MAC Protocol of WiMAX Mesh Network

Ming-Tuo Zhou¹, Peng-Yong Kong²
1: Wireless Communications Laboratory, National Institute of Information and Communications Technology, 20 Science Park Road, #01-09A/10 TeleTech Park, Singapore 117674
2: Institute for Infocomm Research, 1 Fusionopolis Way, #21-01 Connexis, South Tower, Singapore 138632

ABSTRACT
WiMAX based on IEEE std 802.16 is believed one of the important technologies of 4G. It aims to provide high-speed access over distance of several to tens kilometers. In IEEE std 802.16-2004, WiMAX defines an optional mesh mode, with which multi-hop, multi-route, self-organizing and self-healing communications can be achieved in metropolitan-level areas. This chapter presents medium access control (MAC) protocol of WiMAX mesh mode, on frame structure, network configuration, network entry, and scheduling algorithms. It also summaries the most recent progress on data slots resource scheduling and allocation algorithms. Finally, an application example of using WiMAX mesh network for high-speed and low-cost maritime communications is also presented in this chapter.

KEYWORDS
Beyond 3G, Fourth-Generation Wireless Communications, IEEE 802.16, WiMAX, Mesh Network, Ad Hoc Network, Broadband Wireless Communications, Maritime Communications

1. INTRODUCTION
A number of technologies are under development toward next generation wireless networks beyond 3G, such as WiMAX (Worldwide Interoperability for Microwave Access), UMB (Ultra Mobile Broadband), and LTE (Long Term Evolution). Among of them, WiMAX is based on IEEE 802.16 standard, and it aims to provide high-speed data access using a variety of transmission modes, from point-to-multipoint links to portable and fully mobile Internet access.

IEEE std 802.16-2004 is an important member of WiMAX standard family IEEE [802.16-2004]. It specifies layers of Physical (PHY) and Media Access Control (MAC), and it superseded earlier 802.16 documents. This version of standard supports line-of-sight (LOS) connections in 10-66 GHz and non-LOS (NLOS) communication in 2-11 GHz. Two multi-carrier modulation technologies are supported, i.e., OFDM with 256 carriers and OFDMA with 2048 carriers. In 2005, an amendment to 802.16-2004 was completed and named as 802.16-2005. This newer version of standard supports combined fixed and mobile
operation in frequencies below 6 GHz, and it includes many new features such as scalable OFDMA (SOFDMA), Multiple Input Multiple Output (MIMO), Adaptive Antenna Systems (AAS), and hard and soft handoffs.

There are two operation modes defined in IEEE 802.16-2004, i.e., point-to-multipoint (PMP) and mesh. WiMAX PMP networks are based on cellular infrastructure, while WiMAX mesh network operates in a manner of multi-hop and multi-path communications. Some basic terms in WiMAX mesh network are different from that of cellular-like WiMAX PMP networks. In WiMAX mesh, a base station (BS) is a node that has direct connection to backhaul services outside the network and all other nodes are called mesh subscribers (SSs). Uplink and downlink in WiMAX mesh are defined as traffic in the direction to the mesh BS and traffic away from the mesh BS, respectively. In addition, a mesh mode node is different from a PMP mode node in frame structure, procedures of synchronization, network entry, data scheduling, ranging, and power control, etc. Although WiMAX mesh mode is not included in 802.16-2005, it attracts a lot of attention due to a number of advantages and potentials for applications in a variety of scenarios.

Figure 1 shows a typical topology of WiMAX mesh networks. A WiMAX mesh SS can be connected to backbone network through mesh BS. Peer-to-peer communications among mesh nodes is achievable through multi-hop relay. Each WiMAX mesh node is capable of playing a role of wireless router, and then the network capacity can be greatly increased. Since there is no requirement of cellular infrastructure, it is relatively easy to deploy a WiMAX mesh network and the expensive cellular base stations can be saved, hence the cost can be relatively low. As there are multiple paths in a WiMAX mesh network, the network is robust and flexible. In cases of link failure, the network can recover by routing over redundant links. In addition to above, WiMAX mesh network has much longer connection distance (up to tens kilometers) than WiFi mesh network (up to several hundred meters) and ZigBee mesh network (up to several meters). Moreover, unlike WiFi mesh and ZigBee mesh, WiMAX mesh has a Time Division Multiplexing Access (TDMA) MAC protocol, by which easier quality-of-service (QoS) can be achieved.

This chapter serves to introduce MAC protocol of WiMAX mesh mode and summarizes recent research progress on this technology. The frame structure, network configuration, and network entry of WiMAX mesh networks are presented in

![Fig. 1 Typical topology of WiMAX mesh networks.](image-url)
Section 2, 3, and 4, respectively. In Section 5, the three data scheduling schemes: coordinated centralized scheduling, coordinated distributed scheduling and uncoordinated distributed scheduling are introduced, as well as a number of new developments. In Section 6, a distributed adaptive time slots allocation algorithm is described. An example to use WiMAX mesh network for maritime communication is presented in Section 7. And the chapter is concluded by Section 8.

2. FRAME STRUCTURE

WiMAX mesh networks adopt OFDM physical layer and a TDMA-based MAC protocol to support multiple users. As illustrated in Fig. 2, each periodic MAC frame is divided into two sub-frames, namely the control sub-frame and data sub-frame. Each data and control sub-frame is further divided into time slots. Each time slot consists of a number of OFDM symbols. Specifically, each time slot in the control sub-frame is made up of $L_{cslot} = 7$ OFDM symbols, part of which is used as guard time. Thus, the length of the control sub-frame is given by $MSH-CTRL-LEN \times L_{cslot}$ OFDM symbols, where $MSH-CTRL-LEN$ indicates the number of time slots in the control sub-frame. Here, $MSH-CTRL-LEN$ is a 4-bit variable and therefore, there can be at most 16 control time slots in each MAC frame. While the number of time slots in each control sub-frame is a controllable variable, the number of time slots in each data sub-frame is fixed at 256. Let $L_{frame}$ be the number of OFDM symbols in each MAC frame. Then, the number of OFDM symbols in each data time slot, $L_{dslot}$ is given as follows:

$$L_{dslot} = \left\lfloor \frac{L_{frame} - MSH-CTRL-LEN \times L_{cslot}}{256} \right\rfloor.$$  (1)

There are two types of control sub-frame, namely network control sub-frame and scheduling control sub-frame. Network control sub-frame is used to create and maintain cohesion between different nodes in the network. Scheduling control sub-frame is used to facilitate time slot allocation and scheduling for transmissions in the data sub-frame. Each MAC frame only can has either the network control sub-frame or the scheduling control sub-frame.

As illustrated in Fig. 2, network control sub-frame appears less frequently compared to scheduling control sub-frame. Specifically, there is only one network control sub-frame periodically in every SCH-FRM MAC frames, where SCH-FRM is a controllable variable takes a value in multiple of 4.

