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Title	**Evaluation Procedure for 802.16 MAC Protocols**
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Re:	This is a response to the Call for Contributions on MAC-Layer Modeling (IEEE 802.16.1m-00/02) and the Call for Evaluations, Improvements, and Mergers (IEEE 802.16-00/11).
Abstract	The purpose of this document is to jumpstart a debate within IEEE 802.16 on how the current set of 802.16.1 MAC proposals (Documents IEEE 802.16.1mc-00/09 and IEEE 802.16.1mc-00/10) should be evaluated. The document actually goes further by proposing a specific procedure and set of experiments for evaluating the MAC proposals. It contains a brief summary of how the two proposals differ with respect to basic features of a MAC protocol. It then shows an evaluation model along with a range of parameter values for simulations as well as a proposed data traffic model. It then describes the evaluation procedure for several performance measures for the LMDS MAC layer protocol.
Purpose	The 802.16.1 MAC Task Group should consider this document at Session #7.
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Evaluation Process for 802.16 MAC Protocols

Hoon Choi and Nader Moayeri

NIST

1. Introduction

This document defines a general process for modeling, simulation, and evaluation of the current set of 802.16.1 MAC proposals (Documents IEEE 802.16.1mc-00/09 and IEEE 802.16.1mc-00/10). It is a submission to IEEE 802.16 in response to the document IEEE 802.16.1m-00/02, Call for Contributions on MAC-Layer Modeling, and it is based on IEEE 802.16s-99/00r1, 802.16.1 Functional Requirements, Rev. 1 [1].

By carefully defining the evaluation process, we ensure that a common procedure is used to evaluate the performance of the two MAC protocols. Our approach to the evaluation process has similarities to the process defined in an earlier IEEE 802.14 document [2] for evaluating HFC MAC layer protocols. The process is not intended to evaluate other components of an implementation, such as layers above or below the MAC layer. While the PHY layer is part of the standardization process, its evaluation is outside the scope of the present document. Since it is impossible to evaluate the MAC layer in isolation, we have made a minimal set of assumptions about the adjacent layers in the protocol stack to make the MAC evaluation possible.

We begin with a brief overview of how the two proposals differ with respect to the basic features of a MAC protocol. We then present an evaluation model along with a range of parameter values for simulations. Finally, we describe evaluation procedures for several performance measures for an LMDS MAC layer protocol.

2. Comparison of the Two MAC Proposals

The major features of the MAC protocols can be listed as: framing and formatting, initialization/registration procedure, bandwidth request/allocation procedure, contention resolution scheme, data exchange procedure, QoS support, addressing, and management issues. The two proposals for the LMDS MAC protocol, i.e., Documents IEEE 802.16.1mc-00/09 [3] and IEEE 802.16.1mc-00/10 [4], share a number of similar concepts.

2.1. Framing

The frame structure is defined in IEEE 802.16.1mc-00/10 (Editor: J. Mollenauer). The concepts of fixed size frames and slots are also used in IEEE 802.16.1mc-00/09 (Editor: G. Sater), though its frame structure is not provided in either IEEE 802.16.1mc-00/09 or its corresponding physical layer protocol proposal, IEEE 802.16.1pc-00/13 (Editor: J. Foerster).

2.2. Initialization/Registration

The following table shows the steps of the initial registration after timing and synchronization have been performed. In each step, the timer is activated to detect unsuccessful operation. The operation is retried if timer is expired. In case of collision, the procedure is retried after a random delay by the binary exponential back-off algorithm.

IEEE 802.16.1mc-00/09

Step	Operation	Reference [3]
1	Obtain upstream parameters from the Upstream Channel Descriptor Message (UCD) from the BS	5.4.2.2
2	Perform ranging and automatic adjustment procedure. [1]	5.4.2.4
3	Establish IP connectivity. [2]	5.4.2.6.1
4	Establish Time of Day.	5.4.2.6.2
5	Download configuration parameter file.	5.4.2.6.3
6	Perform registration.	5.4.2.6.4

[1] Use of Ranging Request/Ranging Reply Messages. No random delay before sending Ranging Request Message.

[2] IP allocation by Dynamic Host Configuration Protocol

[3] This is the section number in the proposal in which the corresponding step is described.

IEEE 802.16.1mc-00/10

Step	Operation	Reference
1	Wait for a registration opportunity in the MAC Control portion of the downlink subframe.[1]	3.4.1.1
2	In the registration opportunity, the user station randomly picks an available registration slot (random delay).	3.4.1.1
3	Ranging and registration (exchange of Registration Request Message/ Registration Results Message [2, 3, 4])	3.4.1.3 3.4.1.1

This may not occur in every frame depending on the bandwidth availability.

