Design and Implementation of IEEE 802.16 MAC Layer Simulator

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Summary
The IEEE 802.16 provides wireless broadband access for Metropolitan Area Networks (MAN). Due to support for mobility and high bandwidth, it has captured everyone's attention. Cost of the deploying IEEE 802.16 equipment is high, so, it is vital that the network is simulated before deployment. This paper presents the design of 802.16 MAC simulator which implements true frame format, with TDM / TDMA and TDD. QoS and Admission control is also simulated by designing Bandwidth and Service Flow Managers. Simulation topology for a typical wireless network is also presented.

Key words:
Worldwide Interoperability for Microwave Access, Simulator, Quality of Service, Medium Access Control

1. Introduction

Network simulators are widely used in industry and academia alike. Large networks are always simulated before deployment so that the required performance and quality of service can be ensured before making the investment in the infrastructure. Network Simulators are an essential tool in research where new concepts in networking and communication are to be explored and different concepts are to be verified.

It is advisable to generate simulation, since it is a low cost and effective way to come up with an efficient design of the system. It enables to study the relationship between the various components of the architecture in detail. All possible scenarios can be generated, and all aspects of the design can be tested, in a controlled environment. It provides for the analysis of output and measurement of system performance, whereby testing all the assumptions made during the design of the system.

The key to the development of any simulation is devising the selection criteria, and accordingly choosing the most suitable simulation environment and tools for the simulation. A number of simulators, both commercial and non-commercial, such as NS-2, OPNET, QualNet, and OMNeT ++, are available for developing network simulations. These simulators provide varying degree of protocols support. Since most of these simulators are not open source addition of new protocols is limited to expert developers and may take time.

NS-2 is a non-commercial, discrete event driven network simulator. It is widely used for simulating both local area, and wide area network simulations. NS-2 is completely open source. It is frequently used in network simulations, which makes it easier to compare the simulation results with others work. Moreover, NS-2 does not require live network support for running the simulation [2].

This paper describes the design and implementation of IEEE 802.16d (WiMAX) in NS-2 simulator. NS-2 simulator is used for its low cost, wide scientific acceptance, availability of protocols, and support for developing protocols and adding new components.

This paper describes the architectural design of IEEE 802.16d Medium Access Control layer, as it is simulated on NS-2. The paper begins by giving an overview of IEEE 802.16. Section 3 describes the Interfacing of IEEE 802.16 module with NS-2. The architectural design of the IEEE 802.16 Module is presented in Section 4. Section 5 illustrates a simulation scenario.

2. IEEE 802.16 – an overview

IEEE 802.16, also known as WiMAX, provides specifications for fixed broadband wireless Metropolitan Area Networks (MANs). The IEEE 802.16 MAC common part sublayer can operate in both the point to multipoint (PMP) and Mesh mode. In either mode, its operations are defined on the two entities, the Base Station and Subscriber Stations, the later joins the network through network entry and initialization procedures [1].

The 802.16 MAC delivers quality of Service (QoS) by defining 4 Scheduling types, which are UGS, rtPS, nrtPS and BE, in both uplink and downlink direction. Service flows can be created based on the QoS traffic parameters. The BS schedules the uplink and downlink traffic of the SS, using Bandwidth request and allocation procedure such that QoS is guaranteed. MAC Layer encapsulation is shown in Fig. 2.

The packet transmission and reception follow the mechanism of Concatenation, Fragmentation, Packing and Padding. Error detection and recovery is enforced by CRC and ARQ mechanisms. Encryption is applied to introduce security in the network.

3. NS-2 Interfaces

NS-2 can be viewed as a set of libraries that implement the simulation, OTcl scripts to run the simulations, and tools to analyze the simulation results such as NAM (Network Animator) [3].

To add the 802.16 MAC component to NS-2, work was required to:

I. Add & modify components to NS-2 Library / code

Adding the 802.16 MAC layer to the protocol stack of NS-2 required writing the 802.16 MAC, and placing it at the MAC layer in the stack.

