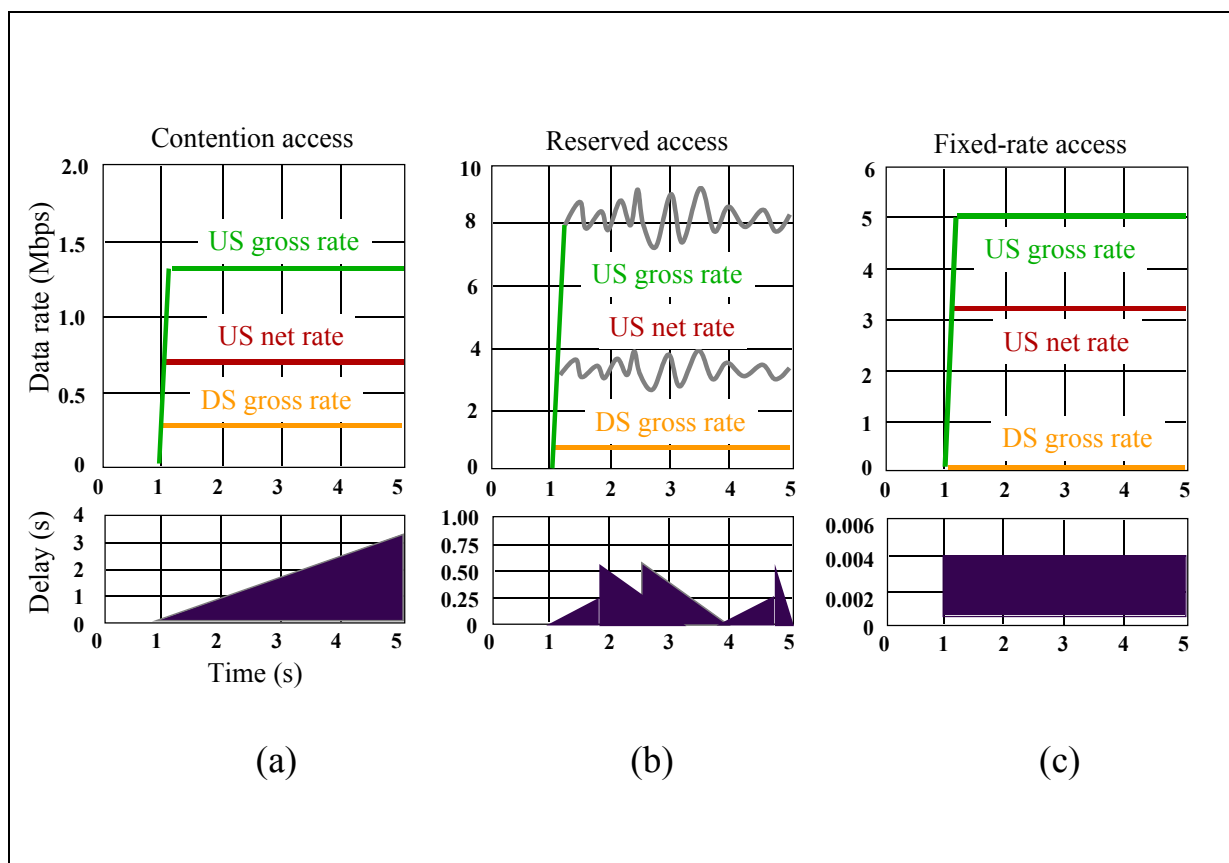
A CM, which has a packet to transmit, must wait until the contention slots, as defined in the last received MAP, arrive. The CM then attempts to request bandwidth by accessing one of the contention minislots. If more than one CM attempts to claim any one minislot then the slot information will be corrupted due to the contention. The CM only becomes aware if it has successfully requested bandwidth when the next MAP arrives. If the request was successful then the CMs SID will be identified along with the minislot number in which it can start transmission and the number of minislots assigned to it, otherwise the CM must repeat its request attempt using the next batch of contention minislots. At registration each CM declares its service priority and so in heavily used networks a low priority CM may have access to very little bandwidth.

