Project	**IEEE 802.16 Broadband Wireless Access Working Group**
Title	**802.16 BWA Air Interface Medium Access Control. Proposal for Standard**
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Source	Leonid Shousterman BreezeCOM Atidim Tech Park, Bldg. 1 Tel Aviv 61131, ISRAEL Voice: +972-3-6456274 Fax: +972-3-6456222 E-mail: leonids@breezecom.co.il
Re:	In response to Call for Proposals for the BWA MAC layer from Sep 22, 1999.
Abstract	A MAC which supports both synchronous and asynchronous traffic, QoS support and both FDD and TDD operational modes is presented.
Purpose	To present a proposal which will serve as a baseline of the BWA MAC layer.
Notice	
Release	
IEEE Patent Policy	

802.16 BWA Air Interface Medium Access Control proposal

Leonid Shousterman
BreezeCOM

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1 General

1.1 Introduction

The paper presents a proposal for 802.16 BWA Medium Access Control. The reference model, which fits the 802.16 system requirement model, including upper layers interface is given in section 3.2. The proposal envisages Traffic Convergence sublayer, which takes care of converting the various transport technologies like IP, ATM, PDH, SDH, etc. into a uniformed traffic format, thus allowing the lower sublayers be agnostic to the original traffic nature (see 3.4). The service is logical channel oriented, allowing logical channel establishment and QoS negotiations.

The proposed MAC allows, but not restricted to, fragmentation of data blocks into fragments and concatenation of several blocks into one body (see Table 3). Thus the granularity of bandwidth assignment is limited by fragment size, which might be fairly small (it can be a manageable parameter or it may even be different for different logical channels). On the other hand, MAC headers are allocated not for every fragment, but rather for group of fragments (blocks) (see Table 3 and Figure 4), which provides for efficient MAC overhead. Using these features the MAC scheduler can provide for efficient and fair bandwidth sharing among the subscribers.

The proposed MAC includes mechanisms to bound delay, by utilizing concept of Fixed Allocation Period (FAP) (see 3.6.3.1). The delays may be bounded with granularity of FAP size, which may be a manageable parameter and can be as small as a few milliseconds.

The proposed MAC doesn’t rely on expensive technology and doesn’t inflict restrictive requirement to other parts of the system so it can be easily implemented using existing technologies.

The proposed MAC protocol provides for great scalabilty of bandwidth allocation per logical channel and does not limit the number of logical channels but rather the aggregate demand of all logical channels.

The proposed MAC fits both TDD and FDD mode of operation (see 3.5.1), and provides for mechanisms to control and adjust the PHY parameters on both downlink and uplink.

The proposed MAC includes authentication (in IEEE 802.11 way) upon registration, thus providing for security of operations. Data encryption parameters might be set upon authentication.

1.2 Abbreviations and Acronyms

ARQ	Automatic Repeat Request
ATS	Atomic Time Slot
BER	Bit Error Rate
CD	Committed Delay (in milliseconds).
CD^{FAP}	Committed Delay (in FAPs)
CDR	Committed Data Rate
CDV	Committed Delay Variation (in milliseconds)
CDV^{FAP}	Committed Delay Variation (in FAPs)
CoS	Class of Service
CP	Contention Period
CRC	Cyclic Redundancy Check
DL	Down Link
DLC	Data Link Control
DLP	Down Link Period
EST	Elapsed Service Time
FAP	Fixed Allocation Period
FER	Frame Error Rate
FTP	File Transfer Protocol
IE	Information Element
LC	Logical Channel

LCC	Logical Channel Control
LCERQ	Logical Channel Establishment Request
MAC	Medium Access Control
OLRT	On Line Reservation Technique
PAT	Polling in Advance Technique
PDU	Protocol Data Unit
PHY	Physical Layer
QoS	Quality of Service
RgTS	Registration Time Slot
RRQ	Reservation Request
RSSI	Received Signal Strength Indication
RsTS	Reservation Time Slot
SF	Super Frame
SFH	Super Frame Header
TTS	Time to Serve
UL	Up Link
ULP	Up Link Period
VoIP	Voice (Video) over IP
WCC	Wireless Logical channel Control
WMAC	Wireless Medium Access Control
WPDU	Wireless Protocol Data Unit
WPHY	Wireless Physical Layer
WTC	Wireless Traffic Convergence
WWW	World Wide Web

2 Reference documents

[Ref1] P802.11D6.1. Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications. By The Editors of IEEE 802.11

[Ref2] Recommendation G.114. One Way Transmission Time. By ITU-T.

[Ref3] IEEE 802.16sc 99/28. Quality of Service (QoS) Classes for BWA. By Arun A. Arunachalam.

[Ref4] Gigabit Networking. By Craig Partridge.

***[Ref5]** Data Networks. By Dimitri Bertsekas and Robert Gallager.*

[Ref6] System Requirements Assuring That Point-to-Multipoint Broadband Wireless Access Networks Are Agnostic to User and Network Protocols. By Ray W. Sanders

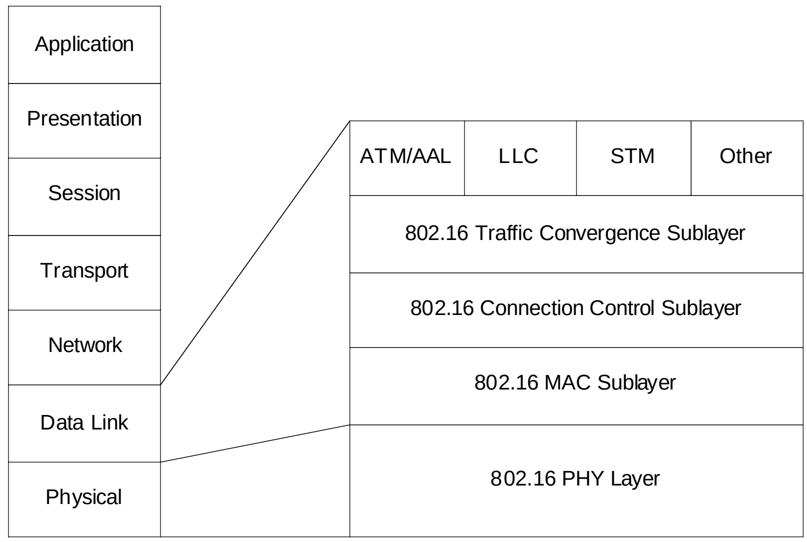
3 General MAC Concepts

3.1 Logical channel Oriented Service Concept

The service is logical Channel oriented. Each logical channel supports the QoS traffic contract which is negotiated upon logical channel establishment.