II. Write OTcl scripts

OTcl scripts have been written to setup a network topology with 802.16 MAC operating at each node with some application and agent injecting and receiving packets over the network as shown in Fig. 1 [4]. The 802.16 MAC has been written and compiled in C++ and linked with OTcl. The class is publicly derived from the MAC class supplied with NS-2.

The code of LL (Link Layer) has been modified such that it does not insert the MAC header, and simply passes down the packet to the MAC without any delay.

The MAC classifier provided by NS-2 is also bypassed in the simulation, since it is upto the 802.16 MAC to decide the destination of the packet, based on the CID. Also in NS-2 the Packets handed over to the LL that have payload length greater than zero, do not contain the actual payload.

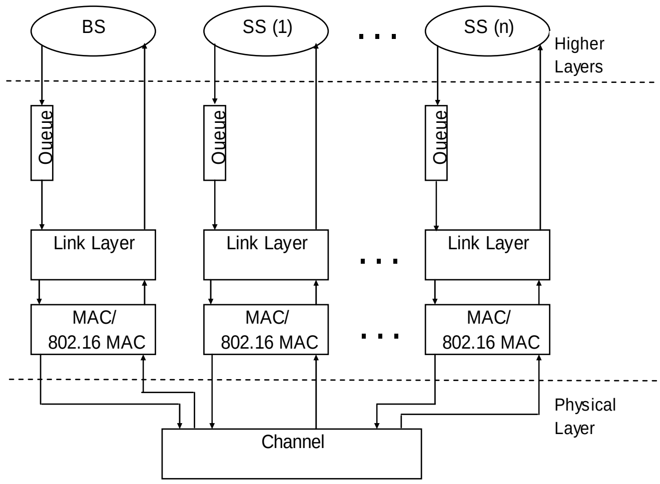

Fig. 1 Placement of MAC Layer

However for the purpose of simulating the principles of construction and transmission of MAC PDUs, the packet class of NS-2 is modified such that the packets have a payload field. The payload, equal to the payload length specified in the header, is randomly generated and added to the packet by the 802.16 MAC (controller/ wrapper part) before processing the packet. Similarly after the reception and processing of the packets by MAC, the payload is stripped off and the bare packet is passed up the stack.

4. Architecture

The functionality of 802.16 MAC is implemented in a modular fashion. Each Module/Unit is responsible for a discrete set of tasks. The modules interact with each other to carry out the MAC layer operations.

The basic architectural design of the MAC layer for both the SS and BS is the same. However, there are some tasks, such as Bandwidth Request and Grant operations, and Network entry procedures, that differ at the SS and BS. This difference is captured in the detailed design, in the responsibility definitions of the modules, and the flow of data and control between them, as per requirement. Fig. 3 shows the data flow at the Base Station. The modules/units, and their responsibilities are shown in Table 1.

2.1 Mac Encapsulation

The MAC layer lies between the Link Layer and the Channel in the NS-2 stack. However in this simulator of 802.16 MAC, upper layer proxy and baseband proxy thin layers are designed to encapsulate the MAC.

