IEEE COMMUNICATIONS SURVEYS
The Electronic Magazine of Original Peer-Reviewed Survey Articles

# AN INVESTIGATION INTO HFC MAC PROTOCOLS: MECHANISMS, IMPLEMENTATION, AND RESEARCH ISSUES

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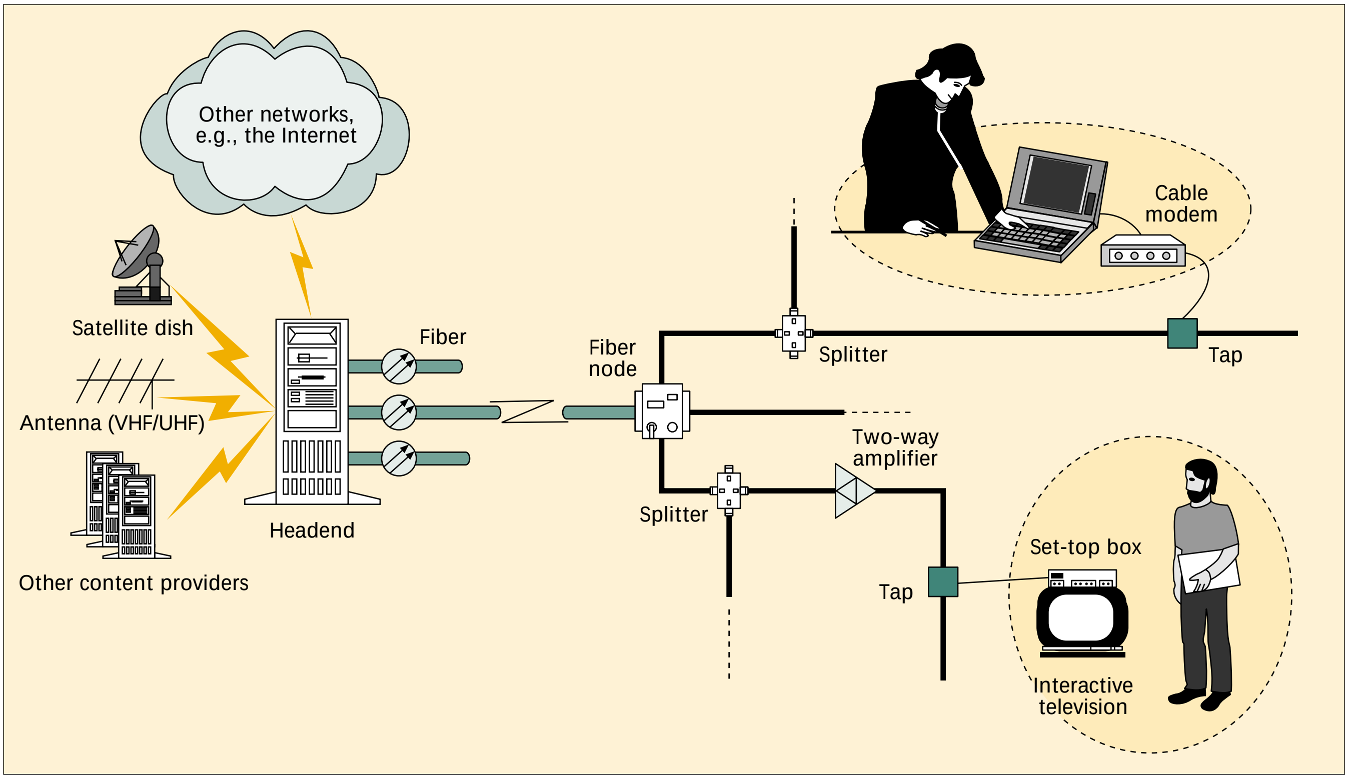
## ABSTRACT

This study comprehensively reviews two HFC MAC protocols: Data-Over-Cable Service Interface Specifications (DOCSIS) and IEEE 802.14a. DOCSIS was approved by the ITU as a standard and is supported by many vendors. However, IEEE 802.14a remains a draft due to the delayed standardization process. After briefly introducing the features of HFC networks, the basic operations and mechanisms of these two MAC protocols are then examined. Both standards view an upstream channel as a stream of minislots and have similar mechanisms for upstream bandwidth management, virtual queue, downstream in MPEG-2 format, data-link-layer security, and ranging. However, the standards adopt different mechanisms for upstream access modes, QoS support, and collision resolution. Moreover, the implementation issues over hardware and software design for DOCSIS networks are investigated. This work also identifies the research issues in HFC MAC protocols, particularly allocation and scheduling issues.

In a conventional cable TV (CATV) network, the service provider sends analog TV programs to subscribers via the cable network. Amplifiers must be installed in the cable network due to a fading signal. The amplifiers provide only one-way capability, accounting for the lack of an upstream channel in the CATV network. Adopted by many cable companies, HFC technology provides upstream channels in a coaxial cable distribution network. With the availability of upgraded amplifiers to support two-way amplification and fiber replacement for long distance transmission, subscribers are able to send data back to the service provider side. Figure 1 depicts an HFC system. A fiber node, capable of serving 500 to 2000 subscribers, receives signals sent from the headend via a fiber. These optical signals are then translated into electrical signals and sent to amplified tree-and-branch feeder cables. Subscribers can receive or transmit signals by connecting their coaxial stations, i.e., set-top boxes or cable modems, to the taps of the network. With multiple access technologies, all subscribers within a branch can share the upstream bandwidth to send data back to the headend. The HFC network possesses the following features [1, 2] that affect the MAC protocol design:

- Point-to-multipoint downstream and multipoint-to-point upstream. It is a point-to-multipoint, tree-and-branch access network in the downstream direction, but a multipoint-to-point bus-like access network in the upstream direction. Subject to collisions, the shared upstream channel needs an efficient scheme to avoid and resolve collisions.
- The inability to detect collisions by stations. Stations can only listen to the downstream traffic, which differs from an Ethernet where adaptors can detect when collisions occur. Thus, stations rely on the headend to notify them of the results of upstream transmissions.
- Large propagation delay. The maximum round-trip-delay (RTD) is significantly longer than that of Ethernet. Therefore, a channel should be utilized to transmit other data frames during the RTD of a transmitted data frame. In an Ethernet, however, no other data frames should be transmitted during the RTD of the data frame if it is to be successful. Furthermore, neutralizing the effect of propagation delay is of synchronization concern so that the transmissions from stations arrive at the right time slots assigned by the headend. Consequently, the MAC protocol should have a ranging scheme to measure the propagation delay for each station.
- Asymmetric upstream and downstream. The downstream data rate is substantially larger than that of the upstream. Thus, the efficiency of upstream channels is critical.
- Non-uniform user distribution. Most subscribers are distributed over the last few miles of the network. Their propagation times to the headend are quite close to each other. Repeated collisions may occur for a straightforward ranging algorithm that does not consider this factor.

This study focuses mainly on the MAC and transmission convergence (TC) layers of the HFC protocols. The rest of this article is organized as follows. Current HFC protocols are




■ **FIGURE 1.** *An HFC network.*

briefed. The basic mechanisms of DOCSIS and IEEE 802.14a are described in the physical and MAC layers. Major mechanisms among DOCSIS and IEEE 802.14a standards are identified and illustrated. Implementation and research issues are then examined and a summary is given.

## STANDARDS

Standardization is required to facilitate interoperability between stations and headends designed by different vendors. The are three major associations working on HFC networks: Multimedia Cable Network System (MCNS) Partners Ltd. [1, 3], the IEEE 802.14 Working Group [2, 4], and the European Cable Communication Association (ECCA) [5, 6]. Formed in May 1994 by several vendors, the IEEE 802.14 Working Group develops international standards for data communications over cables. Due to the delayed progress, four major cable operators, Comcast Cable Communications, Cox Communications, Tele-Communications Inc., and Time Warner Cable, established MCNS in December 1995 to create the DOCSIS standard. Considering the European cable environment, the ECCA started to create the EuroModem specification in December 1998.