Within the head-end there are two scheduling algorithms: the first is responsible for upstream access scheduling within the MAP and the second multiplexes the upstream channels onto the downstream. In both cases the scheduling algorithm attempts to provide the requested service access and when these exceed capacity to prioritise according to established service priority. Herein we are interested in the upstream scheduling algorithm as we assume single upstream and downstream channels with the downstream having the greater bandwidth. In DOCSIS 1.0 the QoS provision is limited to prioritisation and frame concatenation (optional). In DOCSIS 1.1 there is an extensive QoS definition which is derived from the Internet Protocol QoS [DOCSIS, 98]. Some work on DOCSIS scheduling algorithms has been published recently [Lin, 98], and this has focussed on comparisons between IEEE 802.14 and DOCSIS in terms of upstream contention resolution and the interaction with three upstream scheduling algorithms. For scheduling, this work found that under increasing heavy loads each request should be supported by multiple service bursts thereby increasing the likelihood of 'piggybacking' and so establishing an acceptable compromise between data transmission delay and request access delay.

## 6. Performance Characterisation

At the current time very little is known about the performance characteristics of the newly standardised DOCSIS and DVB/DAVIC cable modems. The DVB/DAVIC results reported herein are from work at the EuroCable Labs [Schunke, 98]: this analysis is based upon a discrete event simulation model of the DVB/DAVIC architecture. The model assumes:

- 50 active stations on the upstream channel and these are arbitrarily distributed between 5 and 30km from the head-end;
- The downstream channel data rate is 3Mbps and manages 8 upstream channels each of which have a data rate of 1.544Mbps;
- The transmission delay is 4ns/m.



**Figure 8** DVB/DAVIC constant bit rate performance characteristic.

The performance characteristics in Figure 8 show the variation of the upstream gross (inclusive of protocol overhead), upstream net (user) and downstream (protocol

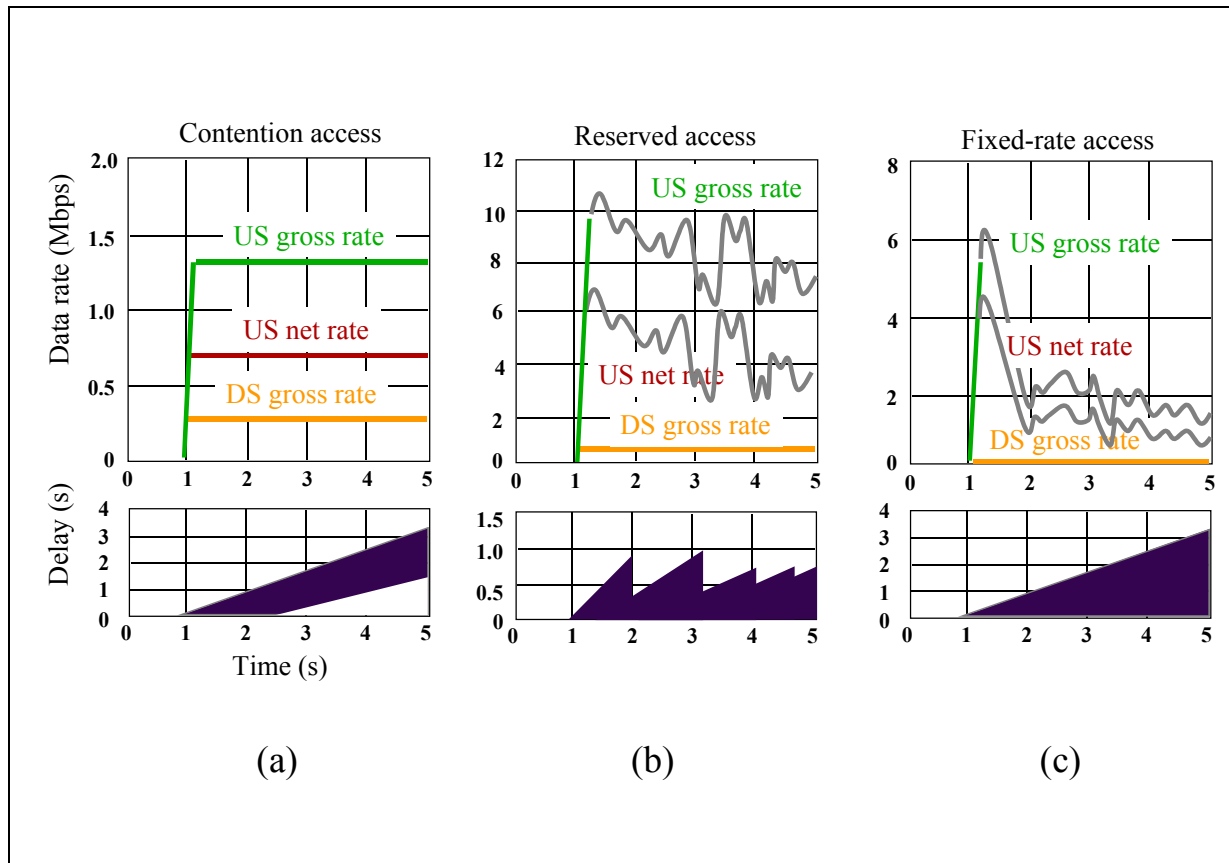
overhead only) data rates and upstream packet delay with system time. In Figure 8 the traffic sources are constant data rate of 64kbps for each station with a fixed packet size of 40bytes – typical of voice telephony. The three scenarios in Figure 8 are:

