ON PROPER SELECTION OF MULTIHOP RELAYS FOR FUTURE ENHANCEMENT OF AEROMACS NETWORKS

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Abstract

As the Aeronautical Mobile Airport Communications System (AeroMACS) has evolved from a technology concept to a deployed communications network over major US airports, it is now time to contemplate whether the existing capacity of AeroMACS is sufficient to meet the demands set forth by all fixed and mobile applications over the airport surface given the AeroMACS constraints regarding bandwidth and transmit power. The underlying idea in this article is to present IEEE 802.16j-based WiMAX as a technology that can address future capacity enhancements and therefore is most feasible for AeroMACS applications. The principal argument in favor IEEE 802.16j technology is the flexible and cost effective extension of radio coverage that is afforded by relay fortified networks, with virtually no increase in the power requirements and virtually no rise in interference levels to co-allocated applications. The IEEE 802.16j-based multihop relay systems are briefly described. The focus is on key features of this technology, frame structure, and its architecture. Next, AeroMACS is described as a WiMAX-based wireless network. The two major relay modes supported by IEEE 802.16j amendment, i.e., transparent and non-transparent are described. The benefits of employing multihop relays are listed. Some key challenges related to incorporating relays into AeroMACS networks are discussed. The selection of relay type in a broadband wireless network affects a number of network parameters such as latency, signal overhead, PHY and MAC layer protocols, consequently it can alter key network quantities of throughput and QoS.

Introduction

The principle function of an airport surface communications system is the guidance and control/ management of aircrafts movement on the airport surface. However, such system is also required to accommodate various communications needs on the part of other mobile and stationary nodes that are essential to the airport operation. In order to accommodate the large volume of data that is planned for the next generation transportation systems (*NextGen*), wideband and network centric wireless communication technologies were deemed required. To this end the 2007 ITU World Radiocommunications Conference (WRC-2007) facilitated the development of a new international standard to support airport surface communications by creating a new allocation in the C-band spectrum that extends from 5091 to 5150 MHz specifically for an airport surface wireless communication system. It was recommended by the joint US-Europe Future Communications Study that this new aviation specific communication technology should be based on the IEEE 802.16 standard; WiMAX (Worldwide Interoperability for Microwave Access). The proposed system, known as Aeronautical Mobile Airport Communications System (AeroMACS) is to support fixed and mobile ground to ground and ground to air data communications applications and services [1].

The IEEE 802.16e adopts OFDMA for improved multipath performance for non-line-of-sight (N-LOS) environment. In addition IEEE 802.16e supports a scalable physical layer (PHY) that enables optimum performance in channel bandwidths of integer multiples of 1.25, 1.5, 1.75 MHz, ranging from 1.25 to 20 MHz. The IEEE 802.16-2009 was amended by IEEE 802.16j-2009. This amendment specifies PHY and MAC layer enhancements to IEEE 802.16-2009, enabling the operation of relay stations (RS) over licensed bands without requiring any modifications in subscriber stations (SS) or mobile stations (MS), and with full backward compatibility with IEEE 802.16-2004 and IEEE 802.16e. In other words, the IEEE 802.16j amendment introduces multihop relay as an optional deployment that enables the extension of

radio outreach and may be used to enhance system capacity in an access network [2].