Ranging is also performed when exchanging Registration Request Message/ Registration Results Message.

There is a Registration Collision Message (available only at BS capable of detecting collisions), so that the BS informs the user station of collision earlier than timer expiration.

If neither a Registration Results Message nor a Registration Collision Message is received, the user station first tries progressively raising its power on subsequent attempts. If it reaches maximum power without receiving a message from the BS, the user station regards it as an undetected collision and uses the contention resolution procedure.

Steps 3,4,5 of IEEE 802.16.1mc-00/09 are not included here.

2.3. Bandwidth Request/Allocation

IEEE 802.16.1mc-00/09

There are two ways to request bandwidth. One is requesting explicitly by sending Request Frame, and the other is requesting implicitly by Piggyback Request in the Extended Header (EHDR) of another frame transmission.

The explicit way of requesting bandwidth is as follows:

1. The BS periodically or aperiodically polls user stations with non-real-time polling service or best effort service flow type. It does this by placing the request contention area in the Allocation Map.
2. The user station receives this map and scans it for request opportunity.
3. If there is a request contention area, the user station calculates a random offset based on the Data Back-off Start value in the most recent map, and then puts the Request Frame in the request contention area after the offset time.
4. If no collision occurs, the BS assigns a data grant for that user station in the next Allocation Map. In case of collision, the BS does not respond.

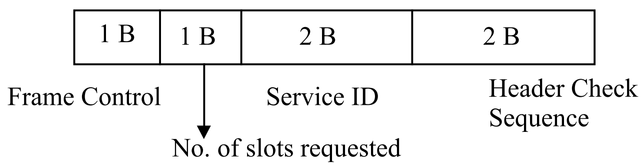


Figure 2-1 Request Frame Format

The intervals in which the BS sends contention slots depend on service flow (QoS) type. For non-real-time polling service, it is in the order of one second or less. For real-time polling service, the BS gives periodic unicast request opportunity. For the unsolicited grant service or the unsolicited grant service with activity detection, the BS gives periodic data grant.

There is a clear definition of message format and usage of piggybacking in the proposal. Piggybacking bandwidth requests may be contained in the following extended headers: Request Extended Header, Upstream Privacy Extended Header, or Upstream Privacy Extended Header with fragmentation. The request includes the service ID making the request and the number of mini-slots requested.

IEEE 802.16.1mc-00/10

Once again, there are two ways to request bandwidth, an explicit way by sending Bandwidth Request Message and an implicit way by piggybacking. There are three explicit way of requesting bandwidth:

1. The user station requests polling by setting “Poll Me” bit in the MAC header, and the BS, in response to the polling request, allocates to the user station bandwidth specifically for the purpose of putting Bandwidth Request Messages.
2. The BS periodically polls an inactive individual user station by allocating bandwidth for the Bandwidth Request Messages whenever available bandwidth allows. If the individually polled user station needs bandwidth, the user station puts a Bandwidth Request Message with the required bandwidth in the bandwidth request contention slot in the uplink subframe. Otherwise, it sends a message with zero length, indicating it does not need any bandwidth.

4 B	2 B
MAC Control Msg Header	Requested Amount

Figure 2-2 Bandwidth Request MAC Message

3. The BS periodically polls multiple user stations whenever bandwidth is available. Only user stations that need bandwidth send Bandwidth Request Messages. No random delay is made before sending such messages. If no collision occurs, the BS allocates the user station bandwidth in the Uplink Map. Otherwise, the BS does not respond.

Piggybacking can be applied for active user stations that have connections already. There is no separate message or information field to represent piggybacking. The regular Bandwidth Request Message is used for this purpose any time in the available bandwidth.

Similar to piggybacking, user stations may steal bandwidth of other lower QoS connections and use that bandwidth for sending Bandwidth Request Messages explicitly. Bandwidth request by “Poll Me” bit is tried only when piggybacking is not available.

2.4. Contention Resolution

When the poll is directed to multiple user stations rather than a certain individual station, user stations belonging to the polled group may send a request message in the contention slot simultaneously. Therefore, there is the possibility of collision among request messages.

Both proposals use the binary exponential back-off algorithm for contention resolution. The only minor difference is that IEEE 802.16.1mc-00/09 uses a counter for the maximum number of retries as well as the maximum back-off window size in order to decide when to stop retransmissions. In IEEE 802.16.1mc-00/10, the maximum back-off window size alone will function for the same purpose.

2.5. Data Transmission and QoS Support

As shown in the following table, both proposals introduce various service classes to support different QoS classes. They also define various message types to carry variable or fixed length payload from their QoS classes. However, concatenation of the MAC messages is not defined in IEEE 802.16.1mc-00/10.

