HYBRID FRAME STRUCTURE METHOD FOR IEEE 802.16 WIMAX MESH NETWORKS

by

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DEDICATION

This thesis is dedicated to a great mentor, my father.

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ABSTRACT

HYBRID FRAME STRUCTURE METHOD FOR IEEE 802.16 WIMAX MESH NETWORKS

In addition to the Point-to-Multipoint mode, WiMAX standard defines the Mesh mode of operation, allowing Subscriber Stations (SS) to exchange data packets directly with each other besides the Internet traffic through the Base Station (BS). The Frame structure defined for the Mesh mode can either use Centralized Scheduling (CS), Distributed Scheduling (DS), or both CS/DS data subframes for resource allocations. CS is coordinated by the BS, thus designed for Internet traffic, whereas DS is more suitable for intranet traffic. The lack of spatial reuse in CS causes scalability issues and performance limitations. In this thesis, a Hybrid Frame Structure (HFS) method is proposed, which sets specific roles to the SSs according to their hop counts to the BS, taking advantage of both CS and DS schemes defined in the standard. Simulation results suggest that by exploiting the spatial reuse property of DS, HFS provides significant improvement in network throughput, while maintaining acceptable latency values.

ÖZET

IEEE 802.16 WIMAX ÇOKGEN BAĞLANTILI AĞLARINDA MELEZ ÇERÇEVE YAPISI YÖNTEMİ

WiMAX standardında Noktadan-Çoklu-Noktaya Bağlantı moduna ek olarak tanımlanan Çokgen Bağlantı modu, Baz İstasyonundan gelen internet trafiğinin yanısıra, Abone İstasyonları arasında da haberleşmeyi mümkün kılmaktadır. Çokgen Bağlantı modu çerçeve yapısına göre, kaynak paylaştırmak için Merkezi Planlama (MP), Dağıtımlı Planlama (DP) veya her ikisinin birden bulunduğu veri alt çerçevelerinden birisi kullanılır. MP, Baz İstasyonu tarafından koordine edilir ve internet trafiği için tasarlanmıştır, fakat hücre içi trafik olduğu durumlarda DP daha iyi sonuç verir. MP sisteminin uzaysal kullanımdan yoksun olması, beraberinde ölçeklenebilirlik ve başarım sorunları getirmektedir. Bu tezde sunulan Melez Çerçeve Yapısı (MÇY) metodu, Abone İstasyonlarının Baz İstasyonuna olan uzaklıklarına göre farklı görevler üstlenmelerini önerir ve bu şekilde standartta tanımlanmış olan MP ve DP yöntemlerinden faydalanmayı amaçlar. Simülasyon sonuçlarına göre, DP'nin uzaysal kullanım olanakları sayesinde, MÇY kabul edilebilir gecikme değerlerini aşmadan, ağ verimliliği açısından önemli bir artış sağlamaktadır.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS/ABBREVIATIONS

B_{sym}	Number of bits one OFDM symbol can carry
B_R	Requested bits per second
C_{ms}	Number of minislots reserved for centralized data subframe
D	Bandwidth demand per subscriber station
D_{max}	Maximum bandwidth demand per subscriber station
D_{ms}	Number of minislots reserved for distributed data subframe
F_i	Flow value of i^{th} node
fse	Flow scale exponent
h	Hop count of a SS to the BS, which it is connected
M	Radius of the network
N_A	Total number of nodes in the network
N_h	Number of nodes, which are h hop away from the base station
N_{st}	Total number of nodes in a subtree connected to a 1-hop SS
R	Ratio of the DS minislots BS uses for supporting CS transmissions
s	Number of OFDM symbols per minislot
T_{fr}	Frame duration
T_{sym}	OFDM symbol duration

BE	Best Effort
BS	Base Station
BWA	Broadband Wireless Access
CDS	Coordinated Distributed Scheduling
CID	Connection Identifier
CPS	Common Part Sublayer
CS	Centralized Scheduling
CSCF	Centralized Scheduling Configuration Message
CSCH	Centralized Scheduling Control Message
DCD	Downlink Channel Descriptor

DL	Downlink
DS	Distributed Scheduling
DSCH	Distributed Scheduling Control Message
EDGE	Enhanced Data rates for GSM Evolution
ertPS	Extended Real-time Polling Service
ETE	End to End
FCH	Frame Control Header
FDD	Frequency Division Duplexing
FEC	Forward Error Correction
GSM	Global System for Mobile Communications
HFS	Hybrid Frame Structure
HOE	Holdoff Exponent
HSDPA	High-Speed Downlink Packet Access
ITU	International Telecommunication Union
ITU-R	ITU Radiocommunication Sector
LOS	Line-of-Sight
MIMO	Multiple Input and Multiple Output
MS	Mobile Station
NCFG	Network Configuration
NCMS	Network Control and Management System
NEMMS	NETLAB WiMAX Mesh Simulator
NENT	Network Entry
nrtPS	Non-real-time Polling Service
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
PDU	MAC Packet Data Units
PMP	Point-to-Multipoint
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase-Shift Keying
rtPS	Real-time Polling Service
SAP	Service Access Point

SCDFS	Standard Centralized and Distributed Frame Structure
SDU	MAC Service Data Unit
SFCFS	Standard Fully Centralized Frame Structure
SFDFS	Standard Fully Distributed Frame Structure
SFID	Service Flow Identifier
SS	Subscriber Station
SSCS	Service-Specific Convergence Sublayer
TDD	Time Division Duplexing
TDMA	Time Division Multiple Access
TO	Transmission Opportunity
UCD	Uplink Channel Descriptor
UDS	Uncoordinated Distributed Scheduling
UGS	Unsolicited Grant Service
UL	Uplink
WiMAX	Worldwide Interoperability for Microwave Access
WLAN	Wireless Local Area Network
WMAN	Wireless Metropolitan Area Network
WWAN	Wireless Wide Area Network

1. INTRODUCTION

Several wireless communication systems have been developed to fulfill the increasing bandwidth demand of emerging applications, such as peer-to-peer file sharing, live TV via internet, and HD video communications. These technologies should also provide mobility, ease of deployment, low deployment, and low maintenance costs. One possible categorization of wireless networks can be based on their coverage. Wireless Local Area Networks (WLAN) can provide Internet access within a cell of 100 m radius, whereas Wireless Metropolitan Area Networks (WMAN) can support moderate sized cities and Wireless Wide Area Networks (WWAN) are defined for networks covering areas larger than a city [1]. GSM and Wi-Fi networks, which promise end users the freedom of wireless communication, have become very popular. Worldwide Inter-operability for Microwave Access (WiMAX) is also one of the most widely used Broadband Wireless Access (BWA) WMAN systems and continuously being improved since 2002 under the standardization number of IEEE 802.16. WiMAX and IEEE 802.16 terms are used interchangeably throughout the text. WiMAX networks are especially suitable for remote, low populated areas which cannot be connected to the Internet by DSL or cable networks and for places where cost of deployment and upgrading the existing land lines are exceedingly expensive [2].

WiMAX standard has two operational modes, namely the *Point-to-Multipoint mode* (PMP) and the *Mesh mode*. In the PMP mode, all subscriber stations (SSs) and Mobile Stations (MSs) are directly connected to a base station (BS), similar to the infrastructure mode of IEEE 802.11. On the other hand, in the Mesh mode an SS can be connected to the BS via multiple hops using any other SS as its parent node. Though scheduling in the PMP mode can be done according to the predefined Quality of Service (QoS) types, scheduling for WiMAX Mesh networks is rather complicated. For the Mesh mode, two different scheduling methods are defined in the IEEE 802.16 standard [3]: Centralized Scheduling (CS) and Distributed Scheduling (DS).

A WiMAX frame is a structured data sequence of fixed duration, which contain portions reserved for control and data packets. Data packets are scheduled to be sent in either centralized or distributed data subframe. CS allocations are used for Internet traffic, whereas DS allocations are mostly used for intranet communications. Using the frame structure in which CS/DS schemes coexist, the size of data subframes are fixed and set once during network initialization. Therefore, the BS cannot dynamically fine tune the boundary between CS and DS data subframes according to the recent traffic conditions, resulting in waste of valuable resources.

According to the definition of CS in the IEEE 802.16 standard, BS assigns each node several transmission slots in the centralized data subframe. Since only the centralized routing tree topology information is broadcast to the network by the help of control messages, SSs do not have the knowledge of interference between mesh links of other SSs. Therefore, CS is designed in such a way that only one node in the cell can transmit its centralized data packets at a given time period using Time Division Multiple Access (TDMA). The spatial reuse limitation of the CS scheme is a major drawback for large networks since even the distant nodes that would not cause any interference are not allowed to transmit concurrently, wasting centralized data slots which could have been utilized otherwise. In addition to this, the multi-hop transmissions require relaying of data packets to/from the BS. Thus, as the number of SSs with large hop counts increase, more network resources are under-utilized.

The problems of WiMAX Mesh mode mentioned above cause scalability constraints and bandwidth limitations. In order to minimize these effects, a *Hybrid Frame Structure (HFS)* method is proposed. HFS takes advantage of low latency transmissions of CS to be used for 1-hop nodes, and exploits the spatial reuse property of DS for the rest of the network by setting specific roles to the SSs according to their hop counts to the BS. This method enables concurrent data transmissions, which are scheduled using the three-way handshake scheme defined for DS, and also in a sense tries to dissolve the boundary between centralized and distributed data subframes by using mesh links to assist carrying CS traffic. Addressing the main problems of the Mesh mode, HFS offers significant network throughput improvement since it is built on CS/DS scheme and nodes with high hop counts only have pure DS data subframes. Therefore in the presence of intranet traffic, the proposed method performs even better compared to the standard WiMAX Mesh mode frame structure.

To evaluate the HFS method, we have developed the NETLAB WiMAX Mesh Simulator (NEMMS), which supports both CS and DS schemes, as a part of this thesis [4]. The simulator is compliant with the IEEE 802.16 standard and it implements the following features, which are ignored in the existing publicly available simulators:

- Network entry and initialization
- Support for CS/DS coexisting frame structure
- Detailed DS three-way handshake procedure and distributed resource allocations.

NEMMS is developed using OPNET [5] framework and the proposed HFS method is implemented by modifying the MAC layer of NEMMS by tuning the frame structure of the SSs according to their hop count to the BS.

1.1. Organization of the Thesis

We first present an overview of IEEE 802.16 WiMAX technology in Section 2. The PMP mode is briefly described and definitions for the Mesh mode are given as background information. Section 3 presents a literature survey covering important studies, which propose improvements to existing protocols and introduce various scheduling methods. In Section 4.1, the drawbacks and limitations of the standard WiMAX scheduling methods are discussed, and Section 4.2 presents the frame structures implemented in HFS, also describing the scheduling methods used to overcome the mentioned problems. Section 5 outlines the standard compliant mesh simulator, NEMMS, which is developed for this thesis to evaluate the standard scheduling methods and to provide a framework for future WiMAX Mesh mode studies. In Section 6, the performance of the HFS method is evaluated for various topologies and using different system parameters to observe the network behavior. Finally, Section 7 concludes this thesis by summarizing the HFS method and discussing the achieved performance improvements.

2. OVERVIEW of WiMAX

WiMAX technology aims to provide wireless communications over long distances by point-to-point links for both mobile and fixed users. WiMAX also supports multi-hop transmissions using the Mesh mode and relay stations, which extend the coverage and make it possible to use less robust modulations to increase the data rate. Theoretically, a WiMAX BS can serve up to 50 km distance for fixed stations and 5-15 km for mobile stations, providing data rates up to 70 Mbps. Some widely used wireless communication methods are listed in Table 2.1 along with range and data rate information [6]. Using multiple-input and multiple-output (MIMO) support, provided by IEEE 802.16m standard which is described in Section 2.1, the given data rates could be increased significantly.

Table 2.1. Data rates of popular wireless communication technologies

Technology	**Range**	**Max. Data Rate**
WiMAX	up to 50 km	70 Mbps
IEEE 802.11g	38 m indoor - 140 m outdoor	54 Mbps
EDGE	few kilometers	384 kbps
CDMA2000	few kilometers	2 Mbps
HSDPA	few kilometers	14 Mbps (DL)

WiMAX standard defines guidelines for both MAC and PHY layers, which should be followed when implementing the WiMAX protocol. The reference model is shown in Figure 2.1 as presented in the standard. MAC layer is composed of the following sublayers:

- **Service-Specific Convergence Sublayer (SSCS):** SSCS receives the external network data units from the SSCS service access point (SAP) and performs transformation or maps them into MAC service data units (SDUs), which are then forwarded to the MAC Common Part Sublayer (CPS) through the MAC SAP. During this operation, SDUs are classified and associated with the corresponding

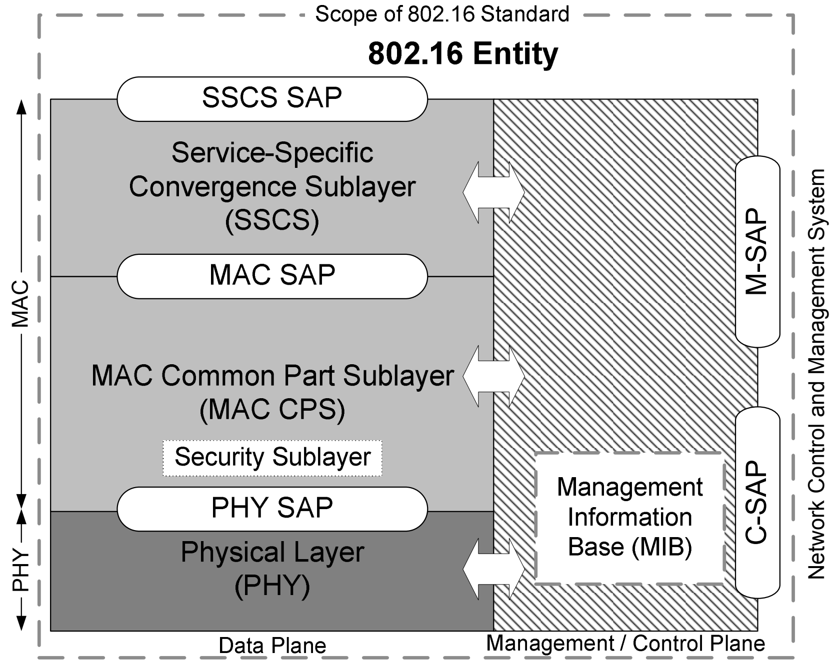


Figure 2.1. Reference model and scope of WiMAX standard [7]

MAC service flow identifier (SFID) and connection identifier (CID).
This sublayer may also include some useful functions such as payload header suppression, suppressing the repetitive part of payload headers to save resources, when transmitting network layer data units. SSCS can interface with different protocols, so the MAC CPS is not capable of extracting any information from the received SSCS payload.

- **MAC Common Part Sublayer:** MAC CPS receives SDUs from several SSCSs transferred over MAC SAP through corresponding MAC connections. Then it converts the received SDUs into MAC Packet Data Units (PDUs) by either fragmenting large SDUs into smaller PDUs or concatenating several SDUs to obtain a single PDU, called packing. Briefly, this sublayer is responsible for bandwidth allocation, connection establishment and connection maintenance as well as the QoS classification.
- **Security Sublayer:** The last MAC sublayer before the PDUs are passed to the PHY layer is the Security Sublayer. It resides in MAC CPS, providing authentication, secure key exchange, and encryption of PDU contents.

Table 2.2. Air interface variants specified in the 2009 standard [7]

Designation	**Applicability**	**Duplexing**
WirelessMAN-SC Release 1.0	10-66 GHz	TDD, FDD
Fixed WirelessMAN-OFDM[1]	Licensed bands below 11 GHz	TDD, FDD
Fixed WirelessMAN-OFDMA	Licensed bands below 11 GHz	TDD, FDD
WirelessMAN-OFDMA TDD Release 1.0	Licensed bands below 11 GHz	TDD
WirelessMAN-OFDMA TDD Release 1.5	Licensed bands below 11 GHz	TDD
WirelessMAN-OFDMA FDD Release 1.5	Licensed bands below 11 GHz	FDD
WirelessHUMAN	License-exempt below 11 GHz	TDD

The 802.16 Entity in Figure 2.1 applies to the BS, SSs, and MSs in the network. The Network Control and Management System (NCMS) abstraction is introduced in the 2009 standard, which works as a black box, containing the entities to interface with any other network components. The NCMS provides flexibility since the PHY and MAC layers of the WiMAX standard are independent of the network architecture, transport network, and protocols used at the backend. The communication between NCMS and IEEE 802.16 Entity is done using Control SAP (C-SAP) and Management SAP (M-SAP) interfaces.