WiMAX; Technology Highlights

The IEEE 802.16 consists of a large collection of standards, thus for any particular driven technology the scope of the standard is reduced to smaller sets of design choices. A case in point is WiMAX technology that was originally designed to enable low cost mobile access to the internet and to provide integrated wireless fixed and mobile services using a single air interface and network architecture. Consequently WiMAX uses a subset of the IEEE802.16 standard's mandatory and optional specifications consisting of selected PHY and MAC layer protocols. WiMAX applies **Scalable Orthogonal FDMA (SOFDMA)** access technology for both downlink and uplink. This enhances performance against the frequency selective fading effect of multipath channels and enables bandwidth scalability over several spectral ranges. WiMAX predominantly supports **Time Division Duplex (TDD)** architecture. TDD architecture supports the exchange of asymmetric traffic. **Adaptive modulation and coding (AMC)** is another key feature of WiMAX networks. In this manner WiMAX supports a variety of modulation format/ coding scheme combinations. These "***burst profiles***" are selected in an adaptive fashion depending upon channel conditions for the objective of network throughput optimization. A multilayer **Automatic Repeat Request (ARQ)** and **Hybrid ARQ (HARQ)** error control scheme is also included in the WiMAX standards. OFDMA groups thousands of orthogonal subcarriers to form user's subchannels. When neighboring WiMAX cells use the same subchannels for signal transmission "***co-channel interference***" occurs. To mitigate the effect of this form of interference, WiMAX applies a widely accepted method known as **fractional frequency reuse (FFR)**. Among the many new technologies integrated into WiMAX standards is **multiple-input multiple-output (MIMO)** antenna technology. MIMO plays a central role in delivering high-speed and reliable wireless broadband services over an extended coverage area. The WiMAX frame structure, defined in the original IEEE 802.16-2009 TDD implementation, consists of downlink and uplink sub-frames, as illustrated in Figure 1. This is based on Release 1 WiMAX Forum system profile.

We note that **TDD requires system-wide synchronization to counter interference**, this is one of the down sides of using TDD; nevertheless, TDD is the preferred duplexing mode for many reasons, some of which are listed below. TDD is the duplexing mode for AeroMACS as well.

AeroMACS

The most recent version of AeroMACS System Profile is still based on WiMAX Forum Mobile System Profile Release 1, while WiMAX Forum has already published two versions of WiMAX Mobile System Profile Release 2 [3].

Operational Applications

AeroMACS users groups in an airport setting vary depending upon the size of the airport. Three major groups that need to transport application information over AeroMACS are the airport authority, airlines, and civil aviation authorities. User applications for transport over AeroMACS have been classified in 5 different functional domain categories.

- *Air Traffic Management/Air Traffic Control*
- *Aeronautical Information Services and Meteorological Data (AIS/MET)*
- *Aircraft Owner / Operator*
- *Airport Authority*
- *Airport Infrastructure*

Applications associated with different categories in this list may have different performance characteristics, security needs, and QoS requirements. The type of information content for each application ranges from live video streaming to low throughput data exchanges.

