Comparative Analysis of Wireless Broadband Mesh and Multi-hop Networks

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Abstract— This paper provides a comparative analysis of wireless broadband mesh and multi-hop networks. This analysis focuses on synchronization and centralized and distributed scheduling in wireless broadband mesh networks. In addition, it also describes the additional addressing and connection definition that applies to multi-hop relay systems. The comparative analysis is made on the basis of conceptual flow diagrams.

Index Terms— Wireless broadband mesh networks, wireless broadband multi-hop networks, Worldwide Interoperability for Microwave Access (WiMAX).

I. INTRODUCTION

WiMAX (Worldwide Interoperability for Microwave Access) is an emerging wireless technology that is expected to provide high data rate communications in metropolitan area networks (MANs). In the past few years, the IEEE 802.16 working group has developed a number of standards for WiMAX. The first standard, published in 2001 [1], provides communications guidelines in the 10-66 GHz frequency band. In 2003 the IEEE 802.16a standard was introduced to provide additional physical layer specifications for the 2-11 GHz frequency band [2]. These two standards were further revised in 2004 (IEEE 802.16-2004) [3]. The IEEE 802.16e standard, approved in 2005, is presently the official standard for mobile applications [4]. Recently, a new draft, P802.16jD1, has been proposed for fixed and mobile broadband wireless access systems-multihop relay specification [5].

The IEEE 802.16x standards provide four PHY specifications for the licensed bands in the physical layer. These four specifications are Wireless-MAN-SC (single carrier), -SCa, -OFDM, (orthogonal frequency – division multiplexing), and –OFDMA (orthogonal frequency –division multiple access). In addition, the standards also support different PHY specifications (-SCa, -OFDM, and –OFDMA) for the unlicensed bands: wireless, high-speed, and unlicensed MAN (WirelessHUMAN). Most PHYs are designed for non-line-of-sight (NLOS) operation in frequency bands below 11 GHz, except –SC, which is for operation in the 10-66 GHz frequency band. To support multiple subscribers, IEEE 802.16 supports both time-division duplex (TDD) and frequency-division duplex (FDD) operations.

In the medium access control (MAC) layer, IEEE 802.16-2004 supports two modes: point-to-multipoint (PMP) and mesh. The former organizes nodes into a cellular-like structure consisting of a base station (BS) and subscriber stations (SSs). The channels are divided into uplink (from SS to BS) and downlink (from BS to SS), and both uplink and downlink channels are shared among the SSs. PMP mode requires all SSs to be within the transmission range and clear line of sight (LOS) of the BS. On the other hand, in mesh mode, an ad hoc network can be formed with all its nodes acting as relaying routers in addition to their sender and receiver roles, although there may still be nodes that serve as BSs to provide Internet connectivity.

In multi-hop relay networks, according to the new P802.16jD1 draft, all connection types specified in PMP mode should be supported between the multi-hop relay – base station (MR-BS) and multi-hop station (MS). In MR networks, these connections may pass through one or more RSs.

The remainder of this paper is organized as follows: Section 2 describes the wireless broadband mesh and multihop networks. Section 3 explains the wireless broadband mesh networks in more detail. Section 4 analyses the wireless broadband multi-hop networks. Finally, Section 5 summarizes our work and proposes future research.

II. WIRELESS BROADBAND MESH AND MULTI-HOP NETWORKS

The definition of a wireless broadband mesh network is specified in the 802.16-2004 standard. The main difference between the PMP and Mesh modes is that traffic only occurs between the BS and SSs in the PMP mode, while traffic can be routed through other SSs in the Mesh mode and can occur directly between SSs. Depending on the transmission protocol algorithm used, this can be done on the basis of equality using distributed scheduling, or on the basis of superiority of the Mesh BS, which effectively results in centralized scheduling. Within a Mesh network, a system that has a direct connection to Internet services outside the Mesh network is termed a Mesh BS. All the other systems of a Mesh network are termed Mesh SS. In a Mesh architecture, the uplinks and the downlink are defined as traffic directed toward the Mesh BS and traffic relayed away from the Mesh BS, respectively.