3.2 Protocol Layering Concept

Table 1 Protocol Layers



Sublayer	Description
Traffic Convergence	It is responsible for transforming various original traffic streams into a uniformed BWA Traffic Streams and vice versa. While different original traffic streams may be of quite different nature (E1, Ethernet, ATM, etc.), the resulting uniformed traffic streams will look alike and will be handled in similar ways. Thus the lower sublayers will be agnostic to the original traffic nature. If the original traffic is connection oriented (like ATM) then original connections will be translated into BWA logical channels. If it is connectionless then logical channels will be established according to the convergence rules.
Logical Channel Control	The layer provides for control of already established logical channels. It takes care of data integrity as well as of adaptation to environmental conditions (i.e rate, power control, time advance control, etc.).
MAC	Wireless Medium Access Layer. It is responsible for multiplexing the Logical channel Control demands into the WPDUs (see Table 3) and SFs and vice versa.
PHY	Wireless Physical Layer.

3.2.1 Class of Service

The MAC distinguishes between three main CoS. The QoS traffic contracts mentioned in the requirements document are mapped onto these CoS classes by the appropriate Convergence Layers.

Table 2 Class of Service and Traffic Contract Description

Class of Service	Description		
Committed Delay			
	Parameters		
	Parameter	***Mnemonic***	***Description***
	Minimum Burst Size	MBS	The minimum size in bytes of the bursts to be transmitted over either Up or Down Link.
	Committed Delay	CD	If logical channel is accepted the medium access delay on the specified direction will be kept in range of CD ± CDV.
	Committed Delay Variation	CDV	
	Tolerable Block Loss Rate	TBLR	The maximum tolerable block loss rate, which is to be calculated as $\frac{Discarded\_Blocks}{Transmitted\_Blocks}$. Those blocks that have been discarded are also counted as transmitted so the loss rate cannot exceed 100%
Committed Rate			
	Parameters		
	Parameter	***Mnemonic***	***Description***
	Committed Data Rate on Down Link	CDR-DL	If logical channel is granted, a stream of bursts of at least CDR Kbit/sec will be delivered, measured in an interval of 1 sec, in the specified direction.

	Committed Data Rate on Up Link	CDR-UL	
	Tolerable Block Loss Rate	TBLR	The maximum tolerable block loss rate, which is to be calculated as $\frac{Discarded\_Blocks}{Transmitted\_Blocks}$. Those blocks that have been discarded are also counted as transmitted so the loss rate cannot exceed 100%
Uncommitted QoS			
	Parameters – None		

3.2.2 Registration

Subscriber Station will scan the allowed range of frequencies, while passively listening in hope to receive a Super-Frame Header. Upon receiving a Super-Frame Header the Subscriber Station will issue a Registration Request packet during the Registration Period. The Base Station responds with registration response, which contains, among other things, the round-trip delay measurement. Afterwards the Subscriber Station and the Base Station execute the Authentication and Association Protocols, which ensures that the Subscriber Station is allowed being connected to the Base Station.

3.2.3 Re-Registration

If the Subscriber Station stops hearing the Super Frame Headers for a predefined duration of time it repeats the registration procedure.

3.2.4 Logical channel Admission

If the Subscriber Station wishes to establish a logical channel it may send a logical channel establishment request (LCERQ) to the Base Station as a separate frame during the Contention Period. The LCERQ contains the desired traffic contract. The Base Station may then accept the request or reject it. The LCERQ may be also piggybacked in the WPDU (using the signalling logical channel), which carries data of another logical channel.

3.3 Control Protocols Concept

A special Signalling Logical channel will be allocated to each Subscriber Station upon registration. This signalling logical channel will be dedicated to control protocols (see below) and LCERQ. This channel will be used for adapting the transmit power and data rate for each subscriber station.

3.4 Traffic Convergence Concept

3.4.1 Convergence of Streams into Logical channels

The original traffic streams are mapped onto logical channels (see Figure 1 below).

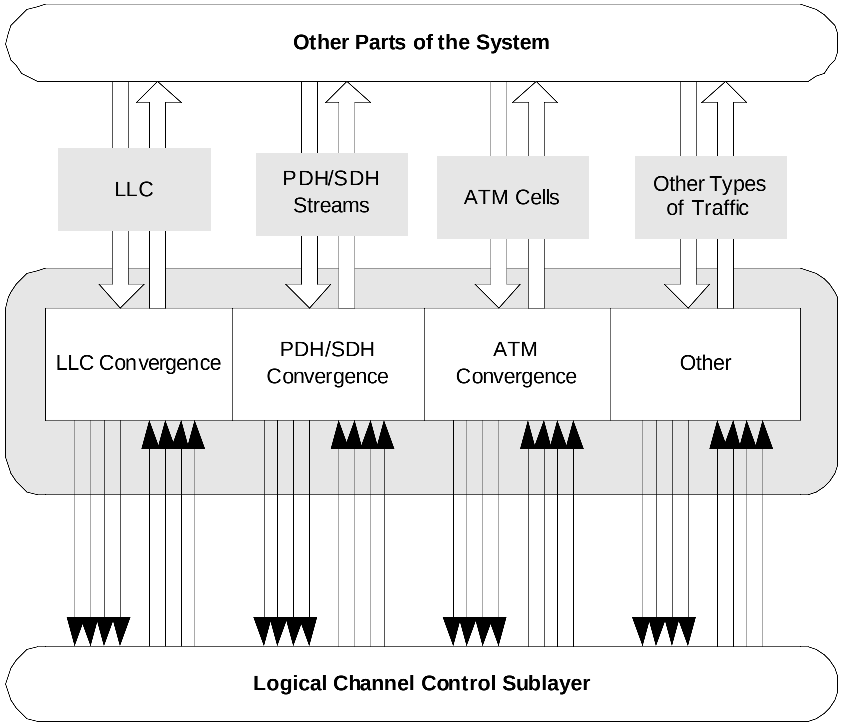


Figure 1 Convergence into Logical Channels

If the original traffic is connection oriented (like ATM), the original connections are translated into the 802.16 WBA logical channels. If the traffic is connectionless the logical channels might be established according to the convergence rules.