DOCSIS v1.0 was approved as a standard by the ITU on March 19, 1998, and currently dominates the market. In addition, DOCSIS v1.1, whose major feature is supporting QoS service, was released on July 31, 1999. Also, Broadcom and Terayon are working with the MCNS to implement an IEEE 802.14-endorsed advanced PHY technology into the DOCSIS specification. The emerging standard will be known as DOCSIS 1.2. Currently the certification program is ready for DOCSIS v1.0-compliant products. In contrast, the IEEE 802.14 Working Group was disbanded in March 2000, and IEEE 802.14a will remain as a draft afterward. The group has careful intentions and its specification is undoubtedly better than that developed by MCNS from a technological perspective. However, timing is critical and if the group had one downfall, it was its inability to develop a specification in a short period of time. Moreover, the EuroModem v1.0 was approved by the European Telecommunications Standard Institute (ETSI) on May 12, 1999.

In addition to IEEE 802.14, MCNS, and ECCA, other standards associations working on topics related to cable networks include the Internet Engineering Task Force (IETF) IP over Cable Data Network Working Group [7], the ATM Forum Residential Broadband Working Group [8], the Society of Cable Telecommunications Engineers [9], and ITU.

## OVERVIEW OF DOCSIS AND IEEE 802.14A PROTOCOLS

Since the development of DOCSIS v1.0 followed the development of IEEE 802.14, it imitates good mechanisms from IEEE 802.14, including virtual queue, minislot, downstream MPEG-2 format, security module, piggybacking, synchronization procedure, and modulation schemes. However, to reduce implementation complexity, variable length frames and relatively simple collision resolution schemes are defined in DOCSIS v1.0. In order to support QoS, six scheduling services are included in DOCSIS v1.1. Also, segmentation and concatenation of IP traffic are specified to increase system throughput in this version. Figure 2 schematically depicts their protocol stacks. Both DOCSIS and IEEE 802.14a provide the capabilities to transport 802.2 logical link xontrol (LLC) protocol data units (PDUs) over HFC networks. IEEE 802.14a attempts to provide complete support of Asynchronous Transfer Mode (ATM), thus making the MAC-CS layer and the ATM layer necessary. The MAC-CS transforms data passing through the LLC SAP into ATM PDUs for transmission over the network. The general features of PHY, including TC and PMD, and MAC layers are described in the following subsections.

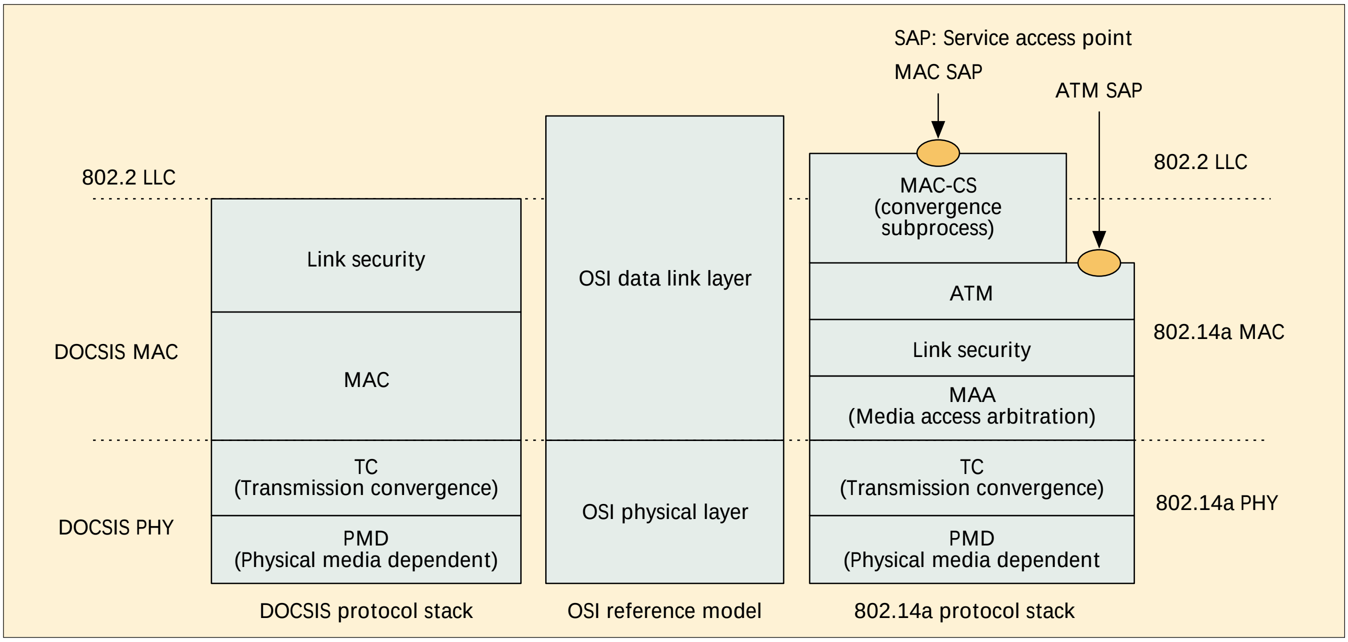



**FIGURE 2.** *Protocol stacks of DOCSIS and IEEE 802.14a.*

## PHYSICAL FEATURES

Both DOCSIS and IEEE 802.14a adopt a channelized approach, i.e., frequency division multiple access (FDMA), in downstream as well as upstream transmission. Each FDMA channel is further slotted by time division multiple access (TDMA). Table 1 summarizes key features of the PHY layer specifications of DOCSIS and IEEE 802.14a. The 810 MHz band, ranging from 50 MHz to 860 MHz, is divided into downstream channels by frequency division. Each channel, having a width of 6 MHz in the NTSC (National Television Systems Committee) system or a width of 8 MHz in the PAL (Phase Alternate Line) system, can be used to carry conventional analog broadcast video, digital video, telephony, or data services. The modulation schemes adopted on the downstream channels are 64 QAM and 256 QAM. In addition, frequencies ranging from 5 MHz to 42 MHz are divided into the upstream channels with smaller width to carry data, telephony, and video services. The modulation schemes adopted on the downstream channels are QPSK and 16 QAM. The TC sublayer provides a PMD interface for the MAC layer. To improve demodulation robustness and facilitate the multiplexing of video and data, both DOCSIS and IEEE 802.14a employ an MPEG-2 transport stream as the TC sublayer.

| | | | DOCSIS | IEEE 802.14a |
|---|---|---|---|---|
| TC sublayer | | | MPEG-2 | MPEG-2 |
| PMD sublayer | Downstream | RF range | 50/54~860 MHz | 88~860 MHz |
| | | Modulation | 64 and 256 QAM | 64 and 256 QAM |
| | | Channel width | 6 MHz | 6 or 8 MHz |
| | Upstream | RF range | 5~30 or 5~42 MHz | 5~42 MHz |
| | | Modulation | QPSK and 16 QAM | QPSK and 16 QAM |
| | | Symbol rate* | 160*M Kbaud M = 1, 2, 4, 8, 16 | 160*M Kbaud M = 1, 2, 4, 8, 16, 32 |

*:The minimum channel spacings is $(1 + \alpha) R_s$ where $\alpha$ is the spectral roll-off factor, and $R_s$ is the symbol rate.

**Table 1.** *Key features of DOCSIS's and IEEE 802.14a's physical layer specifications.*

## MAC MECHANISMS

We now investigate the MAC mechanisms from the initialization procedure of a startup station and the normal operation of an initialized station.

### *Initialization*

**1) Channel acquisition:** Upon initialization or after recovering from signal loss, a station should acquire a downstream channel by scanning the downstream frequency band until its receiver identifies a valid downstream signal. After achieving physical-level synchronization, the station can learn the characteristics of the upstream channel from the specific management messages broadcast by the headend. Thus, the station tunes its transmitter to the upstream frequency band specified in the messages. Furthermore, when determining that the channel is overcrowded, the headend may ask some stations to switch to another channel.

**2) Ranging:** Owing to the large propagation delay in the HFC network, each station must learn its distance from the headend and compensate for this distance such that the station and the headend have a consistent system-wide view of time to synchronize their MAC operations. This process is referred to as ranging. Later, we further describe the ranging process.

**3) Operational parameters download:** After performing the ranging process, a station downloads operational parameters from the headend. These operational parameters include IP address, security information, channel configuration, class of service configuration, SNMP MIB object, etc.

**4) Registration with the headend:** In DOCSIS, a station sends a registration request, which contains the operational parameters, to the headend. The headend then performs the following functions:
- Confirms the validity of the operational parameters.
- Builds a profile for the station.
- Assigns a service ID (SID), as discussed later.
- Sends back a registration response to the station.