In a network control sub-frame, the first time slot is for network entry, followed by up to 15 network configuration time slots. In the network entry time slot, a new node may gain synchronization and initial entry to the network. In the network configuration time slots, each SS announces its basic information to its neighboring nodes.

In a scheduling control sub-frame, the first $x$ (see Fig. 2) time slots, where $x = MSH-CTRL-LEN - MSH-DSCH-NUM$ are for centralized scheduling messages, while the remaining $MSH-DSCH-NUM$ time slots are for distributed scheduling messages, since WiMAX mesh supports both centralized and distributed scheduling mechanisms.

Similar to scheduling control sub-frame, each data sub-frame is also divided into two sections as shown in Fig. 2. The first section is reserved for data transmission allocated by centralized scheduling while the second section is for data transmission allocated by distributed scheduling. The variable $MSH-$
Table 1 WiMAX mesh control messages.

<table>
<thead>
<tr>
<th>Message Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSH-NENT</td>
<td>Mesh Network Entry Message</td>
</tr>
<tr>
<td>MSH-NCFG</td>
<td>Mesh network Configuration Message</td>
</tr>
<tr>
<td>MSH-DSCH</td>
<td>Mesh Distributed Scheduling Message</td>
</tr>
<tr>
<td>MSH-CSCF</td>
<td>Mesh Centralized Scheduling Configuration Message</td>
</tr>
<tr>
<td>MSH-CSCH</td>
<td>Mesh Centralized Scheduling Message</td>
</tr>
</tbody>
</table>

Fig. 2 WiMAX mesh MAC frame structure.

CSCH-DATA-FRACTION is 4-bit long and it specifies the number of data time slots in the first section. As such, there are only \( y \) (see Fig. 2) time slots for distributed scheduling in the second section, where \( y = 256 \times (1 - \text{MSH-CSH-DATA-FRACTION} \times 6.67) \). While each data sub-frame is divided into centralized scheduling section and distributed scheduling section, there is no clear separation between uplink and downlink. In WiMAX mesh, uplink and downlink generally refers to transmission directed to and from the BS, respectively.

MAC layer control messages in WiMAX mesh are listed in Table 1.

3. NETWORK CONFIGURATION

WiMAX mesh networks configure the network by MSH-NCFG messages. A MSH-NCFG message contains physical layer information of the node, time synchronization information, scheduling information of MSH-NCFG messages, information of BS and neighbors, network parameters, and network entry information.
3.1 Network Description

The basic description parameters of a WiMAX mesh network are included in MSH-NCFG:NetworkDescriptor information element (IE). The parameters are information of frame duration, control sub-frame length, scheduling frames (SCH-FRM), number of burst profiles, operator ID, channels, and so on.

The frame duration is represented by a 4-bit entry FrameLengthCode and there are seven frame lengths, ranging from 2.5 to 20 ms as shown in Table 2. Control sub-frame length is the number of control slots in a control sub-frame and is indicated by a 4-bit MSH-CTRL-LEN. Among the MSH-CTRL-LEN control slots, the number of opportunities for MSH-DSCH messages is given by MSH-DSCH-NUM and the rest are for MSH-CSCF and MSH-CSCH messages, which are used for centralized scheduling.

The burst profiles are indicated by FECCodeType, each of which represents a type of modulation and coding format. For each burst profile, an exit and an entry threshold are specified. When the carrier-to-interference-and-noise ratio (CINR) is at or below an exit threshold, a more robust burst profile is required. The entry threshold is the minimum CINR that is required to start using this burst profile when a more robust profile is needed.

The number of logical channels of a WiMAX mesh network is given by a 4-bit entry Channels in MSH-NCFG:NetworkDescriptor IE. Each logical frequency channel is described by a MSH-NCFG:Channel IE. Both licensed and licensed-exempt frequency channels can be employed in WiMAX networks. For licensed frequency channels, the physical channel center frequency and channel width are indicated, as well as the channel reuse parameter – the minimum hop number that the channel can be reused. For license-exempt channel, a list is used to map physical channel to logical channel and the physical channel code, the corresponding reuse hops, the maximum transmission power and the maximum effective isotropic radiated power (EIRP) of the logical channel are included in the MSH-NCFG:Channel IE.

3.2 Neighbor and Base Station Information

A WiMAX mesh node broadcasts information of neighbors by MSH-NCFG:NbrPhysical IE and MSH-NCFG:NbrLogical IE. MSH-NCFG:NbrPhysical IE contains physical connection information of this neighbor, such as scheduling information of next MSH-NCFG message of the neighbor NbrNextNextMx and NbrXmtHoldoffExponent, hops to the neighbor, and estimated propagation delay to the neighbor, etc. MSH-NCFG:NbrLogical IE presents logical connection information such as burst profile, transmission power and antenna, and so on, of the reported neighbor. Existing of a physical connection means the neighbor node is able to exchange MSH-NCFG

<table>
<thead>
<tr>
<th>FrameLengthCode</th>
<th>Frame Duration (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>2.5</td>
</tr>
<tr>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>3</td>
<td>8</td>
</tr>
<tr>
<td>4</td>
<td>10</td>
</tr>
<tr>
<td>5</td>
<td>12.5</td>
</tr>
<tr>
<td>6</td>
<td>20</td>
</tr>
<tr>
<td>7–255</td>
<td>reserved</td>
</tr>
</tbody>
</table>
messages with other nodes. In order to exchange data a node requires a logical link with the desired neighbor. This node indicates whether it has a logical link with the reported neighbor, and if not and necessary, it can request to set up a logical link with this neighbor, or it can approve the request of setting up a logical link from the neighbor, all by entries contained in MSH-NCFG:NbrLogical IEs.

In WiMAX mesh network, base station is the node has access to backbone network. Base station information that a node is aware of is also broadcasted by MSH-NCFG messages. The information includes the node ID of the reported base station, the number of hops between this node and the base station, and the required energy per bit needed to reach the base station through this node. The number of hops is the lowest one reported by its one-hop neighbors plus one. The required energy per bit is calculated as the following:

\[ E_{\text{req}} = E_{\text{min}} + \gamma, \]  

where \( E_{\text{req}} \) is the required energy per bit, \( E_{\text{min}} \) is the minimum value its one-hop neighbors reported, \( \gamma \) is the ratio between the transmission power and achievable physical data rate to that one-hop neighbor. This parameter \( E_{\text{req}} \) is helpful to balance the number of hops and the data rates to achieve better capacity.

3.3 MSH-NCFG Scheduling

WiMAX mesh nodes schedule MSH-NCFG messages among two-hop neighbors in a distributed manner by exchanging schedule information of next MSH-NCFG message of its own and its one-hop neighbors.