- (a) Contention access – here it can be seen that for each upstream channel the delay linearly increases with time, effectively blocking the network, and so it should not be used for constant bit rate services. The total net upstream throughput is 0.4Mbps. The system rapidly saturates;
- (b) Reserved access – here it can be seen that a total throughput of 3Mbps is transmitted for a full upstream load of 8Mbps (fully loading the downstream channel). The variations in the delay values are too large to support real-time applications and this mode should only be used for non-real time variable bit rate and similar services;
- (c) Fixed rate access – here it can be seen that a data rate of 3Mbps is supported (fully loading the downstream channel). The delays are bounded with a maximum of 0.004s. This access mode is ideal for constant bit rate services and real-time data transfer.

The performance characteristics in Figure 9 show the variation of the upstream gross (inclusive of protocol overhead), upstream net (user) and downstream (protocol overhead only) data rates and upstream packet delay with system time. In Figure 9 the traffic source are bursty with an average packet size of 1.6kbyte/s (an average on-time of 0.05s and off-time of 0.95s, exponentially distributed). The three scenarios in Figure 9 are:

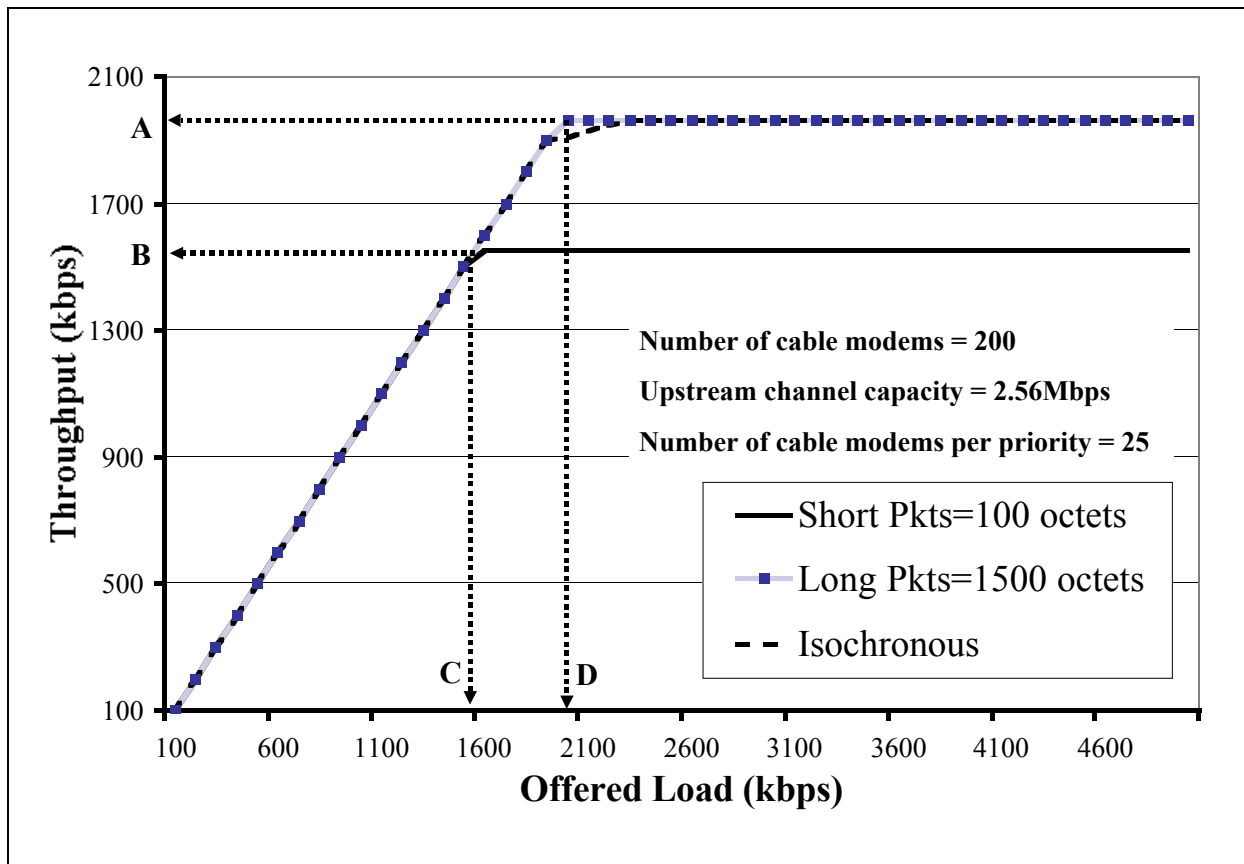
- (a) Contention access - once again this mode leads to excessive delays and 'blocking' of the network. Again a saturation data rate of 0.4Mbps is sustained;
- (b) Reserved access – A peak data rate of 6.4Mbps quickly subsides to a sustained rate of 3.2Mbps. Again the delay has a large variance but non-real-time variable data transfer can be sustained;