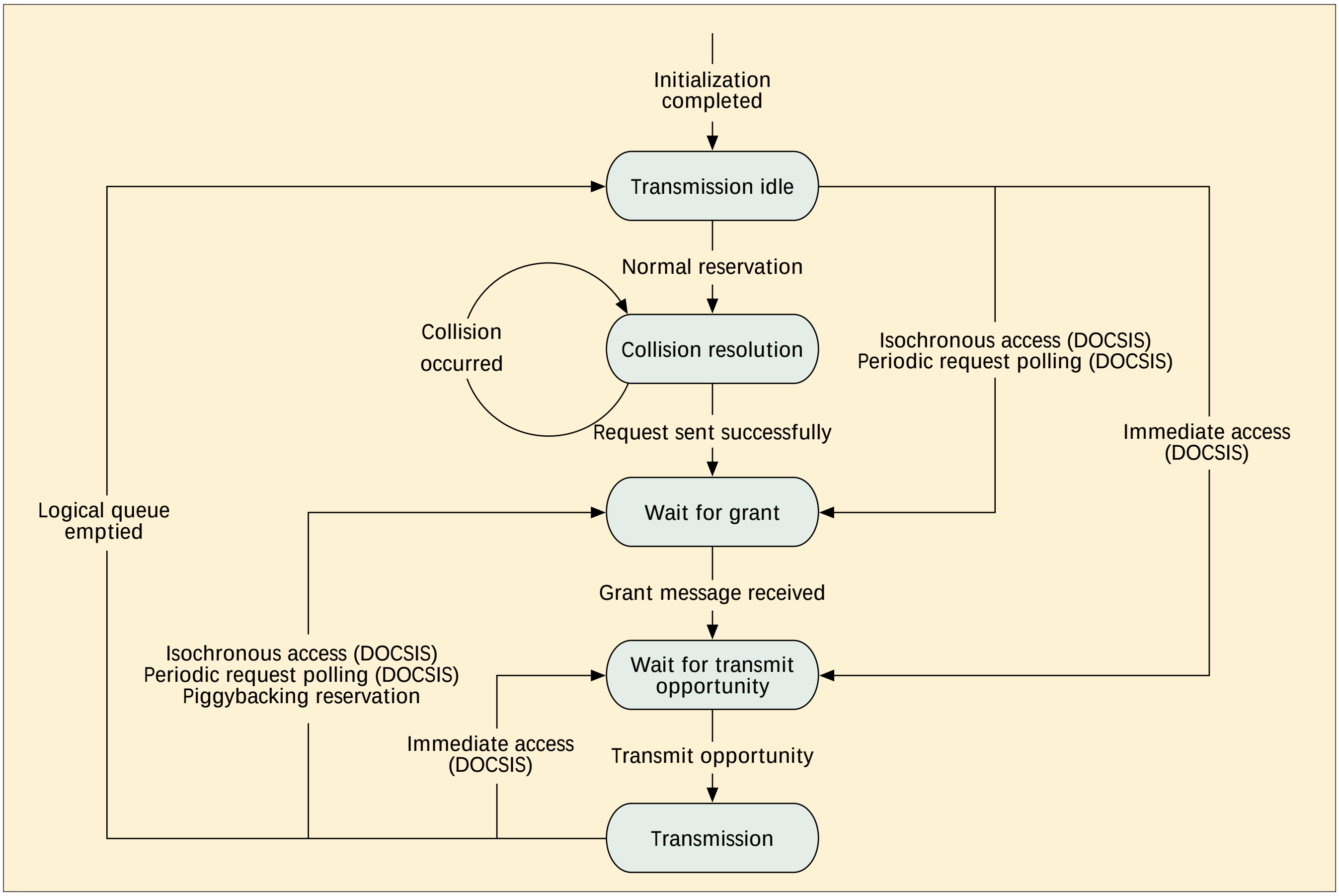



**FIGURE 3.** *The operation state diagram of initialized DOCSIS and IEEE 802.14a stations.*

In IEEE 802.14a, once a newly arriving station is properly ranged and power is leveled, the headend sends to the station an "assign parameter" message containing a primary local ID (LID), as discussed later, a bandwidth management LID, and an initial security exchange. The station then registers by replying to the "assign parameter" message.

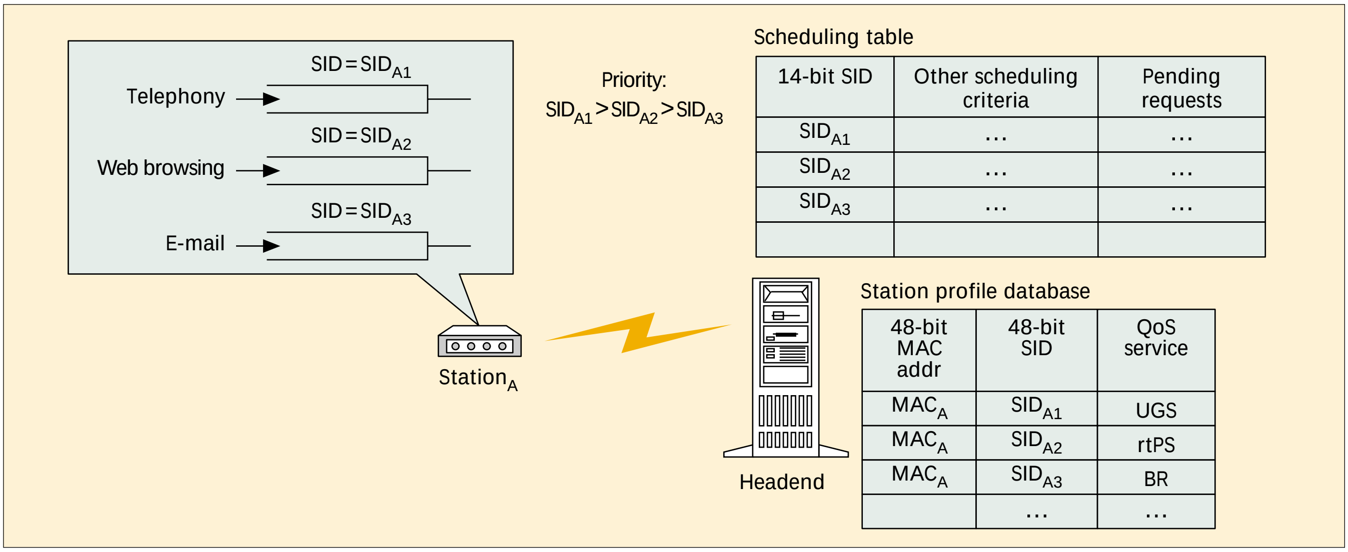
After these initialization steps, the station enters normal operation.

***Normal Operation*** — Both DOCSIS and IEEE 802.14a model an upstream channel as a stream of minislots. The headend must coordinate accesses to this shared bandwidth since stations cannot listen to the upstream channel. The headend assigns the usage of upstream bandwidth and describes the assignment in the *bandwidth allocation map*. Once the map is sent over the downstream channel, stations can learn the assignment from the map and proceed accordingly. Basically, some of the upstream minislots are assigned as *request minislots*, each of which can accommodate a request packet data unit (PDU). The other minislots are *data minislots* where a data PDU may occupy multiple contiguous minislots. To reduce bandwidth waste due to collisions, stations first send small request PDUs, which are subject to collisions, to the headend. The headend then schedules the requests and informs stations, through downstream channels, so that their upstream data PDUs can be sent collision-free. A specific field in the header of upstream data PDUs is reserved to request piggybacking. Therefore, stations may send requests for bandwidth, bypassing the contention process. Consequently, the access delay can be reduced if most of the requests are piggybacked instead of contending for request minislots. Moreover, this mechanism decreases the required number of request minislots. Figure 3 presents the state diagram of the normal operation for both the DOCSIS and IEEE 802.14a stations.

In addition to the normal reservation and piggybacking reservation modes, DOCSIS also provides isochronous access, periodic request polling, and immediate access modes, as depicted in Fig. 3. A flow with constant bit traffic rate may periodically get data transmission opportunities via the isochronous access mode, while a flow with variable bit traffic rate could request bandwidth on-demand through the periodic request polling mode. Once a DOCSIS station has short data that occupies few minislots, the station may even bypass the request process and burst its data directly in the *immediate access* region, if allocated by the headend when the traffic load is not heavy.