In order to make all WiMAX mesh nodes have chance to send MSH-NCFG messages, a WiMAX mesh node is not eligible to transmit in a number of MSH-NCFG opportunities after sending a MSH-NCFG packet. The number of MSH-NCFG opportunities \( \text{XmtHoldoffTime} \) is calculated by

\[ \text{XmtHoldoffTime} = 2^{(\text{XmtHoldoffExponent} + 4)}, \]  

where \( \text{XmtHoldoffExponent} \) is a 5-bit parameter included in MSH-NCFG messages.

The eligibility interval of next MSH-NCFG message \( \text{NextXmtTime} \) is computed as the range

\[ \left( 2^{\text{XmtHoldoffExponent}} \cdot \text{NextXmtMx}, 2^{\text{XmtHoldoffExponent}} \cdot (\text{NextXmtMx}+1) \right] \]  

where \( \text{NextXmtMx} \) is a 3-bit parameter included in a MSH-NCFG message.

A WiMAX mesh node determines its next MSH-NCFG transmission time right before the current MSH-NCFG sending time using the following procedure:

1. For each neighbor, it adds the node’s \( \text{NextXmtTime} \) to the node’s \( \text{XmtHoldoffTime} \) to arrive at the node’s \( \text{EarliestSubsequentXmtTime} \).
2. It sets a \( \text{TempXmtTime} \) equal to its \( \text{XmtHoldoffTime} + \) its current \( \text{XmtTime} \).
3. It determines the eligible competing nodes. Eligible competing nodes are all its neighbors that meet any of the following conditions:
   a. The neighbor’s \( \text{NextXmtTime} \) interval includes \( \text{TempXmtTime} \)
   b. The neighbor’s \( \text{EarliestSubsequentXmtTime} \) is equal to or smaller than \( \text{TempXmtTime} \)
c. The neighbor’s NextXmtTime is unknown
4. It holds Mesh Election among the eligible competing nodes and this node. Mesh Election is a procedure of comparison of values generated by a 32-bit reversible pseudo-random mixing function [online]. The input of Mesh Election is TempXmtTime, this node’s ID, and IDs of all competing nodes. If the values generated with this node’s ID are biggest it wins Mesh Election and TempXmtTime is set as this node’s NextXmtTime of its MSH-NCFG message. Otherwise, it sets TempXmtTime equal to the next MSH-NCFG opportunity and repeats steps of 3 and 4, until it wins Mesh Election or it has no competing nodes.

An example of determining competing nodes for MSH-NCFG message scheduling is illustrated in Fig. 3. As illustrated, the node in consideration has three competing neighbors with temporary transmission time shown in the figure (TempXmtTime).

With above algorithm, in each MSH-NCFG opportunity only one node among two-hop neighborhood is allowed to transmit, i.e., MSH-NCFG sending is contention free within two-hop neighborhood.

3.4 Coarse Synchronization
Time-synchronization information of a MSH-NCFG message is indicated by field TimeStamp, which consists of parameter FrameNumber, NetworkControlSlotNumberInFrame, and SynchronizationHopCount. As control slot number in one frame, control sub-frame duration, and frame duration are fixed, upon receiving a MSH-NCFG message, a new node can determine the start time of the frame. This is called coarse synchronization. Fine synchronization is achieved through PHY functions.

The parameter Synchronization-HopCount is used to determine superiority between nodes. A master time keeper node has a SynchronizationHopCount of zero. A
WiMAX mesh nodes will keep synchronization to nodes with lower SynchronizationHopCount, or if hop counts are same, to the node with smaller node ID.

3.5 Multi-channel Operation
A WiMAX mesh network may incorporate up to 16 logical frequency channels. The logical channels are a map of a subset of possible physical channels and are described in MSH-NCFG Network Descriptor.

The data schedule control information, i.e., MSH-DSCH, MSH-CSCH, and MSH-CSCF messages are broadcasted in a base channel that is indicated by a parameter NetworkBaseChannel in MSH-NCFG messages. All nodes use this common channel to exchange data schedule information.

To ensure that all nearby nodes are able to receive MSH-NCFG and MSH-NENT messages, the channel used for their transmission is cycled through the available frequency channels in the band. The channel selection is based on the FrameNumber. For FrameNumber $i$, the logical frequency channel is determined by the array lookup given by

$$\text{NetConfigChannel} = \text{Logical channel list}[(\text{FrameNumber} / (\text{SchedulingFrames} \times 4 + 1)) \% \text{Channels}]$$

where SchedulingFrames $\times 4$ (i.e., SCH-FRM in Fig. 2) defines how many frames have a schedule control sub-frame between two frames with network control sub-frames, and Channels is an entry indicating the number of logical channels in operation.

4. NETWORK ENTRY
Network entry in WiMAX mesh networks is accomplished by MSH-NENT and MSH-NCFG messages. When a new node wishes to join a network, it continuously scans all possible frequency channels to receive MSH-NCFG message, and then to establish coarse synchronization with the network and to acquire network parameters. When a new node receives MSH-NCFG messages from a node at least twice and at least one MSH-NCFG message contains NetworkDescriptor IE, it selects that node as potential sponsor node and synchronizes itself to the node. In the first control slot of a network control sub-frame, the new node sends MSH-NENT:Request to the potential sponsor node. Upon receiving MSH-NENT:Request, the potential sponsor node can reject the request by replying a MSH-NCFG:NetEntryReject or accept the request with a MSH-NCFG:NetEntryOpen. The MSH-NCFG:NetEntryOpen IE contains a temporary schedule for transmission of higher layer authentication and configurations for the new node. This temporary schedule is in data sub-frame, and is called sponsor channel. Upon reception of MSH-NCFG:NetWorkEntryOpen, the potential sponsor node is confirmed as sponsor node, and the new node sends back a MSH-NENT:NetEntryAck to confirm the sponsor channel. And the new node uses the sponsor channel to perform basic capacity negotiation with the sponsor node, node authorization, registration, IP connectivity establishment, time-of-day establishment, and operational parameters transfer with the security sub-layer. When this procedure is finished, the new node sends a MSH-NENT:NetworkClose to the sponsor node. And the sponsor node ends the network entry by replying a MSH-NENT:NetworkAck. By now the new node is regular in the network.
5. SCHEDLING ALGORITHMS

Data transmission scheduling is the key to provide good quality of service and avoid congestion. WiMAX adopts a TDMA-based MAC protocol. In this context, data transmission scheduling equals to time slots allocation, where time slots are allocated to a link (link scheduling) or a packet (packet scheduling) to achieve a certain performance objective. In the literature, various data slots scheduling algorithms have been proposed for WiMAX PMP networks. However, these PMP scheduling algorithms are not directly applicable to WiMAX mesh networks because there are mainly packet scheduling algorithms limited to single hop scenarios where interference from concurrent transmissions over multiple hops is not considered.