After the MAC layer packs the data units into PDUs, the PDUs are transmitted to the PHY layer using implementation specific PHY SAP. IEEE 802.16-2009 standard supports seven air interface variants for both licensed and license exempt bands as presented in Table 2.2.

[1]This air interface is used by the proposed HFS method.

Air interfaces using Orthogonal Frequency Division Multiplexing (OFDM), and Orthogonal Frequency Division Multiple Access (OFDMA) can also be used for unlicensed bands [8]. A transmission sent towards the BS is called an uplink (UL) transmission and the transmission direction away from the BS is named the downlink (DL). In WiMAX, nodes communicate using structured data sequences of fixed duration, called frames, which contain reserved parts for control and data messages. The method for allocating these messages in a frame depends on the operation mode (PMP or Mesh) and the duplexing method. In all of the schemes, a resource allocation unit exists such as the DL and UL bursts in PMP mode, transmission opportunities (TOs) used for Mesh mode control messages, and minislots used in Mesh mode data messaging. According to the standard, only specific values can be chosen as the frame duration and once the frame duration is set by the BS, it should not be changed, since changing it will require resynchronization of all SSs. The frame duration values allowed for PMP and Mesh networks using WirelessMAN-OFDM are listed in Table 2.3.

Table 2.3. WirelessMAN-OFDM frame durations [7]

Code	**Frame duration (ms)**	**Frames per second**
0	2.5	400
1	4	250
2	5	200
3	8	125
4	10	100
5	12.5	80
6	20	50
7-255	*Reserved*	*Reserved*

The Fixed WirelessMAN-OFDM air interface is used by the proposed HFS method. The modulation and coding rates allowed for this air interface are listed in Figure 2.4. The following sections describe the progression of WiMAX technology, briefly outline the PMP mode and present definitions of the Mesh mode in detail, which are required to understand the proposed method more clearly.

Table 2.4. OFDM interface channel coding for supported modulations [9]

Modulation	Coding Rate	Uncoded block size (byte)	Coded block size (byte)
QPSK	1/2	24	48
QPSK	3/4	36	48
16-QAM	1/2	48	96
16-QAM	3/4	72	96
64-QAM	2/3	96	144
64-QAM	3/4	108	144

2.1. WiMAX Standard Progression

The first WiMAX standard, IEEE 802.16-2001, was completed in October 2001 and published in April 2002 which supported the PMP mode, allowing only single-hop communication to the BS similar to GSM networks. The primary motivation of this first standard was to provide last-mile BWA and be an alternative to DSL, cable, and T1 networks [10]. This initial standard specified that 10-66 GHz licensed frequency band should be used and because of the short wavelength, only line-of-sight (LOS) transmissions were allowed [3]. The LOS requirement was not practical and makes the network vulnerable to outside effects decreasing the reliability, thus IEEE 802.16a was released in 2003 introducing non-LOS transmissions using frequency bands below 11 GHz. Additional MAC features were also added such as the initial version of the Mesh mode.

IEEE 802.16d-2004 standard, which is also used for designing the proposed HFS method, provides major improvements in physical layer by introducing support for aforementioned OFDM and OFDMA methods. Shortly after the 2004 release, IEEE 802.16e amendment was published providing many new features and functionalities focusing on mobility support and enhanced QoS [11].

International Telecommunication Union (ITU) released IMT-2000 specifications in 1999, which is also known as the global standard for 3G networks. WiMAX was not approved until 2007 where five radio interfaces were approved fulfilling the requirements right after the release. Two more WiMAX standards with major improvements were released recently: IEEE 802.16j-2009 introduced relay capabilities for multi-hop transmissions and IEEE 802.16-2009 revised the MAC and PHY procedures for mobile communications and includes the following changes [10]:

- Half-duplex mobile terminal operations in OFDMA frequency division duplexing (FDD)
- Load balancing
- Robust header compression
- Enhanced mechanisms for resource allocation
- Support for location based services
- Support for multicast and broadcast services [11]
- Removing some stale features such as the Mesh mode.

Recently the focus on WiMAX standardization has shifted to next-generation systems, completion of IEEE 802.16m, which amends both IEEE 802.16-2009 and IEEE 802.16j standards to fulfill the IMT-Advanced requirements (commonly referred as 4G) defined by ITU. In October 2009, IEEE 802.16 *IMT-Advanced Candidate Proposal* was submitted to ITU Radiocommunication Sector (ITU-R) by the IEEE 802.16 Working Group [12].

A technical overview of the IEEE 802.16j standard and its implementation challenges are presented in [13]. Further discussions about Mobile WiMAX structure and scheduling methods can be found in [6, 11]. Since the Mesh mode definitions were removed in the 2009 standard in order to focus on fulfilling 4G requirements, this thesis will focus on the MAC and PHY layer definitions of IEEE 802.16d-2004 document, which will be referred as the WiMAX standard throughout the text.

2.2. WiMAX PMP Mode

WiMAX PMP networks are composed of a BS and SSs which are directly connected to the BS. As shown in Figure 2.2, the BS can serve both mobile and fixed SSs in its coverage. In the PMP mode, each node transmits its data packets using traffic bursts allocated to itself by the BS. Using the MAC messages called Downlink Map (DL-MAP) and Uplink Map (UL-MAP) broadcast by the BS, SSs can extract the relevant traffic burst information. If DL-MAP does not specify any SS for a traffic burst, all SSs are capable of listening the transmission done during that period, which is mostly used for multicast or broadcast messages. SSs check the CID fields of the received MAC PDUs and discard the packets which are not addressed to them.

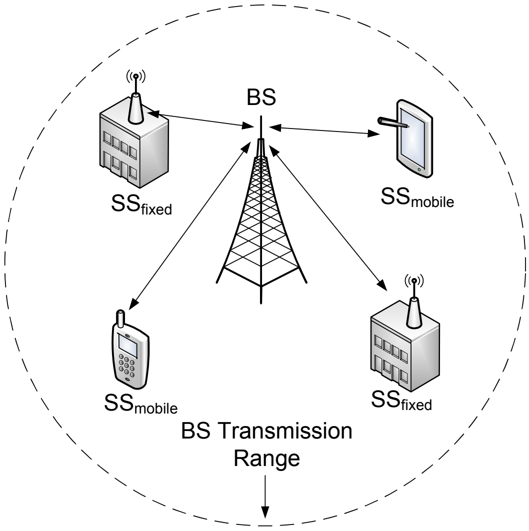


Figure 2.2. Sample WiMAX PMP mode topology

For UL traffic either continuous allocation is done by the BS or the allocation is done on a request/grant basis depending on the scheduling service (QoS type), which may use unsolicited bandwidth grants, polling and contention based messaging. When nodes connect to the network corresponding scheduling services are associated with each connection according to the node's subscription type. These scheduling services are mainly used for connection based traffic prioritization and QoS purposes. There are five scheduling services specified for the PMP mode, four of them defined in the IEEE 802.16d-2004 standard, and one was included in IEEE 802.16e-2005 amendment [3,14]:

- **Unsolicited Grant Service (UGS):** UGS is the highest priority scheduling service defined in the standard. It reserves fixed network resources to support continuous real-time traffic (Constant bit rate) such as T1/E1 and Voice over IP without silence suppression. This way the overhead and latency of request/grant mechanism is eliminated, which are required for real-time and latency intensive applications. BS provides periodic grants in the DL-MAP for the SSs using UGS according to the Maximum Sustained Traffic Rate parameter of the connection. SSs use Grant Management subheader to inform the BS regarding the UGS connection status by setting up a Slip Indicator flag. If there is a discrepancy in the connection, such as lost UL-MAP and DL-MAP, or clock rate mismatches, the BS compensates this problem by providing additional grants up to 1 per cent of service flow bandwidth. Furthermore poll-me flag may be set by the SS, demanding to be polled for another lower priority connection.
- **Extended Real-time Polling Service (ertPS):** ertPS is added to the preexisting scheduling services in IEEE 802.16e amendment. It is designed for supporting real-time applications, which use variable size data packets. ertPS takes advantage of the unsolicited unicast grants of UGS to eliminate the request/grant overhead and utilizes the system resources by dynamic sized grants, thus eliminating the waste of network resources caused by SSs not using some of the reserved slots. When the connection is established the grant size is set to the Maximum Sustained Traffic Rate but SS may request changing this value using the Grant Management subheader. The BS can not change the size of the UL grants unless it is demanded by the SS itself.
- **Real-time Polling Service (rtPS):** rtPS suffers more request/grant overhead compared to UGS but supports variable bit rates. It is designed to provide real-time UL connections such as MPEG video. SSs using this scheduling service cannot use contention based request opportunities and should only convey its request in periodic unicast request opportunities provided by the BS.
- **Non-real-time Polling Service (nrtPS):** This service uses both contention based request opportunities and unicast request opportunities provided by the BS. Designed for non-realtime applications and gets unicast polls periodically, guaranteeing request opportunities even when the network is congested. The

polling frequency for SSs using nrtPS should be on the order of one second or less.

- **Best Effort (BE):** For BE traffic SSs can only use the contention based request opportunities, as a result no bandwidth or latency is guaranteed by the BS. This scheduling service is suitable for applications, which are not delay sensitive, such as web surfing.

Since the MAC layer is connection oriented, for all data connections using various QoS parameters, different service flows are created. Only one connection can be associated with a service flow and additional new connections can be formed when a SS requires new type of service. SS uplink requests are done on a per connection basis using the SFID and the CID associated with it. Even the control messages are sent through the formed connections, thus during network entry and initialization phase each SS assigns three CIDs for control messaging purposes. These connections differ by the priority of specific control messages assigned to them.

2.2.1. PMP Mode OFDM Frame Structure

There are several frame structures defined for the PMP mode using different air interfaces. Since the Mesh mode only allows OFDM air interface just the PMP OFDM frame structures will be presented in this text. Detailed information about frame structures used by other air interfaces can be found in [3]. In licensed bands either Time Division Duplex (TDD) or Frequency Division Duplexing (FDD) scheme can be used as the duplexing method, in license exempt bands only TDD is allowed. Illustrations of both TDD and FDD frame structures are shown in Figure 2.3 and Figure 2.4 respectively.

A PMP mode frame includes a DL subframe and a UL subframe. The DL subframe is composed of one single piece, DL PHY PDU, which begins with a long preamble used for synchronization. Then one OFDM symbol long Frame Control Header (FCH) is sent with the most robust burst profile carrying the length information of following DL bursts. The first DL burst carries broadcast control messages such as DL-MAP and

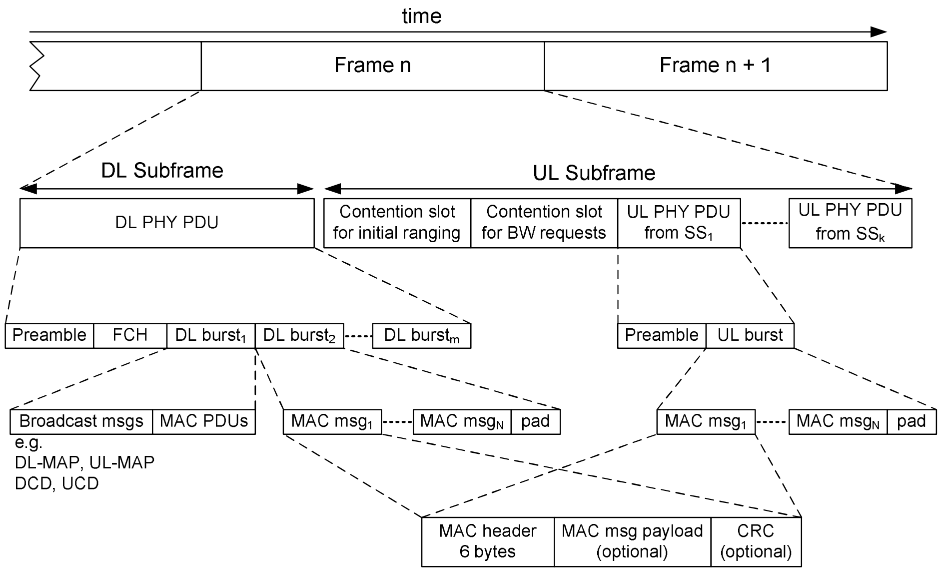


Figure 2.3. PMP mode OFDM frame structure using TDD [3]

UL-MAP containing burst allocations, along with Uplink Channel Descriptor (UCD) and Downlink Channel Descriptor (DCD), describing the physical layer characteristics of UL and DL channels, respectively.

The UL subframe is composed of contention intervals, which are used for initial ranging messages and bandwidth requests, and one or more UL PHY PDUs, each transmitted by different SSs. If an SS does not have any data packets to send in its' allocated UL time, it should transmit an UL PHY burst containing Bandwidth Request header of BR = 0 and its basic CID. If more allocated slots are left then the SS should fill those using the standard padding mechanism.

In TDD scheme the UL and DL transmissions are done consecutively and most of the time both of them use the same frequency. As shown in Figure 2.3, a TDD frame has a fixed length and composed of one DL and one UL subframe. The sizes of DL and UL subframes are not fixed and may change according to the traffic allocations done by the BS.

In FDD scheme, the UL and DL transmissions are sent from different channels using different frequencies as shown in Figure 2.4. Similar to the TDD scheme total

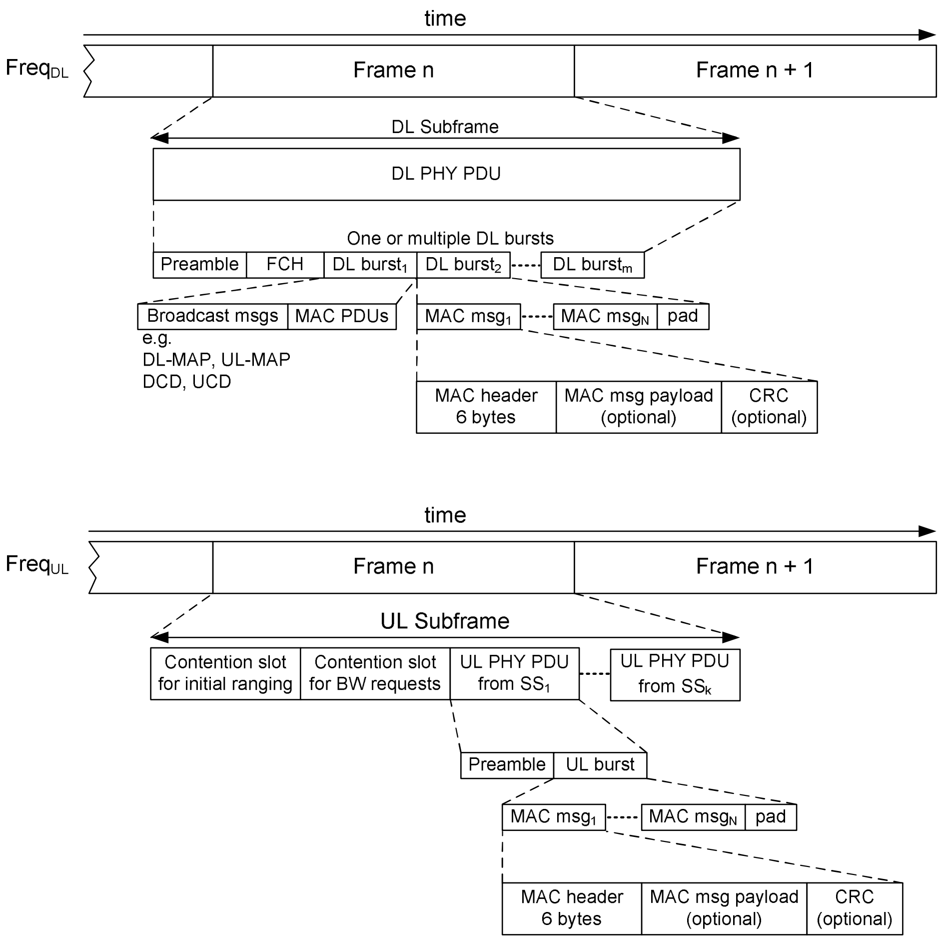


Figure 2.4. PMP mode OFDM frame structure using FDD [3]

frame duration is fixed but in FDD both DL and UL subframe lengths are equal to the total frame duration since they are sent concurrently. Therefore different modulations can be used and both full-duplex and half-duplex SSs can coexist. Since both DL and UL have the same duration, scheduling algorithms can be simplified for FDD, keeping in mind that a full-duplex SS can listen the DL channel continuously, while a half-duplex SS can listen the DL channel when it is not transmitting.