AeroMACS Technical Profile

1. AeroMACS total radiated power will be limited to stay within the interference thresholds established by the ITU-R for shared spectrum users.
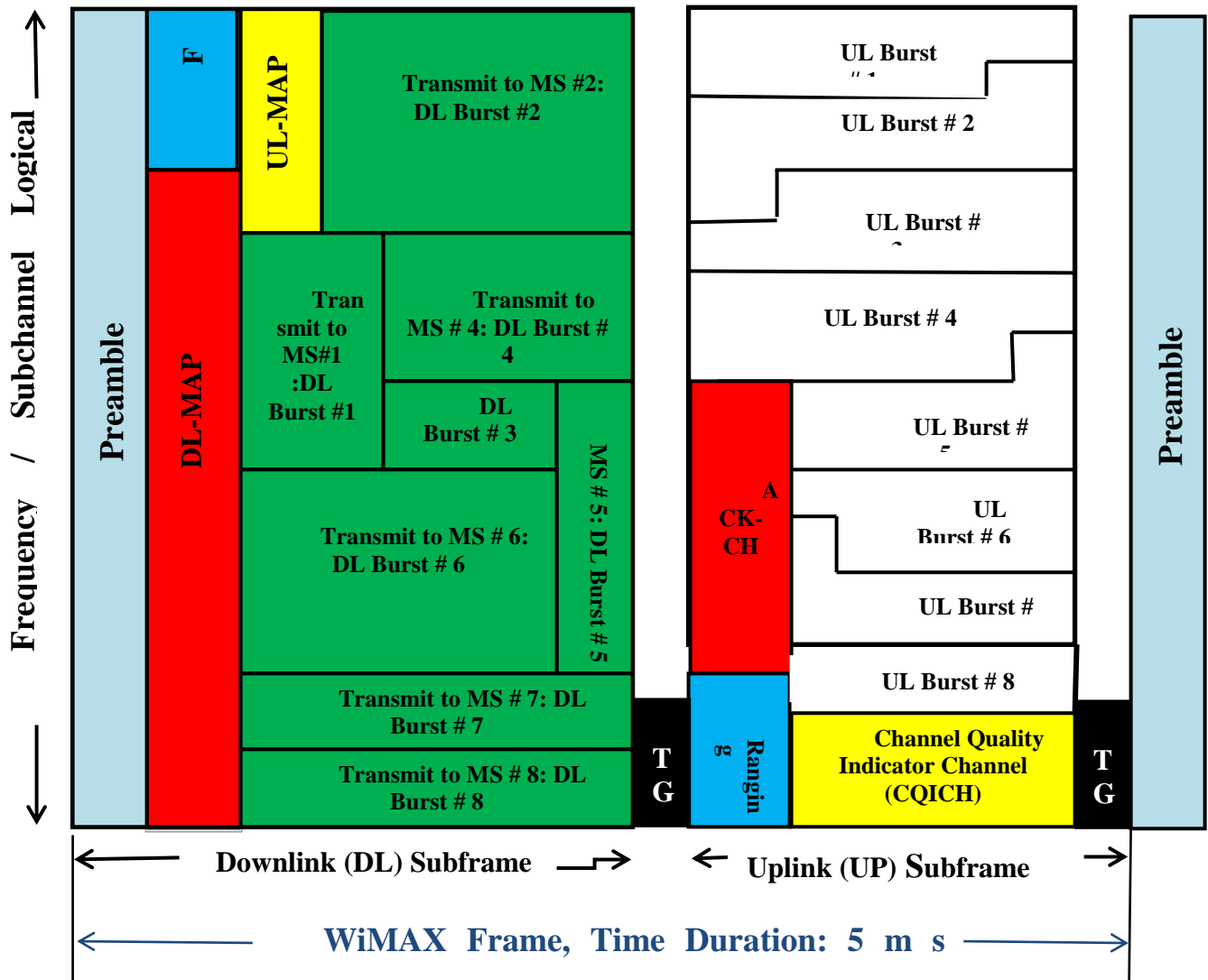
Figure 1: IEEE 802.16e-Based TDD WiMAX Frame Structure

2. AeroMACS shall use the IP-based end-to-end WiMAX network architecture.
3. AeroMACS will support roaming between NSPs (Network Service Providers).
4. AeroMACS will be designed to efficiently utilize allocated spectrum and take full advantage of the technical capabilities of the most recent version of mobile WiMAX.

Radio Profile Requirements and RF Characterization

The radio characterization of the AeroMACS network is the key to the design and implementation of the airport surface communications system. The potential band of operation for AeroMACS will be from 5000 MHz to 5150 MHz, although current ITU allocations allow for operations in bands including

the 5091 to 5150 MHz. The following passage outlines the main radio related parameters formulated for AeroMACS [4].

1. Network synchronization setting is one of AeroMACS's unique profile settings or modifications. The other AeroMACS setting is the transmitter output spectral content or mask which protects spectrally adjacent applications from AeroMACS interference. The spectrum mask for AeroMACS is taken from "Title 47 CFR part 90.210".
2. The AeroMACS profile supports, at this point, only the 5 MHz bandwidth with the corresponding FFT size of 512 points.
3. The AeroMACS core allocated band is 5091-5150 MHz, however, the AeroMACS Profile Working Group (AWG) has defined preferred center frequency assignments for the spectrum 5000 to 5150 to accommodate any potential future spectrum allocations. Such allocations may be implemented on a national, rather than international (i.e., ITU) basis. Maximum Doppler velocity for AeroMACS is assumed to be 50 nautical miles per hour.
4. All modulation formats required in the WiMAX profile, i.e. BPSK, QPSK, 16-QAM, and 64-QAM shall be required in AeroMACS.