Table 1: Task Distribution Table

Unit	***Responsibility / Task***	***Relevance***
Bandwidth Grant Manager (BWG)	Downlink/Uplink Scheduling	BS
Bandwidth Request Manager	Bandwidth request per connection.	SS
Network Entry Manager (NEM)	Network entry operations that include: ▪ Scanning ▪ Ranging ▪ Authorization ▪ Registration	BS and SS
Service Flow Manager (SFM)	▪ Service Flow Creation ▪ Service Flow Modification ▪ Service Flow Deletion ▪ Admission Control	BS and SS
Slot Manager (SM)	▪ Frame synchronization ▪ Clock synchronization ▪ Slot counting ▪ Contention Resolution	BS and SS
Tx Manager	Transmission operations that include: ▪ Concatenation ▪ Packing ▪ Fragmentation Tx Manager also invokes the CRC manager, ARQ manager and SA Manager to carry out the transmission operations.	BS and SS
Rx Manager	Reception Operations that include: ▪ Concatenation ▪ Packing ▪ Fragmentation Rx Manager also invokes the CRC manager, ARQ manager and SA Manager to carry out the receive operations.	BS and SS
Rx Multiplexer	Multiplex the packets between the NEM, BWG manager, BWR manager or UL proxy at reception.	BS and SS
ARQ Manager	ARQ operations	BS and SS
CRC Manager	CRC operations	BS and SS
MIB Manager	MIB add, create and delete operations	BS and SS
Security Association (SA) Manager	Security Association operations.	BS and SS
Queue Manager	Queue Management.	BS and SS

The interaction between the Link Layer and MAC is intervened by the Upper Layer Proxy. Upper Layer proxy provides the upper layer interface to the MAC. It manages the packet transcend from the upper layer into the MAC layer queues, and the handing over of packets received by the MAC to the upper layer.

The BB proxy implements the Baseband interface to the MAC. It manages the packet exchange between the MAC and the Lower layer.

The concept of keeping an upper layer proxy and a baseband proxy is to keep the design and implementation of MAC independent of the development environment. This way, the MAC is pluggable into any implementation of the network stack, by just rewriting the Upper Layer Proxy and the Baseband proxy, and with only minimal changes to the MAC modules.

2.2 Queuing Operations

The Mac maintains four sets of queues for storing packets.

Tx Service Flow Queues

The Packets arriving at the upper layer proxy are classified to some service flow based on their QoS requirements. The packet, along with its metadata, is queued in the Tx Service flow queue corresponding to the service flow to which the packet belongs. If the queue for the service flow does not exist, it is created and added to the list of Tx Service Flow queues.

For ARQ enabled connections, packet is queued as a number of ARQ blocks, with the necessary metadata indicating the block information.

Rx Service Flow Queues

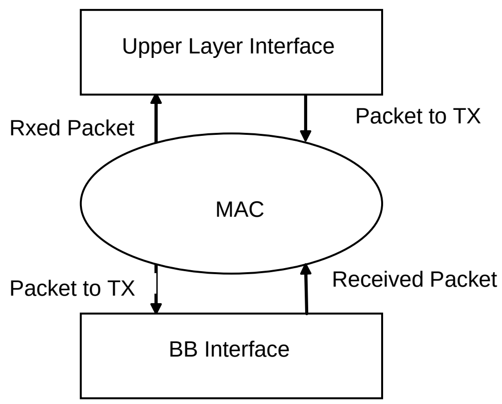

Fig. 2 MAC Encapsulation

The packets received by the MAC, from the channel, are queued in their corresponding RX Service Flow Queues. If the queue for a service flow does not exist, it is and added to the list of Rx Service Flow queues.

For ARQ enabled connections, packet is queued as a number of ARQ blocks, with the necessary metadata indicating the block information. Duplicate ARQ blocks are also detected at the time of inserting the blocks in the queue.

<u>Initial Ranging Queue</u>

A Queue is maintained for the packets exchanged using contention resolution during initial ranging.

The Bandwidth Request Packets are queued in the Bandwidth request queue by the bandwidth request manager, and transmitted from this queue by the Tx Manager.

2.3 Packet transmission & reception operations

The Packet Transmission and reception operations are carried out by Tx Manager and the Rx Manager respectively. However, the Tx and Rx Manager may invoke the ARQ manager, SA Manager and CRC module to bring about the Tx and Rx operations.