IEEE 802.16.1mc-00/09	IEEE 802.16.1mc-00/10
● Best effort service flow ● Non-real-time polling service flow ● Real-time polling service flow ● Unsolicited grant service flow ● Unsolicited grant with activity detection service flow	● Best effort DAMA service ● Average rate DAMA service ● Guaranteed rate DAMA service ● Real time DAMA service ● Continuous grant service

DAMA : Demand Assign Multiple Access

3. System Model

3.1 Model Topology

We evaluate the LMDS MAC protocol in a wireless access network that is modeled as a cell consisting of one base station (BS) in the center and multiple stationary user stations. We assume that user stations are distributed uniformly in the cell.

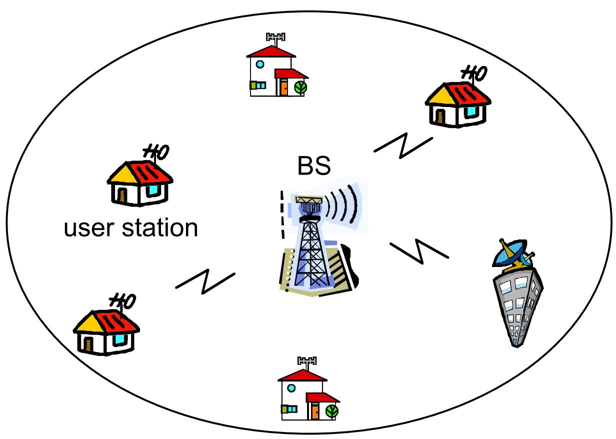
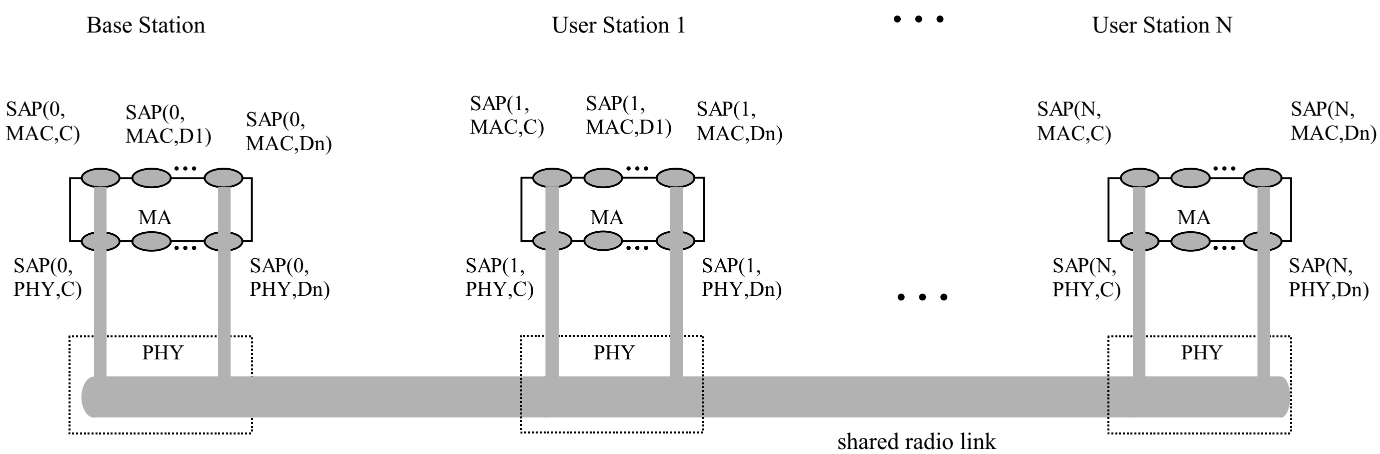


Figure 3-1 A wireless access network for LMDS system

Figure 3-2 represents protocol modules at each station along with the service access points. The user stations in the cell are shown in the ascending order of its distance from the base station. User station 1 is the nearest station and user station N is the farthest one. The MAC and PHY must be properly implemented based on the protocol specifications. Only the functions to be evaluated may be implemented.



SAP(0,MAC,C) : SAP for Control information at MAC layer in the Base Station
SAP(*k*,MAC,*Dn*) : SAP for Data connection *n* at MAC layer in the User Station *k*

Figure 3-2 Service Access Points (SAP) of LMDS Stations

Any simulation language or tool may be used for this purpose. Some of the simulation parameters as well as the configuration information of the model are chosen as below.

