IEEE 802.16 MAC Layer

MAC Protocol

- Objective: to manage the resources of the air-link in an efficient manner and provide Quality of Service (QoS) differentiation.
- Supporting Point to Multipoint (PMP) and Mesh network models.
- To perform link adaptation and Automatic Repeat Request (ARQ) functions to maintain target Bit Error Rates (BER) while maximizing the data throughput.

MAC Layer Functions

- Transmission scheduling
  - Controls up and downlink transmissions so that different QoS can be provided to each user
- Admission control
  - Ensures that resources to support QoS requirements of a new flow are available
- Link initialization
  - Scans for a channel, synchronizes the SS with the BS, performs registration, and various security issues

MAC Layer Functions

- Support for integrated voice/data connections
  - Provide various levels of bandwidth allocation, error rates, delay and jitter
- Fragmentation
  - Sequence number in the MAC header is used to reassemble at the receiver
- Retransmission
  - Implement an ARQ (Automatic Repeat Request)
Channel Access

- Uplink direction
  - SS to BS
  - Combine TDMA (time division multiple access) and DAMA (demand assigned multiple access)
- Downlink direction
  - BS to SS
  - TDM (time division multiplexing)
- Duplexing can be frequency division or time division

Time-Division Duplex

- The frame is subdivided into an uplink subframe and a downlink subframe
  - The division can be dynamic

Frequency-Division Duplex

- The division between uplink and downlink is static

Downlink vs. Uplink

- Downlink (from BS to SS)
  - The data packets are broadcasted to all SSs and an SS only picks up the packets destined to it
- Uplink (from SS to BS)
  - BS determines the number of time slots that each SS will be allowed to transmit in an uplink subframe
  - This information is broadcasted by the BS through the uplink map message (UL-MAP) at the beginning of each frame
  - UL-MAP contains information element (IE) which include the transmission opportunities
IEEE 802.16 Frame Structure

- FCH: Frame Control Header
- DLFP: Downlink Frame Prefix
- DCD: Downlink Channel Descriptor
- UCD: Uplink Channel Descriptor

Broadcast message

Downlink Subframe

- Downlink Interval Usage Code (DIUC) indicates a particular downlink burst profile

Each TDM portion carries the data, organized into bursts with different burst profiles and therefore different level of transmission robustness.

The bursts are transmitted in order of decreasing robustness.
- For example, QPSK modulation, followed by 16-QAM, followed by 64-QAM

Uplink Subframe

- Uplink Interval Usage Code (UIUC) indicates a particular uplink burst profile

TDD downlink subframe structure

TDD uplink subframe structure
DL-MAP and UL-MAP

Management messages are broadcast or sent on three CIDs (dedicated for each SS) in each direction: Basic, Primary, and Secondary

- Uplink Channel Descriptor
- Downlink Channel Descriptor
- UL-MAP
- DL-MAP
- DSA-REQ
- DSA-RSP

MAC Management Connections

Three management connections in each direction are established between the SSs and the BS

- Basic connection: During initial registration and for transport MAC management messages with short delay
- Primary management connection: For exchange of longer, more delay-tolerant MAC management messages
- Secondary management connection: For delay-tolerant, standards-based (DHCP, TFTP, SNMP, etc.) management messages

MAC Management Messages

- Downlink Channel Descriptor (DCD) and Uplink Channel Descriptor (UCD)
  - Periodic broadcast
  - The physical layer characteristics of the downlink and uplink channels
    - The burst profile which has information: modulation type, forward error-correction type, preamble length, etc.