IEEE 802.16j Amendment and Multihop Relays

The IEEE 802.16j amendment updates and expands IEEE 802.16 standard, specifying OFDMA PHY and MAC sub-layer enhancements to IEEE 802.16 for licensed bands to enable the operation of relay stations (RS) while maintaining SS/MS specifications intact [5]. The main idea in incorporating multihop relays in cellular systems is to complement the base station (BS) with less complex, less costly, and easier-to-install relay stations instead of adding new BSs to the network. The augmented BS, known as multihop relay base station (MRBS), covers an extended area beyond what the BS alone covers which is called "multihop relay cell" (MR-cell). The MRBS manages all communications resources within a MR-cell through a *centralized* or

distributed procedure. Resource management of mobile or stationary subscriber stations may be carried out directly by the MRBS or via radio links through relay stations. Traffic and signaling between MRBS and the SS/MS may be routed through "*access RSs*" or via a direct link between MRBS and the SS/MS. The physical channel between the MRBS and a relay is called a *relay link*, and the channel between an access relay and a SS/MS is termed an *access link*. In more complex multihop relay networks for which more than two hops may occur, the signaling between the MRBS and an access RS may be relayed through intermediate RSs. In those cases the link between MRBS and the access RS is called *relay path*. In general, a radio link that is originated or terminated at an MS or an SS is called an *access link*. The channels connecting the MRBS to RSs or RSs to other RSs are denoted by *relay link*. In some literature the link that connects the MRBS to the RS is called *backhaul link*, links connecting relays to relays are called *relay links*, and links connecting relays to MS/ SS, and/ or MRBS to MS/SS are called *access links*.

There are a number of potential benefits in employing multihop relays in a wireless network. First and foremost among these benefits is the fact that the IEEE 802.16j relay deployment strategy presents a cost-effective, low-complexity, and easy-to-install-infrastructure, for wireless network radio outreach extension in a variety of situations. Secondly, the relays can provide throughput enhancement in areas which are not sufficiently covered by the associated BSs. Increase in throughput may be translated to either capacity improvement or QoS enhancement. In the majority of usage models, however, relays are deployed to satisfy a combination of the two objectives just mentioned. One other important result of deployment of the relay-fortified wireless infrastructure, in comparison with the all-BS architecture, is the reduction of aggregate output power of the cellular network. For the AeroMACS application, this translates into less interference into co-allocated applications such as MSS feeder link [6].

The allocation of bandwidth and other resources for RSs and SS/MSs may be controlled using one of the two modes; *centralized* and non-centralized, i.e.,

distributed scheduling. In centralized scheduling mode, the bandwidth allocation for an RS's subordinate SS/MSs is determined at the MRBS; whereas in distributed scheduling mode, the bandwidth allocation of an RS's subordinate SS/MSs are determined by the RS in cooperation with the MRBS, in other words RSs share resource allocation responsibilities with their superordinate MRBSs .

Relay Modes: Transparent versus Non-Transparent

IEEE 802.16j defines two relay modes; transparent relay stations (TRS) and Non-transparent relay stations (NTRS). The NTRS assigns and manages radio resources within its own "cell". On the other hand, TRS shares cell IDs and control messages with its MRBS. Hence the major difference between these two modes is whether or not the relay is allowed to transmit frame header information which contains crucial scheduling data needed to determine when a node can transmit or receive information. Therefore the TRS exclusively transmits traffic data to the subordinate MS/SS, and the framing information is directly communicated from the MRBS to the MS/SSs, This implies that TRSs can only operate in centralized scheduling format and cannot be used for radio extension. The NTRSs, on the other hand transmits both traffic data and control signals to its subordinate MS/SSs, thus they may operate either in centralized or distributed mode and may be used for radio outreach extension.