Simulation Parameters	**Values**
Cell radius, *r*	0.5 km, 1 km, <u>1.5 km,</u> 2 km
Number of sectors in a cell	1, <u>3</u>, 6
Number of channels in a sector	<u>1</u>
Duplexing schemes	<u>TDD</u>, FDD
Ratio of uplink slots to downlink's in TDD	10% ~ <u>50%</u> ~ 70%
Number of user stations in a sector	30, 60, <u>90</u>, 120, 150
Downstream data transmission rate	2 Mbps, 9 Mbps, <u>45 Mbps</u>, 155 Mbps
Aggregated upstream data transmission rate	2 Mbps, 9 Mbps, <u>45 Mbps</u>, 155 Mbps
Propagation delay	3.3 μsec/km
Bit error ratio	10E-4, 10E-6, <u>10E-9</u>
Initial back-off parameter	1 (window size = 2)
Maximum back-off parameter	15 (window size = 32K)
Length of simulation run, *T*	Depends on the statistical confidence of output
Length of the run prior to gathering statistics	5 % of the simulation time

Table 3-1. Simulation Parameters

* The underscore denotes the default value

3.2 Input Traffic Model

Message arrival at the MAC layer from its higher layer can be classified into two types: bursty type traffic and smooth type traffic. Data applications such as Web browsing or file transfer will cause bursty arrival traffic, while real time applications such as voice communication will generate smooth arrival traffic. We use 5 traffic classes that represent various traffic characteristics. The classes for the bursty type traffic have been taken from [5].

For bursty traffic source

Class A : bursty traffic (e.g. Internet telnet service data)

Class B : bursty and bulky traffic (e.g. Web browsing, file transfer type data)

Class C : sporadic data traffic (e.g. Web traffic on the upstream link or E-mail type data)

For smooth traffic source

Class D : constant data rate traffic (e.g. CBR data, circuit simulation)

Class E : variable data rate traffic (e.g. compressed voice/video)

The model used for bursty traffic is shown in Figure 3-3 where the highest entity is a "session" arriving with a Poisson distribution [5]. A packet call in the session represents a collection of bursty data packets. The time gap between packet calls is the packet call interval time and the time between the beginning of one packet to the beginning of the next one is the packet inter-arrival time.

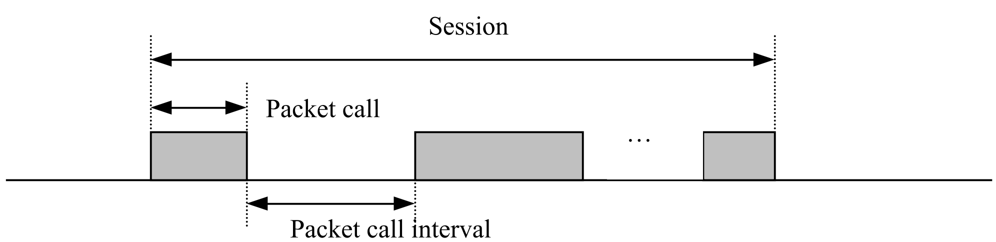


Figure 3-3 A bursty traffic model

The characteristics of each class are as follows.

Class A: Poisson arrivals of sessions (arrival rate λ_A),

Geometrically distributed number of packet calls per session with mean 114,

Geometrically distributed interval time between packet calls with mean 1 second,

One packet per packet call,

Geometrically distributed packet sizes with mean 90 bytes.

Class B: Poisson arrivals of sessions (arrival rate λ_B),

Geometrically distributed number of packet calls per session with mean 5,

Geometrically distributed interval time between packet calls with mean 120 seconds,

Geometrically distributed inter-arrival time between packets with mean 0.01 second,

Pareto distributed number of packets per packet call with parameters α=1.1, k =2.27 (mean=25), where Pareto distribution with parameters α and k is given as $F(x) = 1 - (k/x)^{\alpha}$ if $x >= k > 0$, or 0 if $x < k$.

Fixed packet sizes of 480 bytes.

Class C: Poisson arrivals of sessions (arrival rate λ_B),

Geometrically distributed number of packet calls per session with mean 5,

Geometrically distributed interval time between packet calls with mean 120 seconds,

Geometrically distributed inter-arrival time between packets with mean 0.01 second,

Pareto distributed number of packets per packet call with parameters α=1.1, k =2.27 (mean=25).

Fixed packet sizes of 90 bytes.

Class D: Deterministic arrival of packet. Rate is dependent on an application.

Fixed packet sizes of 53 bytes.

Class E: Arrivals of packets by Markov Modulated Poisson Process (arrival rates λ_{E1} and λ_{E2})

Geometrically distributed packet sizes with mean 180 bytes.