2.3. WiMAX Mesh Mode

In the Mesh mode of operation SSs, can also exchange packets with each other in addition to the transmissions sent to the BS. Similarly, the BS can send packets destined to SSs that are multiple hops away, by using several SSs on the route as relay nodes for that transmission. Data transmissions in the Mesh mode can be done on the "Basis of Equality" using DS, on the "Basis of Superiority" of the Mesh BS using the CS scheme or using both CS and DS schemes coexisting in the same frame structure [3]. The Mesh mode has several advantages compared to the PMP mode of operation:

- Allows multi-hop nodes to connect to the BS for extended coverage and extinguishing black holes in the topology.
- Provides additional capacity by enabling DS scheme, which makes BS independent data subframe allocations benefiting from spatial reuse.
- Less interference using more efficient modulation choices over multiple hops.

A WiMAX Mesh network is composed of a single Mesh BS that is directly connected to backhaul services and other entities connected to the network that are called Mesh SSs. These devices will be referred as simply BS and SS.

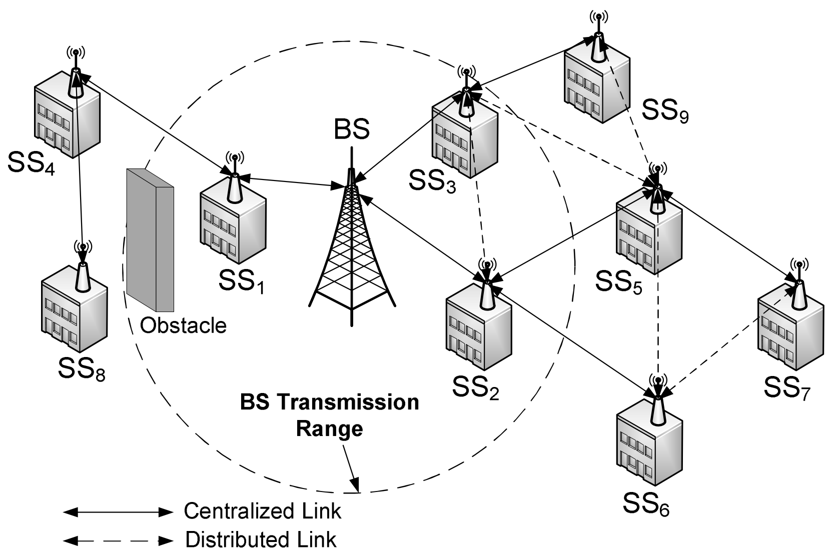


Figure 2.5. Sample WiMAX Mesh mode topology

A centralized link is the link formed between an SS and its parent during network initialization whereas a distributed link is formed with the neighboring nodes other than the parent. The SSs which an SS has centralized or distributed links in between are referred as its *neighbors*. An SS's *neighborhood* is defined as the set of its neighbors, whereas *extended neighborhood* also includes the SSs, which are 2-hops away. An SS

For Broadcast transmissions:

Logical Network ID (8 bits)	Transmitter Link ID (8 bits)

For Unicast transmissions:

Type (2 bits)	Reliability (1 bit)	Priority/Class (3 bits)	Drop Precedence (2 bits)	Transmitter Link ID (8 bits)

Figure 2.6. Unicast and broadcast mesh CID contents [3]

trying to enter the network is referred as a *candidate node* and during the network entry process, it needs to select a *sponsor node*, which can either be the BS, or another SS. The sponsor node relays all of the necessary information for network entry and initialization, in its own allocated slots until the candidate node is registered to the network. When a candidate node is successfully registered to the network, it becomes a functional SS, and the sponsor node becomes its *parent node*. They form *centralized links* with each other for centralized messaging purposes. The newly registered SS also forms *distributed links* with all other neighbors for distributed transmissions by using the link establishment procedure. An example of a Mesh topology is given in Figure 2.5.

In the Mesh mode, all communications are done in the context of the link between the transmitter and receiver node. Unlike the scheduling services in the PMP mode, Mesh mode provides QoS over the links, separately for each message. No scheduling service or QoS parameters are assigned to a link but each unicast message traveling through that link, carries the service parameters in the CID field of its header as shown in Figure 2.6. The service parameters are sent through the MAC SAP along with the payload of the message.

Each node in the network must have a 48-bit unique *MAC address*, which is used in network initialization to identify newly connecting nodes. Additionally as a part of the authorization process, the MAC address is used between the BS and the candidate node to verify the identity of each other. After the candidate node completes the registration process, it is assigned a 16-bit *Node Identifier* (Node ID), unique in the Mesh network. This Node ID is placed in the Mesh subheader, which follows the generic MAC header in each transmission. 8-bit *Link Identifiers* (Link IDs) are assigned to centralized and distributed links for addressing nodes in the local neighborhood. These Link IDs are selected using a challenge/response mechanism, which is performed using link establishment embedded packets in network configuration messages. Nodes use assigned Link IDs in the generic MAC header as part of the CID and for DS request/grants to allocate transmission slots. Figure 2.6 presents the contents of the CID:

- Logical Network ID is the Node ID of the BS and only used in broadcast messages.
- Type field could be either MAC Management or IP.
- Reliability field specifies whether any retransmissions will be done for this packet or not.
- Priority/class indicates the message class.
- Drop precedence is set to high values for the packets which are more likely to be dropped during a network congestion.
- Transmitter Link ID specifies the destination of the current packet in the local neighborhood.

2.3.1. Mesh Mode Frame Structure in the Standard

For NLOS transmissions in the Mesh mode of operation, only WirelessMAN-OFDM TDD frame structure is defined in the standard. Each Mesh mode frame is composed of a *Control Subframe* followed by a *Data Subframe*. Control subframes are used for network configuration, network entry and initialization, and coordination of both scheduling methods. Figure 2.7 shows the general structure of a Mesh mode frame. The control subframe contains either a *Network Control Subframe* or a *Schedule Control Subframe* depending on the period of the network configuration subframes set by the BS. This information along with other network parameters are broadcast for new nodes using the *Network Descriptor* embedded packet in the *Network Configuration* (NCFG) messages. The boundary between the Centralized and Distributed Data Subframes is set once when the network initiates, according to the expected traffic type and can not be changed later on.

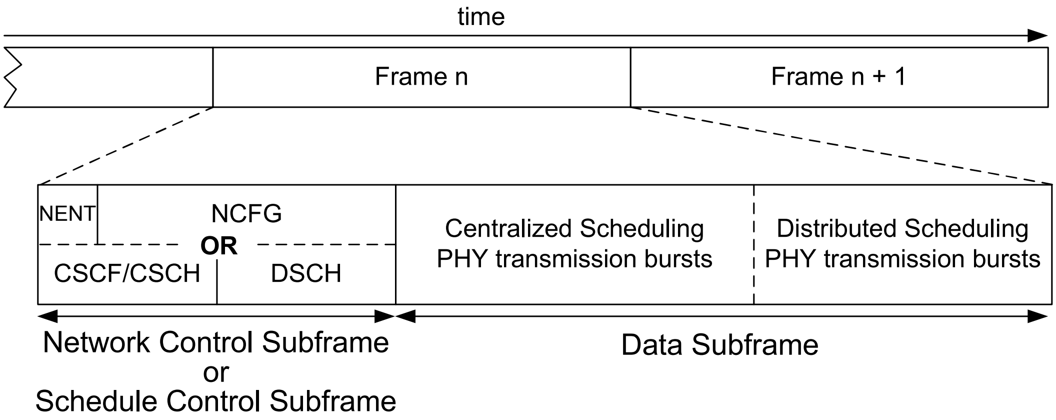


Figure 2.7. Mesh mode OFDM frame structure

2.3.1.1. Control Subframe and Control Messages. The size of the control subframe is fixed and equal to the *MSH-CTRL-LEN* × *7* OFDM symbols, where *MSH-CTRL-LEN* is a four bit parameter extracted from *Network Descriptor*, an embedded packet in NCFG, and specifies the number of TOs in the control subframe, each TO having seven OFDM symbols. Control messages are sent using 1/2 QPSK, which is the most robust modulation coding allowed for the Mesh mode. A Control Subframe can either be a network control subframe or an ordinary schedule control subframe. The number of ordinary scheduling control subframes between each network control subframe is defined by the "Network Config Period" field of Network Descriptor packet.

During a Network Control Subframe first TO is reserved for a single Network Entry (NENT) message, followed by *MSH-CTRL-LEN - 1* NCFG TOs as illustrated in Figure 2.7. The first TO is contention based and shared between the SSs trying to enter the network. Once an SS starts the initialization procedure, rest of the candidate nodes keep radio silence in the NENT TOs until that node completes its registration.

NCFG messages are broadcast by each node periodically in the Network Configuration Subframe. The period of TOs for NCFG transmissions depend on each node's *Holdoff Exponent* (HOE) value defined as:

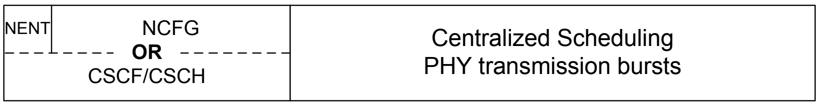
$$Xmt\ Holdoff\ Time = 2^{Xmt\ Holdoff\ Exponent + Holdoff\ Constant} \tag{2.1}$$

where *Xmt Holdoff Time* represents the time in TOs for the node to wait before transmitting the next NCFG packet. *Xmt Holdoff Exponent* is a three bit parameter, which can have different values for each node, and *Holdoff Constant* is defined as four in the standard. Since using the given constant value causes extensive delay during initialization and DSCH messaging as pointed out in [15], Holdoff Constant value can be decreased.

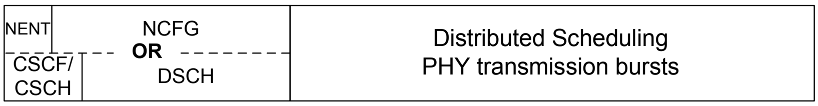
The TO to transmit a NCFG message is chosen according to a Mesh Election algorithm. This algorithm takes the target TO number and ID's of all nodes who are eligible to send NCFG in that TO. Using this algorithm each node can calculate its next NCFG transmission TO without any collisions since Mesh Election gives the same winning node for a specific TO, selected from the set of eligible nodes. The same scheme is used for DS control messages as well. On the contrary the Mesh Election mechanism is vulnerable to the *hidden terminal* problem, suffering from possible collisions at newly entering nodes as pointed out in [16]. Wang *et al.* propose a refined NENT scheme eliminating this issue by using the "Sponsor Node ID" field of NENT request messages.

As shown in Figure 2.7, the Schedule Control Subframe is split into two parts: First part is reserved for the centralized control messages and the second part is reserved for distributed control messages. The number of TOs reserved for DSCH messages are specified by the BS using the *MSH-DSCH-NUM* parameter in the Network Descriptor packet. This parameter can be tuned considering the ratio between expected distributed and centralized traffic.

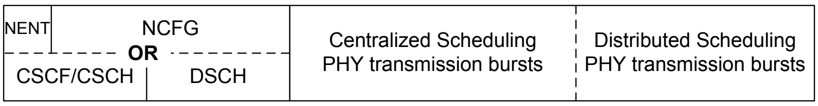
In the centralized control message subframe, either *Centralized Scheduling Control Messages* (CSCH) or *Centralized Scheduling Configuration Messages* (CSCF) are transmitted depending on the value of "Configuration Flag" field set in the last CSCH-Grant packet initiated by the BS. A CSCF packet carries the topology information and link updates to notify all SSs about the topology changes. By processing the CSCF message, SSs can calculate their CSCH-Grant, CSCH-Request, and CSCF TOs as well as the latest centralized routing tree information.



(a) SFCFS



(b) SFDFS



(c) SCDFS

Figure 2.8. Mesh frame structure types according to the scheduling methods

In the distributed control message subframe, *Distributed Scheduling Control Messages* (DSCH) are exchanged between the neighboring nodes using a holdoff scheme suggested for the NCFG transmissions. By exchanging DSCH packets, three-way handshakes are performed between the nodes to schedule their DS data transmissions.

2.3.1.2. Data Subframe. Similar to the TOs in the control subframe, data subframe is divided into 256 transmission units called *Minislots*. Data subframe scheduling should be done allocating resources in units of minislots. The number of OFDM symbols in a minislot is found by the following equation:

$$s = \left\lfloor \frac{OFDM\ symbols\ per\ frame - MSH\ CTRL\ LEN \times 7}{256} \right\rfloor \tag{2.2}$$

The size of centralized and distributed data subframes are defined by the parameter *MSH-CSCH-DATA-FRACTION*. This parameter gives the number of minislots, which should be reserved for CS data packets. Depending on this parameter, the frame structure can be Standard Fully Centralized (SFCFS), Standard Fully Distributed (SFDFS) or a combination of both, Standard Centralized and Distributed (SCDFS), as shown in Figure 2.8(a), Figure 2.8(b), and Figure 2.8(c), respectively. Before the network is formed, the BS can select one of these frame structures to utilize network resources and tune the number of centralized and distributed control message TOs accordingly.

When SFCFS scheme is being used, DSCH messages are not necessary since they only carry DS requests and grants. On the contrary, using the SFDFS scheme, centralized control messages are still needed since they contain topology and link information for the new entering nodes. Network configuration subframe should remain as it is for all frame structures since it carries the Network Descriptor packet carrying vital network parameters throughout the network.

2.3.2. Standard Scheduling Methods

2.3.2.1. Centralized Scheduling. CS guarantees collision-free resource allocations over the centralized links distributed in the CSCF messages. Since continuous allocation is done in each scheduling cycle, this method is more suitable for traffic streams compared to the DS. In order to function properly CS requires CSCF and CSCH control messages, which keeps recent topology information and manages centralized data scheduling request/grant information. SSs need to be synchronized with the BS before transmitting any control messages. There are three types of control message sequence: CSCH-Request, CSCH-Grant and CSCF. General rules describing the order of centralized control message sequences are the following: CSCH-Grant is followed by either CSCH-Request or CSCF according to the flag set in CSCH-Grant. CSCF is always followed by CSCH-Request and CSCH-Request is always followed by CSCH-Grant. A NCFG frame is reserved once in every network configuration period frames and it overrides the present control message sequence. After NCFG frame ends, the control message sequence resumes from where it left off.

Since CSCH-Grant and CSCF packets are only forwarded by the nodes with children, they take fewer TOs than CSCH-Request sequence, which is sent by all nodes, regardless of child count, excluding the BS. An example of a CSCH-Request sequence followed by a CSCH-Grant sequence is shown in Figure 2.9. In this example scenario, five TOs are reserved for centralized control messages and in order to complete CSCH-Request sequence, two frames are required, where CSCH-Grant sequence can be completed in a single frame. SSs derive the length of these sequences from the latest CSCF broadcasted and this way they remain synchronized with the network. When

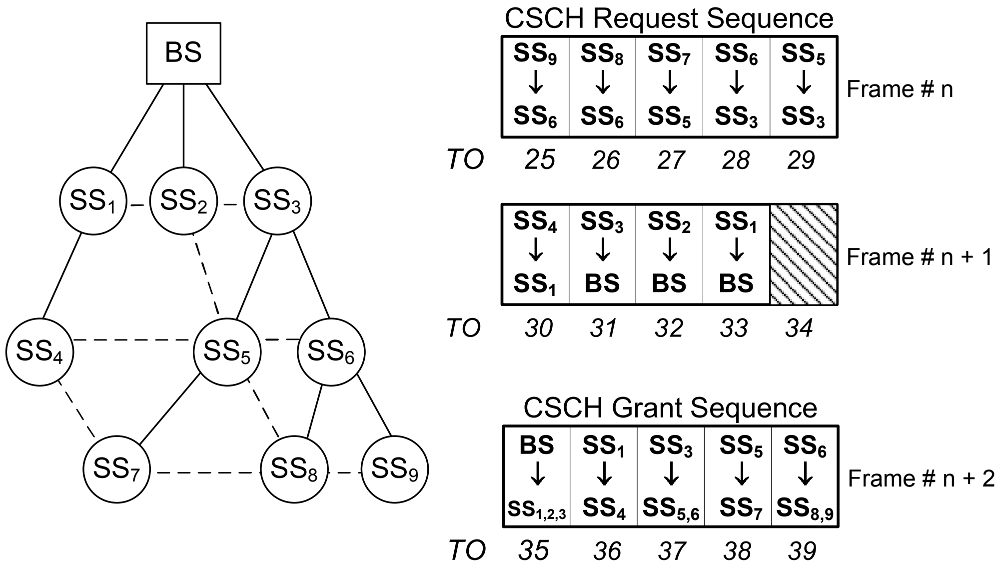


Figure 2.9. CS control message sequence

the current messaging sequence ends, the new sequence starts on the first TO of the following frame and like the 34^{th} TO in Figure 2.9, some TOs may be wasted because of this rule.