(c) Fixed-rate access – here the data rate is reduced to 0.4Mbps (see the contention access rate) and the delay increases linearly with time. This mode cannot be used with bursty source loads.



**Figure 9** DVB/DAVIC bursty data performance characteristic.

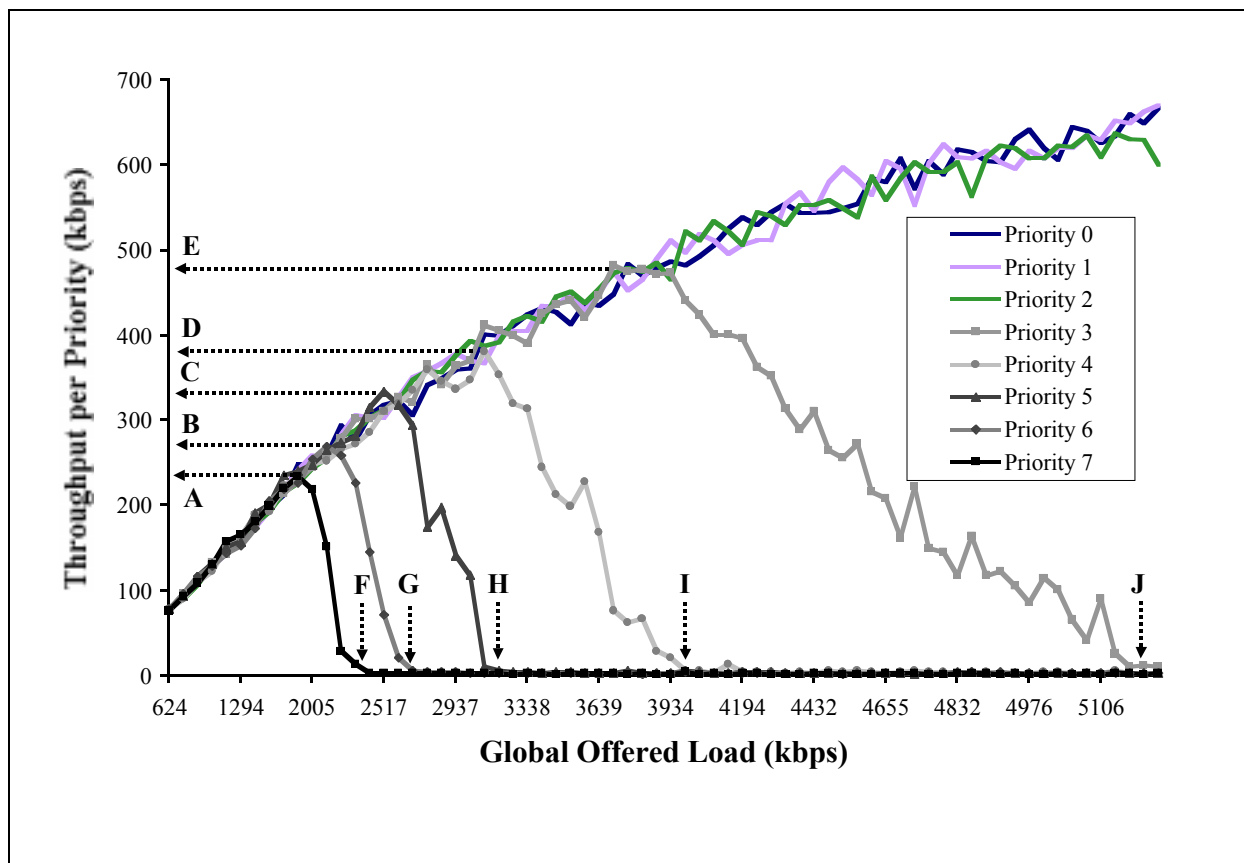
In the case of DOCSIS the results are taken from work in progress [Sdralia, 99] and [Tzerefos, 99]. The downstream capacity was set as 27Mbps and the upstream channel capacity as 2.56Mbps. The MAC protocol operates on a contention based reservation system with the head-end confirming, or otherwise, bandwidth allocation via a MAC management message (MAP). The cable modems are assigned a service priority (from 0-7) and so the service provision is determined with respect to this priority. This quality of service is provided by the scheduling algorithms implemented in the head-end (these are not defined within the DOCSIS standards) and for the simulations described herein a prioritised First Come First Served (p-FCFS) algorithm has been used.