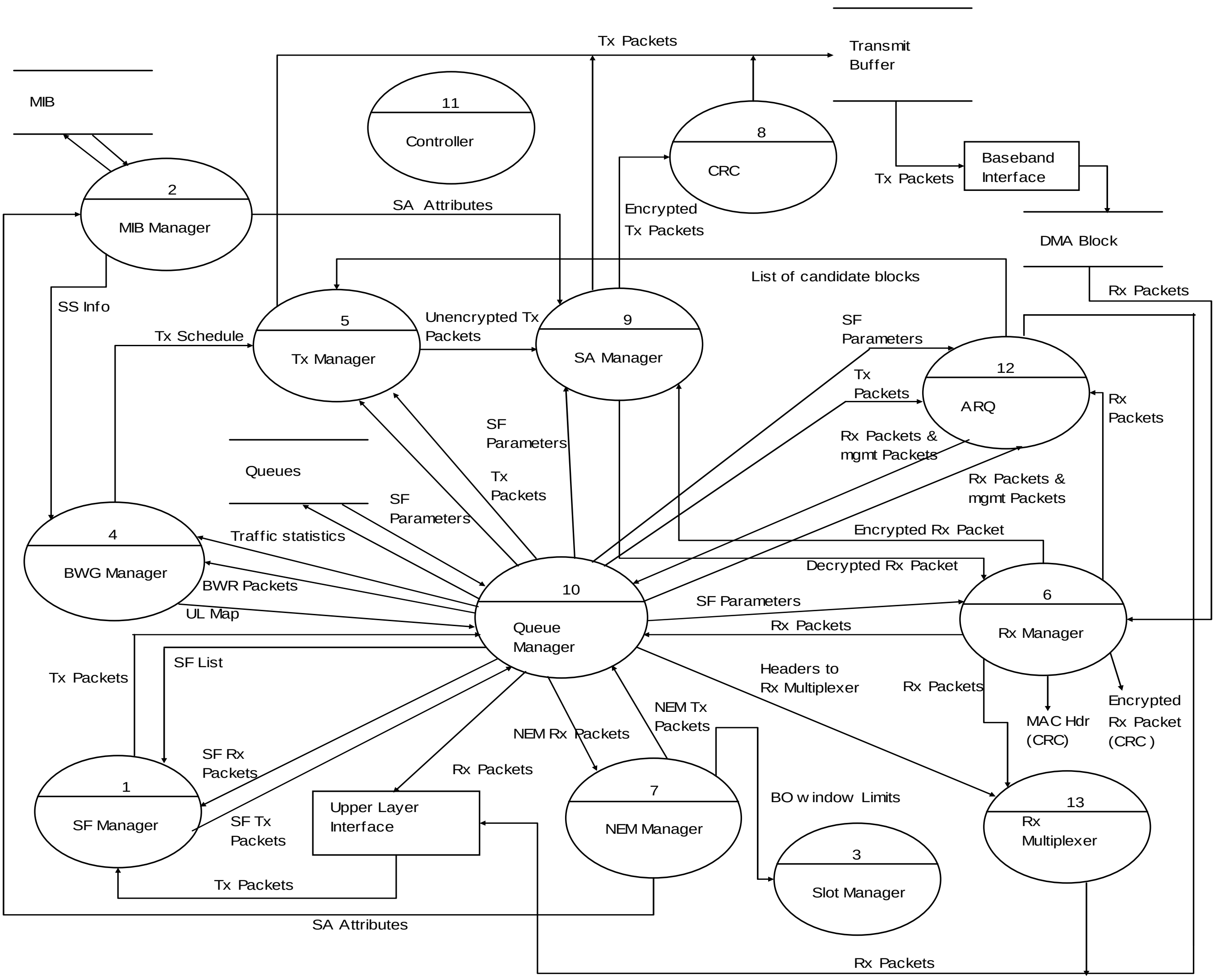

Fig. 3 Dataflow Diagram on the Base Station

These operations include:

- Composing the Generic Mac Header, Fragmentation sub header, and packing sub header.
- Fragmentation and reassembly.
- Packing
- Concatenation
- ARQ
- CRC
- Security Association.