The choice of relay mode is dictated by the application for which the relay is employed. For AeroMACS networks the major applications of relays is radio coverage extension to severely shadowed areas and to nodes that are located far outside of airport territory, and capacity/ throughput enhancement at certain locations of an airport. For the first application NTRSs are required, however for the second, TRSs represent the mode of choice.

Transparent mode can only operate in centralized scheduling format and therefore they cannot support mobile relays. Moreover, they may not be used for extension of radio coverage. However, TRSs are ideal for cooperative communications within the framework of AeroMACS networks. The main application of the TRS is to facilitate

throughput/capacity increase within a BS cell footprint. Transparent relays are of low complexity, therefore they are cost efficient.

Non transparent mode may operate in centralized or distributed scheduling schemes. The main feature of NTRS is their capabilities in extension of radio coverage into severely shadowed areas; which makes them suitable candidates for AeroMACS applications, where the objective is to extend radio coverage without adding a new BS and without requiring a reconfiguration of the entire AeroMACS network that is already in place. NTRS essentially act like a "mini BS" and therefore they are of high complexity and expensive to the extent that they can affect the total system cost. NTRSs may be used in any fashion in a multihop-relay augmented wireless network, i.e., it does not need to be the last hop in a multihop transmission system. It should be also noted that since NTRSs transmit framing information, they can create high inter-relay interference and thus not much capacity improvement can be achieved with this relay mode.

Clearly transparent and non-transparent relays have different advantages and disadvantages. Conceptually, there can be cases in AeroMACS networks that call for simultaneous application of both TRS and NTRS in an airport. The IEEE 802.16j standard provides very little detail of how this can be handled/ realized [7].

Frame Structure for Double –Hop IEEE 802.16j TDD TRS

The physical layer frame with TDD architecture for WiMAX networks containing transparent relays more or less contains the same framing and management/control information as does the original IEEE 802.16e physical frame (Figure 1).