In general the original streams are converted into the per logical channel streams of blocks. Each block is divided into fragments. Each fragment is of equal length except for the last one in the block, which might be smaller). Convergence specific data is added to each block descriptor. The block descriptors will be transmitted to the peer convergence layer to allow correct reassembly of the original streams.

3.4.2 LLC Traffic Convergence

For IEEE 802.x LLC traffic the block descriptor contains only Block ID, number of fragments in the block and the length of the last fragment. The blocks are the original LAN frames. Fragment size is not a decisive issue. The mapping of the LAN traffic onto the logical channels might be according to 802.1q VLAN ID or according to IPv6 flow labels or other methods.

3.4.3 PDH and SDH Traffic Convergence

For E1 the block size is E1 multi-frame (2 milliseconds). Fragment size is not a decisive issue. Time stamp needs to be added to the block descriptor for source clock recovery at the receiver. On the receiving side, the packetized data shall be output at a constant pace, determined by the timestamps. The specifics of the incorporation of these timestamps into IEs is an issue for further study.

3.4.4 ATM Traffic Convergence

Fragment size should be chosen equal to the ATM cell size. The block represents the SAR-PDU of the corresponding AAL. VP/VC might be converted into logical channels.

3.5 Data Framing Concept

3.5.1 Super-Frame

Uplink and Downlink transmissions are organized into Super Frames (SF). Each SF begins with the Super Frame Header (SFH) which describes the structure of the following SF (see also Table 7).

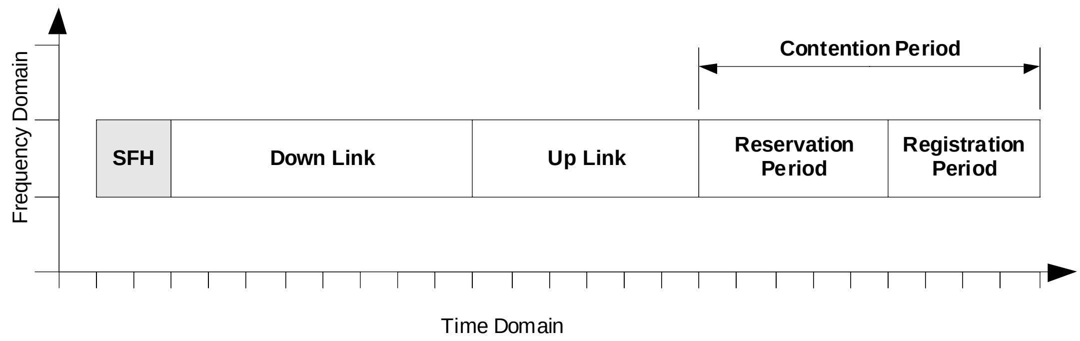


Figure 2 TDD Super-Frame Structure

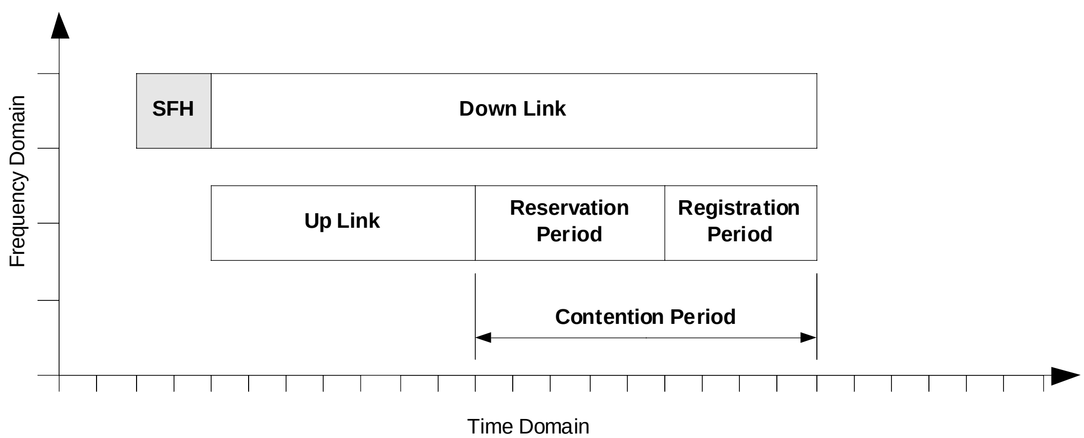
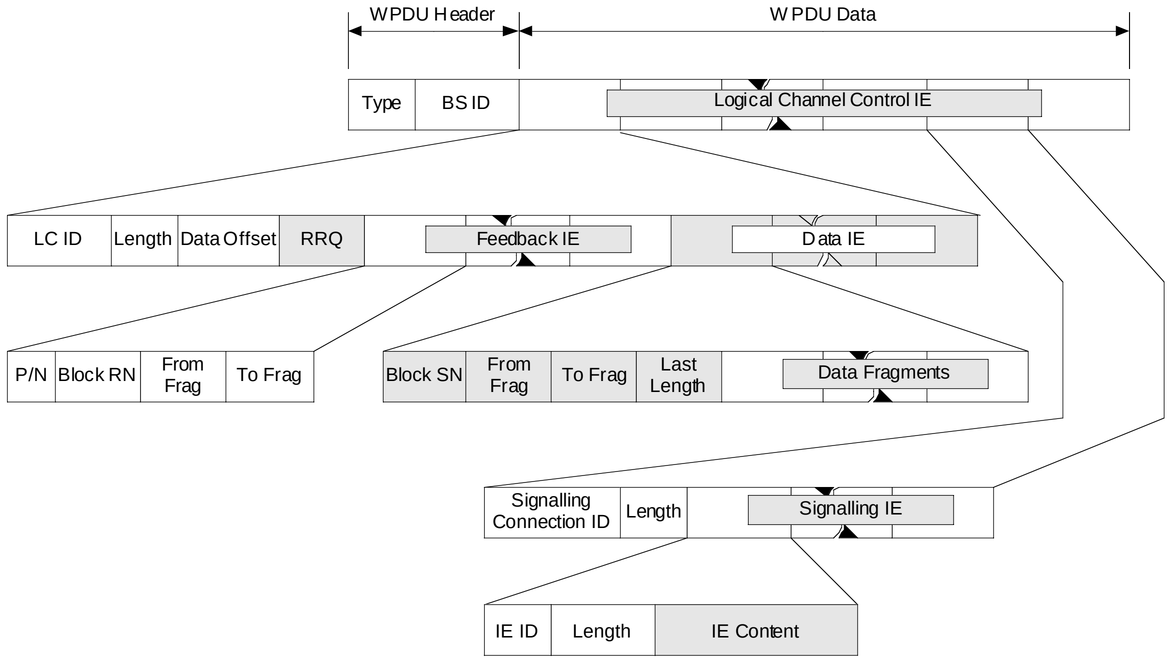


Figure 3 FDD Super-Frame Structure

3.5.2 Wireless Protocol Data Unit (WPDU)

The data is transmitted in information elements that are combined into the WPDUs. Each WPDU is submitted to PHY to be transmitted over wireless medium.