**Figure 10** System throughput vs. offered load for varying packet size.

The simulation results, Figure 10, show that for an upstream channel capacity of 2560kbps with 200 cable modems, the maximum throughput (without concatenation) cannot exceed 1965kbps. For packet sizes of 1500 octets and variable length packet sizes the maximum capacity is 1965kbps even when the offered load exceeds the upstream channel capacity. For packet sizes of 100 octets the maximum upstream throughput is 1550kbps because the 200 cable modems are not capable of utilising the maximum MAP size. The difference between the maximum throughput and the channel capacity is caused by the MAC and Physical layer packet overheads, unused capacity and the multiple access scheme's MAP structure. In the case of the small packets, the lower throughput (1550kbps) could be improved by the use of concatenation which would enable a cable modem to request bandwidth for more than one packet at a time. The maximum access delay (defined as the time between the packet arriving at the cable modem's MAC and the head-end's MAC) is typically 12-900ms for an isochronous service with variable length packets and 2.5s when this offered load exceeds the system's throughput capacity. For on-off traffic sources the delay varies between 14-480ms for short length packets (100 octets) and 25-400ms

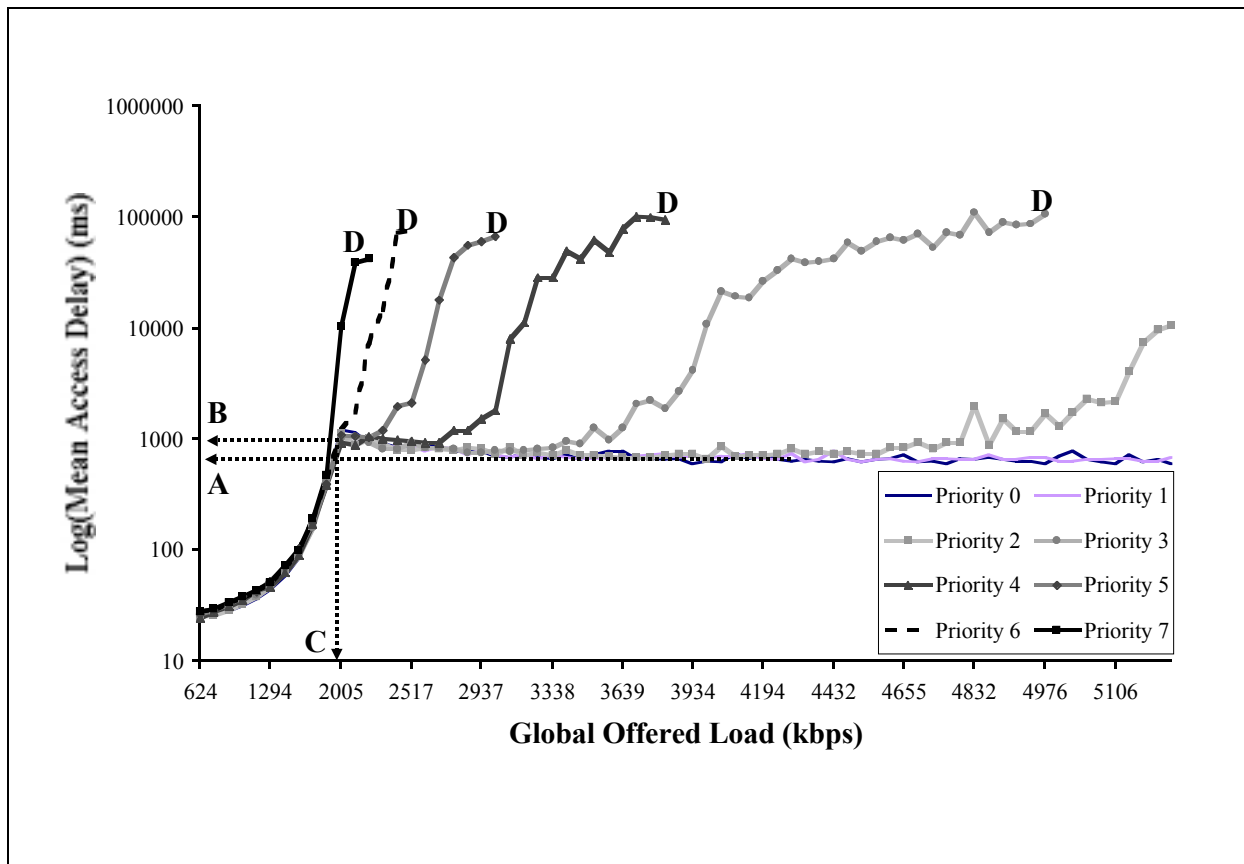
for long packets (1500 octets), as shown in Figures 11 and 12. At saturation (when the offered load exceeds the system's throughput capacity) the delays become 62s (short packets) and 700ms (long packets). The shorter long packet service is because the low priority services have been starved of service whereas in the short packet case all eight priorities are still obtaining a full service.



**Figure 11** Throughput per priority vs. global offered load (on-off traffic of length 1500 octets).

From a service perspective it is clear that an isochronous service e.g. voice over the internet protocol (VoIP), can only be supplied using proprietary committed information rate capabilities. In the case of variable rate services, 'bursty', the average length of packets has a major effect on the system throughput and mean access delay. Small packet sizes (typically 100 octets) result in