The MS receives all of control data directly from MRBS. The IEEE 802.16j Time-division Transmit and Receive RS shares the time frame to handle relay and access links. During DL subframe the RS receives the payload from the MRBS, or any other superordinate station, and transmits the payload to the MS, or any other subordinate station (a dual function). Similarly, during the UL subframe the TRS receives payload from the MS and transmits that to the MRBS.
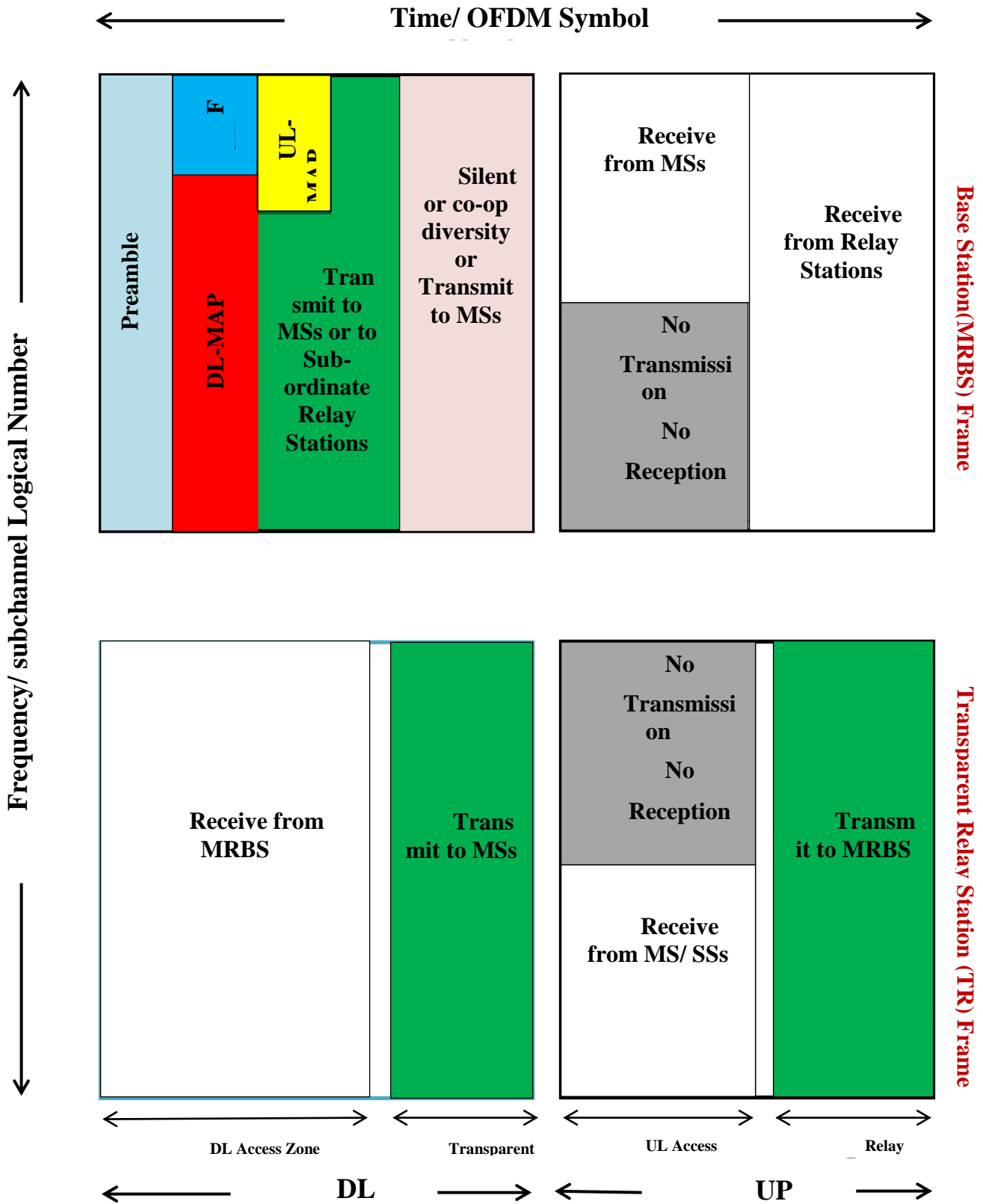
Figure 2: Frame Structure for IEEE 802.16j-Based Dual-Hop Transparent Relays

Figure 2 describes the frame structure of IEEE 802.16j-based dual-hop MRBS/RS/MS. Like in the original IEEE 802.16e standard, the frame is divided into two time-domain sub-frames separated by a guard time interval. The figure illustrates both MRBS and RS frame structures.

In so far as **MRBS frame makeup** is concerned, the control part of DL subframe is identical to that of 802.16e. The payload part of DL subframe, however, is divided into two zones. In the first zone the MRBS transmits to subordinate MSs and RSs. In the second zone MRBS has several options; it can stay silent, transmit to MSs that are being served directly by MRBS, or participate in cooperative communication. The MRBS UL subframe is also divided into two time-domain zones. The zone is divided into two frequency domain sectors. In the first sector MRBS receives data from the MSs that it directly serves. In the second sector the MRBS is silent since the spectrum of this sector is being used by the MSs to RSs. The DL subframe of the RS frame is divided into two time zones compatible with those of MRBS, but separated by a guard time. In the first zone, called the DL access zone, the RS receives from MRBS. Whereas in the second time zone, known as transparent zone, the RS transmits to the MSs that it serves the payload that it has received from the MRBS. The UL subframe is also divided into two zones in the time domain to match the division in the MRBS frame structure. The first zone is divided into two sectors in the frequency domain, compatible with that MRBS frame composition. In the first sector the RS is silent, allowing the MRBS to use the same spectrum to receive from MSs it directly serves. In the second sector the RS receives payload from the MSs that are communicating with MRBS through the TR. In the second time zone of the TR UP subframe, designated as relay zone, the RS transmits to MRBS the payload that it had received from the MSs in the previous UL subframe.