Table 3 WPDU Hierarchy (Data and Signalling IE)



Field	**Description**
Field	**Description**
Type	Type of the WPDU. Broadcast, Unicast, etc.
BS ID	Access Unit Identifier. It is 48-bit IEEE address.
WPDU Data	The data field might be of variable length and consist of Logical channel Control IEs. The format of the Logical channel Control IE is given below

Field	**Description**
Logical channel ID	A number which identifies a logical channel. In consists of a 48-bit IEEE address which identifies an SU and one byte channel ID.
LCC Length	Length in octets of the Logical channel Control IE
Data Offset	Offset in octets to the Data IE.
RRQ	Reservation Request. Present only in Up Link WPDUs.
Feedback IE	Contains the feedback (acknowledgments) for the received data blocks. Contains the fields outlined below

		Field	**Description**
		P/N	Positive/Negative Feedback
		Block RN	Block Received Number.
		From Frag	Starting from Fragment ID.
		To Frag	Ending with Fragment ID
	Data IE		
		Field	**Description**
		Block SN	Block Sequence Number
		From Frag	Starting from Fragment ID
		To Frag	Ending with Fragment ID
		Last Length	Last Fragment Length.
	Signalling Logical Channel ID	A number which identifies signalling logical channel. In consists of a 48-bit IEEE address which identifies an SU and one byte signalling channel ID.	
	Signalling LCC Length	Length in octets	
	Signalling IE	A structure to transfer the signalling information.	
		Field	**Description**
		IE ID	IE Identifier.
		IE Length	Length of the IE in octets.
		IE Content	Content of the IE

3.5.2.1 Error Control

The Error Control mechanism is not shown in the Table 3 and needs further study. The MAC envisages using of ARQ mechanisms of Data Integrity Control, but is not restricted to them. The location of CRC field is an issue for further study. It might be allocated per WPDU, per LCC IE, per Data Block or per fragment.

3.5.2.2 Down Link Broadcast WPDU

A special broadcast logical channels will be used for downlink broadcasting. No feedback IE shall be transmitted.

3.5.3 Data Integrity Control

Data Integrity Control is a common name for re-transmission control and duplication control. The Data Integrity control ensures that the data blocks arrive in sequence they have been sent, the duplicate blocks are filtered and there are no errors in block content. Block loss is allowed as long as it doesn't violate the QoS required.

3.5.3.1 Data IE building

The data is transmitted in Data Information Elements that are sub-elements of the Logical channel Control Information Elements. The Figure 4 below shows an example of the Data IE building.

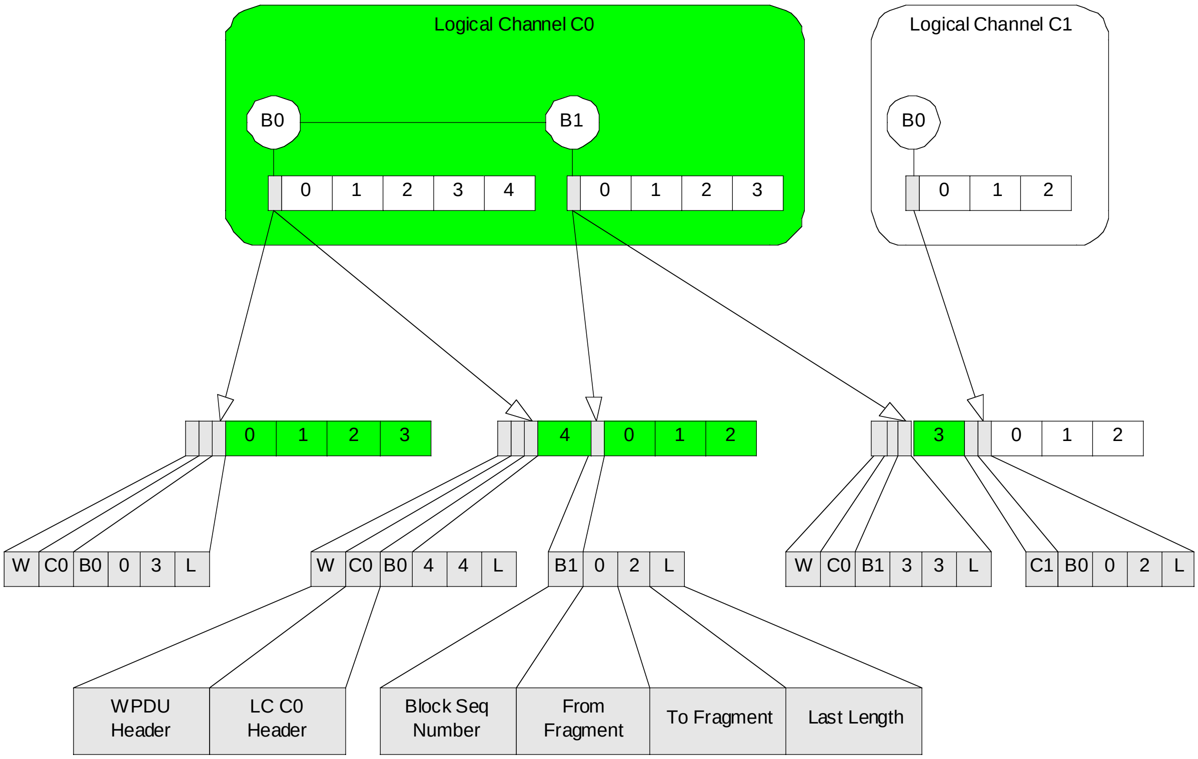


Figure 4 Example of Data Elements Building

Data fragments of the Logical channel C0 and Logical channel C1 are divided between 3 WPDUs. No feedback is added. Each WPDU contains 4 Data Fragments. See Table 3 above for reference.