The downstream traffic will be modeled as in either Class A, Class B, Class D, or Class E. The upstream traffic model is for one user station and is modeled as in either Class A, Class C, Class D, or Class E. The traffic models shown here will evolve in time as more information becomes available on the type of traffic.

4. Measures and Evaluation Procedures

4.1 Delivered Bandwidth

According to the functional requirement document [1], the 802.16 protocol shall be optimized to provide the peak capacity from 2 to 155 Mbps to a user station sufficiently close to the base station. This simulation is intended to check if each of the MAC proposals supports transmission at this data rate. We perform the following test for each proposal.

Evaluation procedure (it actually consists of two experiments):

Experiment A:

1. Choose a user station *k* that is away from the base station by about 1/3 of the cell radius.
2. Feed Class D traffic at SAP(*k*, MAC, D1). Increase the data rate from 0 Mbps to 155 Mbps while other user stations do not generate a traffic.
3. Measure the amount of received data at SAP(0, MAC, D1), and measure the elapsed time.
4. Plot the received (delivered) bandwidth vs. generated traffic.

Experiment B:

1. User station *k* keeps generating data at the rate of 155 Mbps and the aggregated traffic volume from the remaining user stations increases from 0 Mbps in 2 Mbps increments.
2. Measure the amount of received data at SAP(0, MAC, D1) from user station *k*, and measure the elapsed time.
3. Plot the received bandwidth vs. the offered load, that is, the total traffic from all the user stations.

Check which protocol allows higher peak data rate to user station *k*.

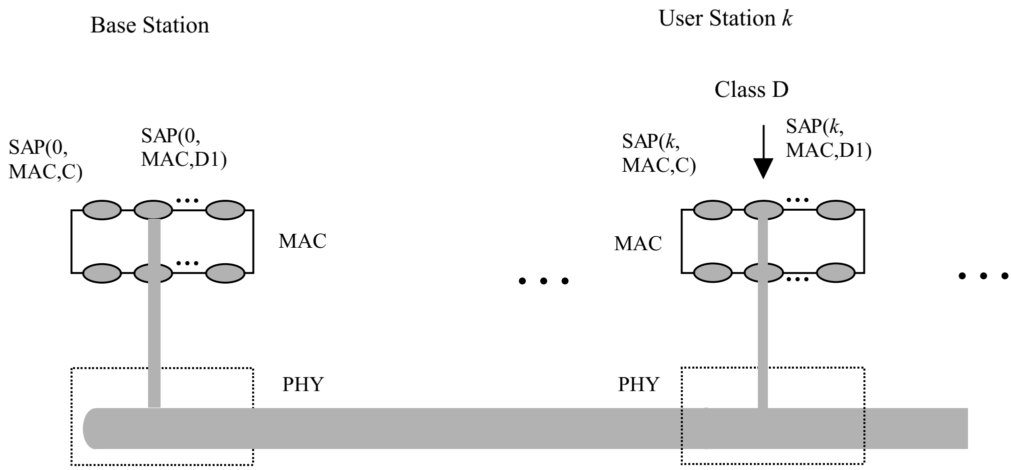


Figure 4-1 Measurement of the delivered data rate

4.2 Delay

The purpose of this simulation is to measure the mean delay as well as delay variation from a user station to the BS. We measure four types of delays, including the initial registration delay, the bandwidth request delay, the MAC transit delay, and the access network transit delay. The FIFO scheduling policy is assumed for servicing registration or bandwidth requests in the BS.

4.2.1 Evaluation procedure for the initial registration delay

1. Choose 7 user stations that belong to the same sector and are located at $i*r/7$ km (i = 1,2,…,7, and r denotes the cell radius) from the base station. The reason for having 7 user stations at different locations is to investigate the effect of distance from the base station on the protocol performance.
2. Generate the initial registration request by a Poisson process whose arrival rate is the sum of Poisson arrival rates of sessions of Class A and Class C. Apply the same amount of traffic to all the other user stations in the cell.
3. Measure the time difference between the instance at which the request is made at SAP(*k*, PHY, C) and the instance at which the registration acknowledgement (Registration Results Message or equivalent information) is received at SAP(*k*, PHY, C). For a fair comparison, the steps 3~5 of IEEE 802.16.1mc-00/09, shown in Section 2.2, are not included in the measurement. Count the number of collisions, if any.
4. Repeat steps 2~3 for a simulation of duration *T* seconds and compute the mean.
5. Repeat steps 2~4 for each of the other 6 user stations.
6. Plot a graph of the mean registration delay for each of the 7 user stations along with the average of these 7 values.
7. Let the registration request rate increase at all user stations and repeat steps 4~6.
8. Plot a line graph of the mean delay vs. the offered load, that is, the sum of registration requests by all the

user stations.