The Tx Manager is invoked for packet transmission, which it carries out as per Tx Schedule prepared by the BWG/BWR Manager.

The Rx Manager is invoked each time a packet is received. It is also the responsibility of the RX Manager to invoke Rx Multiplexer, so that the packet is passed on the concerned module (NEM, SF Manager, BWR/BWG Manager or UL proxy) depending on the packet type.

2.4 Bandwidth Management

Bandwidth Request and Grant operations are the essence of the Scheduling MAC of IEEE 802.16. The Bandwidth Grant Manager at the BS is responsible for catering the Bandwidth requests and allotting Uplink bandwidth to the SS according to the Service flow requirements of the SS. The Downlink Map is constructed keeping in view the availability of Data for the Service Flow and the Service Flow Parameters of the Transmission Service Flows. The BWG Manager prepares the UL and DL maps just prior to the start of each frame.

The BW Request Manager at the SS, is responsible for generating Bandwidth requests and interpreting the received UL Map. The BW Request Manager extracts the allotted bandwidth from the UL Map and decides keeping in view the Service Flow Parameters, which Service Flows are to be granted transmission opportunity. The BW Request Manager then divides the total allotted bandwidth to the selected Service Flows.

2.5 Connection Establishment

A list of Allowed/authorized QoS parameter set is defined at the BS. The list is defined in the SF Manager at the time of initialization. The provisioned QoS parameter set is always equal to some authorized parameter set. The admitted and active parameter sets are a subset of the provisioned QoS parameter set.

The Convergence Sublayer, implemented at SF Manager, classifies the incoming packets from the Upper layer. The classification is based on:

- Type of Service' (TOS) in the IP Header
- Source address in the IP Header
- Destination address in the IP header

These parameters are used to map the incoming data at the CS to the service flows.

BS supports two authorization models, i.e. static and dynamic authorization model. The BS active authorization model is defined by a MIB variable. Service Flow creation, modification and deletion is carried out by the SF manager according to the active authorization model.

2.6 Frame Synchronization

The start of frame is marked by the Frame Start Preamble. At the start of each frame, an event is generated at the BS. Event generation for counting slots and frames at the BS is aided by the timer handler class provided by NS-2. The BS then transmits the Frame Start Preamble at the start of the frame.

SS marks the start of frame upon receiving the frame start preamble from the BS. It adjusts the frame start time by subtracting the ranging response Timing Adjust value from the time when the frame start preamble is received. The value of "timing adjust" for each node is calculated offline by noting the frame transmission and arrival times at the MAC of the transmitting and receiving nodes.

2.7 Network Entry Management

The network entry management by the Network Entry Manager (NEM) is guided by the rules defined in the 802.16 standard. NEM implements the state machines for scanning and synchronization, initial ranging, registration and authorization. The network entry state machines are heavily loaded with timers. These timers are implemented using timer handler class provided by NS-2.

2.8 Contention Resolution

Contention resolution is used while

- Initial Ranging
- Bandwidth Request (Support for Bandwidth request in Req region Full)

The contention resolution parameters are communicated in the UCD message and updated by the slot manager at the SS. The calculation of BO for initial ranging or Bandwidth request is done by Slot Manager, when invoked by either the NEM incase of initial ranging, or BWR manager incase of transmitting Bandwidth request.

5. Simulation Topology

This section describes an example implementation of a typical wireless network topology.

This scenario is setup with 1 BS and 2 SS. For simplicity, bandwidth allocation is illustrated in the uplink direction only. The following parameters are used for the simulation:

Duration of Frame = 100 ms
Duration of Uplink sub frame = 50 ms
Duration of Contention slot for Initial Ranging + Duration of Contention slot for BW Request = 2ms
Effective Uplink sub frame to be granted to SSs = 50 -2 = 48 ms
Phy Type = OFDM
Phy Symbol Duration = 4us
UIUC Burst Profile with Modulation type, FEC code such that the number of data bits per symbol = 48
Max Phy Bandwidth = 48 bits / 4us = 12Mbps
Effective Bandwidth for Uplink = (Number of bits per symbol * Number of symbols in uplink subframe) / Frame duration = 6Mbps
Application Type = FTP over TCP connection.