- Downlink map (DL-MAP) and uplink map (UL-MAP)
  - The burst start times on the downlink and the uplink
MAC Management Messages

- Ranging process
  - SSs transmit ranging request at initialization and periodically at the request of the BS to determine power and burst profile changes
- Bandwidth request
  - SSs request bandwidth allocation from the BS

Key Management Messages (1)

<table>
<thead>
<tr>
<th>Type</th>
<th>Message name</th>
<th>Message description</th>
<th>Connection</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>UCD</td>
<td>Uplink Channel Descriptor</td>
<td>Broadcast</td>
</tr>
<tr>
<td>1</td>
<td>DCD</td>
<td>Downlink Channel Descriptor</td>
<td>Broadcast</td>
</tr>
<tr>
<td>2</td>
<td>DL-SAP</td>
<td>Downlink Access Definitions</td>
<td>Broadcast</td>
</tr>
<tr>
<td>3</td>
<td>UL-SAP</td>
<td>Uplink Access Definitions</td>
<td>Broadcast</td>
</tr>
<tr>
<td>4</td>
<td>RNG-REQ</td>
<td>Ranging Request</td>
<td>Initial Ranging  or Basic</td>
</tr>
<tr>
<td>5</td>
<td>RNG-RSP</td>
<td>Ranging Response</td>
<td>Initial Ranging  or Basic</td>
</tr>
<tr>
<td>6</td>
<td>REG-REQ</td>
<td>Registration Request</td>
<td>Primary Management</td>
</tr>
<tr>
<td>7</td>
<td>REG-RSP</td>
<td>Registration Response</td>
<td>Primary Management</td>
</tr>
<tr>
<td>8</td>
<td>received</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>PGM-REQ</td>
<td>Privacy Key Management Request</td>
<td>Primary Management</td>
</tr>
<tr>
<td>10</td>
<td>PGM-RSP</td>
<td>Privacy Key Management Response</td>
<td>Primary Management</td>
</tr>
<tr>
<td>11</td>
<td>DSA-REQ</td>
<td>Dynamic Service Addition Request</td>
<td>Primary Management</td>
</tr>
<tr>
<td>12</td>
<td>DSA-RSP</td>
<td>Dynamic Service Addition Response</td>
<td>Primary Management</td>
</tr>
<tr>
<td>13</td>
<td>DSA-ACK</td>
<td>Dynamic Service Addition Acknowledge</td>
<td>Primary Management</td>
</tr>
<tr>
<td>14</td>
<td>DSC-REQ</td>
<td>Dynamic Service Change Request</td>
<td>Primary Management</td>
</tr>
<tr>
<td>15</td>
<td>DSC-RSP</td>
<td>Dynamic Service Change Response</td>
<td>Primary Management</td>
</tr>
<tr>
<td>16</td>
<td>DSC-ACK</td>
<td>Dynamic Service Change Acknowledge</td>
<td>Primary Management</td>
</tr>
<tr>
<td>17</td>
<td>DSG-REQ</td>
<td>Dynamic Service Deletion Request</td>
<td>Primary Management</td>
</tr>
<tr>
<td>18</td>
<td>DSG-RSP</td>
<td>Dynamic Service Deletion Response</td>
<td>Primary Management</td>
</tr>
</tbody>
</table>

Key Management Messages (2)

<table>
<thead>
<tr>
<th>Type</th>
<th>Message name</th>
<th>Message description</th>
<th>Connection</th>
</tr>
</thead>
<tbody>
<tr>
<td>26</td>
<td>SBB-REQ</td>
<td>SS Basic Capability Request</td>
<td>Basic</td>
</tr>
<tr>
<td>27</td>
<td>SBB-RSP</td>
<td>SS Basic Capability Response</td>
<td>Basic</td>
</tr>
<tr>
<td>28</td>
<td>CLX-CMD</td>
<td>SS network clock companion</td>
<td>Broadcast</td>
</tr>
<tr>
<td>29</td>
<td>DREG-CMD</td>
<td>De/Re-register Command</td>
<td>Basic</td>
</tr>
<tr>
<td>30</td>
<td>DSN-RVD</td>
<td>DSN Received Message</td>
<td>Primary Management</td>
</tr>
<tr>
<td>31</td>
<td>TFTP-CPLT</td>
<td>Config File TFTP Complete Message</td>
<td>Primary Management</td>
</tr>
<tr>
<td>32</td>
<td>TFTP-RSP</td>
<td>Config File TFTP Complete Response</td>
<td>Primary Management</td>
</tr>
<tr>
<td>33</td>
<td>ARQ-Feedback</td>
<td>Standard ARQ Feedback</td>
<td>Basic</td>
</tr>
<tr>
<td>34</td>
<td>ARQ-Discard</td>
<td>ARQ Discard message</td>
<td>Basic</td>
</tr>
<tr>
<td>35</td>
<td>ARQ-Reset</td>
<td>ARQ Reset message</td>
<td>Basic</td>
</tr>
<tr>
<td>36</td>
<td>REP-REQ</td>
<td>Channel measurement Report Request</td>
<td>Basic</td>
</tr>
<tr>
<td>37</td>
<td>REP-RSP</td>
<td>Channel measurement Report Response</td>
<td>Basic</td>
</tr>
<tr>
<td>38</td>
<td>FPC</td>
<td>Fast Power Control</td>
<td>Broadcast</td>
</tr>
</tbody>
</table>