reduced maximum throughput and very large mean access delays (tens of seconds); this delay could be reduced by using concatenation. Long packet sizes make more efficient usage of the bandwidth (cf. classical Ethernet performance capabilities) but under saturation the quality of service received by the end-user is heavily dependent upon the prioritisation mechanism.





**Figure 12** Mean access delay per priority vs. global offered load (on-off traffic of length 1500 octets).

## 7. Conclusion

The definition of a standard for multimedia applications over Hybrid Fibre Coaxial (HFC) networks is a challenging task due to the high bandwidth demand of such applications and their physical idiosyncracies (noisy upstream frequencies, tree and branch architecture etc.). The three predominant standards for cable modems are: the Data Over Cable Service Interface Specification (DOCSIS) for the USA, the DVB/DAVIC ETS300800 specification for Europe, and the IEEE 802.14 for its Advanced Physical layer specification. The DVB/DAVIC specification has three primary data transfer access modes: contention (as per the carrier sense multiple access with collision detection technique), reserved (demand allocation) and fixed-rate (constant bit rate assignment). Initial analysis of the performance characteristics of these services indicate that the fixed-rate access mode must be used for real-time and constant bit rate services whereas bursty loads must be supported using the reserved access mode. In DOCSIS the head-end scheduling algorithm is not defined within the standard but it is the key function for providing the required performance

capability. If a prioritised first-come-first-served scheduling algorithm is considered it can be shown, through simulation, that the maximum sustainable system throughput is 1965kbps for a channel capacity of 2560kbps and a packet size of 1500 octets, whereas for packet size of 100 octets the maximum sustainable throughput is only 1550kbps. The mean access delay is found to vary between 10-900ms depending on the offered load and assuming that the offered load does not exceed the capacity of the channel. Excess offered load causes service starvation according to the assigned priority.

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