From the perspective of the MS/SS a NTRS functions like a serving BS. As such a NTRS may provide most of the network capabilities offered by a standard IEEE 802.16 base station. For instance an NTRS can generate control signals consisting of preamble, FCH, UP MAP, DL MAP and etc.

Additionally it can handle mobility tasks such as handover, as well network entry and MS ranging. Hence NTRSs can serve MS/SSs that are beyond the reach of the MRBS. Therefore the **NTRS may be used to extend the radio outreach of the MRBS to severely shadowed areas as well as extending the coverage to nodes that are located far beyond the boundary of the cell footprint**. The NRTS can also provide a modest capacity enhancement.

Some Challenges of Incorporating Relays in AeroMACS Networks

One of the downsides of using Relay-fortified WiMAX technology for AeroMACS is the design of QoS mechanism and the scheduler that supports it. This is due to the fact that the MS-BS and BS-MS connections may involve more than a single link. In other words relay links might be included in both uplink and downlink. These links, in general, have different channel conditions which make the scheduling process more complicated than the conventional WiMAX network. Clearly as the number of hops increases, the scheduling process becomes more complicated.

Another issue in designing IEEE 802.16j-based WiMAX system is the maximum number of hops that is allowed in the network. The standard does not specify the optimum number of hops, perhaps for the reason that different applications might require different optimum number of hops. The maximum number of hops is a critical parameter as it has direct bearing on latency, throughput, and QoS. As the number of hops increases, so does the latency and the time it takes for the signal to get through the channel, thus the effective system throughput decreases. Two other issues related to application of IEEE 802.16j relays in AeroMACS are network scheduling procedure and relay mode. The IEEE 802.16j-based AeroMACS could use either a centralized or distributed scheduling procedure. This selection has direct bearing on signaling overhead, latency, and MAC protocol complexity. As a consequence other network operating and functional parameters, such as throughput, overall delay, spectral efficiency, and QoS are affected.

Concluding Remarks

The air interface for IEEE 802.16j amendment was defined originally with minimum requirement that the relay devices should support all licensed bands that are allocated for 802.16 standards. No modifications are required for the legacy IEEE 802.16e-based MS/SS, and relays support point-to-multipoint network topology and not mesh topology.

From the MAC layer perspective, relays can operate in two scheduling mode; centralized or distributed. The same can be said about security arrangement; i.e. relays can function in centralized or distributed security modes. A relay operating in distribute scheduling mode is capable of scheduling and bandwidth allocation for its subordinate MS/SSs. A relay with distributed scheduling capability may operate either in distributed security mode or in centralized security mode. However, the centralized scheduling mode is normally coupled with centralized security mode.

Considering *four key networking issues; throughput, radio coverage extension, signaling overhead/ latency, and bandwidth efficiency* for different classes of IEEE 802.16j supported relays, the following applications and usage scenarios are deemed feasible.

1. TRSs may be used for low-cost intra-cell throughput improvements but not for coverage extension.
2. NTRSs in centralized scheduling provides throughput improvement and coverage extension; particularly in low mobility scenarios because of its latency issues.
3. NTRSs with distributed scheduling mode present versatile relays for multi-purpose applications. They may be used for simultaneous throughput improvement and radio outreach extension in various environments [8].
4. NTRS with Distributed Scheduling and Security: Reference [8] argues and demonstrates by system level simulation that NTRS with distributed scheduling and security achieves the best performance, at least in regards to intra-cell coverage and capacity.

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