A CSCF packet originates from the BS and then forwarded by each node, which has at least one child, in its reserved TO calculated according to the node's position in the broadcast topology. Besides the topology information, all of the burst profile information between the nodes' children and parent are also present in CSCF packet contents. Without the topology information, SSs cannot transmit their control and data packets. The BS can initiate a CSCF sequence triggered by two conditions:

- The BS broadcasts the number of topology changes since the latest CSCF was sent, periodically in CSCH-Grant messages. When amount of topology changes exceed a preset threshold, the BS sets the CSCF sending flag.
- Every time a CSCF is being sent, a timer is set. If this timer expires and a CSCF has not yet been transmitted the flag is set to initiate CSCF sequence.

During a CSCH-Request message sequence, request packets are generated starting from the leaf nodes and sent to their parents. This way requests propagate to the BS cumulatively as can be seen in frames n and $n+1$ of Figure 2.9. The requests are represented by *Flow Scale Exponent* (fse) and *Flow Value* of i^{th} node (F_i), which are both 4 bit parameters in a CSCH packet. The requested bandwidth, B_R, of i^{th} node is calculated using the following equation.

$$B_R = F_i \times 2^{fse+14}\ bits/second \tag{2.3}$$

According to this relation as the request values get larger the fse parameter increases. Since fse is common for all requests in a CSCH packet, there exists a rounding problem, where nodes' requests are rounded up to the nearest minislots, especially in conditions, where traffic amount differs significantly between the nodes. As requests are collected from the leaf nodes to the BS, value of fse changes according to the updated request values in the packet. This results in under-utilization and introduces additional transmission delay for some nodes. After collecting the request packets from its children, the BS performs the scheduling and prepares a CSCH-Grant message. The grant message does not contain an actual schedule but each node can calculate its own transmission time by using the F_i and fse values of every other node listed before itself in the topology tree. The scheduling algorithms used for UL and DL allocations are not defined in the standard and left to the vendors.

The length of the CSCH scheduling cycle is the total number of frames it takes to collect all of the requests and distribute the grants to the network. So SSs need to calculate the following, when they receive a CSCH-Grant message [3]:

- Absolute time that this CSCH packet will be forwarded to children, if any present.
- The frame number, in which the last node of the topology tree will receive this grant message.
- The time when BS transmitted this CSCH-Grant message.

If there is a NENT request from a new node, the Sponsor Node uses its CSCH request packet to transmit this request to the BS. After obtaining all of the Sponsor Node requests, the BS chooses one of the Candidate Nodes and grants it. Only one Candidate

Node can make network entry at a time. Until the network entry of the current Candidate Node is done, other requests are rejected by the BS. Therefore Mesh mode is not very suitable for dynamic topologies since in such case network entry of nodes will require longer periods.

The *MSH-CTRL-LEN* parameter is defined in the frame structure section and it can take values between 1-16. Schwingenschlögl *et al.* investigate the effects of this parameter on CS for SFCFS networks in [17]. This study concludes that there exists a trade-off between the scalability and performance in the CS method, which is mostly influenced by the selection of *MSH-CTRL-LEN* parameter. It is shown that over 49 nodes, which is nearly one fifth of the total WiMAX network capacity, scheduling delays reach significant values for a medium *MSH-CTRL-LEN* value, thus making it impossible to support real time traffic.

2.3.2.2. Distributed Scheduling. Coordinated Distributed Scheduling (CDS), requires all of the nodes in a WiMAX Mesh network, including the BS, to be coordinated for data transmissions in their extended neighborhood. They should also broadcast their available minislots, requests, and grants periodically using the DSCH control message. According to the frame structure type, some of the control message TOs may be reserved for CDS DSCH messages. These DSCH messages are exchanged on a common channel throughout the network to transmit schedule information. CDS transmissions are done independent of the BS, thus according to the definition in the standard, the transmission direction does not have to be UL or DL.

Uncoordinated Distributed Scheduling (UDS) can be used for rapid and ad-hoc scheduling. UDS is performed using directed requests and grants between the transmitter and the receiver. This scheduling scheme needs to guarantee that the uncoordinated data transmissions should not collide with the CDS, CS data, and CS control messages, thus not a very reliable scheduling scheme. In UDS, DSCH messages are sent in the data subframe reserved for distributed data packets and may cause collisions between UDS DSCH packets. The response to requests should be done in the same order as the present requests in the DSCH packet, since TO allocations cannot be done in this scheme. The 2^{nd} grant message should immediately follow the minislot, in which the 1^{st} grant is received.

Using the information extracted from the DSCH messages exchanged in the neighborhood, each node modifies its availabilities accordingly. If there is a receiver in a node's neighborhood, the node marks those minislots so that it will not be able to transmit. That node can still receive other transmissions during these minislots depending on the interference of the transmitter.

UL and DL requests are sent using the same DSCH messaging process. Both CDS and UDS use the same three-way handshake procedure as defined in the standard [3]:

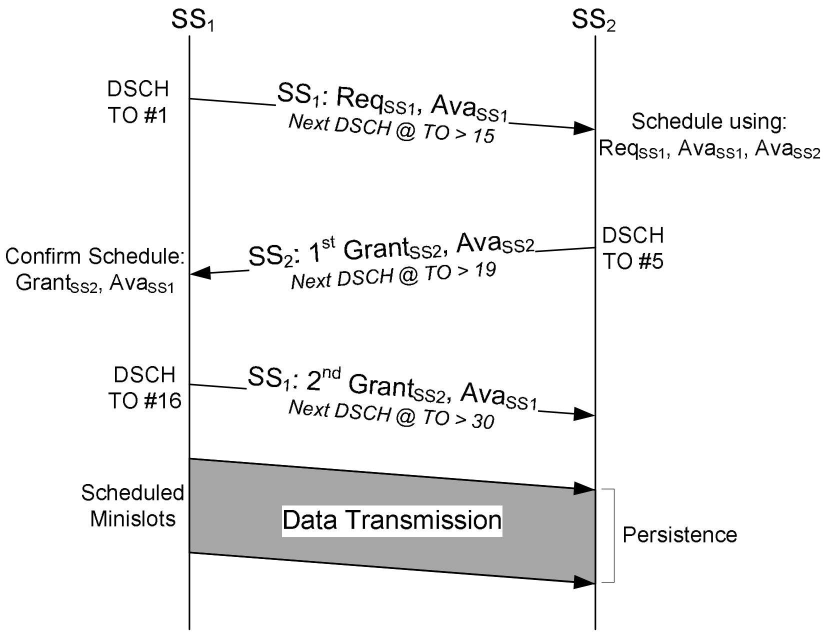


Figure 2.10. DS three-way handshake mechanism

- **Request:** MSH-DSCH sent by the requester node contains: next DSCH transmission information, request Link ID, demand, and persistence values along with available minislots. Demand level is the number of minislots requested and persistence value represents the number of frames this demand level should be maintained. Persistence can only take the following values specified in the standard: 1, 2, 4 , 8, 32, 128, and *Good Until Canceled.*

- **1^{st} Grant:** Upon receiving this request message, granter node processes this request by comparing both the requester's and its own available minislots and schedules a region if possible, which fulfills the requirements of the request in question. Other neighbors of the granter node also receive this grant message and record the region granted by marking it in their own availability matrices.
- **2^{nd} Grant:** Last confirmation grant, called the 2^{nd} grant, is sent by the original requester by checking its latest availabilities to make sure the granted period is still available since the request was sent. Other neighbors of the requester node should record this granted region in order to avoid collisions.

An example of this three-way handshake mechanism is illustrated in Figure 2.10, where SS_1 is the requester and SS_2 is the granter. The optional UDS scheme may also be used for exchanging DSCH messages in the data subframe by contenting with other nodes in the neighborhood, which will not be used in this thesis. Therefore, Coordinated Distributed Scheduling will be referred simply as Distributed Scheduling throughout the text.

Mesh election procedure and the number of TOs that SSs holdoff before sending the next DSCH message have significant effect on DS performance. Every node calculates its next DSCH transmission time (nxmt), during the current transmission time (cxmt). An SS is not eligible to send another DSCH message until *Xmt Holdoff Time* expires, which is defined by the equation presented in section 2.3.1.1. Along with each DSCH the five bit *mx* parameter is sent, which specifies the interval that the nodes will transmit their next DSCH message is calculated as follows [18]:

$$2^{exp} \cdot mx < nxmt \leq 2^{exp} \cdot (mx + 1) \tag{2.4}$$

where *exp* is the *Xmt Holdoff Exponent* parameter defined in the standard, which can be set seperately for each node. The Mesh election algorithm uses the eligibility interval defined above, when considering which nodes to include in the DSCH contention calculations.

There are several studies evaluating and pointing out limitations of the DSCH messaging scheme defined in the standard. Cao *et al.* develop an analytical model for the control channel access of DSCH messages using the Mesh election algorithm in [19]. The model estimates DSCH transmission interval of SSs and the connection setup delay caused by the three-way handshake procedure, which are required for throughput and end-to-end (ETE) delay calculations. Similarly in [15, 18], Bayer *et al.* discuss the performance of CDS control messages and propose improvements to solve the scalability problem of dense WiMAX Mesh networks. [18] proposes a dynamic *Xmt Holdoff Time* scheme, which tunes the HOE parameter dynamically on every node to decrease contention problems.

3. LITERATURE SURVEY ON SCHEDULING IN WiMAX MESH NETWORKS

IEEE standard specifies the guidelines for CS and DS mechanisms, giving the definitions for all control messages but the implementation details of both scheduling methods are left to the vendors. There are many studies in the literature implementing and evaluating various scheduling and routing schemes for both WiMAX PMP and Mesh networks. For Mesh networks, most of the research is done on CS and the combined frame structure. There are also extensive studies on the DS control messaging, which evaluate the existing three-way handshake and DSCH transmission mechanism and propose several improvements to fix scalability and performance issues.

There are several comprehensive survey papers on scheduling in WiMAX Mesh networks such as [20–23], addressing many scheduling methods proposed in the literature. Ghosh *et al.* focus on multi-hop WiMAX Networks in [20] including both Mesh mode and relay networks, they also point out the advantages of using CS, DS and UDS methods by comparing their strengths and weaknesses. [20] and recently published [23], both include research issues and open challenges regarding WiMAX mesh networks. In addition to various CS and DS methods Zhang *et al.* present the Mesh mode network entry and initialization process in detail but the main focus of [21] is on QoS differentiation schemes.

The proposed scheduling methods for WiMAX Mesh networks can be broadly divided into three categories: centralized, distributed, and mixed schemes.

3.1. Studies on Centralized Scheduling

Papers about CS investigate either scheduling using spatial reuse enabling concurrent transmissions or the standard version, where spatial reuse is not allowed. In majority of these scheduling works [24–29], spatial reuse is applied by using the common interference model. According to the interference model, for a transmission to be successful the following conditions should hold:

- No node can transmit and receive at the same time.
- No node can transmit to or receive from multiple nodes.
- There must be only one receiver among the neighborhood of a transmitter.
- There must be only one transmitter among the neighborhood of a receiver.

These rules are typically referred as primary and secondary interference [30]. *Primary interference* is caused by a node doing multiple operations at a time period such as receiving from different transmitters or trying to transmit and receive. *Secondary interference* is caused by receiving an unintended transmission, when already receiving another transmission destined to the node in question.

In [24], Tao *et al.* propose a concurrent transmission scheme by constructing a routing tree, where each new node chooses the parent with lowest interference value. As new nodes enter the network, previously formed links' interference may change, so SSs can change their parents accordingly. Similarly in [31] a cross-layer design is proposed, defining a blocking metric, $B(k)$, which is the cumulative summation of blocked neighbors at each hop, assigned to a route from the BS to a SS. This $B(k)$ metric is used to construct the routing tree just like the interference value in [24]. Another study focusing on the routing tree construction is presented in [29], which solves for the maximum concurrent flow metric during scheduling and creates the routing tree based on that. A uniform slot allocation algorithm is proposed in [25], in which each node generates an uplink slot demand matrix and a downlink slot demand matrix by using their transmission queues and the grant message from the BS. Then the nodes construct a link interference matrix (LIM), which is used for concurrent slot allocations with the help of demand matrices in order to achieve higher spatial reuse. LIM is assumed to carry the binary interference status of all links, even the distributed links, which are only known to the neighboring nodes. Another collision-free concurrent transmission method is proposed in [26]. Different from previously mentioned papers on CS, Kim *et al.* consider fairness amongst SSs. They define a *satisfaction index*, which is derived from the weight of the node and the bandwidth allocated to this node in the last preset *satisfaction window* time period. This also provides node based QoS by setting the weight of a node during network entry. Nodes are ordered according to their satisfaction indices but in a "low hop count first" manner as defined in the standard. El Najjar *et al.* introduce a power-aware routing method in [32] for enabling spatial reuse in the CS. Two schemes are discussed in the paper: The *Power Aware* scheme, where each node uses minimum power for data transmissions and *Max Power* scheme, where each node transmits packets to reach maximum coverage. They also address the effect of hidden terminal nodes. In [27] a fair $O(n^2)$ Transmission-tree scheduling algorithm is proposed. The routing tree construction is done considering: minimum scheduling time, increase in the channel utilization ratio, and low transmission latency. They implement a service token mechanism, in which after a transmission is done over a link, the transmitter node loses a token and the receiver's token count is increased by one to help relaying neighbor packets. In [28] an analytical optimal scheduling model is proposed for chain topologies using WiMAX Mesh mode. Jin *et al.* present different routing and scheduling algorithms for general mesh networks such as: maximum parallelism routing, min max degree breadth first tree, interference aware routing from [31], concurrent transmission from [24] for comparison purposes.

The scheduling and routing schemes mentioned above enable spatial reuse by either modifying some control messages defined in the standard or assuming that each node has the interference knowledge of all network including the distributed links, which is not possible. According to the standard, SSs can learn link quality information of the nodes in their extended neighborhood or burst profile information of centralized links only from CSCF messages. Unlike the studies presented above, HFS aims to benefit from spatial reuse without changing the standard definitions of CS and control message contents.

In [33] a BS scheduler is proposed, which prioritizes the SSs with low traffic demand and high traffic class and grants them the first minislots of the data subframe. The aim of this scheduler is to decrease average delay and to serve higher number of requests.

Besides single channel schemes, there are also several studies on multi-channel CS in the literature. In [34] a multi-channel single-transceiver scheduling and channel assignment method is proposed. Proposed scheduling method considers the bandwidth requests and assigns them to proper channels by using an active link scheduling algorithm similar to the token based method used in [27]. Another multi-channel single transceiver work is presented in [35], which discusses the cases with large and limited number of channels. They draw an interesting conclusion from the simulation results that in multi-channel multi-transceiver WiMAX Mesh networks, the number of channels should not be more than twice the number of transceivers since performance stays the same. HFS uses a single channel transmission model for focusing on the protocol behavior, which can be extended in the future studies to include multi-channel transmissions.

MSH-CTRL-LEN parameter's effect on network performance is investigated in [17]. It points out that for large networks, the scalability and efficiency of CS mechanism is at stake and it is vital to choose a proper *MSH-CTRL-LEN* value according to the topology and traffic type. For large values the control message cycle is completed faster, thus giving better latency but as *MSH-CTRL-LEN* parameter increases, data subframe gets smaller and network throughput decreases.