Uplink Periods

- Initial Maintenance opportunities
  - Ranging
  - To determine network delay and to request power or downlink burst profile changes
- Collisions may occur in this interval
- Request opportunities
  - SSs request bandwidth in response to polling from BS
  - Collisions may occur in this interval as well
- Data grants period
  - SSs transmit data bursts in the intervals granted by the BS
  - Transition gaps between data intervals for synchronization purposes.
Uplink Periods

- Three ways are used to determine which SS has the right to transmit
  - Unsolicited bandwidth grants
  - Polling
  - Contention

Two BW-Request Modes in Uplink

- There are two modes of transmitting the BW-Request
  - Contention mode
    - SSs send BW-Request during the contention period. Contention is resolved using back-off resolution
  - Contention-free mode (polling)
    - BS polls each SS and SSs reply by sending BW-request
    - Due to the predictable signaling delay of the polling scheme, contention-free mode is suitable for real time applications

Bandwidth Requests

- All bandwidth requests are in terms of the number of bytes needed to carry the MAC header and payload, but not the PHY overhead
  - The actual time required will depend on the modulation format that is used
- A SS requests uplink bandwidth on a per-connection basis
- The BS grants bandwidth on an aggregate basis for the entire SS
  - Each bandwidth grant is addressed to the SS’s Basic CID, not to individual CIDs
  - SS can use bandwidth stealing internally

Bandwidth Requests

- Types of bandwidth requests
  - Incremental
  - Aggregate
- Types to send BW-Requests
  - Standalone bandwidth request
  - Piggyback bandwidth request
    - always incremental
- SSs should periodically use aggregate bandwidth requests
Contention Resolution

- Based on a truncated binary exponential backoff
  - The initial/maximal backoff window is controlled by the BS
- The SS shall randomly select a number within its backoff window
  - This random value indicates the number of contention transmission opportunities that the SS shall defer before transmitting
- For bandwidth requests, if the SS receives a unicast Request IE or Data Grant Burst Type IE at any time while deferring for this CID, it shall stop the contention resolution process

Polling

- Polling is the process by which the BS allocates to the SSs bandwidth specifically for the purpose of making bandwidth requests
- These allocations may be to individual SSs or to groups of SSs
- Allocations to groups of connections and/or SSs actually define bandwidth request contention IEs
- The allocations are not in the form of an explicit message, but are contained as a series of IEs within the UL-MAP

Polling Way

- Unicast
  - When an SS is polled individually, no explicit message is transmitted to poll the SS. Rather, the SS is allocated bandwidth sufficient to respond with a Bandwidth (BW) Request (in the UL-MAP)
- Multicast and broadcast
  - If insufficient bandwidth is available to individually poll many inactive SSs, some SSs may be polled in multicast groups or a broadcast poll may be issued
  - Certain CIDs are reserved for multicast groups and for broadcast messages
Unicast Polling

1. BS polls for the SS in the uplink subframe via the IEs in UL-MAP
2. SS receives poll message to send a BW request
3. BS allocates available next frame time slots via UL-MAP in respond to the SS’s request
4. SS uses allocated time slots to send data

IEEE 802.16 MAC Framing

MAC Frame Format

- Each MAC packet consists of the three components,
  - A MAC header, which contains frame control information
  - A variable length frame body, which contains information specific to the frame type
  - A frame check sequence (FCS), which contains an IEEE 32-bit cyclic redundancy code (CRC)