978-0-7695-3320-9/08 $25.00 © 2008 IEEE
DOI 10.1109/CERMA.2008.25

In a Mesh system, not even the Mesh BS can transmit without having to coordinate with other nodes. Distributed scheduling requires all nodes, including the Mesh BS, coordinate their transmissions in their two hop neighborhood and broadcast their schedules (available resources, requests and grants) to all neighboring nodes. Optionally, the schedule may also be established by directed uncoordinated requests and grants between two nodes. Nodes ensure that the resulting transmissions do not cause collisions with the data and control traffic scheduled by any other node in the two-hop neighborhood. There is no difference in the mechanism used in determining the downlink and uplink schedules. Centralized scheduling manages resources from a coordinating Mesh BS. The Mesh BS, therefore, gathers resource requests from all the Mesh SSs within a specified hop range. It also determines the resources allocated for the downlink and uplink and communicates this information to all the Mesh SSs within the hop range. The grant messages do not contain the actual schedule, but each node computes it by using the predetermined algorithm within given parameters.

The wireless broadband multi-hop network described in the 802.16j unapproved standard provides for an optional deployment that offers additional coverage in an access network. In Multi-hop Relay (MR) networks, the BS may be replaced by a Multihop Relay BS (MR-BS) and one or more Relay Stations (RS). Traffic and signaling between the SS and MR-BS are relayed by the RS thereby extending the coverage and performance of the system in areas where RSs are deployed. Each RS is under the supervision of a parent MR-BS. In a more than two hop system, traffic and signaling between an access RS and MR-BS may also be relayed through intermediate RSs. The RS may be located in a fixed location (i.e. attached to a building) or, in the case of an access RS, it may be mobile (i.e. traveling with a transportation vehicle). The SS may also communicate directly with the MR-BS.

III. WIRELESS BROADBAND MESH NETWORKS

The wireless broadband mesh network standard specifies two types of scheduling modes: distributed and centralized scheduling. In distributed scheduling, stations that are directly linked are called neighbors and form a neighborhood. Neighbor nodes are defined as nodes that are “one hop” away from the transmitting node. A two-hop extended neighborhood additionally contains all the nodes of the immediate neighborhood. In the coordinated distributed scheduling mode, all the stations (BS and SSs) coordinate their transmissions in their extended two-hop neighborhood. The coordinated distributed scheduling mode uses part of the control frame to transmit its own schedule and propose schedule changes on a PMP basis to all its neighbors.

All neighbor stations receive the same transmission schedule within a given channel. All the stations in a network use this same channel to transmit schedule information in a format of specific resource requests and grants.

Coordinated distributed scheduling ensures that transmissions are scheduled in a manner that does not rely on the operation of a BS, and that are not necessarily directed to or from the BS. Within the constraints of the coordinated schedules (distributed or centralized), uncoordinated distributed scheduling can be used for fast, ad-hoc setup of schedules on a link-by-link basis. Uncoordinated distributed schedules are established by directed requests and grants between two nodes, and are scheduled to ensure that the resulting data transmissions (and the request and grant packets themselves) do not cause collisions with the data and control traffic scheduled by the coordinated distributed nor the centralized scheduling methods.

Both the coordinated and uncoordinated distributed scheduling employ a three-way handshake.

— MSH-DSCH: Request is made along with MSH -DSCH: Availabilities, which indicate potential slots for replies and actual schedule.

— MSH-DSCH: Grant is sent in response indicating a subset of the suggested availabilities that fits, if possible, the request. The neighbors of this node not involved in this schedule assume the transmission takes place as granted.

— MSH-DSCH: Grant is sent by the original requester containing a copy of the grant from the other party, to confirm the schedule to the other party. The neighbors of this node not involved in this schedule assume the transmission takes place as granted.

The differences between coordinated and uncoordinated distributed scheduling are as follows: In the coordinated case, the MSH-DSCH messages are scheduled in the control subframe in a collision free manner; whereas, in the uncoordinated case, MSH-DSCH messages may collide. Nodes responding to a Request should, in the uncoordinated case, wait a sufficient number of minislots of the indicated Availabilities before responding with a grant, such that nodes listed earlier in the Request have an opportunity to respond. The Grant confirmation is sent in the minislots immediately following the first successful reception of an associated Grant packet.

The schedule using centralized scheduling is determined in more of a centralized manner than in the distributed scheduling mode.