The packets from the higher layers are mapped to different scheduling services (UGS, nrtps, rtps and BE) on the basis of their QoS requirements. The QoS requirements are derived from the Type of service (TOS) field in the IP header. The priority/ TOS field of the packets are set through the OTcl scripts. The mapping of TOS to Mac Layer Service and the average bandwidth requirements as defined for each service class are listed Table 2.

The output files were generated at BB Proxy level to see the traffic flow. Following screen shots of the BB Proxy File at the BS depict the traffic flow at given time. The files have been formatted for enhanced readability.

Table 2 TOS mapping and Bandwidth requirements

Mac Layer Service	Precedence (TOS/DS5-3)	Typical Bandwidth/ Throughput
UGS	101	64Kbps to 2Mbps
rtPS	100/ 011/ 010	90Kbps
nrtPS	001	50Kbps
BE	000	NA

RX/TX	Time	Pkt Length	CID	Packet Type
Rx	0.250016	29	00 00	04 (RNG_REQ)
Tx	0.300000	26	ff ff	02 (DL-MAP)
Tx	0.300012	41	ff ff	03 (UL-MAP)
Tx	0.300024	204	ff ff	00 (UCD)
Tx	0.300096	264	ff ff	01 (DCD)
Tx	0.300188	73	00 00	05 (RNG-RSP)
Tx	0.400000	26	ff ff	02 (DL-MAP)
Tx	0.400012	41	ff ff	03 (UL-MAP)
Tx	0.400024	204	ff ff	00 (UCD)
Tx	0.400096	264	ff ff	01 (DCD)
Tx	0.500000	26	ff ff	02 (DL-MAP)
Tx	0.500012	41	ff ff	03 (UL-MAP)
Tx	0.500024	204	ff ff	00 (UCD)
Tx	0.500096	264	ff ff	01 (DCD)
Tx	0.500188	162	04 01	0b (DSA-REQ)
Rx	0.555456	37	04 01	0c (DSA-RSP)

Fig. 4 Packet Flow at the BS (Time 0.25 to 0.6 sec)

RX/TX	Time	Pkt Length	CID	Packet Type
Tx	2.500188	143	04 01	0e (DSC-REQ)
Tx	2.600000	22	ff ff	02 (DL-MAP)
Tx	2.600008	41	ff ff	03 (UL-MAP)
Tx	2.600020	204	ff ff	00 (UCD)
Tx	2.600092	264	ff ff	01 (DCD)
Rx	2.655456	37	04 01	0f (DSC-RSP)
Tx	2.700000	30	ff ff	02 (DL-MAP)
Tx	2.700012	41	ff ff	03 (UL-MAP)
Tx	2.700024	204	ff ff	00 (UCD)
Tx	2.700096	264	ff ff	01 (DCD)
Tx	2.700188	37	04 01	10 (DSC-ACK)
Tx	2.700204	254	08 04	01 Data
Tx	2.800000	22	ff ff	02 (DL-MAP)
Tx	2.800008	41	ff ff	03 (UL-MAP)
Tx	2.800020	204	ff ff	00 (UCD)
Tx	2.800092	264	ff ff	01 (DCD)
Rx	2.855456	1254	08 03	01 Data
Tx	2.900000	26	ff ff	02 (DL-MAP)
Tx	2.900012	41	ff ff	03 (UL-MAP)
Tx	2.900024	204	ff ff	00 (UCD)
Tx	2.900096	264	ff ff	01 (DCD)
Tx	2.900188	254	08 04	01 Data
Rx	2.955456	1254	08 03	01 Data

Fig. 5 Packet Flow at the BS (Time 2.5 to 3 sec)

The upper layer interactions are traced by the NS-2 trace functionality. Fig. 6 shows the upper layer packet exchange. The TCP connection on both SS and BS were initiated at 2 sec, which signify the transmission of DSC-REQ message in the Fig. 5.