MAC Header Types

- A generic frame
  - Be used to transmit data or MAC messages
- A bandwidth request frame
  - Be used by the SS to request BW on the UL
Generic Downlink Header

<table>
<thead>
<tr>
<th>EC</th>
<th>EKS</th>
<th>Length</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Connection Identifier: A unidirectional, MAC-layer address that identifies a connection to equivalent peers

Header Type: Indicates whether this is a generic or bandwidth request header

ARQ Indicator: Indicates whether the frame belongs to an ARQ enabled connection

Fragment Control: Used in fragmentation and reassembly

Fragment Sequence Number: Sequence number of the current fragment

Header Check Sequence: 8-bit CRC to detect errors in the header

Fragmentation

- If fragmentation is not used, FC is set to 00
- Otherwise, all of the fragments are assigned the same FSN and the FC has the following interpretation
  - First fragment (10)
  - Intermediate fragment (11)
  - Last fragment (01)

Generic Uplink Header

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<tr>
<th>EC</th>
<th>EKS</th>
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Header Check Sequence: 8-bit CRC to detect errors in the header

Unsolicited Grant Service

S1 PM

Unsolicited Grant Service with activity detection

S1 Grants per interval

All Others

Piggy-Back Request

(b) Generic uplink header
Generic Uplink Header

- Slip indicator: indicate a slip of uplink grants relative to the uplink queue depth
- Poll-me: request a poll by the base station
- Grants per interval: the number of bandwidth grants required in the next time interval
- Piggyback request: the number of bytes of uplink capacity requested

When a SS finds that its queue of data to send has exceed a threshold for a certain unsolicited grant service (UGS)
- Setting the SI bit and the PM bit
- Or setting the SI bit and using the grants per interval
  - only for UGS with activity detection (flow may become inactive for substantial periods)

Bandwidth Request Header

- Used by a SS to request additional bandwidth
  - No payload field
- Bandwidth request field indicates the number of bytes of capacity requested

DCD Message Format

<table>
<thead>
<tr>
<th>Syntax</th>
<th>Size</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>DCD_Message_Format()</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Management Message Type = 1</td>
<td>8 bits</td>
<td></td>
</tr>
<tr>
<td>Downlink channel ID</td>
<td>8 bits</td>
<td></td>
</tr>
<tr>
<td>Configuration Change Count</td>
<td>8 bits</td>
<td></td>
</tr>
<tr>
<td>TLV Encoded information for the overall channel</td>
<td>variable</td>
<td>TLV specific</td>
</tr>
<tr>
<td>Begin PHY Specific Section ()</td>
<td></td>
<td>See applicable PHY section</td>
</tr>
<tr>
<td>for (i = 1; i &lt;= n; i++) {}</td>
<td></td>
<td>For each downlink burst profile 1 to n</td>
</tr>
<tr>
<td>Downlink_Burst_Profile</td>
<td>PHY specific</td>
<td></td>
</tr>
<tr>
<td>}</td>
<td></td>
<td></td>
</tr>
<tr>
<td>}</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
DCD Message Format

- **Downlink Channel ID**
  - This identifier is arbitrarily chosen by the BS

- **Configuration Change Count**
  - Incremented by one (modulo 256) by the BS whenever any of the values of this channel descriptor change

- **Downlink_Burst_Profile**
  - PHY characteristics that shall be used with a particular DIUC
  - An unordered list of PHY attributes, encoded as TLV values

UCD Message Format

- **Ranging Backoff Start/End**
  - Initial/Final backoff window size for initial ranging contention

- **Request Backoff Start/End**
  - Initial/Final backoff window size for contention BW requests

- **Uplink_Burst_Profile**
  - PHY characteristics that shall be used with a particular UIUC
  - An unordered list of PHY attributes, encoded as TLV values

DL-MAP Message Format

```plaintext
Syntax | Size |
--- | --- |
DL-MAP_Message_Format() | |
  Management Message Type = 2 | 8 bits |
  PHY_Synchronization_Field | variable |
  DCD_Count | 8 bits |
  Base Station ID | 48 bits |
  Begin PHY Specific Section | |
    for (i = 1; i <= m; i++) | |
      DL-MAP_ELEM | variable |
    } |
  } |
  padding { | |
    Padding Nibble | 4 bits |
  } |
```