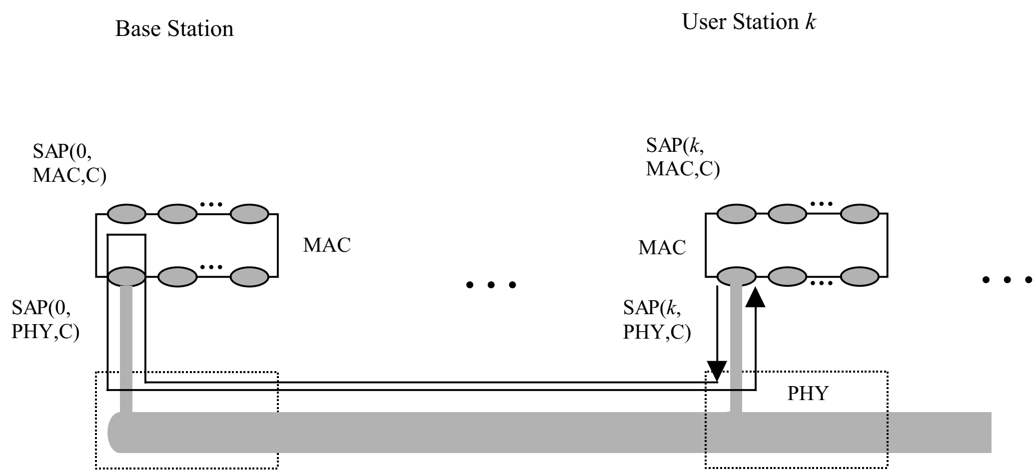


Figure 4-2 Measurement of the initial registration delay

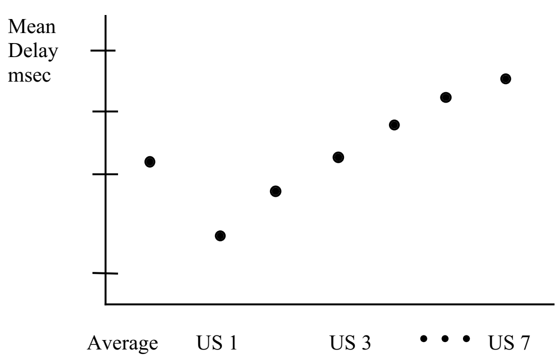


Figure 4-3 Graph of the delay for each station

Figure 4-4 Delay vs. offered load

4.2.2 Evaluation procedure for the bandwidth request delay

Both explicit and implicit (piggybacking, poll me bit) bandwidth request mechanism should be implemented according to each proposal. We assume that the BS allocates slots for bandwidth request contention in each frame and it uses FIFO scheduling policy for servicing bandwidth requests. In the simulation of IEEE 802.16.1mc-00/10, the bandwidth stealing of other connections will be also included. We assume the probability of being able to steal bandwidth is 0.1.

1. Choose 7 user stations that belong to the same sector and are located at *i***r*/7 km (*i* = 1,2,…,7, and *r* denotes the cell radius) from the base station.
2. Associate Class A service to connection D1 at SAP(*k*, MAC, D1), Class C service to connection D2 at SAP(*k*, MAC, D2), Class D service to the connection D3 at SAP(*k*, MAC, D3), and Class E service to connection D4 at SAP(*k*, MAC, D4). We assume that SAP(*k*, MAC, D1), SAP(*k*, MAC, D2), SAP(*k*, MAC, D3), and SAP(*k*, MAC, D4) map to SAP(*k*, PHY, D1), SAP(*k*, PHY, D2), SAP(*k*, PHY, D3), and SAP(*k*, PHY, D4), respectively.
3. All user stations in the cell generate Classes A, C, D, and E traffic according to the parameters of the traffic classes.
4. Generate a bandwidth request each time a new session of Class A or C arrives.
5. Measure the time difference between the instance at which the request is made at SAP(*k*, PHY, C) and the instance at which the grant is received at SAP(*k*, PHY, C). Count the number of collisions, if any.
6. Repeat steps 4~5 for a simulation of duration *T* seconds and compute the mean.
7. Repeat steps 4~6 for each of the other 6 user stations.
8. Plot a graph of the mean registration delay for each of the 7 user stations along with the average of the 7 values.
9. Plot a graph of the number of collisions for each of the 7 user stations along with the average of the 7 values.
10. Let the registration request rate increase at all user stations and repeat steps 4~6.
11. Plot a line graph as in Figure 4-4 of the mean delay vs. the offered load, that is, the sum of bandwidth requests by all the user stations.