The network connections and topology are the same as in the distributed scheduling, but the scheduled transmissions for the SSs are defined by the BS. The BS determines the flow assignments from the resource requests from the SSs. Subsequently, the SSs determine the actual schedule from these flow assignments by using a common algorithm that divides the frame proportionally to the assignments. Thus, the BS acts just like the BS in a PMP network, although not all of the SSs have to be directly connected to the BS, and the assignments determined by the BS extends to those SSs not directly connected to the BS. The SS resource requests and the BS assignments are both transmitted during the control portion of the frame.

Centralized scheduling ensures that transmissions are coordinated to ensure collision-free scheduling over the links in the routing tree to and from the BS in a generally more optimal manner than the distributed scheduling method for traffic streams (or collections of traffic streams that share links), which persists over a duration that is greater than the cycle time to relay the new resource requests and distribute the updated schedule.

When using coordinated distributed scheduling, all network stations use the same channel to transmit schedule information as specific resource requests and grants in MSH-DSCH messages.
A station indicates its own schedule by regularly transmitting a MSH-DSCH, which is transmitted during the control portion of the frame. The relevance of any specific MSH-DSCH is variable and the transmission is entirely up to the station.
MSH-DSCH messages are transmitted regularly throughout the whole Mesh network to distribute node schedules and, together with network configuration packets, provide network synchronization information.

When employing a centralized scheduling strategy, the BS act as a centralized scheduler for the SSs. Using centralized scheduling, the BS provides schedule configuration (MSH-CSCF) and assignments (MSH-CSCH) to all the SSs.
The BS determines the assignments based on the resource requests received from the SSs. Intermediate SSs are responsible for forwarding these requests as specified by the last, most distant MSH-CSCF update received from the BS. All the SSs first listen and jointly compute the schedule and then forward the MSH-CSCH message to the most distant neighborhood nodes from the BS.

III.1 MESH NETWORK SYNCHRONIZATION

Network configuration (MSH-NCFG) and network entry (MSH-NENT) packets provide a basic level of communication between nodes in different nearby networks, whether from the same or different equipment vendors or wireless operators. These packets are used to synchronize both centralized and distributed control Mesh networks.
This communication is used to support basic configuration activities such as: synchronization between nearby networks used (i.e., for multiple, co-located BSs to synchronize their uplink and downlink transmission periods), communication and coordination of channel usage by nearby networks, and discovery and basic network entry of new nodes.
MSH-NCFG, MSH-NENT, and MSH-DSCH can assist a node in synchronizing frame transmission. For these messages, the control subframe, which initiates each frame, is divided into transmit opportunities. The first transmit opportunity in a network control subframe may only contain MSH-NENT messages, while the remainder **MSH-CTRL-LEN**-1 may only contain MSH-NCFG messages. In scheduling control subframes, the **MSH-DSCH-NUM** transmit opportunities assigned for MSH-DSCH messages come last in the control subframe. The MSH-NCFG messages also contain the number of their transmit opportunity, which allows nodes to easily calculate the frame start time.
III.2 NETWORK ENTRY AND INITIALIZATION

Node initialization and network entry procedures in Mesh mode are in some aspects different from those in PMP mode. A new node entering the Mesh network obeys the following procedures (Figure 1).