3.2. Studies on Distributed Scheduling

Majority of the published work on DS is about evaluating or improving the *Mesh Election* based DSCH control message transmissions, such as [36–44]. [36] provides a mathematical formulation for the proper range of mx and HOE parameters, which are used to report next DSCH TO interval to the nodes in the extended neighborhood. They suggest that these parameters should be chosen wisely or collisions may occur. Another study about possible DSCH collisions is presented in [42], modifies the definition of the mx value and doubles DSCH transmission interval accordingly. This modified scheme considers TOs of the extended neighborhood instead of assuming their interval unknown. A more realistic approach to the collisions in DSCH TOs is presented in [45]. Zhu *et al.* use a non-quasi-interference model addressing the neglected interference effect in the common interference model used in majority of the Mesh mode studies. They present the collision percentage of DSCH messages for various physical layer propagation models. In addition to the realistic interference model, some modifications in the DSCH format are also proposed, such as $8 + 8 \cdot neighbor\ count$ bits to be periodically broadcasted for scheduling bitmap.

Chakraborty *et al.* propose an intelligent distributed search scheme in [37] to tune the HOE by observing the expected number of TOs between two successive DSCH messages, $E[\tau_k]$, for every member of extended neighborhood. This scheme requires a modification in DSCH packet format since nodes need to exchange $E[\tau_k]$ parameters periodically.

Kim *et al.* suggest to assign the HOE according to the presence of any other transmitting or receiving nodes in the extended neighborhood in [38]. An advanced neighborhood table is used to record the required communication information, which is extracted from the DSCH messages, but does not require any modification in the standard. Similar to [38] Cesar *et al.* use the pending transmissions and pending receptions for the proposed Gradual HOE Adjustment algorithm in [44], modifying HOE gradually in each scheduling period.

In [39] a soft holdoff time is defined and until the node reaches that limit it may give its DSCH TOs to higher priority nodes. After the soft holdoff time expires SS is required to send its DSCH as soon as it can. This scheme is also combined with a minislot allocation method, which considers the QoS and reserves some slots before granting a request. [43] implements QoS using the service classes similar to the PMP mode and also considers the contention intensity in the neighborhood for tuning the HOE. According to the proposed method, a service class is assigned to each new node when they enter the network and its HOE parameter is set to 0 initially. A queue size based dynamic HOE adjustment is presented in $[40, 41]$, prioritizing the nodes with large queue sizes. Loscri *et al.* define an overloaded node as the node having at least half of its queue full, the rest of the nodes are called underloaded. Underloaded nodes take HOE values of one, two or three with equal probabilities of one thirds, where others are fixed at zero since they require fast DSCH transmissions and they do not have time to holdoff.

In addition to the extensive studies on improving Mesh Election scheme there are several papers on distributed data subframe scheduling. For instance in [46], Teng *et al.* propose a fair scheduling algorithm, which uses the mean slot allocations in the extended-neighborhood. The performance of the proposed algorithm is evaluated in terms of throughput and efficiency. Another data subframe scheduling study proposes a link based proactive requester in [47]. The proactive requester considers the past packet arrivals and current buffer status to send requests in advance so that the bandwidth will be granted when actual packets arrive. This requester works combined with a differential bandwidth requester mechanism, which takes into account various service classes and bandwidth reservation policies.

Various routing methods are also studied such as the analytical model proposed in [48] to estimate ETE delay values for multi-path DS routing scheme. Saha *et al.* apply queueing analysis at each hop and choose a proper path for the data packets accordingly. In [49] another routing method is proposed using a *Shortest-Widest Efficient Bandwidth* metric, which depends on packet error rate, present capacity on the link and hop count to destination. A token bucket based admission control scheme is used to smoothen the bursty traffic for more accurate parameter estimation.

One of the few examples of multi-channel DS studies is presented in [50], which is a fair ETE bandwidth allocator trying to maintain fairness even between traffic flows with different path lengths. Proposed method is especially effective in dense networks.

3.3. Other Studies

Other than the studies on SFCFS and SFDFS there are several studies, which use the SCDFS providing service for both Internet and intranet traffic. In [51], Kuran proposes a queue aware cross-layer routing mechanism, referred as Centralized Queue Aware Routing. This mechanism suggests that, in the presence of local congestions in the network, an SS may route its Internet traffic, which should normally be sent to the parent node, to a neighbor node (pseudo parent) using a distributed link.

Another study using SCDFS proposes to eliminate the boundary between centralized and distributed data subframes in [52] using the Combined Distributed and Centralized scheme. Cheng *et al.* suggest that distributed data messages can be sent in the idle centralized data minislots. A more generic scheme proposed for both Mesh mode and IEEE 802.16j presents a dynamic frame partitioning method in [53]. Albluwi *et al.* use a dynamic markov model to utilize the frame partitions by forecasting the traffic behavior. The frame partition boundary is tuned according to the expected frame occupancy.

HFS also uses the SCDFS for the BS and 1-hop SSs. It does not actually remove the data subframe boundary but it allows DS minislot allocations to support the Internet traffic. Therefore it provides more flexibility for transmissions between 1-hop SSs and the BS. Table 3.1 summarizes the studies discussed in this section by categorizing them according to the problems they focus on.

Table 3.1. Literature Survey Summary

Scheduling Type	**Focus**	**Publication**
CS	Spatial Reuse	[24–29, 31, 32]
CS	Scheduling Prioritization	[33]
CS	Multiple Channel	[34, 35]
CS	MSH-CTRL-LEN	[17]
DS	DSCH Collisions	[36, 42, 45]
DS	Adjusting HOE	[37, 38, 40, 41, 43, 44]
DS	Subframe Scheduling	[46, 47]
DS	Routing	[48, 49]
DS	Multiple Channel	[50]
CS/DS	Scheduling	[51]
CS/DS	Routing	[52, 53]

4. HYBRID FRAME STRUCTURE

4.1. Problem Definition

According to the IEEE 802.16 standard, the division boundary between the distributed and the centralized data subframe should be defined during network initialization. This boundary represents the maximum number of minislots reserved for CS. However, in practical implementations this boundary is fixed since distributed packet transmissions specify a minislot offset, which is selected during the grant procedure, and the boundary can not be forecasted at that time. The fixed sized boundary problem is also addressed in [52], which suggests the boundary should be flexible for utilizing the minislots but their method requires modifications in CS control messaging defined in the standard and has limitations using the DS scheme.

Another important weakness of the Mesh mode is the spatial reuse problem in CS. WiMAX standard states that in the centralized data subframe only one node can transmit data packets at a given time. This results in significant waste of minislots when dealing with large networks since all remaining nodes should keep radio silent during that period even if they are not in the range of the transmitting node. Figure 4.1 illustrates an example of a standard 4-hop CS transmission and wasted transmission opportunities, which could have been used by the nodes far away enough to transmit without causing any interference. This figure assumes a simple 2-hop interference model in which only the nodes in the neighborhood interfere with each other. Left part of the figure presents the end-to-end transmission of packet *A*, which is generated by the BS and destined for a 4-hop SS, consuming all four of the minislots. On the other hand, right side of the figure shows that packets *B, C, D, and E* could have been transmitted successfully without causing any interference. This figure only points out the wasted minislots for one branch of the BS, it is possible to magnify the gain if there are several similar branches, in which SSs can make concurrent transmissions meanwhile the ongoing CS transmission occurs. As discussed in Section 3.1, there are many studies proposing spatial reuse schemes either by modifying the standard

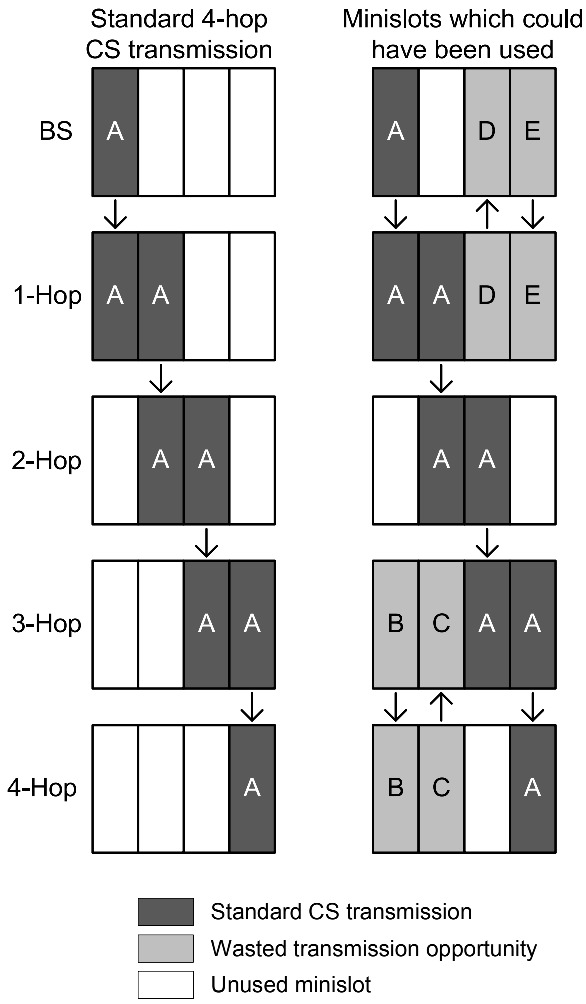


Figure 4.1. Wasted minislots during a standard CS transmission

packet structures or assuming that each node has the whole networks' link interference information.

WiMAX Mesh mode and any other multi-hop network suffer from the resources consumed while relaying the packets hop by hop. If there are many SSs having large hop counts, most of the bandwidth is allocated for relaying. Combined with the aforementioned problems, total achievable network throughput suffers dramatically. Assuming each SS has similar traffic demand D (in bps), Equation 4.1 gives the maximum capacity of a SFCFS data subframe.

$$T_{fr} \cdot D \cdot \sum_{h=1}^{M} (N_h \cdot h) \leq B_{sym} \cdot C_{ms} \cdot s \tag{4.1}$$

where T_{fr} is the frame duration, M is the maximum hop count in the network, N_h is the number of nodes having hop count h, B_{sym} is the number of bits that can be sent using one OFDM symbol depending on the modulation coding used, s is the number of OFDM symbols per minislot and C_{ms} is the total number of minislots allocated for CS. The right hand side of Equation 4.1 is the total number of bits that can be sent in one frame and the left side represents the summation of all traffic demands per frame. It can be clearly observed that as the topology dependent h and N_h values get larger, the maximum capacity of the centralized data subframe is reached quickly. The same situation can also be seen in Figure 4.1 where a 4-hop transmission uses four times the network resources compared to a single hop transmission. Using the 24 SS topology given in Figure 6.1(d), for $T_{fr} = 10\,ms$, $B_{sym} = 864\,bits/symbol$, $C_{ms} = 256\,minislots/frame$, and $s = 3\,symbols/minislot$, D_{max} is calculated to be 1.23 Mbps by using Equation 4.1 as shown below.

$$0.01 \cdot D_{max} \cdot [(1 \cdot 6) + (2 \cdot 6) + (3 \cdot 12)] = 864 \cdot 256 \cdot 3$$

This value of D_{max} corresponds to 29.5 Mbps total network throughput for 24 SSs and considering the total capacity of the network, which is 66.4 Mbps, overall utilization is 44 per cent for the given scenario. As the topology gets larger the utilization will suffer even more. Both CS and DS have various advantages for specific conditions which are presented in Table 4.1.

Specifically for large networks, DS connection setup overhead is lower than CS but for multihop transmissions this advantage may be lost since CS only schedules once (even the multi-hop transmissions) where DS requires a three-way handshake at each hop introducing significant latency. On the other hand, CS performs scheduling cycles in which one TO is reserved for a single SS, without spatial reuse support. Therefore, as the number of nodes increases, either the *MSH-CTRL-LEN* value should be increased at the cost of reducing the number of data subframe minislots [17] or each centralized request-grant cycle takes longer, introducing additional connection setup delay. On the contrary, DS is not that much effected directly by the network size since only the nodes in its extended neighborhood are coordinated, which we call network density.

Table 4.1. Centralized scheduling versus distributed scheduling [20]

Centralized Scheduling	**Distributed Scheduling**
BS determines the schedule for all nodes in the network	Data transfer between neighboring SSs is done without BS involvement
Connection setup overhead is high	Connection setup overhead is lower than CS
MSH-CSCF and MSH-CSCH messages are used for scheduling and routing	Nodes compete for sending MSH-DSCH messages to schedule packets using the Mesh Election algorithm
Suitable for consistent continuous traffic	Suitable for intermittent and bursty traffic

We can derive the following conclusions from this section regarding the scheduling methods: CS is more suitable for the Internet traffic and local minislot allocations of DS can be more beneficial in the presence of intranet traffic. The proposed frame structure aims to combine the useful features of both scheduling methods to achieve better network throughput.

4.2. The HFS Method

The *Hybrid Frame Structure* method is mainly based on the SFDFS and SCDFS defined in the WiMAX Mesh standard as illustrated in Figure 2.8(b) and Figure 2.8(c), respectively. Drawbacks of both CS and DS methods are discussed in the previous subsection. HFS aims to overcome the spatial reuse problem of CS by relaying packets that belong to the SSs with high hop counts using the DS. Consequently, some additional latency is introduced due to the three-way handshakes performed at each hop. HFS limits the CS transmissions up to 1-hop nodes. Beyond the first hop, unlike the standard frame structure, nodes can only communicate using DS, even to communicate with their parents. This way, the messages are not relayed using CS and network can exploit the spatial reuse property of DS for better network performance.

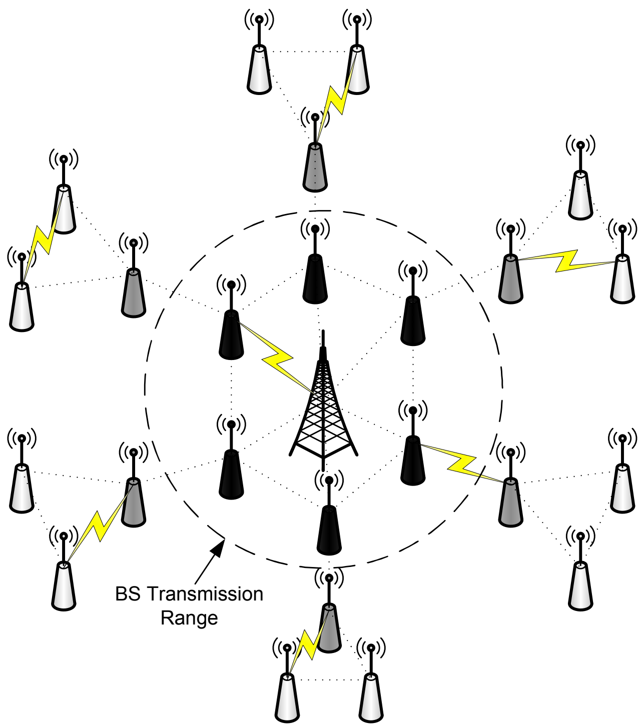
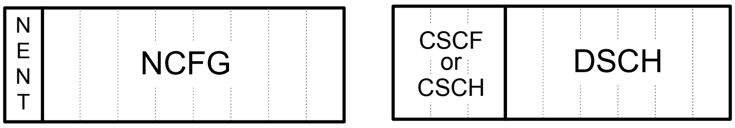


Figure 4.2. HFS concurrent transmissions

Proposed HFS method uses the control message formats as defined in the standard. It only requires modifications in the MAC layer for assigning different frame structures to the SSs according to their hop counts. As a result, SSs schedule their data transmissions in the corresponding CS or DS minislots. Figure 4.2 illustrates an example topology using the HFS method which enables concurrent transmissions.

4.2.1. Control Subframe

The control subframe is completely standard compliant and no change is necessary, but the number of centralized and distributed control message TOs should be tuned in order to achieve better performance. Since the only CS traffic is between 1-hop SSs and the BS, the number of CS TOs may be smaller compared to the DSCH TOs. This would introduce some delay for NCFG messages but it only effects the initialization process and has no effect on network performance. The number of DSCH TOs directly effect the three-way handshake performance, thus large portion of the control subframe should be assigned for distributed messages. At a first glance, it may seem that the nodes only using DS might not need to exchange centralized scheduling packets, but CSCH messages carry link update information for burst profiles as well as sponsor node information, which are required for network entry process. Therefore, all of the nodes are required to send CSCH, CSCF, and DSCH messages independent of their hop count to the BS. This introduces some additional latency but it is possible to fix this issue by modifying the DSCH contents defined in the standard. Since we choose to use the standard control message definitions for HFS method, we left this improvement as a future work. HFS network configuration control subframe and HFS scheduling subframe are shown in Figure 4.3(a) and Figure 4.3(b), respectively. These subframes are actually same as the standard control subframes but Figure 4.3(b) shows the recommended ratio of TO assignments in HFS method.