	Time	From	To	Pkt Type	Pkt Length	Flags	IP Flow ID	Src IP	Dest IP	Seq ID	Pkt ID
h	2	1	2	tcp	40	---A---	0	1.0	0.0	0	0
h	2	0	2	tcp	40	---A---	0	0.1	1.1	0	1
+	2.001	1	2	tcp	40	C------	0	1.0	0.0	0	0
-	2.001	1	2	tcp	40	C------	0	1.0	0.0	0	0
+	2.001	0	2	tcp	40	C------	0	0.1	1.1	0	1
-	2.001	0	2	tcp	40	C------	0	0.1	1.1	0	1
r	2.456466	2	1	tcp	40	C------	0	0.1	1.1	0	1
h	2.456466	1	2	ack	40	CP-AEFN	0	1.1	0.1	0	2
+	2.457466	1	2	ack	40	C------	0	1.1	0.1	0	2
-	2.457466	1	2	ack	40	C------	0	1.1	0.1	0	2
r	2.701209	2	0	ack	40	C------	0	1.1	0.1	0	2
h	2.701209	0	2	tcp	1040	CP-AEFN	0	0.1	1.1	1	3
h	2.701209	0	2	tcp	1040	CP-AEFN	0	0.1	1.1	2	4
+	2.702209	0	2	tcp	1040	C------	0	0.1	1.1	1	3
-	2.702209	0	2	tcp	1040	C------	0	0.1	1.1	1	3
+	2.702209	0	2	tcp	1040	C------	0	0.1	1.1	2	4
-	2.702209	0	2	tcp	1040	C------	0	0.1	1.1	2	4
r	2.856461	2	1	tcp	1040	C------	0	0.1	1.1	1	3
h	2.856461	1	2	ack	40	CP-AEFN	0	1.1	0.1	1	5
+	2.857461	1	2	ack	40	C------	0	1.1	0.1	1	5
-	2.857461	1	2	ack	40	C------	0	1.1	0.1	1	5
r	2.901193	2	0	ack	40	C------	0	1.1	0.1	1	5
h	2.901193	0	2	tcp	1040	CP-AEFN	0	0.1	1.1	3	6
+	2.902193	0	2	tcp	1040	C------	0	0.1	1.1	3	6
-	2.902193	0	2	tcp	1040	C------	0	0.1	1.1	3	6
r	2.956461	2	1	tcp	1040	C------	0	0.1	1.1	2	4
h	2.956461	1	2	ack	40	CP-AEFN	0	1.1	0.1	2	7
+	2.957461	1	2	ack	40	C------	0	1.1	0.1	2	7
-	2.957461	1	2	ack	40	C------	0	1.1	0.1	2	7

Fig. 6 Packet Flow at the BS (Time 2.5 to 3 sec)

The following table gives the detail of the symbols used in the first column of Fig. 6.

Table 3 NS-2 Symbol explanation in Trace file

Symbol	***Meaning***
+	Queue Packet
-	Dequeue Packet
h	Hop
r	Received packet

6. Conclusion

The MAC common part sub layer of 802.16 can be successfully simulated on NS-2, in its entirety by implementing the entire protocol specification. This provides a useful means to evolve and test the design of the MAC, and better understand the specifications.

NS-2 can been an effective platform for development of Bandwidth allocation algorithms and implementation of 802.16 for the purpose of QoS testing and throughput analysis.

Since the MAC layer is encapsulated between an Upper layer proxy and the baseband proxy, its implementation is almost independent of the development environment and can be ported to the actual system with minimal changes.

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