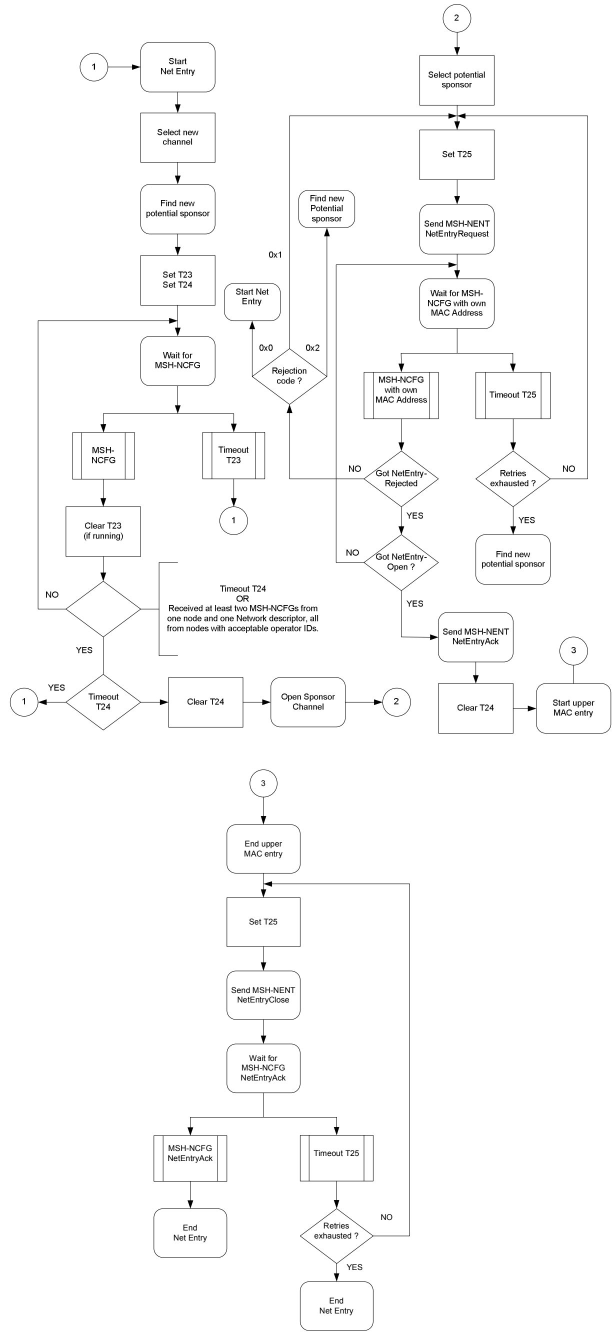

Figure 1: Mesh network synchronization and entry- new node.

For a node to enter the Mesh, it must first:

1) *scan for active network and establish network synchronization.*
2) *obtain network parameters (from MSH-NCFG messages).*
3) *open a Sponsor Channel.*
4) *receive node authorization.*
5) *perform node registration.*
6) *establish IP connectivity.*
7) *establish time of day.*
8) *transfer operational parameters.*

On initialization or after signal loss, the node search for MSH-NCFG messages to acquire synchronization with the mesh network. Upon receiving a MSH-NCFG message, the individual nodes acquire the network time from the message **Timestamp** field. Nodes may have nonvolatile storage in which the most recent operational parameters are stored and first try to re-acquire coarse synchronization with the network. If this fails, nodes begin to continuously scan the possible frequency band channels until a valid network is found. Once, the PHY has actually achieved synchronization, the MAC attempts to acquire network parameters while, at the same time, the each node build its physical neighbor list.

A node remains in synchronization as long as it receives MSH-NCFG messages. A node accumulates MSH-NCFG messages at least until it receives a MSH-NCFG message from the same node twice and until it has received a MSH-NCFG: Network Descriptor with an operator ID matching (one of) its own if it has any. In parallel, the new node builds a physical neighbor list from the acquired information.
From the established physical neighbor list, the new node selects a potential Sponsoring Node out of all nodes having the Logical Network ID of the node for which it found a suitable Operator ID (Figure 2). The new node then synchronizes its time to the potential sponsor assuming 0 propagation delay after which it sends a MSH-NENT: NetEntryRequest including the Node ID of the potential sponsor.
Once the Candidate Node has selected a Sponsoring Node, it uses the Sponsoring Node to negotiate basic capabilities and perform authorization. For that purpose the Candidate Node first request the sponsoring node to open sponsor channel for more effective message exchange.

After, the new node has selected one of its neighbors as the candidate sponsoring node it becomes a candidate node. To get further in the initialization procedure, the candidate node request the candidate sponsoring node to established a temporary schedule that could be used for further message delivery during the candidate node initialization. The temporary schedule requested is termed sponsor channel.

The process is initiated by the candidate node, which transmit a MSH-NENT: NetEntryRequest message (a MSH-NENT message with type set to 0x2) to the sponsoring node.
Upon reception of the MSH-NENT: NetEntryRequest message with the sponsor node ID equal to node ID of its own. The candidate sponsoring node assess the request and either opens the sponsor channel or reject the request.