4.2.3 Evaluation procedure for the MAC transit delay

We define the MAC transit delay as the time difference between the instance at which the first bit of a service data unit crosses SAP(*k*, MAC, D*) and the instance at which the last bit of the same service data unit crosses the SAP(*k*, PHY, D*). This time includes the bandwidth request delay, contention resolution delay (if necessary), and the messaging delay, including fragmentation/concatenation. We assume a constant amount of time is needed to frame a single message, regardless of the message type. Fragmentation delay depends on the number of fragments *n,* and it is equal to *n* times the delay of a single message. Concatenation delay is also assumed to be dependent on the number of messages to be concatenated.

1. Choose 7 user stations that belong to the same sector and are located at *i***r*/7 km (*i* = 1,2,…,7, and *r* denotes the cell radius) from the base station.
2. Associate Class A service to connection D1 at SAP(*k*, MAC, D1), and Class C, D, and E service to connections D2, D3, and D4 at SAP(*k*, MAC, D2), SAP(*k*, MAC, D3), and SAP(*k*, MAC, D4), respectively.

3. All user stations in the cell generate Classes A, C, D, and E traffic according to the parameters of the traffic classes.
4. Measure the time difference between the instance at which the first bit of a data crosses SAP(*k*, MAC, D*) and the instance at which the last bit of the same data crosses the SAP(*k*, PHY, D*) for each connection.
5. Repeat steps 3~4 for a simulation of duration *T* seconds and compute the mean and the variation of delay for each connection.
6. Repeat steps 3~5 for each of the other 6 user stations.
7. Plot a graph of the mean transit delay for each of the 7 user stations along with the average of the 7 values as in Figure 4-6.
8. Plot a graph that shows the coefficient of variation of the MAC transit delay for Class D vs. station number.

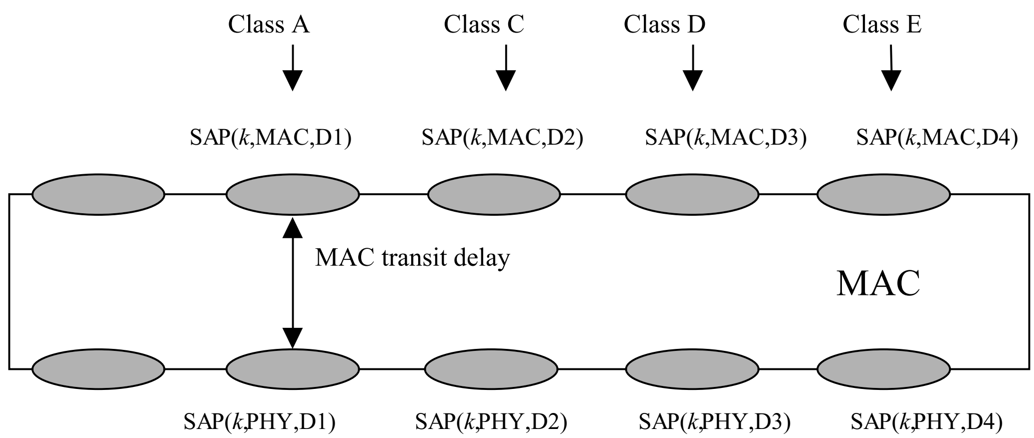


Figure 4-5 Definition of MAC transit delay

4.2.4 Evaluation procedure of the access network transit delay

We define the access network transit delay as the time difference between the instance at which the first bit of a service data unit crosses SAP(*k*, MAC, D*) and the instance at which the last bit of the same service data unit crosses SAP(0, MAC, D*).

1. Choose 7 user stations that belong to the same sector and are located at $i*r/7$ km (i = 1,2,…,7) from the base station.
2. Associate Class A service to connection D1 at SAP(*k*, MAC, D1), and Class C, D, and E service to connections D2, D3, and D4 at SAP(*k*, MAC, D2), SAP(*k*, MAC, D3), and SAP(*k*, MAC, D4), respectively.
3. All user stations in the cell generate Classes A, C, D, and E traffic according to the parameters of the traffic classes.
4. Measure the time difference between the instance at which the first bit of a service data unit crosses SAP(*k*, MAC, D*) and the instance at which the last bit of the same data crosses SAP(0, MAC, D*) for each connection.
5. Repeat steps 3~4 for a simulation of duration *T* seconds and compute the mean and the variation of delay

for each connection.

6. Repeat steps 3~5 for each of the other 6 user stations.
7. Plot a graph of the mean transit delay for each of the 7 user stations along with the average of the 7 values as in Figure 4-6.
8. Plot a graph that shows the coefficient of variation of the MAC transit delay for Class D vs. station number.
9. Let the registration request rate increase at all user stations and repeat steps 3~5.
10. Plot a line graph of the mean delay vs. the offered load, that is, the sum of bandwidth requests by all the user stations.