## MECHANISMS

DOCSIS and IEEE 802.14a have many similarities, as shown in Table 2. Both DOCSIS and IEEE 802.14a provide data-link-layer security, i.e., downstream and upstream traffic are encrypted. Downstream traffic is carried in MPEG-2 transport streams. An upstream channel is modeled as a stream of minislots, each of which can be assigned through the *bandwidth allocation map* by the headend as a *request minislot* or *data minislot*. A bandwidth request is associated with a *virtual queue* which accommodates a flow in a station and is an elementary entity in the MAC protocol. Moreover, synchronization between the stations and the headend and power-level adjustment are achieved via the *ranging process*. We describe and compare these common features in the following paragraphs.




■ **FIGURE 4.** *Scheduling and SIDs in DOCSIS.*

### UPSTREAM AS A STREAM OF MINISLOTS

Both DOCSIS and IEEE 802.14a view an upstream channel as a stream of minislots. A minislot is the unit of granularity for upstream transmission opportunity. With the minislot mechanism, the upstream transmission efficiency is increased since the right size of transmission opportunity is allocated to a specific request, and the bandwidth allocation is thus more flexible. In DOCSIS, the size of the minislot depends on the adopted modulation scheme and must be a multiple of 6.25 microsecond. In IEEE 802.14a, the duration of a minislot which is designed to carry a request PDU is equal to the time required to transmit 6 bytes of data and other overhead,

| | DOCSIS | IEEE 802.14a |
|---|---|---|
| Upstream as a stream of minislots | Minislot size depends on the modulation scheme. | Minislot size = time of transmitting 6 bytes and other overhead. |
| Piggybacking | Stations can piggyback extra bandwidth requests when they transmit data in the data minislots. | |
| Upstream bandwidth management | The minislot usage assignment is described in the allocation map, composed of several kinds of information elements. | The minislot usage assignment is described in the bandwidth management cells, composed of several kinds of information elements. |
| | The information element is used to describe the usage of some contiguous upstream minislots. | |
| Virtual queue | Each SID of a station maps to a virtual queue. | Each (LID, LQ) of a station maps to a virtual queue. |
| Downstream MPEG-2 format | MPEG-2 PID = 0x1FFE. | MPEG-2 PID = 0x01FFD. |
| Data-link security | Encryption: DES CBC mode.<br>Key management protocol: RSA public key system. | Encryption: DES CBC mode.<br>Key management protocol: Dellfie-Hellman algorithm. |
| Ranging | Ranging request + ranging response.<br>Collision resolution: binary exponential backoff + backoff window. | Ranging invitation + ranging response + ranging feedback.<br>Collision resolution: p-persistent algorithm. |
| Transport mechanisms | Variable length frames<br>Segmentation<br>Concatenation | ATM adaptation layer |
| Access modes | Normal reservation<br>Piggybacking reservation<br>Isochronous access<br>Periodic request polling<br>Immediate access | Normal reservation<br>Piggybacking reservation |
| QoS support | UGS, UGS-AD, rtPS, nrtPS, BE, CIR | CBR, VBR, ABR, UBR |
| Collision resolution algorithms | Binary exponential backoff + backoff window<br>Non-blocking mode | First transmission rule: priority + FIFO<br>Retransmission rule: n-ary tree<br>Multiple collision resolution engines<br>Blocking mode |

■ **Table 2.** *Similarities between the MAC layers of DOCSIS and IEEE 802.14a.*

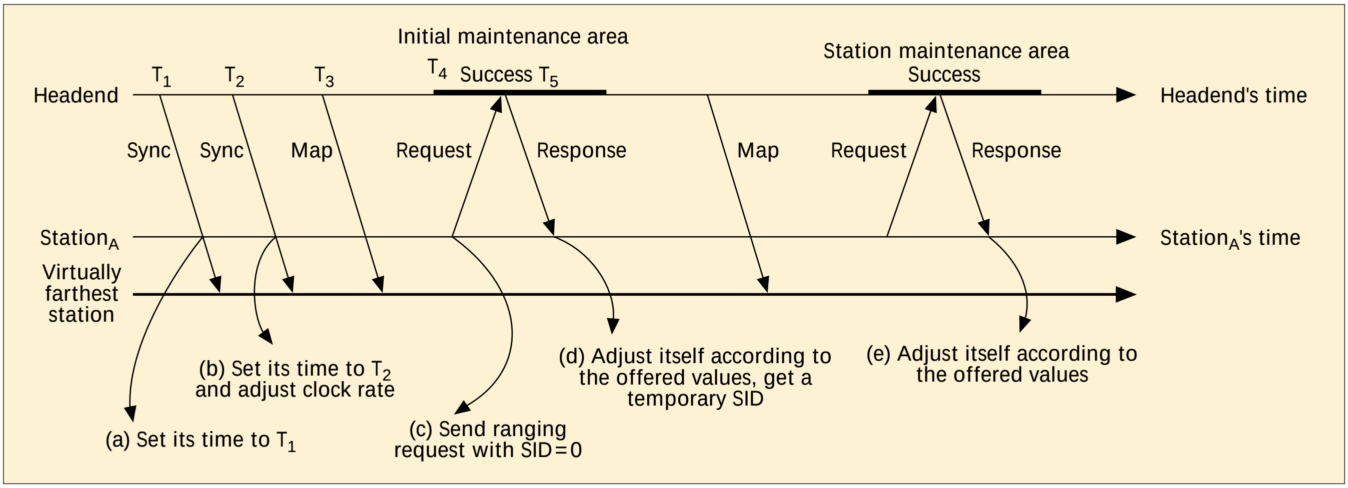



**FIGURE 5.** *The DOCSIS ranging process.*

including the physical layer header and the guard time. Each minislot has an integer identifier, called the *minislot number*, which is assigned by the headend. When the minislot number counts its maximum value, it wraps back to zero. Stations and the headend should be able to recognize the minislot number. Notably, concatenated multiple minislots can be used to transmit a data PDU.

### UPSTREAM BANDWIDTH MANAGEMENT

Upstream bandwidth management is achieved by broadcasting, multicasting, or unicasting the *bandwidth allocation map*, which is called the allocation map in DOCSIS and the downstream bandwidth management cell in IEEE 802.14a. The bandwidth allocation map consists of several kinds of *information elements* (IE). Each IE is used to describe the usage of some *contiguous* upstream minislots. This mechanism is intuitively-designed based on the feature that the downstream is a one-to-many broadcast media. Also, encapsulating the scheduling results into a bandwidth management message and broadcasting it to all stations simplifies the implementation complexity of the headend and enables the headend to better control the upstream transmission.

### VIRTUAL QUEUE

In addition to a globally unique 48-bit MAC address, a station would be assigned one or more identifiers by the headend during the registration process. The identifier, which is called the 14-bit SID in DOCSIS and the 14-bit LID plus 6-bit local queue (LQ) in IEEE 802.14a, refers to the virtual queue for a flow in a station. Furthermore, the identifier is used for QoS management. A virtual queue is an elementary entity that participates in the MAC protocol. Hence, a registered station maintains a separate state machine, as illustrated in Fig. 3, for each of its virtual queues. Therefore, when performing scheduling or collision resolution, the headend considers each virtual queue instead of each station. In DOCSIS, we can imagine that each SID of a station maps to a *virtual queue* inside the station. In Fig. 4, $station_A$ is assigned three SIDs, each corresponding to a virtual queue and a QoS service.

### DOWNSTREAM MPEG-2 FORMAT

To improve the robustness of demodulation, facilitate common hardware for both video and data, and provide an opportunity for the possible future support of other types of traffic over HFC networks, both DOCSIS and IEEE 802.14a adopt the MPEG-2 [10] technology to multiplex the downstream traffic. The headend encapsulates PDUs into MPEG-2 transport stream (TS) packets to form an MPEG-2 transport stream. Multiple TSs could be multiplexed into a single TS and then be transmitted over the HFC network to residential stations. Each type of MPEG-2 stream has a unique MPEG-2 stream program ID (PID). Once received by stations, an MPEG-2 stream is demultiplexed by the TC sublayer and passed to the corresponding upper layer.