In WiMAX mesh networks, three scheduling mechanisms have been standardized. The three mechanisms are called coordinated centralized scheduling, coordinated distributed scheduling and uncoordinated distributed scheduling [Najah A. Abu Ali, et al., 2008].

5.1 Coordinated centralized scheduling

In coordinated centralized scheduling, a BS collects bandwidth requests from all mesh SSs within a certain hop count range and centrally performs the time slots allocation before sending out the allocation outcomes as grants. Thus, two scheduling components are required: (a) Scheduling to transmit requests and grants in control sub-frame, and (b) Scheduling to transmit data packets in data sub-frame.

In the control sub-frames, the requests and grants are transmitted as information elements within MSH-CSCH messages. These MSH-CSCH messages are transmitted in the first part of the scheduling control sub-frame (see Fig. 2) and it is required their transmission being collision free. To ensure collision free transmissions, a node needs to know exactly in which control time slots to transmit its messages. Given a routing tree that spans from the BS, a node transmits MSH-CSCH:Request to its parent toward BS in the order such that the node with the largest hop count transmits first. Similarly, a node transmits MSH-CSCH:Grant to its children away from BS in the order such that the node with the smallest hop count transmits first. In both cases, amongst the nodes with a same hop count, the node with the smallest node index transmits first. All nodes know the routing tree as determined and propagated from the BS in MSH-CSCH messages that are transmitted in the first part of the scheduling control sub-frame (see Fig. 2). Specifically, BS broadcasts the MSH-CSCH in control sub-frame to all its neighbors, and all the neighbors rebroadcast the message accordingly until all SSs have broadcasted the MSH-CSCH message once.

In transmitting MSH-CSCH:Request, each SS includes the requests from its children into its own request size. Upon collecting the requests, BS determines the fraction of data sub-frame allocated to each node such that all requests can be fulfilled within one or two MAC frames. If available data time slots are not sufficient to fulfil all requests, the BS scales down proportionally the sizes of all requests. Only the final allocated fraction of data sub-frame, but not the actual scheduled allocated to each SS is announced in MSH-CSCH:Grant. Each SS derives the actual allocated time slots based on the allocated fractions and the routing tree.

From the operation described above, there will be no transmission collision in control and data time slots within a routing
tree. This collision free allocation is achieved at a high cost where each time slot is allocated to a single node within the routing tree such that no spatial reuse is allowed. In practice, two nodes can transmit concurrently if the interference at their respective receiver nodes is below a certain threshold. This type of interference which is caused by adjacent concurrent transmissions is called secondary interference. In the contrary, primary interference is due to multiple conflicting functions such as simultaneous transmit and receive, or transmit two different packets, at a node at the same time.

In the literature, there are algorithms proposed to deal with secondary interference to promote concurrent transmissions in the coordinated centralized scheduling although it is not sure if these algorithms are really compatible with WiMAX mesh standard. In [Du P., et al., 2007] Active Link Selection (ALS) algorithm has been proposed to eliminate secondary interference for concurrent transmission. In ALS, an interference graph is constructed at the BS. With the interference graph, a set of non-interfering and available links is determined for each time slot. For a given time slot, a link is considered available if the transmitter of the link has a token. Tokens are generated at the traffic source node according to its traffic rate, and are transferred to the receiver node of a link when the link is allocated time slot to transmit. From the set of non-interfering and available links, ALS allocates time slot to the link nearest in terms of hop count to its respective traffic destination node. Here, ALS allocates for as many links as possible from the set before moving on to the next time slot repeating the same process. The efficiency of ALS in improving concurrent transmission is measured in terms of transmission schedule length where a shorter schedule is produced by a more efficient algorithm.

Similar to ALS, in an earlier work, [Han B., et al., 2006] has proposed the Transmission-Tree Scheduling (TTS) algorithms to reduce schedule length with concurrent transmissions. Compared to [Du P., et al., 2007] that select links based on minimum hop count (nearest) to destination, [Han B., et al., 2006] evaluated another three link selection criteria: (a) farthest (maximum hop count) to destination, (b) random selection, and (c) minimum interference. The maximum farthest link selection is simply the opposite of the nearest link selection criteria. In random selection, a link is selected randomly from the set of active links to find out if it can be scheduled concurrently. In the minimum interference selection, the link that interferes with least number of neighboring links is selected. The evaluation results show that these three selection criteria are not as efficient as the nearest link selection.

Concurrent transmissions (spatial reuse) can be improved by careful construction of the routing tree which is rooted at the BS and propagated through MSH-CSCF message as described earlier. In [Wei H. Y., et al., 2005], an interference-aware routing tree construction algorithm and a time slot allocation algorithm are proposed. Here, a blocking value and a blocking metric are separately defined to quantify the interference level of a node and a route, respectively. The blocking value of a node is essentially the total number of neighboring nodes blocked by its transmission. This definition of blocking value is similar to the way of quantifying minimum interference in the concurrent link selection criteria in [Han B., et al., 2006]. Then, the blocking metric of a route is simply the sum of blocking values of all its intermediate nodes. As such,
routing tree should be constructed to minimize the blocking metric. This is achieved through a heuristic such that each new node will join the routing tree through a node with the minimum blocking metric to the BS. With the constructed routing tree, the centralized scheduling algorithm allocates a time slot to SS with the largest unfilled request size. For the same allocated time slot, the algorithm will search for other non-blocked SSs with the largest unfilled request size so that more than one transmission can happen concurrently. The scheduling algorithm will move to the next time slot only if no other unblocked SS is found. This process is repeated until all requests are fulfilled.

In [Ghosh D., et al., 2007], a centralized scheduling algorithm has been proposed to take into consideration flow (link) rate and delay requirements while providing concurrent transmissions. To capture the delay requirement, each link is assigned a start time, \( T_s \) which is the time slot within a MAC frame by which the link must be scheduled so that the flow can reach its destination by its deadline. Assuming each link has the same rate, \( T_s \) of a link is calculated as follows:

\[
T_s = \frac{d - f_s - k \times t_i}{t_2},
\]

where \( d \) is the deadline, \( f_s \) is the start of next MAC frame, \( k \) the number of hops to destination, \( t_i \) is the propagation delay, and \( t_2 \) is the duration of each time slot.

For a route, its entire component links must be scheduled time slots in or before their respective \( T_s \). This time slot allocation algorithm consists of two phases. In the first phase, each link is scheduled sequentially. For a link, it is allocated a sub-channel in all available time slots before \( T_s \) or until the link’s maximum bandwidth requirement is fulfilled. Here, a time slot is considered available when this link does not cause secondary interference to other links already allocated the time slot. Here, we notice that [Ghosh D., et al., 2007] allocates sub-channel in a time slot but this contradicts the WiMAX mesh standard. There is no notion of sub-channel in OFDM adopted by WiMAX mesh. At the end of first phase, all links of a route have been allocated time slots. If the allocated time slots meet or exceed the minimum bandwidth requirement of all links, there is no need to proceed to the second phase. In the second phase, all the time slots that have been allocated to a link but exceed the link’s minimum bandwidth requirement, are taken away to be re-allocated to the links that have not had their minimum bandwidth requirement fulfilled.