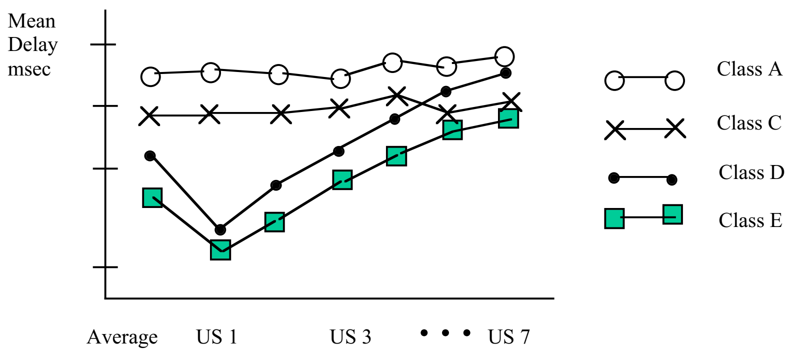


Figure 4-6 Mean delay at different stations for each connection

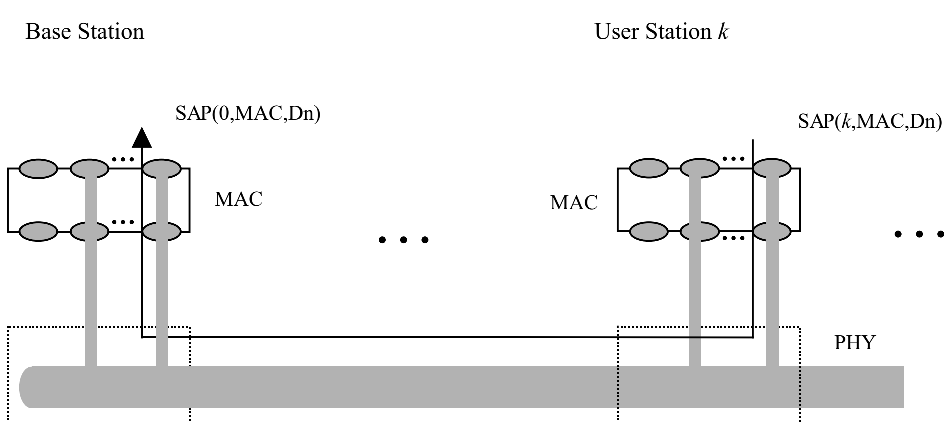


Figure 4-7 Measurement of the access network transit delay

4.2.5 Delays with respect to the number of stations

1. Choose a user station *k*.
2. Generate Class E traffic at SAP (*k*, MAC, D1). Make other stations generate 1 Mbps at each station.
3. Measure the time difference between the instance at which the first bit of a service data unit crosses SAP(*k*, MAC, D1) and the instance at which the last bit of the same data crosses SAP(*k*, PHY, D1).
4. Repeat steps 3~4 for a simulation of duration *T* seconds and compute the mean and the variation of the delay.
5. Vary the number of user stations as in Table 3-1 and repeat steps 3~4.
6. Plot a graph of the mean MAC transit delay vs. the number of user stations.
7. Plot a graph that shows the coefficient of variation of the MAC transit delay vs. the number of user stations.

4.3 Flexible Asymmetry

The MAC protocol shall support for flexibility between delivered upstream and downstream bandwidth. Simulate and plot the above measures when the ratio of aggregated upstream bandwidth to downstream varies according to Table 3-1.

Measure and plot the bandwidth of downstream when the aggregated upstream bandwidth varies from 2 Mbps to 155 Mbps. Check which protocol gives higher downstream bandwidth and smooth change.

4.4 Fairness

The graphs of delays at 7 stations show the performance variation of the MAC protocols with respect to distance. The preferred protocol should give smaller difference in the amount of various delay times regardless of the distance of the user station from the base station.

5. References

[1] IEEE 802.16s-99/00r1, 802.16.1, Functional Requirements, Rev. 1.

[2] IEEE 802.14/96-083R2, Performance Evaluation Process for MAC Protocols.

[3] IEEE 802.16.1mc-00/09, Media Access Control Layer Proposal for the 802.16 Air Interface Specification, Editor G. Sater, Feb. 25, 2000.

[4] IEEE 802.16.1mc-00/10, MAC Proposal for IEEE 802.16.1, Editor J. F. Mollenauer, Feb. 25, 2000.

[5] TIA TR45.5.4/98.03.30.04, Revised working draft for ITU-R RTT candidate submission (V0.14) IS-95 3G System Description Draft, April 1998.