(a) HFS NCFG subframe (b) HFS scheduling subframe

Figure 4.3. HFS method control subframe

4.2.2. Data Subframe

In the HFS method, the data subframe is allocated according to the hop count of SSs to the BS. Figure 4.4 presents the proposed frame structure and transmission details of SSs at different hops. In addition to the transmissions shown in Figure 4.4, each node can also communicate with the nodes having the same hop count as itself. There are mainly three kinds of data subframe allocation schemes used:

4.2.2.1. BS and 1-Hop SSs. The BS and 1-hop SSs use the SCDFS frame structure, which allows both centralized and distributed data transmissions separated by a fixed boundary. They should mostly use the CS part to exchange data packets since 1-hop nodes are required to reserve the DS minislots for 2-hop nodes. The details of this tradeoff between allocating distributed minislots to the BS and 2-hop nodes will be observed in Section 4.4. 1-hop nodes are vital to HFS method since they act like hubs

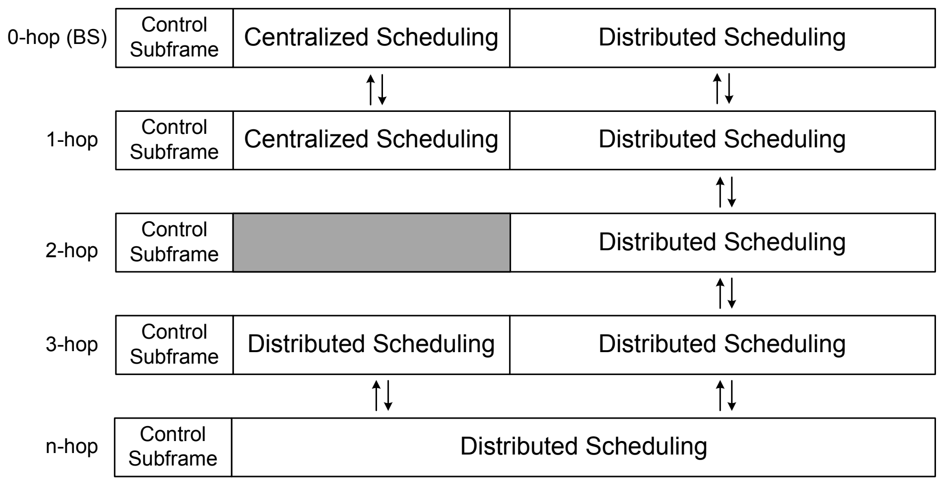


Figure 4.4. Proposed HFS

collecting distributed data packets from their children and pass them up to the BS using CS.

<u>4.2.2.2. 2-Hop SSs.</u> 2-hop SSs are in the transition region of the nodes using SFDFS and SCDFS. As can be seen from Figure 4.4 according to the HFS method, 2-hop nodes should keep radio silent in the first part of their data subframe to maintain the collision-free nature of TDD WiMAX data transmissions. Their 1-hop neighbors use CS and 3-hop neighbors use DS in the same minislots concurrently. Thus, it is impossible to overlap their transmissions. Any transmission done by 2-hop SSs during that period may cause collisions. Since the standard frame structures are the same for each node in the network they do not require such modification.

The part of the data subframe, in which 2-hop nodes keep radio silent can be a bottleneck in densely deployed topologies. To overcome this issue, the boundary between the data subframe regions can be fine-tuned keeping in mind that, as first part gets smaller, frame structure converges to the SFDFS scheme. Using SFDFS results in higher latency since all packets will require an additional three-way handshake to reach the BS. In that case, the BS will not be able to serve SSs having higher hop counts because of extensive delay. On the other hand, because of the spatial reuse limitations using the SFCFS scheme, similar radio silence periods will be present, distributed to each node regardless of the hop count and fragmented into minislots. This results in an overall network performance worse than the HFS method, which uses the frame structure defined in this section since limited number of SSs keep radio silent. If the node density in the topology is low, such as the topology shown in Figure 4.2 where the BS has six separate branches, then the bottleneck effect disappears since six times more concurrent transmissions are possible providing enough extra minislots to carry data packets to the BS.

4.2.2.3. 2+ Hop SSs. The SSs having larger hop counts than the transition nodes should use the SFDFS. This frame structure is quite beneficial at the presence of intranet traffic since nodes can use all of their data subframe minislots to communicate with each other. On the other hand for the Internet traffic, packets are relayed to the parent nodes using distributed links, which are passed along to the BS.

4.3. Routing and Scheduling Choices in HFS

HFS uses a simple routing mechanism, where each node sends packets to its parent node, unless the destination of the packet is in the near vicinity. If so, it may send those packets directly using the distributed links. The definition of near vicinity is adjusted by a parameter which may be different for each SS and set once before the node initializes. If SS has no knowledge of the destination of the packet, it should be passed to the BS first, which has the record of the whole topology tree.

Between the 1-hop SSs and the BS, packets can be sent using either CS or DS, so they check their packet queues and the ratio parameter, before requesting and make their demands accordingly. SSs need to consider the next node in the path of a packet they send since at each hop different data subframe structures are used. 1-hop and 3-hop nodes should only schedule distributed minislots in the right part of the data subframe for 2-hop nodes, similarly 2-hop nodes should not schedule any transmissions in the first part of the data subframe since they are required to maintain radio silent.

4.4. HFS Network Throughput Upper Bound

In order to show the performance gain of HFS the upper bound of the maximum achievable throughput is derived in this subsection. This derivation roughly shows the proposed frame structure performance compared to the standard frame structure. Some assumptions are made to simplify the problem:

- All of the SSs have similar demands D.
- Topology is symmetrical such that each branch of the BS has similar sub-trees.
- No intranet traffic is present.
- This equation only gives the ideal throughput, considering the data subframe and scheduling methods used, whereas the real throughput will suffer from network node density, scheduling failures, etc.

Since the CS scheme lacks spatial reuse, limited number of transmissions can be sent in the centralized data subframe between 1-hop nodes and the BS. Additionally the unused distributed data subframe minislots can be scheduled for transmissions between 1-hop nodes and the BS. The ratio of the DS minislots of the BS, which is used for supporting CS transmissions, is called R. Equation 4.2 states that total demands from all of the SSs in the network should be able to reach the BS using both centralized and some of distributed data subframes:

$$B_{sym} \cdot s \cdot (C_{ms} + R \cdot D_{ms}) = N_A \cdot D_{max} \cdot T_{fr} \tag{4.2}$$

In Equation 4.2, R depends on how many DS minislots are required for transmissions between 1-hop and 2-hop SSs, which is also related to SSs' demands. Considering the spatial reuse property of the DS, it is possible to say that ideally all SSs under a branch of a 1-hop SS can successfully transfer their packets to that 1-hop SS, which connects them to the BS. Equation 4.3 estimates how much of the DS minislots are used for these transmissions:

$$B_{sym} \cdot s \cdot (1 - R) \cdot D_{ms} = N_{st} \cdot D_{max} \cdot T_{fr} \tag{4.3}$$

Then, we have two equations and two unknowns, namely R and D_{max}, which can be solved to obtain Equation 4.4 and Equation 4.5. These equations show us the relation between the topology structure, node count, and the throughput values:

$$R = \frac{N_A \cdot D_{ms} - N_{st} \cdot C_{ms}}{N_{st} \cdot D_{ms} + N_A \cdot D_{ms}} \tag{4.4}$$

$$D_{max} = \frac{B_{sym} \cdot s}{T_{fr}} \cdot \frac{D_{ms} + C_{ms}}{N_{st} + N_A} \tag{4.5}$$

By rearranging Equation 4.1, which presents the general capacity constraint of the SFCFS and substituting maximum demand, Equation 4.6 can be obtained for comparison purposes:

$$D_{max} = \frac{B_{sym} \cdot s}{T_{fr}} \cdot \frac{C_{ms}}{\sum_{h=1}^{M} (N_h \cdot h)} \tag{4.6}$$

Since $D_{ms} + C_{ms}$ in Equation 4.5 and C_{ms} in Equation 4.6 are both equal to the total number of minislots in a frame, the only difference between these equations is the denominators of the second fraction. Topology related terms in that denominator show that, in SFCFS performance is rather limited since it is dependant on all of the SSs in the network. On the contrary, HFS exploits the spatial reuse property and allows concurrent transmissions, which eliminates the dependency of SSs far away from each other and can communicate without interfering any transmissions. On the other hand, HFS performance is closely related to the number of SSs sharing the distributed data minislots of 1-hop nodes.

5. NETLAB WiMAX MESH SIMULATOR

Various WiMAX PMP mode simulators with built-in support are already available such as OPNET 14.5, QualNet, and NCTUns. In the literature WiMAX Mesh mode simulators are less frequent compared to the simulators supporting the PMP mode. First publicly available popular mesh mode simulator in the literature is NCTUns [54], followed by WiMsh [55], both only supporting SFDFS scheme. To the best of our knowledge there are no simulators capable of managing both CS and DS. Such a simulator is required in order to observe the effects of Centralized and Distributed traffic loads on WiMAX networks. To fulfill this need and provide a framework for future studies, *NETLAB WiMAX Mesh Simulator* (NEMMS) was developed as a part of this thesis. NEMMS incorporates both CS and DS as defined in the IEEE 802.16d standard [3]. Also the network entry and initialization mechanism and a detailed three-way handshake procedure have been implemented. NEMMS also provides base station and distributed schedulers as well as the flexibility of supporting addition of new more advanced algorithms. NEMMS implements a simplified physical layer and do not explicitly consider non-collision-related channel errors. Multi-hop cumulative interference problem is not considered and left as a future work. Although the simulator lacks a complex physical layer model, according to the burst profile parameters used by each link, the corresponding forward error correction (FEC) rate is applied. Therefore more robust FEC rates should be used for fragile links.

Since significant work was done to develop NEMMS for this thesis, which provides a framework for further studies on the WiMAX Mesh mode, it will be presented in detail in the following sections.

5.1. MAC Module

Two separate MAC modules are designed for NEMMS to be used in the BS and SS node models. The BS MAC module structure is composed of two parts in which control subframe and data subframe states are grouped. After a node completes the network entry it starts to cycle through these states. A simplified version of the state diagrams of these subframes are presented in Figure 5.3. In this diagram each transition is triggered by a timer interrupt, which are set at the beginning of every frame. The SS MAC module has an additional component of *Network Entry and Initialization* part to perform network entry before the node becomes operational. A simplified version of network entry and initialization state diagram is shown in Figure 5.1. After network initialization phase is over, SS starts to cycle through control and data subframe states just like the BS.

In order to initiate network entry procedure, first the Candidate Node starts searching a preset frequency band for any NCFG packet transmissions from neighboring nodes. When a NCFG message is encountered, the Candidate Node records the necessary information of the transmitting node and extracts packet contents to create a new entry in its neighborhood table until it receives a second NCFG message from the same node.

After receiving the second NCFG from the same node that denotes the completion of the neighborhood table, the Candidate Node chooses a Sponsor Node from the entries in that table. In NEMMS, this decision is based on the minimum hop count to the BS to which that Sponsor Node is connected. Then, the Candidate Node prepares a *MSH-NENT:Net Entry Request* packet for requesting sponsorship. This packet is sent in a NENT TO only if the selected Sponsor Node is available to accept a new candidate node and there is no indication of any network entry from the neighboring nodes. The Candidate Node can track whether some other node is trying to enter the network in the 2-hop neighborhood by checking the *NetEntry MAC Address* field sent in every NCFG packet. Thus, the Candidate Node can determine whether its selected Sponsor Node is busy or not. NENT packets may still collide if more than one node is trying to acecss the network simultaneously. Since NENT TOs arrive once in each NCFG subframe, for dense networks there is a higher probability of NENT collisions. If NENT packets collide, the colliding nodes wait for a random back off period and try again.

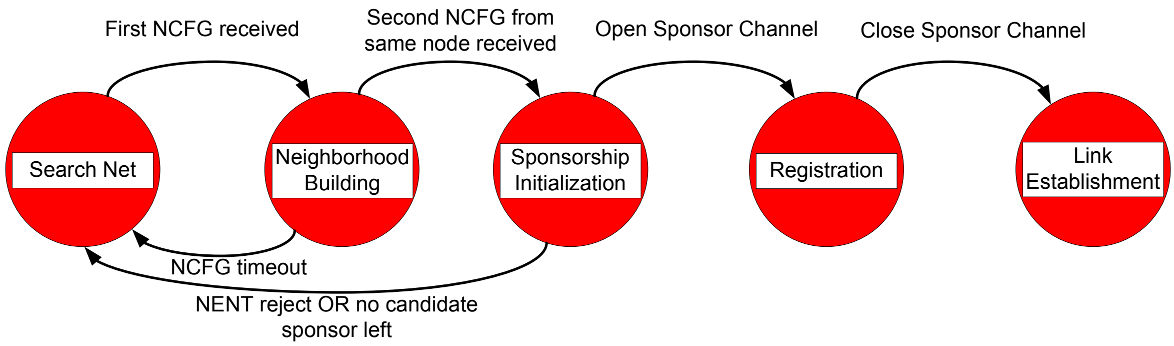


Figure 5.1. Initialization procedure simplified state diagram

Before responding to the NENT request, the selected Sponsor Node sends a link update in a CSCH-Request message to the BS. This message contains the burst profile information between the selected Sponsor Node and the Candidate Node, which will be used in the future CS transmissions between these nodes, after the Candidate Node becomes operational. Upon receiving the CSCH-Request, the BS decides whether a Candidate Node should be allowed to enter the network or not and broadcasts its decision through a CSCH-Grant packet by setting the *Sponsor Node Index* field. Since the Candidate Node cannot process CSCH packets yet, the Sponsor Node handles the grant and responds to Candidate Node's network entry request accordingly.

5.1.1. Network Entry and Initialization Implementation

If the selected Sponsor Node accepts the Candidate Node's request, it responds with a *MSH-NCFG:Network Entry Open* packet during its NCFG TO. This embedded packet contains the minislot allocations and the schedule validity information required for transmitting through the sponsor channel. Using this channel, the Candidate Node can send packets to the BS, tunneled by the SSs in between for registering to the network and BS's packets are conveyed to the Candidate node similarly. These registration packets are sent during the centralized data minislots reserved for the Candidate Node. Only *REG-REQ* and *REG-RSP* packets are implemented for this purpose. After Candidate Node receives a positive REG-RSP packet from the BS, it is assigned a unique *node ID* which is sent in every Mesh subheader as its identifier.

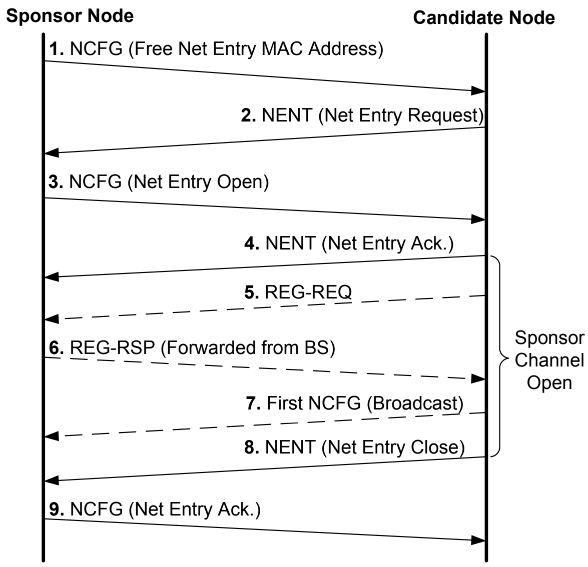


Figure 5.2. Network entry messaging in NEMMS

Although the standard defines how NCFG packets are sent, it fails to specify how the first NCFG packet will be sent by the newly entering node. According to the *mesh election* algorithm, other nodes in the 2-hop neighborhood should consider the newly entering node in their eligible nodes list to prevent unwanted NCFG collisions. To solve this problem, in NEMMS it is proposed to send the initial NCFG through the sponsor channel before *MSH-NENT:Net Entry Close* is sent so that the neighboring nodes add the new node's entry into their neighborhood tables. Thus, all of the nodes that may send a NCFG packet are considered as eligible nodes before any SS runs the mesh election algorithm, guaranteeing collision free NCFG transmissions.