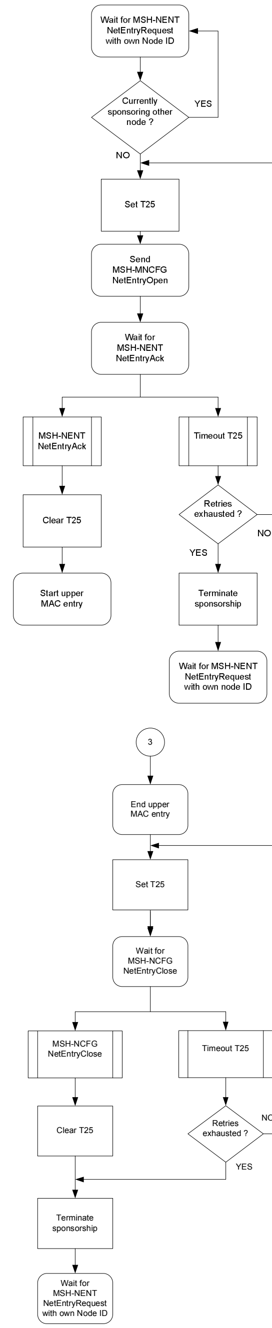

Figure 2: Mesh Network Synchronization and entry-Sponsor node.

The response is given in a MSH-NCFG message with an embedded data. If the candidate sponsoring node does not advertise the candidate node's MAC address in the sponsor's next MSH-NCFG transmission, then the procedure is repeated MSH_SPONSOR_ATTEMPTS times using a random backoff between attempts. If these attempts all fail, then a different candidate sponsoring node is selected and the procedure repeated (including re-initialization coarse network synchronization). If the selected candidate sponsoring node does advertise the candidate node's MAC address, it continues to advertise this MAC address in all its MSH-NCFG messages until the sponsorship its termed.

Once the candidate node has received a positive response (a NetEntryOpen message) from the candidate sponsoring node in the MSH-NCFG message, it shall acknowledge the response by transmitting a MSH-NENT: NetEntryAck message (a MSH-NENT message with type set to 0x1) to the sponsoring node at the first following network entry transmission opportunity. Before that the candidate node performs fine time synchronization. It makes a correction to its transmission timing by the *estimating propagation delay* indicated in the embedded MSH-NCFG: NetEntryOpen message.

If the sponsoring node accepts the request and opens a sponsor channel, the channel is ready for use immediately after the transmission of the acknowledgement message. At the same time, the candidate sponsoring node becomes the sponsoring node.

If the candidate sponsoring node embeds a MSH-NCFG: NetEntryReject, the new node performs the following action based on the rejection code.

0x0: Operator authentication value invalid
    The candidate node selects a new candidate sponsoring node with different operator ID.
0x1: Excess propagation delay
    The candidate node shall repeats its MSH-NENT:NetEntryRequest in the following network entry transmission opportunity to the same candidate sponsoring node.
0x2: Select new sponsor
    The candidate node shall select a new candidate sponsoring node.

If the candidate sponsoring node embedded neither MSH-NCFG: NetEntryOpen nor MSH-NCFG: NetEntryReject, the candidate node waits (with timeout time T23), for the next MSH-NCFG with NetEntryOpen from the candidate sponsoring node and resend the MSH-NENT:NetEntryRequest on timeout.

The candidate node and the sponsoring node use the schedule indicated in the NetEntryOpen message to perform message exchanges. After this is completed, the candidate node terminates the entry process by sending a MSH-NENT:NetEntryClose message to the sponsoring node in the network entry transmission immediately following a MSH-NCFG transmission from the sponsoring node, which Ack termination with MSH-NCFG:NetEntryAck (Figure 3).

IV. WIRELESS BROADBAND MULTI-HOP NETWORKS

On the other hand, in 802.16j, systems support the procedures for entering and registering a new SS, RS or new station to the network. The procedure for initialization of an SS and an RS is shown in Figure 4. This Figure shows the overall flow between stages of initialization in an SS and an RS. The procedure can be divided into the following phases:

1) Scan for the DL channel and establish synchronization with the BS
2) Select the RS access station (RS only)
3) Obtain the *Tx* parameters from the UCD message
4) Perform ranging
5) Negotiate basic capabilities
6) Authorize SS/RS and perform key exchange
7) Register network nodes
8) Obtain R-link parameters (RS only)
9) Establish IP connectivity (SS only)
10) Determine the time of day (SS only)
11) Transfer operational parameters (SS only)
12) Set up connections (SS only)
13) Obtain the neighbor station measurement report (RS only)
14) Select the access station (RS only)
15) Configure the operation parameters (RS only)