5.2 Coordinated Distributed Scheduling

In coordinated distributed scheduling, a SS does not rely on the BS for time slot allocation. When a SS has a packet to send to another SS, it will transmit a bandwidth request to the SS as an information element within MSH-DSCH message. This MSH-DSCH:Request is transmitted in a time slot in the second part of the scheduling control sub-frame (see Fig. 2). The transmitted MSH-DSCH message, amongst others also announces which control time slot the current SS will use to transmit its next control message. No other nodes shall use the announced control time slot and thus, preventing collision. As such, the node must identify its next transmission time slot before transmitting the current MSH-DSCH message. The next transmission control time slot is identified using the Mesh Election Algorithm which ideally allows for only one node to transmit in each time slot. The
algorithm is exactly same as the one used for next MSH-NCFG message scheduling.

A transmitter node sends its MSH-DSCH:Request after winning a time slot for its next transmission through the Mesh Election Algorithm. Upon receiving the request, the receiver node will allocate the first group of available time slots in data sub-frame for transmission. The outcome of this data time slot allocation will be announced by the receiver node as a grant transmitted as an information element in MSH-DSCH message. All the MSH-DSCH:Grants are transmitted in control sub-frame using the same mechanism described above. In response to the grant, the transmitter node will send a grant confirmation as an information element in MSH-DSCH message. This MSH-DSCH:Confirmation is transmitted in the control sub-frame following the same mechanism for a typical MSH-DSCH message. Usually, the data packet will be transmitted in the data sub-frame only after the successful transmission of MSH-DSCH:Confirmation. This process of exchanging MSH-DSCH:Request, MSH-DSCH:Grant and MSH-DSCH:Confirmation between a sender and its receiver is called three-way handshaking and is illustrated in Fig. 4.

From the description above, coordinated distributed scheduling is similar to the coordinated centralized scheduling in the sense that it has to schedule for both control time slots and data time slots. Coordinated distributed scheduling uses the Mesh Election Algorithm to schedule control time slots to transmit request, grant and grant confirmation. For data time slots, a receiver oriented approach is adopted where the receiver node, in response to each received request, allocates the first available time slots.

5.2.1 Scheduling for control sub-frame
In the literature, several algorithms have been proposed to improve control and data time slot allocation in coordinated distributed scheduling. We present the proposed control scheduling algorithms in this sub-section before introducing data scheduling algorithms in the next sub-section.

![Three-way handshake procedure](image-url)
For control scheduling using the Mesh Election Algorithm, the interval between two consecutive successful control messages, $\tau_k$ of node $k$ can be expressed as follows:

$$\tau_k = \text{XmtHoldoffTime}_k + S_k$$  \hspace{1cm} (7)

where $\text{XmtHoldoffTime}_k$ is the holdoff duration of node $k$ and $S_k$ is a random variable experienced by node $k$ due to the Mesh Election Algorithm. Recall that $\text{XmtHoldoffTime} = 2^{\text{XmtHoldoffExponent}+4} \cdot 16$. This means, after each successful transmission in the control sub-frame, a node has to backoff for at least 16 time slots before transmitting another control message. In [Bayer N., et al., 2006], it is argued that in a sparse network with few competing nodes, a node needs not to wait for at least 16 time slots to transmit another control message. Thus, [Bayer N., et al., 2006] has proposed calculating the holdoff duration as follows:

$$\text{XmtHoldoffTime} = 2^{\text{XmtHoldoffExponent}+\alpha}$$  \hspace{1cm} (8)

where $\alpha$ is an integer variable taking value between 0 and 4. It is shown that $\tau_k$ can be significantly reduced by choosing a small $\alpha$.

The algorithm proposed in [Bayer N., et al., 2006] focuses on sparse networks. For a more general case with different node density, [Cao M., et al., 2005] has analyzed the expect value of $S_k$, i.e., $E[S_k]$ assuming that XmtHoldoffExponent is fixed at 4. Assuming the transmission time sequence of the control messages of all nodes are independently and identically distributed renewal processes, [Cao M., et al., 2005] shows that $E[\tau_k] = \text{XmtHoldoffTime}_k + E[S_k]$ and,

$$E[S_k] = \sum_{j=1,j \neq k}^{j=k} \frac{2^{\text{Exp}_j} + E[S_j]}{2^{\text{Exp}_j} + E[S_j]} + \sum_{j=1,j \neq k}^{j=k} 1 + N_{k}^{\text{known}} + 1$$  \hspace{1cm} (9)

where $\text{Exp}_k$ is the XmtHoldoffExponent for node $k$, $N_{k}^{\text{known}}$ is the number of competing neighbors of node $k$ whose next transmission time is known, and $N_{k}^{\text{unknown}}$ is the number of competing neighbors of node $k$ whose next transmission time is unknown. From Eq. (9), the expected interval between two consecutive successful control messages depends on the number of nodes in the network, XmtHoldoffExponent and network topology. Logically, when the number of nodes is increased or when using a larger XmtHoldoffExponent is used, the expected time interval between successful control messages increases.

From [Cao M., et al., 2005], we understand that XmtHoldoffExponent configuration has a different impact in different network scenario. Thus, [Bayer N., et al., 2007] has proposed an algorithm to set XmtHoldoffExponent of a node depending on its status and scenario. In [Bayer N., et al., 2007], a node can have one of the four status: Mesh Base Station (MBS), Active Node (AN), Sponsoring Node (SN) and Inactive Node (IN). Depending on the status, a node’s XmtHoldoffExponent can be set as follows: $0 \leq \text{Exp}_{\text{MBS}} \leq \text{Exp}_{\text{AN}} \leq \text{Exp}_{\text{SN}} \leq \text{Exp}_{\text{IN}} \leq 7$. For example, a node $k$ will adapt its XmtHoldoffExponent, i.e., $\text{Exp}_k$ such that $\text{Exp}_k \leq \text{Exp}_{\text{AN}}$ where node $k$ is an active node. In the adaptation, a node will increase its XmtHoldoffExponent if its NextXmtMX or its neighbor’s NextXmtMX is larger than a threshold. Here, the value of NextXmtMX is used as an indicator to the congestion level. On the other hand, a node will decrease its XmtHoldoffExponent if its status has change in one of the following ways: (a) An IN, SN or AN becomes a MBS, (b) An IN or SN becomes a AN, or (c) An IN becomes a SN. It is shown that such a dynamic adaptation to the XmtHoldoffExponent can reduce control message transmission interval as inactive
nodes increases their XmtHoldoffExponent to reduce contention.