### DATA-LINK-LAYER SECURITY

Both DOCSIS and IEEE 802.14a provide data-link-layer security. In the DOCSIS standard, both upstream and downstream *user data* PDUs are encrypted by the Data Encryption Standard (DES) algorithm using cipher block chaining (CBC) mode [11]. However, the management messages are not encrypted to facilitate the normal operation of the MAC sublayer. The key management protocol is based on the RSA public key system [12]. In IEEE 802.14a, a security element (SE) in the headend secures communication between stations and the headend. All PDUs, except the idle PDUs, broadcast/multicast management messages, and broadcast user data, in both upstream and downstream, are encrypted by the DES algorithm using CBC mode. Details regarding the protocols and algorithms used in encryption, authentication, and key management can be found in the related specifications.

### RANGING

Ranging is an attempt to accurately measure the time offset from the headend to a specific station. Therefore, the synchronization between the headend and the station could be achieved by tuning the station's time according to the measured value. The design rationale is to perform multiple handshakes to conclude an acceptable value. Next, the ranging procedure is examined. The common steps of the ranging procedure for DOCSIS and IEEE 802.14a are listed below.

**1) Obtain the global timing reference:** Once empowered, a station should listen to the *sync* message sent periodically by the headend. The sync message contains a timestamp that records the time at which the headend transmits the message. Upon receiving a sync message, the station sets its local clock to the timestamp. When syncing multiple times, the station's clock rate can be synchronized to that of the headend. Notably, this process continues even after initialization.

**2) Identify the ranging area:** The headend also periodically broadcasts a *bandwidth allocation MAP*, in DOCSIS, and a

| Service | QoS parameters | Access modes | Applications |
|---|---|---|---|
| UGS | Unsolicited grant size<br>Nominal grant interval<br>Tolerated grant jitter | Isochronus access | Videoconference, video on demand |
| UGS-AD | Unsolicited grant size<br>Nominal grant interval<br>Tolerated grant jitter<br>Nominal polling interval<br>Tolerated polling jitter | Isochronous access<br>Periodic request polling | VoIP with silence suppression |
| rtPS | Nominal polling interval<br>Tolerated polling jitter | Periodic request polling<br>Piggybacking reservation | VoIP |
| nrtPS | Nominal polling interval<br>Minimum reserved traffic rate<br>Maximum sustained traffic rate<br>Traffic priority | Periodic request polling<br>Piggybacking reservation<br>Immediate access | High-bandwidth FTP |
| BE | Minimum reserved traffic rate<br>Maximum sustained traffic rate | Normal reservation<br>Piggybacking reservation<br>Immediate access | telnet, FTP, WWW |
| CIR | To be defined by vendors | To be defined by vendors | Depend on service defintion |

**Table 3.** *The six QoS services provided in DOCSIS.*

*ranging invitation*, in IEEE 802.14a, to invite all unranged stations to join the network. A station learns the ranging area from the starting minislot number and the ranging area length described in the message. Notably, the headend must allocate a ranging area sufficiently large to accommodate the longest propagation delay.

**3) Send the ranging message:** After finding the ranging area, a station can send its *ranging request*, in DOCSIS, and *ranging response*, in IEEE 802.14a, back to the headend in the ranging area. If the above ranging message, which is subject to collision, is successfully received, the headend would evaluate the timing offset and other miscellaneous parameters that the station should tune to. These adjustment parameters are then sent back to the station via the *ranging response*, in DOCSIS, and the *ranging feedback*, in IEEE 802.14a.

**4) Adjust according to the feedback message:** A station is roughly ranged after adjusting its parameters, including timing offset, power level, frequency offset, and center frequency, according to the offered values in the feedback message. The ranging process is repeated until the headend determines that no more adjustment is required.

Figure 5 illustrates the detailed ranging steps for DOCSIS. Basically, DOCSIS follows the above ranging steps except for some differences in message formats and operational mechanisms. The bandwidth allocation MAP in DOCSIS contains not only ranging area information but also other bandwidth allocation information. In addition, the ranging process is further divided into initial ranging and station ranging, as shown in Fig. 5. Initial ranging largely focuses on obtaining a temporary SID to facilitate further initialization operations, in which the station uses the station maintenance area to perform periodic ranging. Moreover, during the ranging process, a DOCSIS station adopts a binary exponential backoff algorithm as a collision resolution algorithm, whereas an IEEE 802.14a station exercises a p-persistent scheme to resolve collisions.

### Transport Mechanisms

DOCSIS supports variable length frames to reduce implementation complexity. In addition, segmentation and concatenation are included in DOCSIS v1.1. With these two mechanisms, the granted minislots could be fully utilized to carry a segmented packet or concatenated packets. Therefore, the upstream system throughput is increased. On the other hand, IEEE 802.14a provides complete ATM support. In particular, 802.1 MAC bridging over ATM is supported using the ATM Forum LAN emulation protocol. However, the intention of supporting ATM increases implementation complexity and cost.

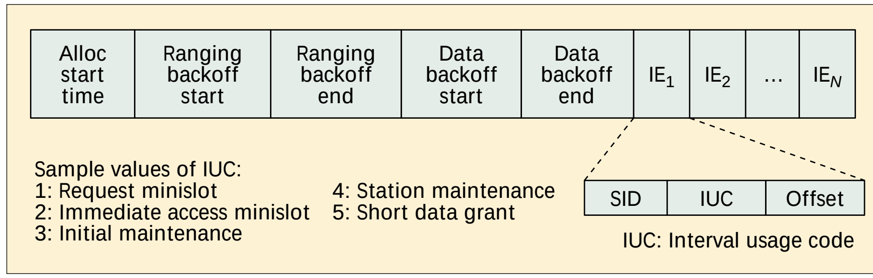
### Access Modes

IEEE 802.14a only supports the normal reservation and piggybacking reservation modes. However, in DOCSIS v1.1, the isochronous access, periodic request polling, and immediate access modes are also provided. The normal reservation mode prevents data transmission from excess collisions, and, the piggybacking reservation mode can reduce request access delays. Isochronous access is fulfilled by periodically allocating data transmission opportunities, whereas periodic request polling is fulfilled by periodically allocating request transmission opportunities. Both access modes are designed for QoS flows. Immediate access is triggered when bandwidth is still available after satisfying all bandwidth requirements, and this access mode is open to both data and request. If the load is light, this access mode could be utilized to reduce data and request access delays.

### QoS Support

To support QoS, DOCSIS defines six QoS services: unsolicited grant service (UGS); unsolicited grant service with activity detection (UGS-AD); real-time polling service (rtPS); non-real-time polling service (nrtPS); best effort (BE) service; and committed information rate (CIR) service. The QoS parameters, access modes, and applications for using these services are shown in Table 3. The headend must provide fixed size data grants at periodic intervals to the UGS flows. However, the reserved bandwidth may be wasted when a corresponding UGS flow is inactive. For the UGS-AD flows, the headend employs an activity detection algorithm to examine the flow state. Once a flow is changing from an active state to an inactive state, the headend reverts to provide periodic request polling. The rtPS and nrtPS flows are polled through the periodic request polling. However, the nrtPS flows receive few request polling opportunities during network congestion, while the rtPS flows are polled regardless of network load. For the BE service, a station must use normal reservation mode or immediate access mode to gain upstream bandwidth. A CIR service can be defined by vendors in a number of different ways. For example, it could be configured by using the nrtPS service with a reserved minimum traffic rate. To meet the QoS requirements, the headend must adopt an admission control mechanism and a scheduling algorithm among difference services to reduce QoS violation probability. Each QoS flow matches to exactly one QoS service. If a station has special bandwidth requirement not specified in the QoS service profile, it could dynamically request a service by sending a dynamic service addition request (DSA-REQ) message to the headend. Moreover, after a QoS flow is established, the payload header suppression (PHS) mechanism can be adopted to efficiently utilize the bandwidth by replacing the repetitive portion of the payload headers with a payload header index.