3.5.3.2 Feedback IE building

The Figure 5 below shows building a single WPDU that carries a single LCC IE with Data IE and Feedback IE. The feedback is positive and reports the fragments that have been received. Only the fragments that have not been acknowledged yet are sent with the Data IE.

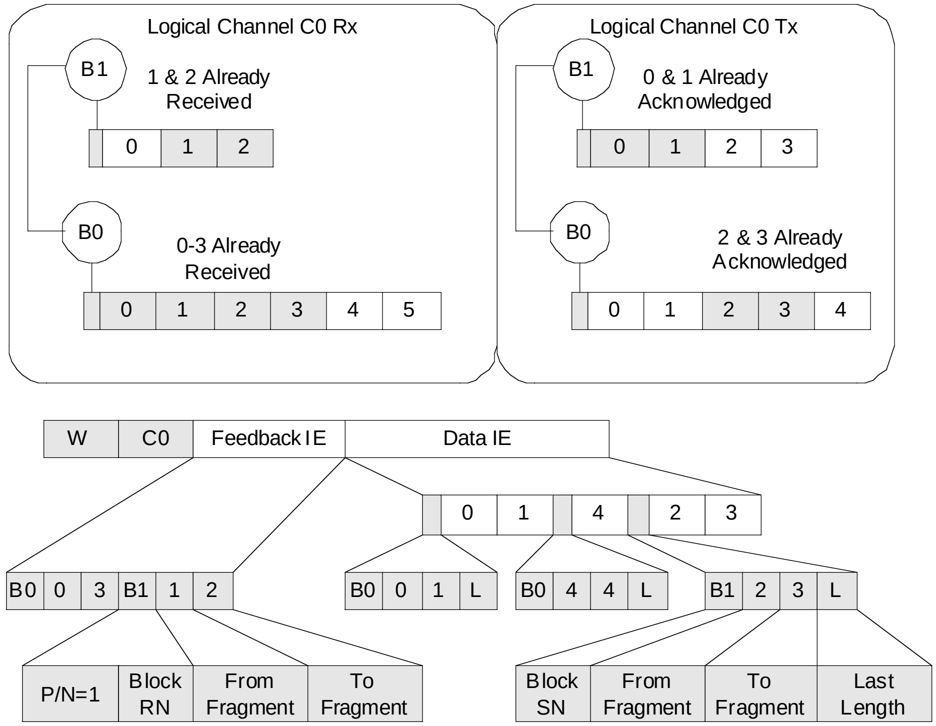


Figure 5 Example of Data Element and Positive Feedback Building

The Figure 6 below shows the same situation but the feedback is negative and reports the fragments that are yet to be received.

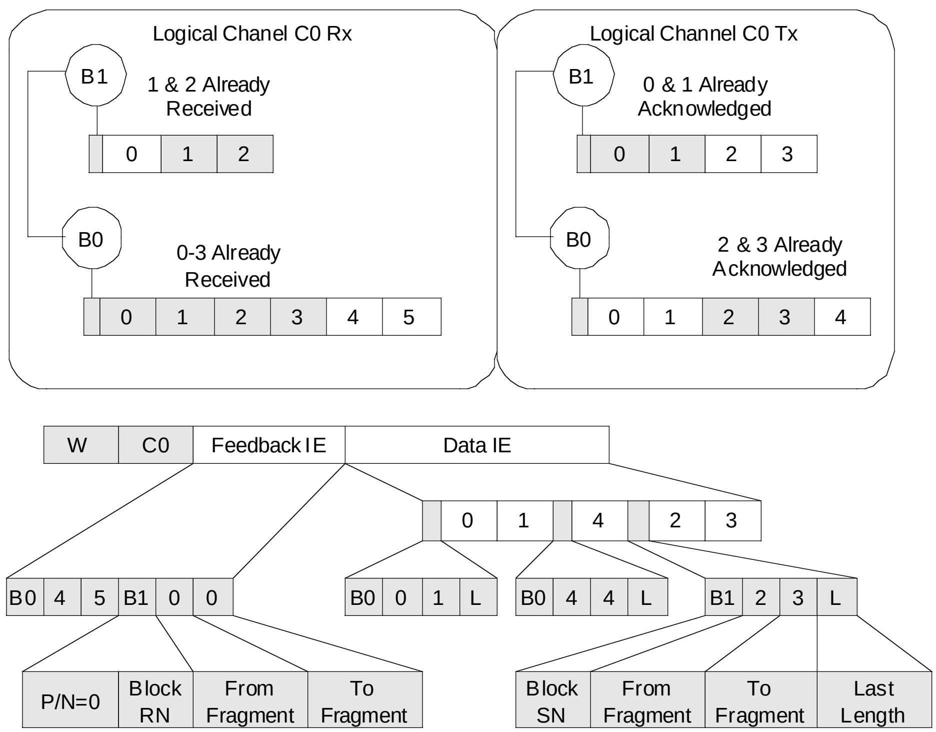


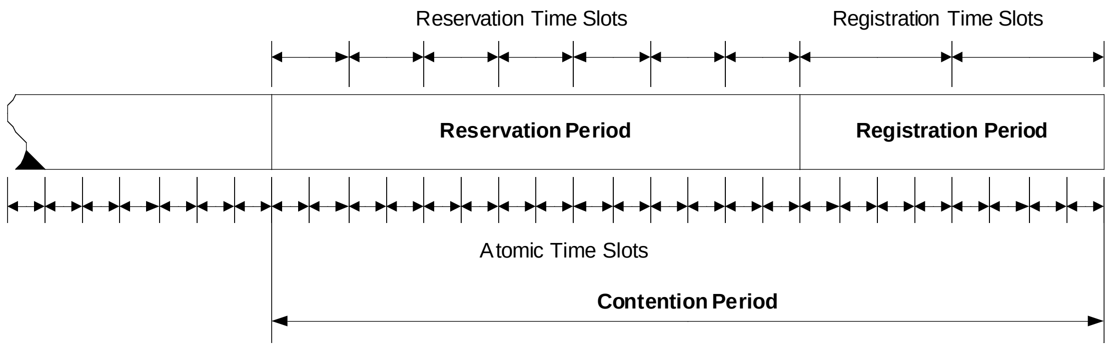
Figure 6 Example of Data Element and Negative Feedback Building

3.6 Reservation and Scheduling

3.6.1 Time Slots

The Access Protocol distinguishes between Atomic Time Slot (ATS), Reservation Time Slot (RsTS) and Registration Time Slot (RgTS).