In [Loscri V., 2007], the author has argued that Mesh Election Algorithm may result in under-utilization of control sub-frame. In order to utilize the control sub-frame more aggressively, [Loscri V., 2007] has introduced an additional operation to redistribute unallocated control time slots. The proposed redistribution operation is carried out frame-by-frame where a node that has no allocated control slot in the current frame will randomly pick an unallocated time slot to transmit its control message. However, [Loscri V., 2007] has not described how a node can find out the set of unallocated time slots. Also, we think that this additional redistribution operation may not be necessary because a properly performed Mesh Election Algorithm should utilize all time slots except during the time interval where all nodes are backing off.

5.2.2 Scheduling for data sub-frame

For uncoordinated distributed scheduling for data slots, it is important to ensure fairness in time slot allocation. Intuitively, fixed allocation is the simplest method in achieving fairness by allocating time slots in data sub-frame to the nodes. Let \( N_i \) denotes the number of time slots allocated to node \( i \), \( N_{fr} \) denotes the total number of time slots in the data sub-frame and \( N \) denotes the total number of nodes in the mesh network. Then,

\[
N_i^{rs} = \left( \frac{N_i^{rs}}{N_{fr}} \right). \tag{10}
\]

This algorithm is fair in the sense that each node gets equal throughput, but the disadvantage of this method is in the mesh network, nodes can be involved in different activities and hence has different demand for traffic. With fixed allocation, some inactive nodes may have nothing to send during its scheduled time slot while some active nodes may have lots of data waiting in the queue. Time utilization is very inefficient.

Therefore, [Makarevitch B., 2006, 1] and [Makarevitch B., 2006, 2] have proposed an improvement for fixed allocation algorithm. The proposed algorithm is called Proportional Scheduling (PS) algorithm, such that number of time slots allocated to a node is proportional to the traffic flow. Traffic flow information in a particular node can be propagated to other nodes in the control message. Let \( N_i^{ps} \) denotes the traffic flow on node \( k \). Then,

\[
N_i^{rs} = \left( \frac{N_i^{ps} \times N_{fr}}{\sum_{k=1}^{N} N_k^{ps}} \right). \tag{11}
\]

This method addressed the problem of different traffic load among nodes. We can say that it is fair in the sense of normalized throughput. By using the traffic load information as a weighting factor, time slots in the data sub-frame are better utilized.

Although PS algorithm solves the problem of different traffic demands among nodes, it does not address the variation of traffic load in the mesh network. In practical situations, a node may frequently change its operation from active to inactive and vice versa. Therefore, an Adaptive Data Dependent Scheduling (ADDS) algorithm is further proposed in [Makarevitch B., 2006, 1]. The idea behind ADDS algorithm is to allocate more time slots in the data sub-frame to the nodes with the highest current traffic demand. This algorithm is distributed, because each node in the mesh network will run it. The ADDS algorithm is also coordinated in a sense that, it makes use of the traffic load information broadcasted by the local and neighboring nodes.
All the nodes will broadcast their request slot number in the MSH-DSCH messages. Eventually each node will get the request slots number of its 2 or 3 hop neighbors. In each node, the algorithm will sequentially compare the request slot numbers and assign slot to the node with the maximal request slot number. If one slot happens to be assigned to the local node itself, the local node will pick the receiver node that the local node has the maximum data queue to send to.

Consider two different nodes in the same mesh network, each running this algorithm. If these two nodes are not among the 3-hop neighbors of each other, they will have distinct set of competing nodes. Thus, it is highly possible that these two nodes assign the same time slot to different transmitters. Collision will occur. On the other hand, if both nodes are in the same neighborhood, they will have the same set of competing nodes. Two nodes will not assign the same slot to the same transmitter. The time slot assignment therefore is consistent for the two nodes. No collision will occur. Therefore, to achieve collision free scheduling, each node must include the nodes within a larger neighborhood. Naturally, to include a larger neighborhood with more hops there will be more signaling overhead as more MSH-DSCH messages need to be propagated.

All the algorithms described above are topology dependent, meaning changes in the network topology requires recalculation of a new schedule. To remove the topology dependency, a Finite Field Based Distributed Scheduling Algorithm is proposed in [Makarevitch B., 2006, 1]. This algorithm ensures each node will have one collision free time slot in the data sub-frame. An initial schedule is performed in advance and is robust to the topology changes in the mesh network. Subsequent schedule is performed whenever traffic load is changed, similar to traffic dependent scheduling.

A degree polynomial \( f(x) = \sum_{i=0}^{k} a_i x^i \) has at most \( k \) distinct roots. So, the difference of two polynomials will also have at most \( k \) distinct roots. In the context of WiMAX mesh network, [Makarevitch B., 2006, 1] assigns each node a unique vector of coefficients, \( a_0, a_1, \ldots, a_k \) over a Galois field GF(q), which is equivalent to assign a unique polynomial to each node. In the data sub-frame, a mapping of polynomials into sets of time slots can be done, which will produce sets having no more than \( k \) common time slots between them. So, as long as the number of time slot in one set is larger than \( k \), we can always ensure each node will have at least one collision free time slot within the data sub-frame. To assign the unique coefficient vector to each node in the mesh network in a distributed manner, we can use a pseudo-random generator that takes in the MAC address of the nodes. By exchanging and comparing the coefficient vector, repeated coefficient vector can be regenerated.

### 5.3 Uncoordinated Distributed Scheduling

In distributed scheduling, each sender-receiver pair requests and allocates time slots locally. In WiMAX mesh networks, distributed scheduling can be further classified into coordinated distributed scheduling and uncoordinated distributed scheduling. For coordinated distributed scheduling, as presented in the previous section, the request-grant-confirmation three-way handshaking takes place in the scheduling control sub-frame. For uncoordinated distributed scheduling, the three-way handshaking is carried out opportunistically in the unused time slots in
data sub-frame, and MSH-DSCH messages may collide. Thus, the performance of uncoordinated distributed scheduling is less predictable compared to the coordinated distributed scheduling.

Uncoordinated distributed scheduling can be used for fast, ad-hoc setup of schedules on a link-by-link basis. While transmitting MSH-DSCH:Request, MSH-DSCH:Grant and MSH-DSCH:Confirmation in data time slots, a SS must ensure that the MSH-DSCH and resulting data transmissions do not cause collisions with the data and control traffic scheduled by the coordinated centralized scheduling or coordinated distributed scheduling. The collisions can be partly avoided by having a node to wait a sufficient number of time slots before responding to a MSH-DSCH:Request with its MSH-DSCH:Grant, such that nodes with earlier requests have an opportunity to respond. In the contrary, MSH-DSCH:Confirmation can be sent out immediately following the first successful reception of an associated MSH-DSCH:Grant.