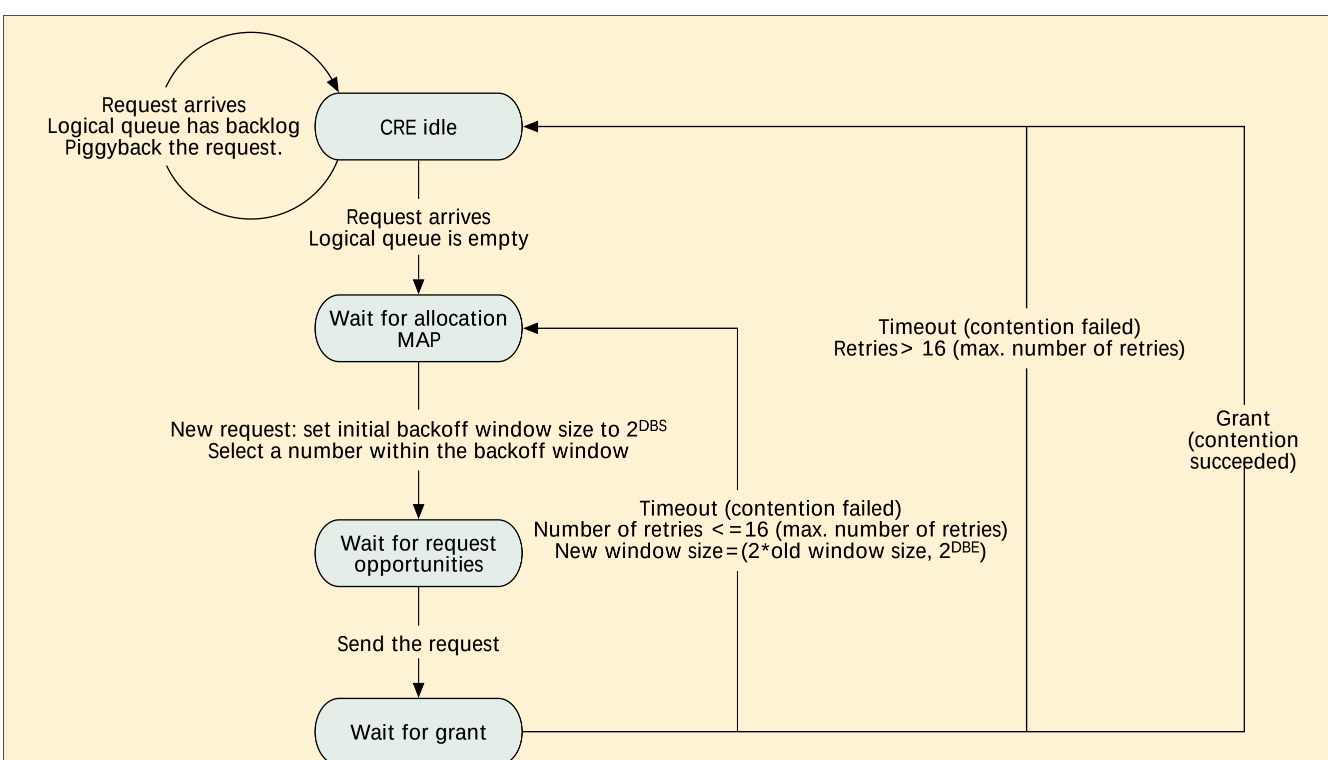
IEEE 802.14a provides QoS support at the ATM layer through MAA, as shown in Fig. 2. Having global knowledge of all stations, the MAA at the headend uses this information to schedule upstream transmissions such that the ATM layer of the HFC access network can meet the traffic contract for all virtual channel (VC) and virtual path (VP) connections. Specifically, at the time of connection setup, a CBR source signals its peak cell rate (PCR) and cell delay variation tolerance (CDTV) traffic descriptors across the HFC network to the MAA, and requests QoS parameters such as cell transfer delay (CTD) and cell delay variation (CDV) from the network. The MAA then reserves PCR amount of upstream slots for the source. Similarly, a VBR source signals its PCR, CDVT, sustainable cell rate (SCR), and maximum burst size (MBS). In contrast to a CBR source, the SCR specifies the upper bound of the average bit rate of the source and the MBS quantifies the burstiness of the source. The MAA uses these extra pieces of information to reserve less than PCR bandwidth in the upstream, while at the same time guaranteeing the QoS parameters. After allocating bandwidth to CBR and VBR sources, the remaining bandwidth is allocated to ABR sources. The MAA must support each ABR source at the least specified minimum cell rate (MCR). In addition, a feedback mechanism, EFCI marking or RM cell marking, and an explicit rate algorithm, should be implemented in the headend, and a rate-based control module should be included in the station.



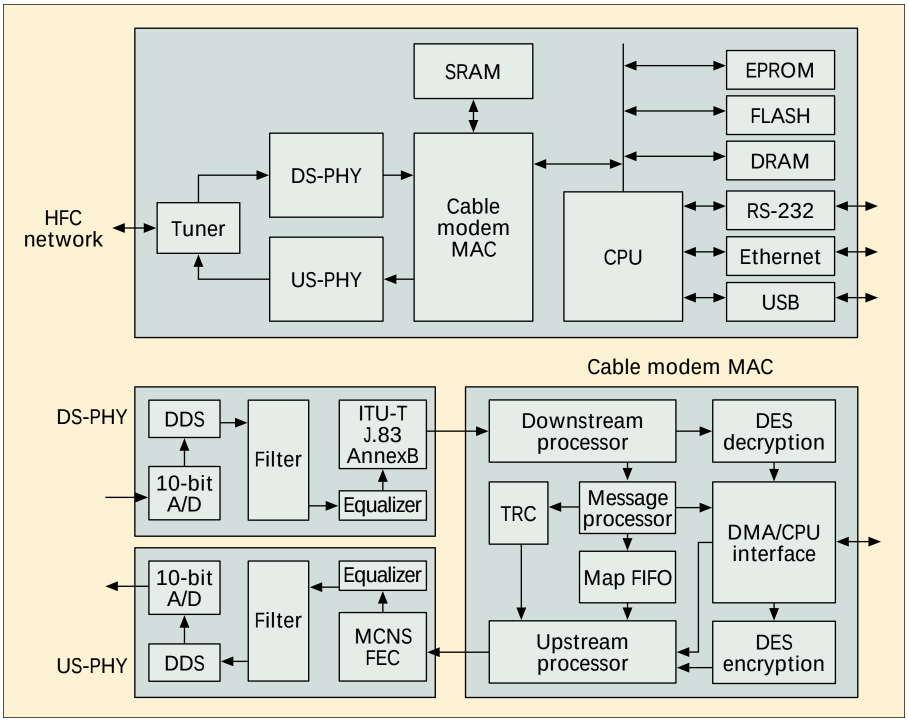

■ **FIGURE 6.** *DOCSIS bandwidth management PDU format.*

### COLLISION RESOLUTION ALGORITHMS

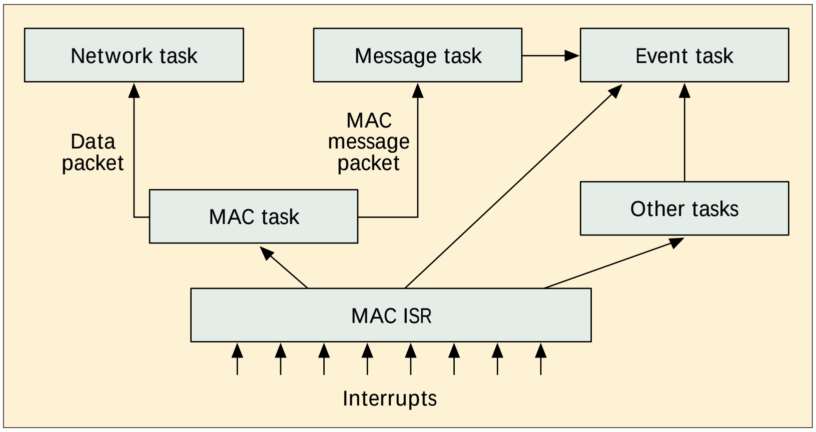
***DOCSIS: Binary Exponential Backoff*** — DOCSIS adopts a simple collision resolution algorithm, known as the Binary Exponential Backoff algorithm, to resolve collisions in the request minislot contention process. The format of a bandwidth-management PDU in DOCSIS is shown in Fig. 6. For detailed usage of header fields, readers are referred to the specification [1]. *Data backoff start* (DBS) and *data backoff end* (DBE) are used to indicate the initial and maximum backoff window size used in the algorithm. Figure 7 shows the state machine of a collision resolution engine (CRE) in a DOCSIS station. Consider a station whose initial backoff window can be any value from 0 to 15, i.e., $2^4 - 1$ given the DBS of 4, and it randomly selects the number 7. The station does not contend for any request minislot until it has deferred seven minislots. If the contention fails, the station increases its backoff windows size by a factor of two, i.e., 32 in this example, as long as it is less than the maximum backoff window size, i.e., $2^{DBE}$. Next, the station randomly selects a number within the new backoff window and repeats the deferring process described above. This retry process continues until the transmission is successful, or the number of collisions reaches 16, at which time the request is given up.