Table 4 Time Slots



Name	Description
ATS	Atomic Time Slot. The minimum possible time quantum, which might be used for bandwidth allocation. All time periods should consist of integral number of ATS.
ReTS	Reservation Time Slots. These time slots are of duration sufficient to accommodate the reservation burst plus inter-burst guard time.
RgTS	Registration Time Slots. These time slots are of duration sufficient to accommodate the registration burst plus the maximum round trip propagation delay.

3.6.2 Up Link Reservation Techniques

3.6.2.1 Polling in Advance Technique (PAT)

Polling is allocation of Up Link time by the Base Station, which is not in response to an explicit reservation request from the Subscriber Station. The Up Link time is allocated for Poll Duration (PD) ATSs.

3.6.2.2 On-Line Reservation Technique (OLRT)

Each Up Link WPDU may contain a piggybacked RRQ for the next SF as it is shown in the Figure 7.

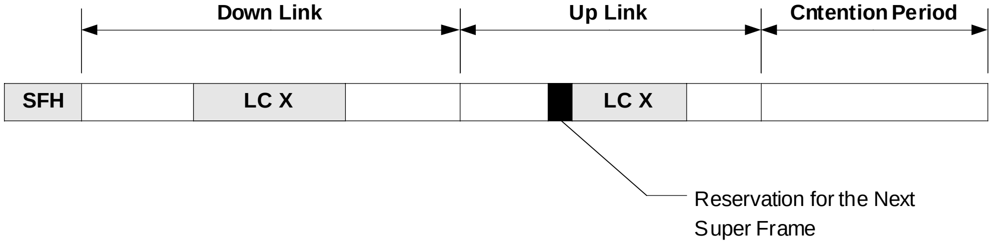


Figure 7 On-line Reservation

The Base Station will try to honor the reservation within the next Super-Frame. The Base Station may postpone the reservation if honoring it may affect QoS of other Logical Channels.

3.6.2.3 Asynchronous Reservation Technique (ART)

The Asynchronous Reservation takes place during the Reservation Period, which is a part of Contention Period (see Figure 8 below).

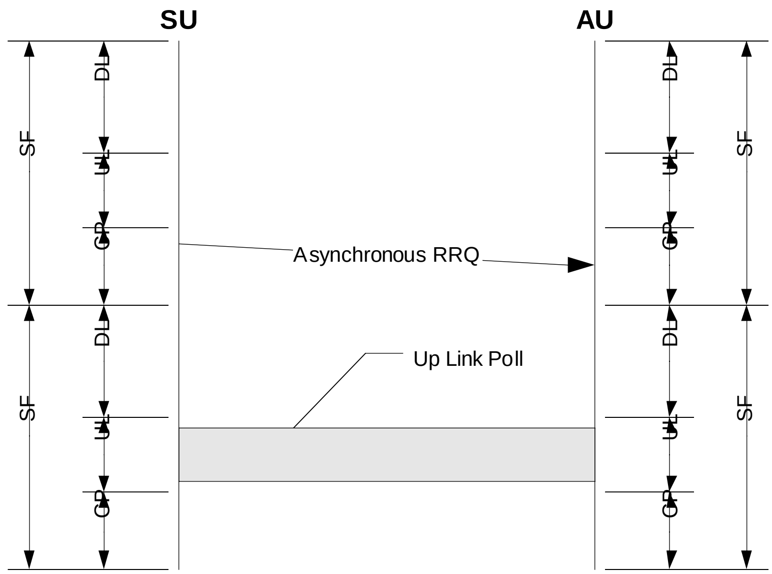


Figure 8 Asynchronous Reservation

The access method during a Reservation Period is ***p**-persistent* Slotted Aloha. The Base Station controls the persistency ***p*** of the Aloha Medium Access in each Reservation Period by distributing in the SFH the number of allocated RsTSs (***m***) and the estimated number of the subscribers that are going to compete (***n***) (see Table 7 for more information).

3.6.2.3.1 Competition Rules

If the Reservation Period consists of ***m*** RsTSs and there are ***n*** subscribers competing for asynchronous reservation, then each Subscriber Station will chose randomly one of the reservation slots and transmit an Asynchronous RRQ with probability $p_t = \min\left(1, \frac{m}{n}\right)$. Thus each subscriber's probability of successful transmission appears as $P_s = \left(\frac{n-m}{n}\right)^{\frac{n-m}{m}}$ for $n > m$, and $P_s = \left(\frac{m-1}{m}\right)^{n-1}$ for $n \le m$.

Correspondingly the mean asynchronous reservation delay appears as $\overline{D_r} = \left(\frac{n}{n-m}\right)^{\frac{n-m}{m}}$ for $n > m$, and

$\overline{D_r} = \left(\frac{m}{m-1}\right)^{n-1}$ for $n \le m$.

For example, if there are 50 RsTSs in each Reservation Period and 100 subscribers compete for reservation, the reservation will succeed within **2** Reservation Periods. Ideally $m \cup n$, however the allocation of m depends on residual capacity. Note that if n is estimated correctly then whatever m such that $n > m > 0$ is allocated, the service acquisition delay will be predictable, and the utilization of the Reservation Period will be ideal.

3.6.3 Scheduling Basics

3.6.3.1 Fixed Allocation Period (FAP) Scheduling.

The FAP is a fixed time period, which consists of at least one Down Link Period and at least one Up Link Period. The FAP may consist of one or more SFs and no SF may cross the FAP time boundaries.