6. DISTRIBUTED ADAPTIVE TIME SLOT ALLOCATION
In distributed scheduling of WiMAX mesh network, a three-way handshake procedure is defined for allocation of data slots. However, there is a lack of detailed algorithm to allocate the data slots. It also has no a solution to deal with conflicts of concurrent transmissions. Conflicts of transmissions may be caused by interference from nodes more than two hops away, and if nodes are mobile, from nodes moving close to the receiver node. To minimize these issues, a distributed adaptive time slots allocation (DATSA) algorithm is proposed in [Kong P.-Y., et al., 2009, 1].

With DATSA, each mesh node keeps track of the availability of its own and its one-hop neighbor’s slots in data sub-frame. A granter marks all slots it granted “busy” and a requester marks all slots it accepted also “busy”. One hop neighbors of the granter and the requester mark their corresponding slots “busy” upon reception of MSH-DSCH:Grant from the granter and MSH-DSCH:Confirmation from the requester. Other slots in data sub-frame are marked as “free”. No states “available for reception only” or “available for transmission only” is allowed. Further, each mesh node broadcasts their slots availability using MSH-DSCH:Availability that defined in the protocol, and each mesh node also keeps track of the slots availability of its one-hop neighbors. If a mesh node is “busy” or any one of its one-hop neighbor is “busy” in a slots range, it cannot transmit or receive data packets in this slots range. By doing so, slots in use by a two-hop neighbor will not be used by this node, and then interference due to concurrent transmissions can be minimized.

A simple application example of DATSA for case with single frequency channel is shown in Fig. 5 (a). Node B is transmitting to its one-hop neighbor node C, and then both of them mark slots range $s_1$ as “busy”. Node D and node A mark their slots range $s_1$ as “busy”, after receiving MSH-DSCH:Grant from node C and MSH-DSCH: Confirmation from node B, respectively. Node D broadcasts DSH-DSCH:Availability, and then its one-hop neighbor node E knows node D is “busy” in slots range $s_1$, and it marks the corresponding slots range in its record of neighbor D’s availability. As result, if node F requests slots to node E, node E will not grant $s_1$ to node F, but will grant other free slots range.
To extend the above method to case of multi-channel, following conditions should be met when grant data slots for a request [Zhou M.-T., et al., 2009]:

In the slots range to be granted, there is no scheduled transmission or reception with the granter and requester in all frequency channels, as well as with their one-hop neighbors in the corresponding frequency channel.

Note here single radio operation is assumed, i.e., a mesh node cannot transmit and receive simultaneously.

When a node scheduled transmission or reception in a slots range of a frequency channel, it marks the corresponding slots range in that frequency channel “busy”. Then in one-hop neighbor’s records of the requester and the granter, the slots range in the granted channel will be marked “busy” while in other frequency channels, the corresponding slots range is still “free”. As results, the one-hop neighbors of both granter and requester can use the corresponding slots range in other frequency channels. Hence, concurrent transmission and reception can occur within two-hop neighborhood in different frequency channels, and the network capacity can be improved.

Figure 5 (b) shows a simple example to apply the above method in case of multi-channel. As shown in the figure, node B and node C are using slots range $s_1$ in frequency $f_1$ channel for data transmission. Marking and broadcasting availability of the granted channel $f_1$ at neighboring nodes A, D, and E are same as the case of single channel. For frequency channel $f_2$ and $f_3$, node B and C leave the corresponding slot range $s_1$ “free”. However, $s_1$ in channel of frequency $f_2$ and $f_3$ cannot be assigned for transmission or reception at node B and C due to single radio operation. Other nodes (A, D, and E) are “free” in $s_1$ of channel $f_2$ and $f_3$, and they can schedule transmission or reception of data in these data slots.

As illustrated in Fig. 5, there is a delay between the time a receiver node receives a request and the time the receiver node sends its next scheduling control message with the respective grant. This delay is a random variable due to the mesh election algorithm. Instead of generating grant immediately upon receipt of a request, DATSA proposes to generate the grant right before transmitting the scheduling control message in the control slot. This helps to avoid spatial reuse conflicts when two neighboring nodes allocate a same time range due to unawareness of each other’s allocation. However, conflict in slot allocation can still occur due to latency in sending confirmation. To handle this issue, DATSA proposes that a sender node checks for its slot availability right before sending a confirmation but not immediately after receiving a grant. Upon the checking, if an allocated slot is already marked unavailable, the node should send a cancellation instead of confirmation. In DATSA, the cancellation should piggyback the original request as re-request, and should inform the receiver node to release its respective allocated time slots. All neighboring nodes that overhear the cancellation should also release their respective time slots by marking them as “free”.

In the example shown in Fig. 4, if there is an absence of node D, then node E is not aware of the allocations of node C, and will possibly allocate the same slots range $s_1$ for transmission and reception with node F. In view of this issue, DATSA proposes to detect conflict in slot allocation by monitoring the number of successful transmissions within a time window $T_d$ at
the receiver node. The value $T_d$ is determined based on probability of zero packet arrival at the sender node for transmission and the probability of transmission failure due to channel error. If there is no successful transmission within the time window, the sender node should send a cancellation. The cancellation message releases the allocated time slot. Different from the cancellation by sender node described earlier, this cancellation by receiver node does not act as a re-request. On the other hand, the sender node, upon receiving the cancellation, should send a re-request if there is still data packet to transmit.

When a cancellation transmitted from the receiver node to the sender node, DATSA interprets this as a detected allocation conflict and proposes to adapt to the detection by not allocating the same time slot to the same receiver node. To realize this, DATSA will only scan for available slot for this receiver node starting from the slot right after the slots range of the last allocation. If this operation reaches the end of the 256 slots data sub-frame, it starts from the first slot.

7. MARITIME WIMAX MESH NETWORKING

In this section, we illustrate an application example of using WiMAX mesh for high-speed and low-cost ship-to-ship/shore communications.
With the development of information technology and maritime industry, there is an increasing need of high-speed and low-cost wireless communications in maritime environment. Similar to the on-land vehicular networks that are under development for better vehicles safety and higher transportation efficiency, maritime wireless networks are required at sea to improve maritime safety and operation efficiency. Such a network can be used for better navigation, ship traffic management, sea condition surveillance, disaster rescue, location reporting and so on. In addition, ship crew and passengers need general communications like Internet, telephone, and FAX etc.; fleet and seaport managers need effective communication means for ship and seaport managements. Unfortunately, there is a lack of such a broadband wireless network in current maritime environment. The present maritime communications are mainly based on analogue HF/VHF networks and satellite links. Marine HF/VHF networks have low-bandwidth and are mainly used for automatic identification system (AIS), weather radio broadcast, and distress rescue, etc. Clearly, they cannot fulfill requirements of modern maritime users. A typical satellite system is Inmarsat. The most recent system is Fleet Broadband that can provide services of voice, FAX, ISDN (64 kbps), standard IP (up to 432 kbps), steaming IP (up to 256 kbps), and text messages. However, all with higher price and lower speed compared to most of the current terrestrial networks.