■ **FIGURE 7.** *The state machine of a CRE in a DOCSIS station.*




■ **FIGURE 8.** *The hardware architecture of the cable modem.*




■ **FIGURE 9.** *The core modules of the system operation.*

***IEEE 802.14a: A Combination Of Priority/FIFO Control, N-Ary Tree Walk, and Multiple Collision Resolution Engines*** — The collision resolution algorithm in IEEE 802.14a consists of two parts. The first part is the first transmission rule designed for newly arriving requests, while the second part is the retransmission rule designed for collided requests. A resolution queue (RQ) value identifies a minislot group so that requests colliding on a minislot can contend for the future minislot group with the specified RQ value. The headend divides request minislots into several groups, each of which has an RQ value, to keep track of the *n*-ary tree walk algorithm. A newly arriving request can only use the request minislots whose RQ value is zero. All requests arriving after the contention process has begun are *blocked* until all collisions are resolved and the next group of minislots with RQ value of zero appears. However, multiple *interleaved* CREs can help to shorten the blocking period. In fact, this algorithm is a combination of MLAP's START-3 algorithm [13, 14], ARAP's p-persistent-based algorithm [15], and XDQRAP's interleaving mechanism [16]. A 3-ary tree walk algorithm is proved to be good enough in terms of throughput [17]. However, a *n*-ary tree walk with dynamically assigned *n* is believed to be near optimal as long as *n* is chosen well. Some performance issues for contention resolution algorithms are studied in [18, 19].

## IMPLEMENTATION

As the cable access market evolves, implementation issues involving cable access devices are of interest. This study addresses hardware and software design issues on the cable modem side in DOCSIS networks.

### HARDWARE

Figure 8 schematically depicts the hardware architecture of a cable modem. The bottom portion details the components of PHY and MAC chips. The US-PHY and DS-PHY chips implement the modulator and demodulator, respectively. The MAC chip handles time-critical mechanisms, such as synchronization and bandwidth allocation MAP messages, and delivers other MAC messages to software modules. The synchronization message is then passed onto the timing recovery circuit (TRC) module, and the MAP message is passed onto the MAP FIFO for further handling. The downstream processor performs the MPEG header extraction, DOCSIS header extractor, header checksum, and CRC validation. The processor also passes the data packet to the DES description module. The upstream processor learns the upstream allocation information from the MAP message extracted from the MAP FIFO, and then conducts data and request transmission at the allocated time. Since the internal and external clock rates differ, asynchronous dual ports FIFO is adopted to buffer overflowed data. Also, the digital oscillator with loop filter is included to generate an internal clock.

### SOFTWARE

The cable modem software consists of three parts: cable modem initialization, system operation, and applications support. The first part tests all circuits, configures PHY and MAC chips, and completes the initialization process between the cable modem and the headend. The second part fulfills the normal operation and mechanisms described earlier. Moreover, the cable modem should support rich applications with QoS requirements. These three parts are examined in the following subsections.

***Cable Modem Initialization*** — When the cable modem is turned on, the bootstrap brings the code into RAM and transfers CPU control into the code. First, circuits including DMA, Ethernet interface, USB, VOIP line card, and LED are tested. The PHY and MAC chips are then configured by updating the control registers. When the hardware is ready, the

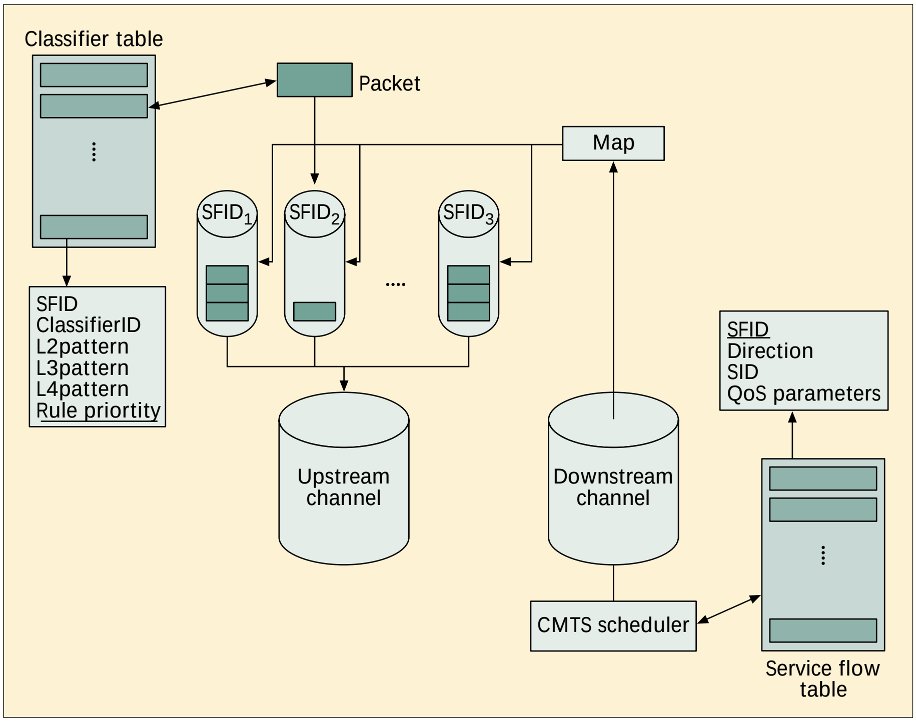



**FIGURE 10.** *The theory of QoS operation.*

initialization process described earlier is performed. Two implementation issues must be addressed: the values used to update the control registers of the PHY and MAC chips, and prevention of the downstream locality among cable modems. Importantly, uncontrolled downstream channel acquisition leads to an unbalanced downstream traffic load since a cable modem cannot change the downstream channel except for a signal loss or restart.

***System Operation*** — Following the initialization process, the cable modem should handle all MAC messages and mechanisms defined in the specifications. Figure 9 depicts the core modules of system operation. The interrupts to be handled are enabled at the cable modem initialization step, and the corresponding service routines are triggered by the interrupts. These interrupts include timers, receiving packets, and transmitting packet interrupts, and the MAC ISR determines which module will handle the corresponding interrupt. Designers must remain cautious of share data consistency since many flags and variables are processed simultaneously by various tasks. Therefore, critical sections should be carefully specified, and the corresponding mechanism to achieve mutual exclusion among tasks depends on which operating system is adopted by the cable modem. In addition, the task priority is critical to some mechanisms. For example, if a syncless interrupt is enabled, the cable modem should resynchronize with the headend and some flags and variables should be reset. Therefore, the MAC ISR should have the highest priority, and the priority of the event task is higher than that of the message task.

***Applications Support*** — To support rich applications, DOCSIS v1.1 defines six QoS scheduling services, as described later. By adopting these services and a packet classification mechanism, individual services can obtain individual bandwidth guarantees. Consequently, service differentiation could be achieved in DOCSIS v1.1 networks. The theory of QoS operation consists of two steps, as depicted in Fig. 10:

- Packet classification: When a data packet comes into a cable modem from the CPE, the cable modem classifies the packet based on certain fields in the layer 2, layer 3, and layer 4 headers. By learning the information in these fields, the cable modem identifies the type of packet. Based on the classification, the packet is matched to exactly one service flow, and queued for transmission. The rule priorities of the classifiers determine the matching sequence. If no classifier is found, then the packet is classified to the primary service flow. The granularity of classification significantly affects the scalability of service differentiation, thereby making classification policy management and enforcement essential.
- Packet transmission: Based on the QoS parameters of the service flows, the CMTS scheduler allocates bandwidth to individual service flows via bandwidth allocation MAP. The packet is then de-queued and transmitted at the appropriate time interval.