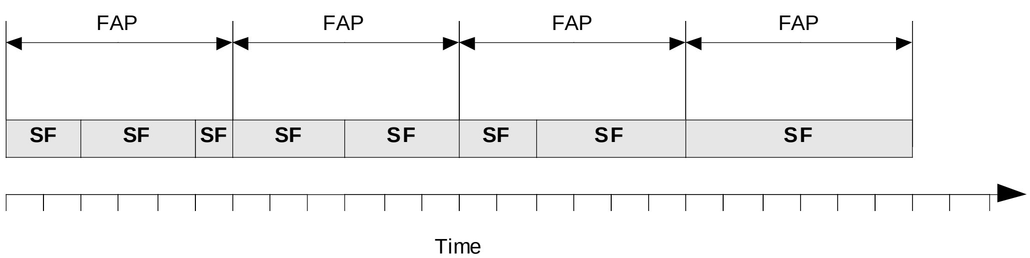


Figure 9 FAPs and Super Frames

Each SF inside a FAP may be of variable length and does not have to contain DLP, ULP and CP altogether, however at least one SF should contain DLP and at least one should contain ULP.

3.6.3.2 Super Frame Scheduling

If the pending Down and Up Link demands service time is smaller than one FAP then multiple SFs per FAP might be scheduled. Otherwise the SF size and FAP size must be equal. Thus in some situations the delays will be lower than FAP however it is impossible to *commit* to such delays.

3.6.3.3 Scheduling CD CoS Logical channels

The FAP defines the time unit in which delay and delay variation commitment might be measured. The Committed Delay CoS logical channels are characterized by CD and CDV that are measured in milliseconds. CD^{FAP} and CDV^{FAP} denote respectively the Committed Delay and Committed Delay Variation measured in FAPs. For this kind of logical channels a data block is supposed to arrive every $CD^{FAP} \pm CDV^{FAP}$ Scheduling Periods (this time period is called Possible Arrival Period). Ideally, the data blocks arrive every CD^{FAP} exactly in the Expected Arrival FAP (see Figure 10).

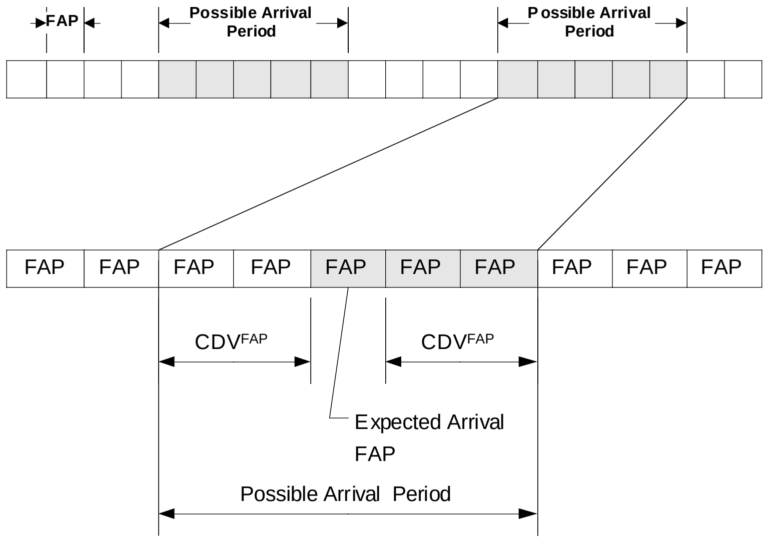


Figure 10 Arrival Expectation for CD CoS

3.6.3.4 Scheduling CR CoS Logical Channels

The rules below should be followed.

1) The CR CoS Down and Up Link transmissions should be served only when there are no more CD CoS Logical Channels to serve.

2) On Down Link direction, when a block arrives, it should be scheduled for transmission in the next available SF.

3) The Up Link will be polled using PAT with interval dependent on the committed rate.

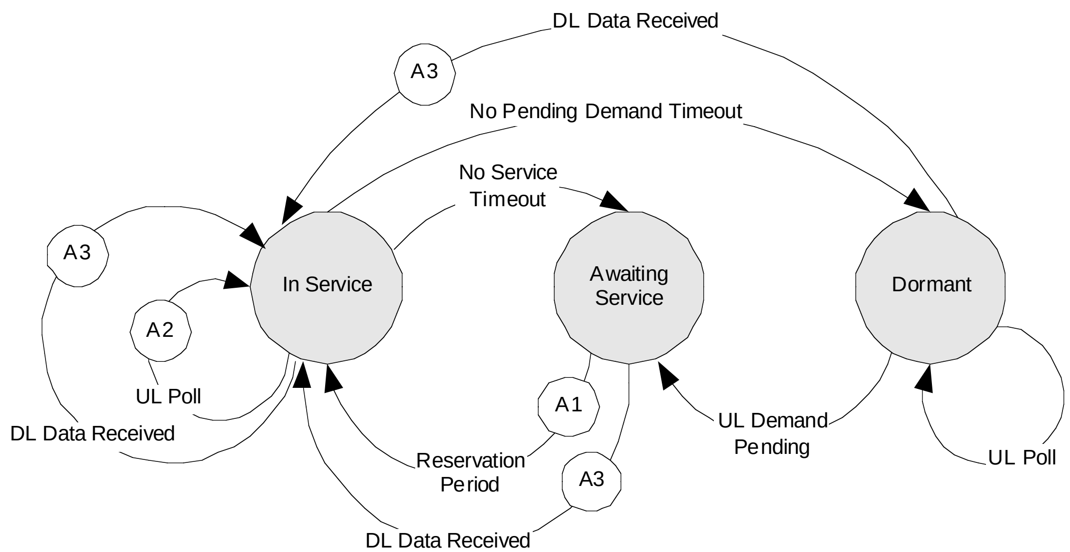
4) The scheduler should achieve service rates not less than CDR.

5) If the limits of outstanding transmission capacity is reached on the Down Link, the Up Link should be polled for a duration which is enough for at least Feedback IE transmission.

3.6.3.5 Scheduling Uncommitted QoS Logical Channels

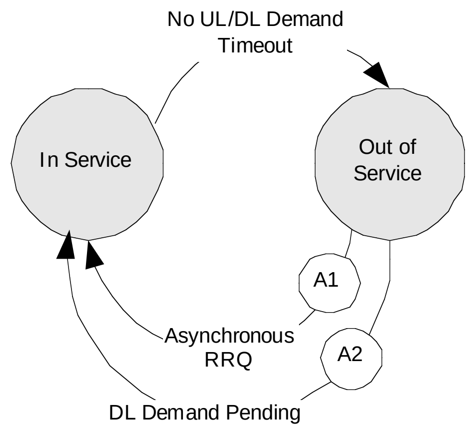
The Uncommitted QoS Logical channels use ART to request service. When in service they are treated as CR CoS logical channels until no demand exists for a time being. Their state transitions in the Subscriber Station and in the Base Station are shown in the Table 5 and Table 6 respectively.