After the Candidate Node receives the REG-RSP message, *NCFG:Neighbor Link Establishment* embedded packets are prepared for each entry in the neighborhood list in order to initiate the link establishment sequence. The network entry and initialization phase of a SS is considered to be complete when all of the link establishment messages are responded by neighboring nodes or the requests which are not responded have expired. The network entry messaging sequence described in this section is illustrated in Figure 5.2.

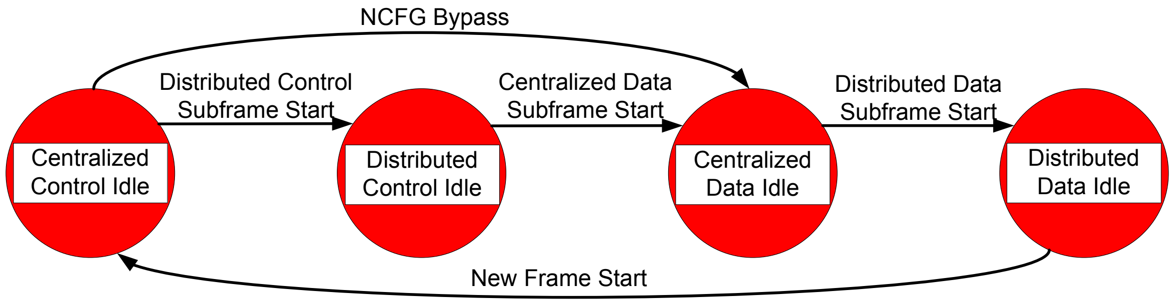


Figure 5.3. NEMMS frame cycle state diagram

5.1.2. Control and Data Subframes

In the control subframe, nodes transmit their NCFG, CSCF, CSCH, and DSCH messages in which scheduling and topology information are carried. These control messages are sent using the topology information extracted from the latest CSCF packet from which all SSs can calculate their corresponding TOs in a collision-free manner. According to the standard, every operational node should embed a *NCFG:Network Descriptor* in some of its NCFG packets but the transmission pattern is not specified. In NEMMS it is suggested that every node should embed this sub-packet in all of its NCFG transmissions since the new nodes need to process this packet and perform coarse time synchronization.

The mesh election algorithm used for NCFG and DSCH transmissions use a hold off mechanism which is addressed in many papers of Section 3.2. As a result of these discussions, in NEMMS the *Holdoff Constant* value is set as a parameter instead of the constant value of 4 given in the standard. Also for the sake of simplicity and simulator performance, NEMMS implements the transmissions of these messages using a global next NCFG/DSCH TO list. Each node enters its next transmission information into this list during their current transmission. Thus, other nodes can determine which nodes are eligible to transmit NCFG/DSCH before running the mesh election algorithm.

The data subframe of NEMMS is composed of two parts: centralized data subframe , where the CS messages are transmitted and distributed data subframe in which the nodes transmit their packets executing the DS mechanism. As described in Section 5.1.1, registration messages tunneled through the sponsor channel which is actually sent in the centralized data subframe.

5.2. BS Scheduler

The BS handles all of the CSCH-Request packets arriving from its children. These packets contain the request values in bps and network entry requests in the form of link updates. The BS has packet queues for all of the nodes in the network and the received requests are only in the uplink direction. When giving downlink grants, the BS converts the queue sizes to flow values for each node.

Giving uplink grants is rather complicated compared to downlink grants. For simplicity, a straight forward scheduling mechanism which prioritizes the nodes according to their node IDs is implemented. The lower the node ID of a SS, the sooner its request is granted by the BS. An exception exists if a Candidate Node is present. In that case the BS traces all of the nodes between the Candidate Node and itselft, and grants the request of any such node that was not granted otherwise. This exception handles the case where small registration packet requests might be rounded down to zero under heavy traffic, causing extensive delays in network entry procedure. In the presence of a Candidate Node if the sponsorship channel is open, the BS allocates an uplink grant for itself (index zero), which is interpreted by all nodes as the grant that belongs to the Candidate Node for sponsorship channel.

5.3. Distributed Scheduler

Three-way handshake procedure is implemented as suggested in the standard and described in Section 2.3.2.2. The request is sent as two-dimensional information where the dimensions are the *number of frames* and the *slots per frame*. During a handshake since every node in the neighborhood records the grant information, a failed handshake should be identified and processed accordingly. In NEMMS, when the granter node waits for a second grant from the requester, it checks the first DSCH message sent by the requester. If this message does not contain a second grant for the ongoing handshake, it is assumed to be forfeited, and the granter rolls back this grant by updating its availability list accordingly. Instead of the availability mechanism suggested in the standard, NEMMS uses unavailabilities. Keeping record of unavailabilities is more scalable and efficient since in the long term availability entries get fragmented and harder to deal with.

The scheduler checks the queue lengths of each distributed link and generates the request by converting these queue length values into minislots and frame counts. If requested traffic is greater than the available bps rate in one frame, the number of frames value is doubled, and slots per frame is divided by two. This loop continues until the request requirements are fulfilled. While this scheduler is fast in terms of computation time, it cannot distinguish between bursty and constant bit rate traffic.

6. HFS PERFORMANCE EVALUATION

The HFS method is implemented and evaluated on OPNET 14.5 [5] using NEMMS [4]. The implementation of HFS method is done by modifying the BS and SS MAC modules of NEMMS. Several features are also added for evaluation purposes such as sleep schedule and mixed traffic types (Internet and intranet) to be used for packet generation. In the rest of this section, the HFS method is evaluated and compared with SFCFS and SCDFS.

6.1. Simulation Parameters and Assumptions

As the standard suggests, nodes use the most robust modulation coding, 1/2 QPSK for the control subframe TOs, and 3/4 64-QAM is chosen to be used for data transmissions. Interarrival times of data packets and the length of active and idle periods of traffic generators are exponentially distributed. In some scenarios packet generator sleep schedule is used in order to implement bursty traffic conditions, which generates packets at full capacity when the generator is active and stops totally in the idle state. Table 6.1 presents the parameters used during the simulations and shows the default values of these parameters as the first item in the row and with boldface characters. These default values are used unless stated otherwise, in the related section.

All simulations are run for a total of five minutes, with two minutes of warm-up period. Data collection is done in the last three minutes in which the results converge to a specific value according to the simulation observations. Each simulation result is the mean value of the 10 runs with different random seeds. The topologies used for the simulations are illustrated in Figure 6.1. The topologies used for performance evaluations are selected as symmetrical because of the comparison purposes with the derived upper bound equations. In asymmetric topologies HFS also behaves similarly since neither CS or DS schemes rely on symmetry. SSs in these figures are shaded according to their hop counts, darkest SSs being closer to the BS. In all of the plots, solid lines are used for the HFS method results and dashed lines represent the SFCFS

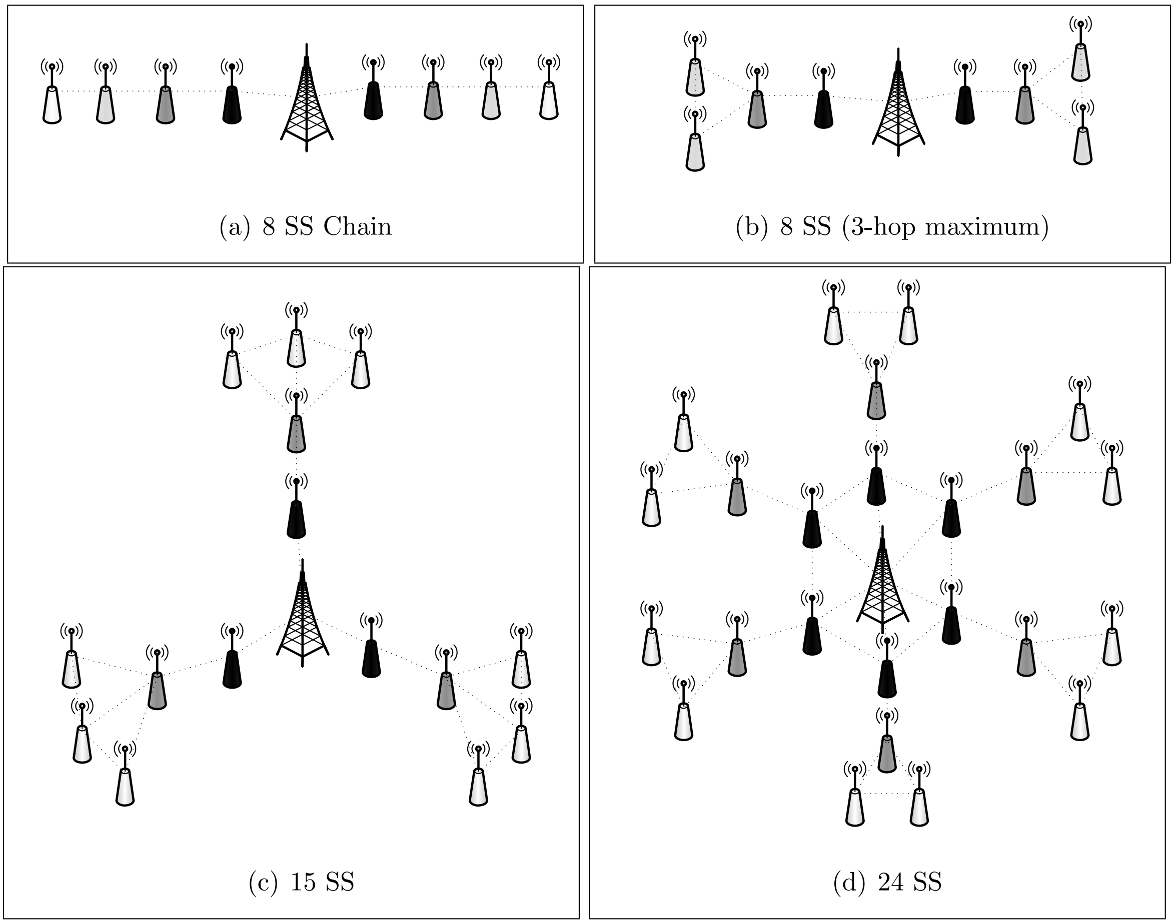
Table 6.1. Simulation parameters

Frame Duration	10 ms
Modulation and Coding Rate	3/4 64-QAM (Data)
Number of Transceivers per Node	1 (Half-duplex)
Data Packet Size	108 bytes
SS Buffer Size	20,000 Packets
NCFG Holdoff Exponent	2
DSCH Holdoff Exponent	1
Sleep/Active Time (Bursty traffic)	exponential(0.7s/0.3s)
Traffic Type	**Bursty**, Continuous
Topology	**24 SS**, 8 SS, 8 SS Chain, 15 SS
Control Subframe Length	**9 TOs**[1], 14 TOs
Constant Exponent	**1**, 4
HFS DS Request Multiplier	**1.5**, 1, 2
Internet Traffic Percentage	**100**, 70, 50

scheme. Dash dot lines are used for scenarios testing SCDFS performance in presence of intranet traffic.

According to the definitions in the standard, in a WiMAX Mesh network only NENT packets may collide. Otherwise, all transmissions are scheduled in such a way that no collisions occur. Since HFS focuses on the MAC layer, the simple channel model implemented in NEMMS is used for the performance evaluations. According to that channel model a node can receive a packet successfully if it is in the range of the transmitter and no other node in the neighborhood of the receiver is transmitting. In the presented plots the packet drops caused by collisions and queue overflows are considered.

[1]In HFS, three TOs are reserved for CS and six are reserved for DS whereas all nine TOs are reserved for CS in SFCFS scheme. In SCDFS, which both uses CS and DS, the TOs are divided according to the given traffic distribution for fair competition.



(a) 8 SS Chain

(b) 8 SS (3-hop maximum)

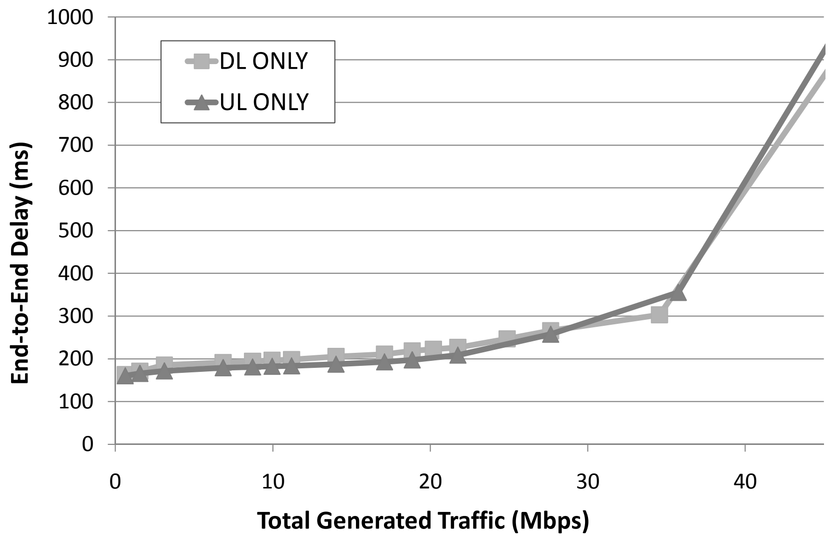
(c) 15 SS

(d) 24 SS

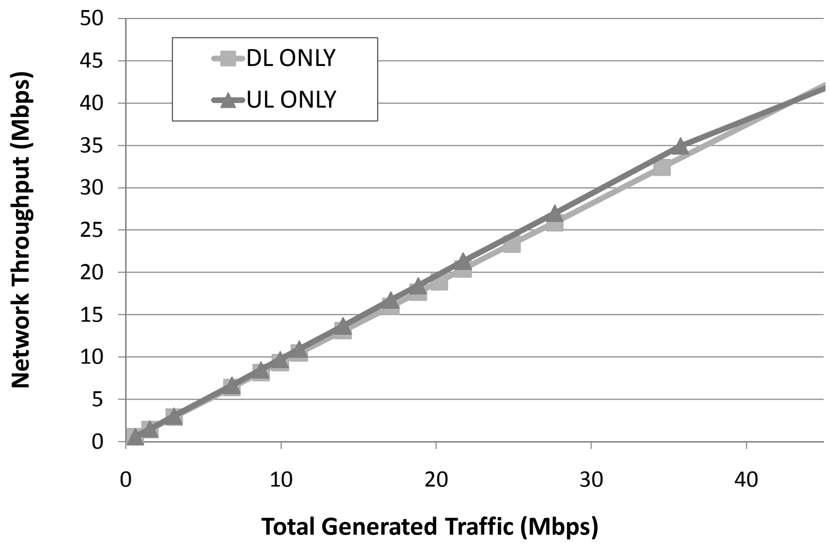
Figure 6.1. Topologies used in simulations

The following metrics are used for the simulations:

- **Network throughput:** This parameter represents the total network throughput achieved including both Internet and intranet communications. Network throughput data is collected by recording the raw data packet size, after the reception is successfully completed at the destination node. Raw data packet size includes the MAC header in order to observe how much the data subframe is utilized.
- **End-to-end (ETE) delay:** ETE delay value is the time between the packet generation at transmitter node and reception at the destination including the queueing and scheduling delays suffered at each hop. ETE delay plots presented in this section are the average delay values of packets generated by either all nodes in the network or observed in a hop-by-bop basis.
- **Jitter:** The jitter is calculated as the percentage of standard deviation from the mean ETE delay values to show the amount of variance in latency.



(a) HFS UL and DL delay



(b) HFS UL and DL throughput

Figure 6.2. HFS UL and DL traffic comparison

- **Percentage of dropped packets:** This metric is the percentage of packet drops due to queue overflows and the total number of generated packets. Queue overflows may occur when a new packet is generated or a multi-hop packet is received to be routed to the destination.
- **Traffic load per node:** It is the maximum bandwidth that each node can demand when its traffic generator is active, similar to the bandwidth limit of DSL subscribers. According to the ratio of active and idle periods of the source, effective generated traffic can be calculated as the average network load. For

example, if an SS with maximum demand value of 5 Mbps uses a 20 per cent active traffic generator, it actually introduces 1 Mbps average traffic to the network.