## RESEARCH ISSUES

Both DOCSIS and IEEE 802.14a were developed to facilitate the interoperability between stations and headends designed by different vendors. However, there are open and vendor-

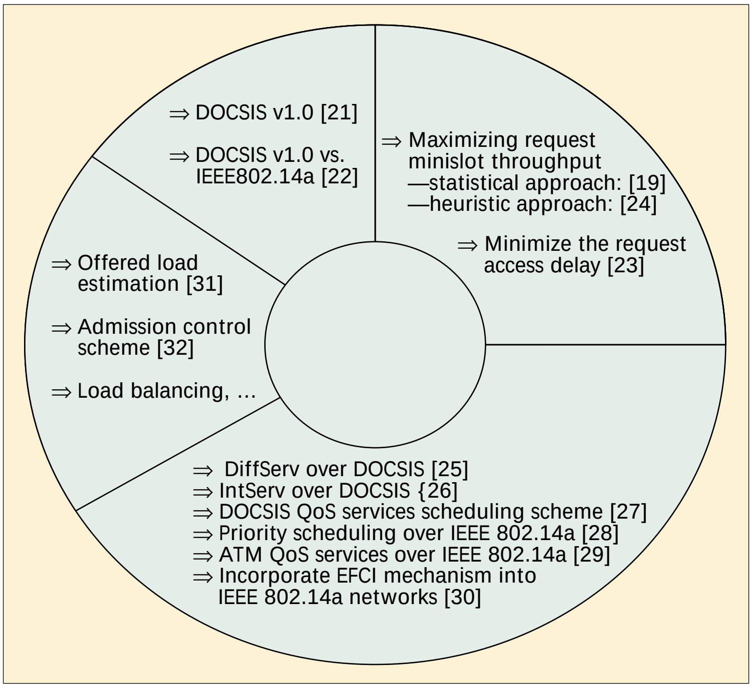



**FIGURE 11.** *The research issues over HFC MAC protocols.*

determined issues, such as request minislots allocation and data minislots scheduling algorithms, significantly influencing the performance of the HFC MAC protocol. We addressed these issues and provided some recommendations for implementation in [20]. In the following, we first investigate the performance behavior of both protocols. Then the above issues are formally stated and some notable researche sources are collected and examined. Figure 11 summaries the research roadmap in HFC MAC protocols.

***Performance Investigation*** — Sdralia *et al.* [21] simulated DOCSIS, using the Common Simulation Framework (CSF) 12 version of the CableLabs DOCSIS v1.0 computer model, to predict the upstream system throughput and mean access delay given the scheduling discipline is prioritized FIFO. The simulation results conclude that small packets result in reduced maximum throughput and large access delay; this decay could be reduced by using concatenation. In addition, Golmie *et al.* [22] compared DOCSIS v1.0 with IEEE 802.14a in terms of contention access, ATM vs. IP transfer, and adequate QoS provision. The *n*-ary tree-based collision resolution used in IEEE 802.14a gives lower access delay and delay variance than the binary exponential back-off used in the DOCSIS standard. IEEE 802.14a provides a friendly ATM environment and provides good support of QoS, while DOCSIS offers more efficient Internet access. However, DOCSIS v1.1 might provide better support of QoS.

***Allocating Request Minislots*** — After a station has a bandwidth requirement and adopts the normal reservation mode to access bandwidth, it randomly selects one of the request minislots allocated by the headend and sends its request on that minislot. The shared request minislot, however, is subject to collision. Therefore, for the headend the object of allocating request minislots is to allocate the right number of request minislots under various traffic loads such that the request minislot throughput could be maximized. However, the headend may allocate more request minislots to shorten the request contention process instead of increasing the request minislot throughput.

In [19] a statistically optimized minislot allocation (SOMA) algorithm is presented that maximizes the request minislot throughput by estimating the number of new requests with a time-proportional scheme and the number of collided requests by looking up a statistical most likelihood number of requests (MLR) table. The SOMA scheme drives the request minislot throughput to the optimal bound by accurately estimating the number of requests and allocating that number of minislots to resolve them. In addition, Sriram [23] presented a request minislot allocation algorithm to shorten the request contention process. The algorithm first estimates the number of requests based on the observed traffic load. Since the theoretical throughput of a request minislot is 0.368, they then try to allocate the number of request minislots three times as many as the number of requests in order to achieve 100 percent request throughput in the first contention. It indeed shortens the request contention process, but the request minislot utilization is low. Moreover, Twu and Chen [24] proposed a P-Tree algorithm that also uses the time proportional scheme to estimate the number of requests. However, the number of request minislots to be allocated is given from an efficiency function defining the ratio of the time spent in successfully sending requests to the time spent in processing the allocated request minislots.

***Scheduling Data Minislots*** — The headend schedules the data minislots to active flows such that each flow can perform collision-free transmission. In fact, the scheduling result highly affects the QoS of each flow. Therefore, the headend must schedule the data minislots to flows according to their QoS parameters. For DOCSIS networks, Golmie *et al.* [25] proposed a scheme that schedules data minislots according to the priority levels of the services to support DiffServ (Differentiated Service). The simulation result shows that the QoS of high priority services is guaranteed. In addition, Rabbat and Siu [26] presented an efficient scheduling algorithm to multiplex constant bit rate traffic and best effort traffic for supporting IntServ (Integrated Service). Alternatively, it can conduct polling dynamically to allow an idling flow to send a bandwidth request again, thus reducing delay in the request contention process. Simulation results show that the minimum bit rate and delay requirements of QoS flows are achieved. Although DOCSIS v1.1 defines six QoS services in the MAC layer, how to map DiffServ and IntServ to these services is worth discussing and the underlying scheduling algorithm for these six service flows needs investigating. We thereby propose a two-phase minislot scheduling algorithm designed to meet the QoS requirements as well as reduce the QoS violation rate [27] . For 802.14a networks, Corner *et al.* [28] presented a scheme that follows a priority order of flows to allocation data minislots. In addition, the fundamental problems and techniques to support ATM traffic classes, e.g., ABR, CBR, VBR, and UBR, in HFC networks were given in [29]. Moreover, Golmie *et al.* [30] presented a solution to resolve the performance degradation due to the delayed backward RM cells on the congested upstream channel when a EFCI control mechanism is employed.

In addition to the above issues, there is other research regarding the HFC MAC protocol. The traffic load is critical for the headend in allocating request minislots and scheduling data minislots. Hence, Abi-Nassif *et al.* [31] proposed load estimation schemes based on a single MAP frame, a window of MAP frames, and a window of weighted MAP frames. The weighted MAP frames estimation scheme outperforms the other two schemes and has an average estimation error of only 14 percent. Basically, measurement-based load estimation schemes perform better than other heuristic schemes. In addition, the admission control scheme for preventing the network from overloading and ensuring flow discrimination is necessary. Adjih *et al.* [32] presented a differentiated admission control scheme that adopts a complete sharing policy and an admissibility probability varying with time to perform flow admission. Simulation results indicates that the loss rate of premium services does not change significantly when the load becomes heavy.

## CONCLUSION

This study has thoroughly investigated two major HFC MAC protocols: DOCSIS and IEEE802.14a. First, the basic MAC operations, including how to register to join the cable network and how to request bandwidth, are illustrated. Major mechanisms among the DOCSIS and IEEE 802.14a are then examined. Despite the differences between these two MAC protocols, DOCSIS can be considered as a simplified version of IEEE 802.14a. It imitates the concepts of minislot, bandwidth allocation map, piggybacking reservation, virtual queue, downstream MPEG-2 format, and ranging in IEEE 802.14a. For collision resolution, in which they differ the most, IEEE 802.14a exercises a fairly sophisticated first transmission rule, which includes priority admission control and FIFO mechanisms, as well as a retransmission rule, which runs an *n*-ary tree walk algorithm. IEEE 802.14a also allows a headend to run multiple collision resolution engines in parallel. In contrast, DOCSIS uses a simple binary exponential backoff algorithm. For QoS support, DOCSIS adopts various access modes in implementing six QoS services, while IEEE 802.14a employees MAA to schedule flows with various ATM classes. Moreover, the implementation issues significantly effecting performance and scalability are also addressed. Finally, the research issues are addressed and the notable researches are collected and examined. We believe that performance improvement and optimization, in HFC MAC protocols, are worth investigating.

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