UCD Message Format

```
UCD_Message_Format() {
  Management Message Type = 0
  Configuration Change Count
  Ranging Backoff Start
  Ranging Backoff End
  Request Backoff Start
  Request Backoff End
  TLV Encoded Information for the overall channel
    for (i = 1; i <= n; i++) {
      Uplink_Burst_Profile
    }
}
```
### DL-MAP Message Format

- **DCD Count**
  - Matches the value of the configuration change count of the DCD

- **Base Station ID**
  - 48-bit long field identifying the BS

### UP-MAP Message Format

<table>
<thead>
<tr>
<th>Syntax</th>
<th>Size</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>UL-MAP_Message_Format()</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>Management Message Type = 3</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>Uplink Channel ID</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>UCD Count</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>Allocation Start Time</td>
<td>32</td>
<td></td>
</tr>
<tr>
<td>Begin PHY Specific Section</td>
<td></td>
<td>See applicable PHY section.</td>
</tr>
<tr>
<td>for (i = 1; i &lt;= n; i++)</td>
<td></td>
<td>For each UL-MAP element 1 to n.</td>
</tr>
<tr>
<td>UL-MAP_ID(i)</td>
<td>variable</td>
<td>See corresponding PHY specification.</td>
</tr>
<tr>
<td>}</td>
<td></td>
<td></td>
</tr>
<tr>
<td>if (byte boundary)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Padding Nibble</td>
<td>4</td>
<td>Padding to reach byte boundary.</td>
</tr>
<tr>
<td>}</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Example: SC DL-MAP_IE

<table>
<thead>
<tr>
<th>Syntax</th>
<th>Size</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>DL-MAP_IE()</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DUC</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>StartPS</td>
<td>16</td>
<td>The starting point of the burst, in units of PS where the first PS in a given frame has StartPS=0.</td>
</tr>
<tr>
<td>if (CID use enabled by burst profile) {</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CID</td>
<td>16 bits</td>
<td>Unicast, multicast, or broadcast value.</td>
</tr>
<tr>
<td>}</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- The physical slot (PS) is the duration of four modulation symbols at the symbol rate of the downlink transmission (for WirelessMAN-SC PHY)

### Example: SC UL-MAP_IE

<table>
<thead>
<tr>
<th>Syntax</th>
<th>Size</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>UL-MAP_IE()</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CID</td>
<td>16 bits</td>
<td></td>
</tr>
<tr>
<td>UIUC</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>if (UIUC == 15)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Extended UIUC dependent IE</td>
<td>variable</td>
<td>See subclasses following 8.1.5.1.2.1.</td>
</tr>
<tr>
<td>} else {</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Offset</td>
<td>12 bits</td>
<td>Offset, in units of mini-slot units, of the preamble relative to the Allocation Start Time.</td>
</tr>
</tbody>
</table>
UP-MAP Message Format

- **Uplink Channel ID**
  - The identifier of the uplink channel to which this message refers
- **UCD Count**
  - Matches the value of the Configuration Change Count of the UCD
- **Allocation Start Time**
  - Effective start time of the uplink allocation defined by the UL-MAP

IEs in Uplink Interval

- **Request IE**
  - The BS specifies an uplink interval in which requests may be made for bandwidth
  - If broadcast or multicast, this is an invitation for SSs to contend for requests
  - If unicast, this is an invitation for a particular SS to request bandwidth

UP-MAP Message Format

- For the SC and SCa PHY layers, the UL-MAP uses units of minislots (the size is specified as a function of PSs)
- For the OFDM and OFDMA PHY layers, the UL-MAP uses units of symbols and subchannels

IEs in Uplink Interval

- **Initial Ranging IE**
  - The BS specifies an interval in which new stations may join the network
- **Data Grant Burst Type IEs**
  - The BS provides an opportunity for an SS to transmit one or more uplink PDUs
- **End of map IE**
  - Terminates all actual allocations in the IE list
- **Gap IE**
  - Indicates pauses in uplink transmissions