On the other hand, broadband wireless technologies are actively studied for use on land. Developments include 3G networks, WiMAX networks, and Wireless LANs, etc. Outputs of these technologies can be used at sea. For this purpose, a project TRITON (TRI-media Telematic Oceanographic Network) is proposed [Pathmasuntharam J. S., et al., 2007]. The network envisaged in TRITON for maritime communications is WiMAX mesh based on IEEE std 802.16-2004, as this technology allows long range access and multi-hop communications. It is a better choice in waters far from shores (like more than 100 km) as it is difficult to setup cellular infrastructure there. Moreover, a mesh network is capable of self-organizing, self-healing, and routing packets through multiple paths, thus it is robust and suitable for maritime environments in which radio links may experience frequent break due to
sea wave movement and occlusion. In addition, WiMAX mesh networks employ TDMA based MAC protocol that can offer more efficient bandwidth utilization through time slot allocation or scheduling compared to contention based random access MAC like that of Wi-Fi.

7.1 High Level Architecture of TRITON

Figure 6 shows the high level architecture of TRITON. The coverage extension is achieved by forming a WiMAX mesh network amongst neighboring ships, marine beacons and buoys. The WiMAX mesh network will be connected to the terrestrial networks via land stations, which are placed at regular intervals along the shoreline. Each ship will carry a WiMAX mesh radio that has the capability of frequency agility where frequencies can be switched to suite the geographic location or sea conditions. In port waters or narrow water channels, the radio frequency usage will be based on radio frequencies that are limited by land based terrestrial communication systems. In locations far away from land, the frequencies could be in UHF, VHF or HF bands. While the mesh network is ideal when there are sufficient ships to relay the transmission, in locations where ships are sparse, the TRITON system can fall back to a satellite communication link.

7.2 Considerations of Maritime WiMAX Mesh Networking

WiMAX mesh network is initially designed for range extension in communities with sparse users. To apply WiMAX mesh network in maritime environment that is different from a terrestrial environment in radio propagation and nodes mobility, some considerations and improvements are necessary.

7.2.1 Distributed Scheduling vs. Centralized Scheduling

Coordinated distributed scheduling is adopted in TIRTON based on following analysis:

- A maritime WiMAX mesh network is highly dynamic due to sea wave movement and ship mobility. This will lead to frequent change of network topology. If centralized scheduling is uses, it will result in frequent change of scheduling tree and flush of MSH-CSCF and MSH-CSCH messages. There is no such an issue with coordinated distributed scheduling as it schedules data transmission in a distributed manner by exchanging MSH-DSCH messages.

- In areas like seaport, the number of nodes in coverage could be tens to hundreds. If centralized scheduling is used the size of MSH-CSCF and MSH-CSCH messages will be possibly larger than the capacity of a control slot.

- Concurrent transmission is not allowed with centralized scheduling with current standard. While, space reuse is possible in coordinated distributed scheduling and then higher capacity is achievable.

7.2.2 Supporting to Mobility

Mobility is not supported in the current WiMAX mesh standard while this is needed in maritime WiMAX mesh networks. This requires the maritime WiMAX mesh nodes can dynamically update the neighbor list and corresponding parameters such as hop counts, estimated propagation delay, transmission power, transmission antenna, and burst profile. Moreover, mechanism of detection of transmission conflicts is required. Conflicts may happen when ships far away moves into each other’s
interference range. This issue can be minimized by DATSA presented in Section 6.

7.2.3 Packets Retransmission
In maritime environment, the communication link quality is affected by sea wave movement, ship mobility, and propagation impairments. In a mild sea condition and with careful designs, the probability to have a good link is high; however, following a good link, a bad link may last several seconds due to the long period of sea waves. In this case, retransmission for a failed packet over the same link may also fail and then it is not an effective solution for link failures. Instead, communication diversity can be used as that presented in [Kong P.-Y., et al., 2008, 1].

7.3 Routing Protocol
In a maritime multi-hop mesh network, a connection link may break often due to wave rocking and occlusion. As such routing protocol is very important in ensuring connectivity and reliable packet delivery. Three well known multi-hop routing protocols have been evaluated with a maritime simulator developed: Optimized Link State Routing Protocol (OLSR), Ad hoc On-demand Distance Vector (AODV) and Ad hoc On-demand Multipath Distance Vector (AOMDV). Simulations for packets transmission have been carried out using a maritime simulator. Simulated results show that OLSR has better performance in initial packet delay (i.e., time delay of the first packet arriving destination), because it is a proactive routing protocol and then routes are set up before traffic flow starts. However, in terms of average packet delay, OLSR is inferior to AODV and AOMDV because of its slow reaction to the link breakages that happen often in maritime environment. AODV has better performance in initial packet delay than AOMDV, but in average packet delay and packet delivery ratio, AOMDV has better performance. However, none of the three protocols is ideal for maritime multi-hop mesh networks. And TRITON developed and uses a new routing protocol called MAC-based Routing Protocol for TRITON (MPRT) [Kong P. Y., et al., 2009, 2].

MPRT is an optimization of the classical routing algorithms tailored to the features of WiMAX mesh network and requirements of maritime communications. Designs and features of MPRT protocol include, 1) proactive; 2) deliver routing information by MSH-NCFG message; 3) maintain multiple routing paths. Routing information is piggybacked on MSH-NCFG messages, and because this message is periodically transmitted in dedicated control slots in a collision-free manner, the overhead and delay for routing information spreading can be greatly reduced. As in a maritime mesh network, nodes are mobile and the network performance is sensitive to routes, thus, MPRT considers both routing cost and stability in selecting route. Hop count is set as routing cost, and MPRT uses Received Signal Strength (RSS) as stability metric. Only if the link's RSS value is above an upper threshold it is eligible for being chosen for routing. A mesh node keeps several candidate links for next hops, and when a better route appears, it switches to it immediately. If a link breaks, a mesh node looks up the list of backup links and chooses the one with least hop count among links having sequence number larger than the broken one. Simulation results show MPRT is better than OLSR, AODV and AOMDV in initial packet delay, average packet delay and throughput.

8. CONCLUSION
MAC protocol of WiMAX mesh network defined in IEEE 802.16-2004 is presented in this chapter. The content includes frame
structure, network entry and configuration, scheduling MAC control messages, as well as a bunch of data slot scheduling algorithms proposed recently. In addition, it also introduced a detailed algorithm DATSA for data slots allocations. Finally, as an application example, a maritime WiMAX mesh network is described, including some considerations and new developments to apply this technology in maritime environment.

REFERENCE

[online] http://home.comcast.net/bretm/hash/