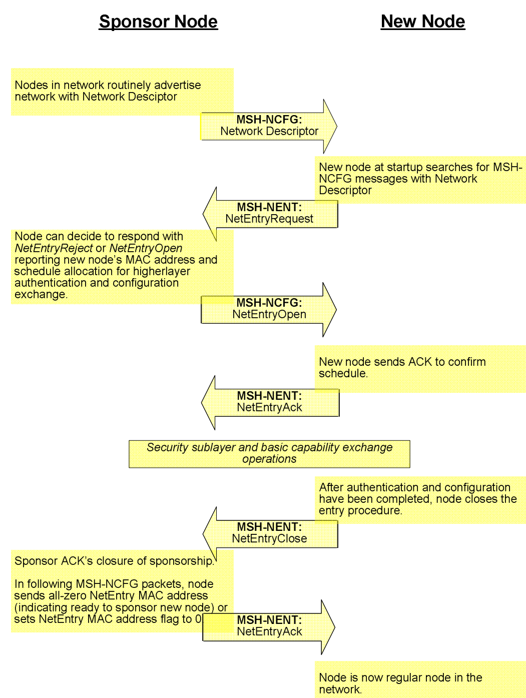

Figure 3: Successful network entry message exchange.

Implementation of phase 6) is optional. This phase can be performed if both SS/RS and BS support an authorization policy. Implementation of phases 9), 10), and 11) at the SS is optional. These phases can only be performed if the SS has indicated that it is a managed SS in the REG-REQ message [5].

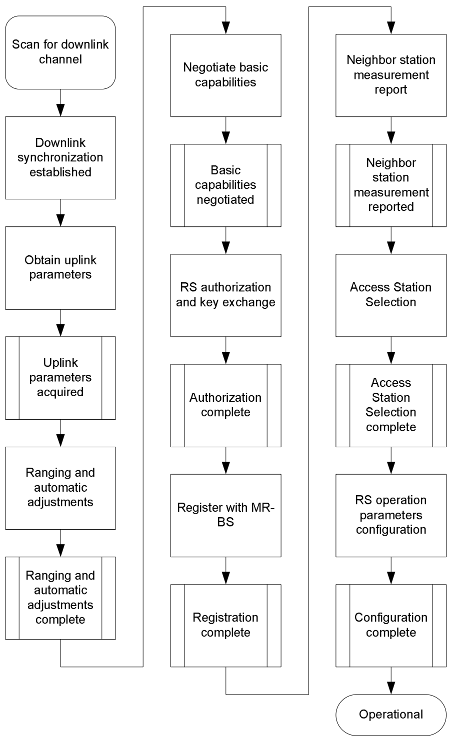

Figure 4: RS initialization overview.

Implementation of phases 2), 13), 14), 15) are optional. The MR-BS may instruct the RS to omit phases 2), 13), 14), and 15) by the RS network entry optimization TLV in the RNG-RSP message [5].

V. CONCLUSIONS

Unlike the PMP mode, there are no clearly separate downlink and uplink sub-frames in the mesh mode. Each station is able to create direct communication links to a number of other stations in the network instead of communicating only with a BS. However, in typical installations, there will still be certain nodes that provide the BS function of connecting the Mesh network to the backhaul links. In fact, when using Mesh centralized scheduling these BS nodes perform much of the same basic functions as do the BS in PMP mode. Thus, the key difference is that in Mesh mode all the SSs may have a direct link with other SSs. Further, there is no need to have direct link from an SS to the BS of the mesh network. This connection can be provided via other SSs. Communication in all these links shall be controlled by a centralized algorithm (either by the BS or decentralized by all nodes periodically), schedule in a distributed manner within each node's extended neighborhood, or schedule using a combination of these.

On the other hand, in RS basic and primary management connections are established between the MR-BS and all RSs within the MR cell. These connections are used for the exchange of management messages between the MR-BS and RS and may pass trough one or more intermediate RSs. Our future work will consist in develop a MAC layer mechanism for wireless mesh networks.

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