Table 5 Uncommitted QoS Scheduling State Transitions in Subscriber Station



Action ID	Description
A1	Send Asynchronous RRQ.
A2	Send data if any demand is pending. Use OLRT to reserve more Up Link time. Reset *No Service Timeout* timer
A3	Reset *No Service Timeout* timer

Table 6 Uncommitted QoS Scheduling State Transitions in Base Station

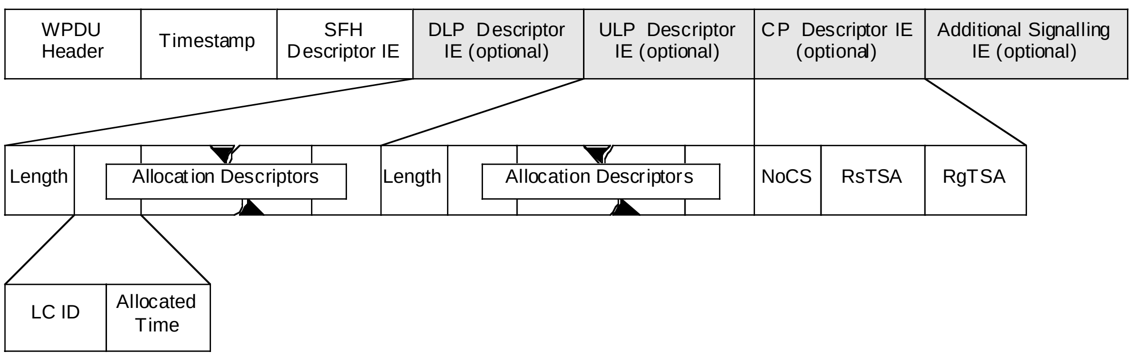


Action ID	Description
A1	Send Asynchronous RRQ.

A2	Send data if any demand is pending. Use OLRT to reserve more Up Link time. Reset *No Service Timeout* timer
A3	Reset *No Service Timeout* timer

3.6.4 Super Frame Header

Table 7 SFH Structure



Field	Description
WPDU Header	WPDU Header of broadcast type.
Timestamp	Global time of SFH transmission (in microseconds)
SFH Descriptor	The field defines what optional fields mentioned below follow this one.
DLP Descriptor IE and ULP Descriptor IE	Both consist of a variable number of Allocation Descriptors that have the structure specified below.

Field	Description
Logical Channel ID	A number which is unique within a Base Station and identifies logical channel.
Allocated Time	Time allocated for transmission (in ATSs).

Field	Description
CP Descriptor IE	Consists of three fields specified below

Field	Description
NoCS	Estimated Number of Competing Subscribers (see 3.6.2.3)
RsTSA	Reservation Slots Allocated.

	RgTSA	Registration Slots Allocated.
Additional Signalling IE	Additional Signalling Information Elements of the same format as specified in Table 3.	

4 Criterion Discussion

4.1 Meets system requirements

The proposed MAC has a wide range of provisions for supporting both time-bounded, connection oriented and conectionless services. In particular, it provides an improved latency for asynchronous services, without compromising the support of delay sensitive services.

4.2 MAC Delays

The MAC has the means for prioritizing and scheduling the transmissions in order to satisfy the delay and delay variation commitments. The delay variation may be further reduced by time-stamping the data blocks and reading those out of jitter-eliminating elastic buffers.

4.3 Payload and bandwidth efficiency

How well does the overhead due to the proposed MAC PDU headers allow for efficient user data transfer over the 802.16 air interface? Is the proposed MAC protocol designed such that the MAC signaling is efficient in terms of not requiring excessive overhead? How well does the proposed MAC protocol provide the mechanisms for fair allocation and sharing of the bandwidth among users?

4.4 Simplicity of implementation/cost

The parsing of the MAC protocol messages (WPDUs) is simple enough for either hardware or software implementation. The transmission scheduling, which is of higher complexity, is performed at the Base station, which is less sensitive to complexity and cost. The protocol described is tolerant enough to implementation efficiency (e.g. message parsing delay in the subscriber stations), so that simpler implementation will result in performance degradation rather than collapse of the system.

4.5 Scalability

The protocol parameters can be adapted to a wide range of operational bandwidths, supported data rates, physical layer characteristics.

4.6 Service Support Flexibility

The MAC described in this document provides the mechanisms required for supporting the services described in 802.16s0-99/5. Those include bounded delay, flexible bandwidth allocation, etc.. The mapping of the specific services onto the MAC mechanisms will be accomplished by the appropriate Convergence Layers.

4.7 Robustness

The protocol does include retransmission mechanisms for error control. Frame numbering prevents out-of-order reassembly. The scheduling mechanisms may include provisions for prioritizing the recovery of time-bounded data.

4.8 Security

The MAC protocol can be coupled with a variety of encryption mechanisms, both for authentication and for user data transfer. This initial presentation of the protocol does not dwell on the specific methods of accomplishing this task.

4.9 Physical Channel Configurability

The MAC protocol has provisions for controlling the PHY parameters. The data rate and transmit power can be altered both in upstream and in upstream per subscriber station or even per logical connection.

4.10 Maturity

The proposed protocol is new.

4.11 Convergence with existing technologies

The proposed protocol draws on some ideas familiar in the industry (DOCSIS, 802.11), however, the specific combination presented here is new.

4.12 Ability to work with physical layer variations, e.g., duplexing, constellation

The proposed MAC protocol supports a wide range of variants of Physical Layer. It can operate both in TDD, FDD and FDD-half duplex modes, depending on the scheduler. The scheduling can readily incorporate the capability of the PHY to transmit at varying data rates (constellations). The protocol assumes packet transmission both in downstream and upstream, but can readily incorporate a continuous downstream in FDD mode, if desired.

4.13 Mean access delay and variance

No submission required for Session #4; will address later

4.14 Sign-on process

No submission required for Session #4; will address later

4.15 Verifiability

No submission required for Session #4; will address later

4.16 Adequacy of management functions

No submission required for Session #4; may address later