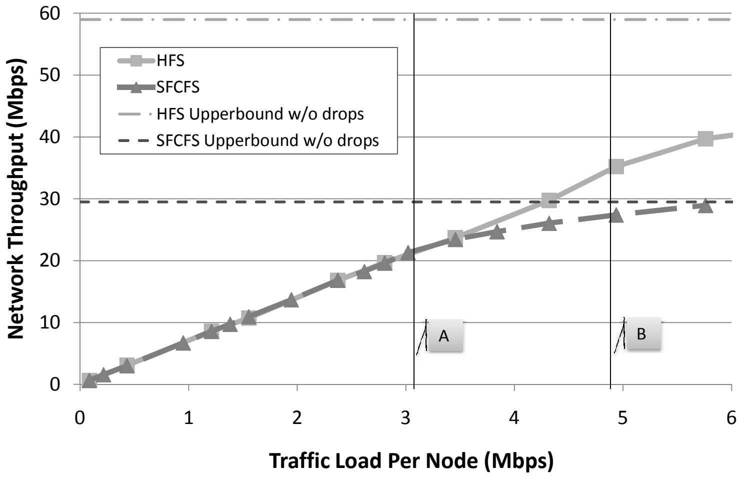
- **Total generated traffic:** If different topologies or constant bit rate versus bursty traffic conditions are being tested, this parameter is used. Total generated traffic is the summation of actual average traffic introduced to the network by all nodes.

Unlike the PMP mode, in the Mesh mode channel access is not limited to the centralized management done by the BS and management is distributed throughout the nodes in the network instead [53]. In the Mesh mode all communication is link based, so there is no differentiation between UL and DL. Therefore, most of the experiments presented here use UL traffic. Figure 6.2 shows the parallelism between the results of continuous UL and DL traffic generation scenarios using HFS.

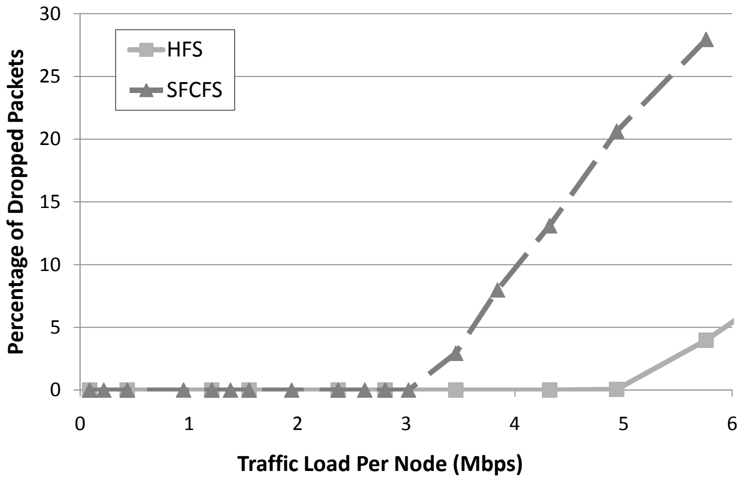
It is recommended by ITU-R in [56] that one way delay of 150 ms should be the upper bound for general network planning but latency values up to 400 ms are acceptable. It also states that under 150 ms latency, most delay sensitive applications are not affected and work properly. The discussions in the following sections consider the 400 ms upper bound to find maximum achievable throughput values. Therefore, when higher latencies are reached and packet drops start to occur, the network is considered as failed.

6.2. HFS Performance

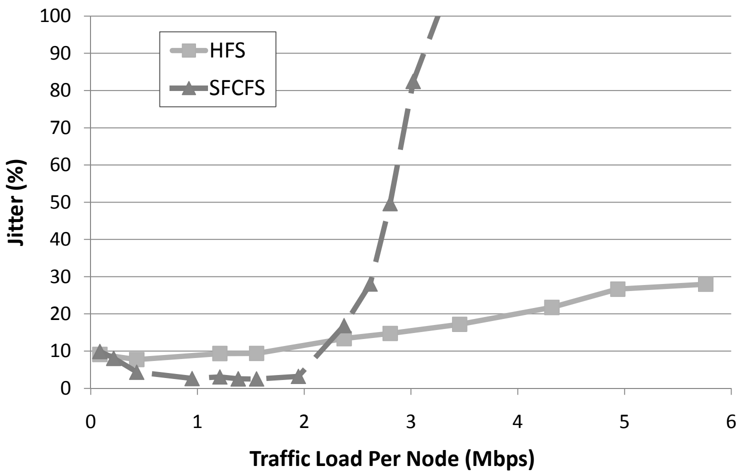
In order to observe the performance of the HFS method in a realistic scenario, first the simulations are done using only bursty Internet traffic. Network load is incremented slightly in each experiment to find out the maximum throughput limits of both HFS and the SFCFS methods. Figure 6.3(a) shows the ideal case upper bounds calculated from Equation 4.5 and Equation 4.6 compared to the simulation results. The throughput plots are linear up to the point packet drops start and beyond that point high hop SSs cannot be granted completely. Since the BS fails to schedule high hop SSs, more grants are given to lower hop SSs resulting in slight increase in throughput, which can be observed from all throughput plots in this section. Simulation results suggest that



(a) Maximum throughput and upper bounds

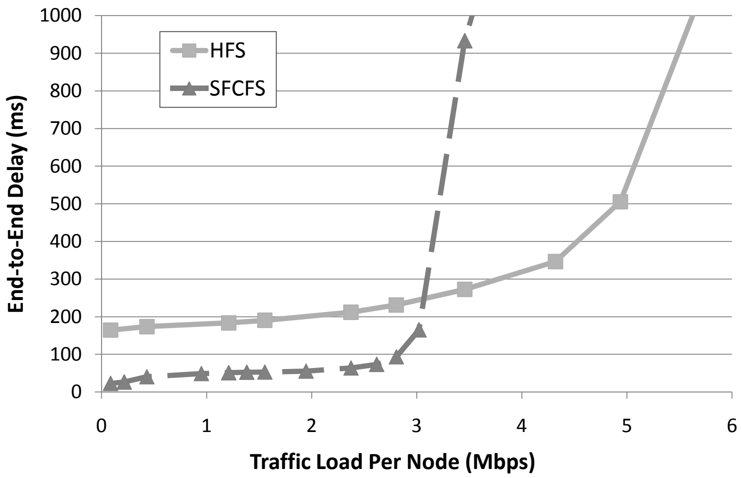


(b) HFS vs SFCFS packet drop

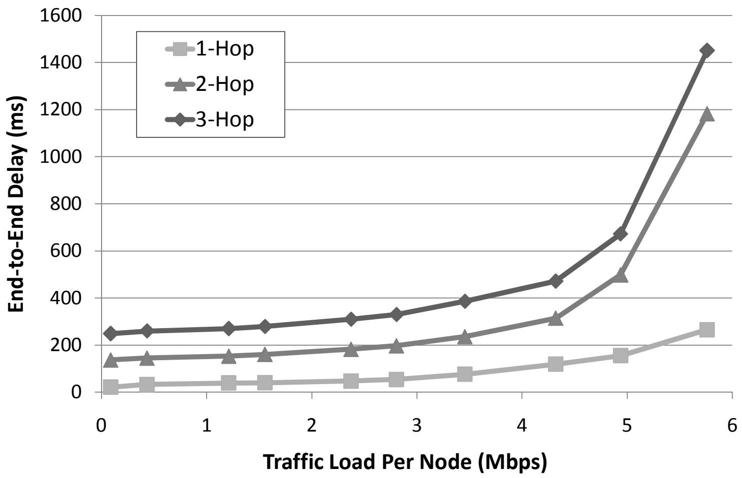


(c) HFS vs SFCFS percentage jitter

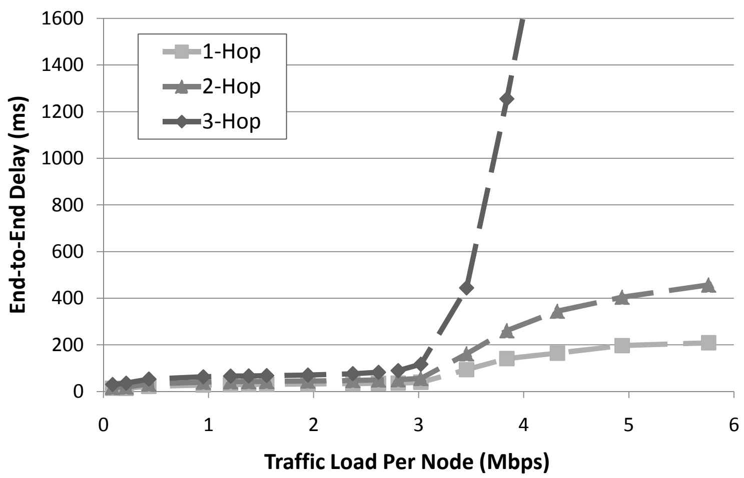
Figure 6.3. General case HFS vs SFCFS comparison



(a) HFS vs SFCFS ETE delay (average of all hops)



(b) HFS ETE delay by hop count



(c) SFCFS ETE delay by hop count

Figure 6.4. General case HFS vs SFCFS ETE performance

SFCFS scheme fails when traffic load per node reaches 3 Mbps (corresponding to 22 Mbps total throughput) as shown with the line labeled A in Figure 6.3(a), whereas the line labeled B shows that HFS method can achieve nearly 5 Mbps (corresponding to 35 Mbps total throughput) before packet drops begin as shown in Figure 6.3(b).

Since CS is more deterministic and completely contention-free, the simulation results of SFCFS scheme are similar to the analytical calculations. On the contrary, HFS is mostly based on DS, introducing contention in the neighborhood. Therefore, maximum throughput values obtained from simulations are rather low compared to the upper bound.

During stable network conditions SFCFS scheme has around 50 ms average ETE delay as shown in Figure 6.4(a). HFS method, although having reasonable jitter values (Figure 6.3(c)), performs poorly with average of 200 ms latency. This is caused by the scheduling delay of multi-hop DS transmissions and if latency values are observed for each hop separately as presented in Figure 6.4(b), it is seen that 1-hop, 2-hop, and 3-hop SSs have 40 ms, 160 ms, and 280 ms delay values, respectively. This suggests that using HFS method, high hop count SSs may suffer more delay but 1-hop SSs have better latencies even compared to the SFCFS method, which has similar delay values for each hop. As shown in hop-by-hop ETE delay plots, under high loads HFS method treats the SSs, who are distant to the BS, more fairly compared to SFCFS scheme.

The decrease in percentage jitter values can be observed in Figure 6.3(c) up to 2 Mbps traffic load per node. This behavior is caused by the stable jitter values of CS under lightly loaded conditions. As network load is increased, average ETE delay increases accordingly but since jitter values do not deviate a lot the percentage jitter decreases until the network is congested.

6.2.1. Performance in Various Topologies

In this section HFS method is tested using different topologies. Since HFS exploits the spatial reuse of DS, as the network size gets larger, more concurrent transmissions

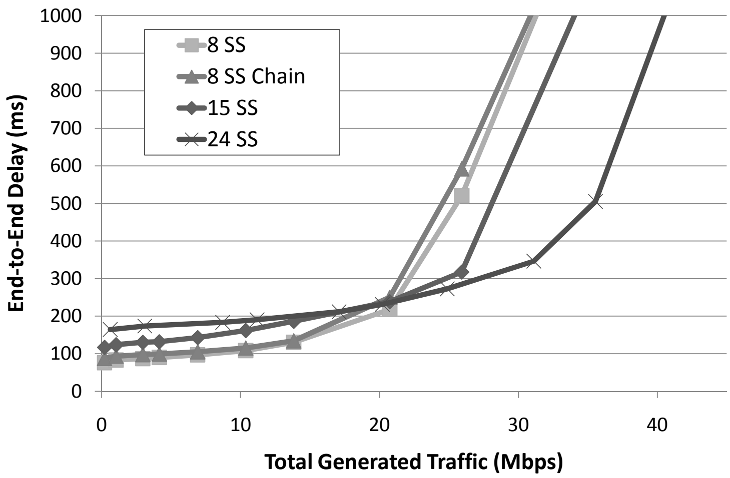
Table 6.2. Node distribution in tested topologies

Topology	1-Hop SS	2-Hop SS	3-Hop SS	4-Hop SS
8 SS Chain	2	2	2	2
8 SS	2	2	4	-
15 SS	3	3	9	-
24 SS	6	6	12	-

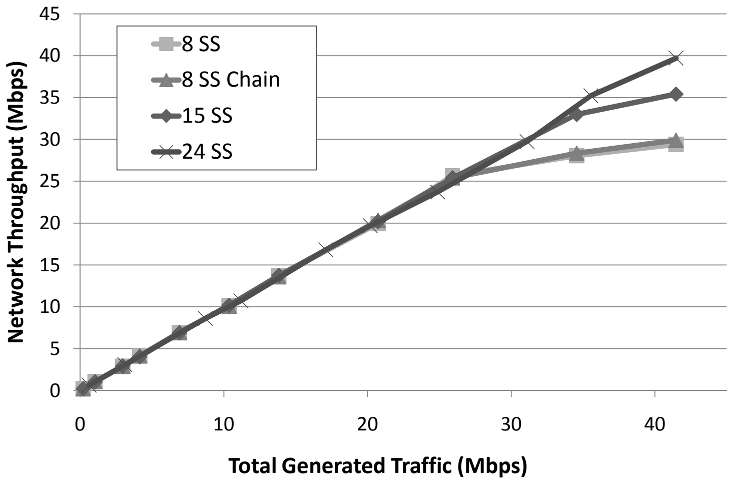
can be done. Four different topologies are tested, which are illustrated in Figure 6.1 and hop count distributions are given in Table 6.2.

For networks using HFS method in small topologies, the average ETE delay values are relatively low. Both 8 SS, and 8 SS Chain topologies have around 100 ms latency whereas 15 SS topology has 150 ms, and 24 SS topology has 200 ms as shown in Figure 6.5(a). It is clearly seen that even though initial delay values are higher for 24 SS topology it can endure the longest providing the best throughput before failure. The reason behind this result is the spatial reuse property of DS. For small networks the number of possible concurrent transmissions are limited since most of the nodes are in the same neighborhood. As the topology gets larger and spreads to a wider space, it can benefit from non-interfering concurrent transmissions, which are not allowed for standard methods using CS such as SFCFS.

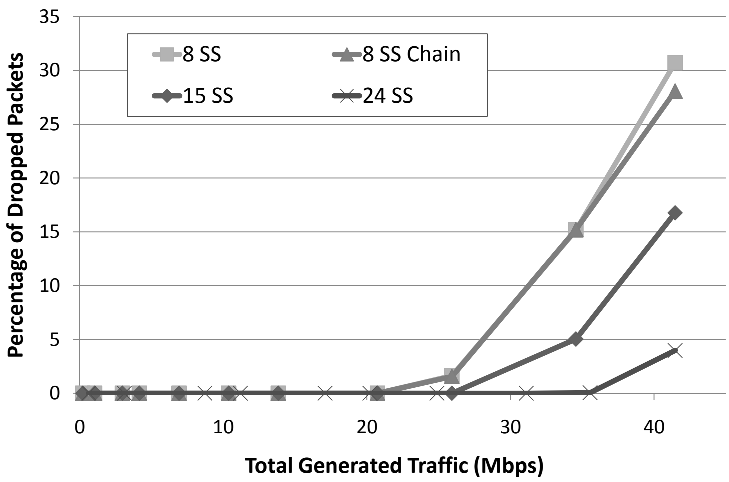
Throughput and packet drop plots in Figure 6.5(b) and Figure 6.5(c) show that HFS method can sustain a stable network up to 20 Mbps for all of the tested topologies. Beyond that point packet drops start for 8 SS topologies and the 15 SS topology fails around 25 Mbps whereas the 24 SS topology has 35 Mbps maximum throughput. The reason behind this behavior is the number of branches generating the same amount of traffic in total. The 24 SS topology performs the best since it can benefit from the spatial reuse more by the concurrent transmissions carried on six separate branches. In all of the plots in Figure 6.5, 8 SS topologies behave very similarly. Since 8 SS Chain topology has two 4-hop SSs spending more resources for each transmission, it fails slightly early compared to the other 8 SS topology having maximum 3-hop nodes.



(a) HFS ETE delay

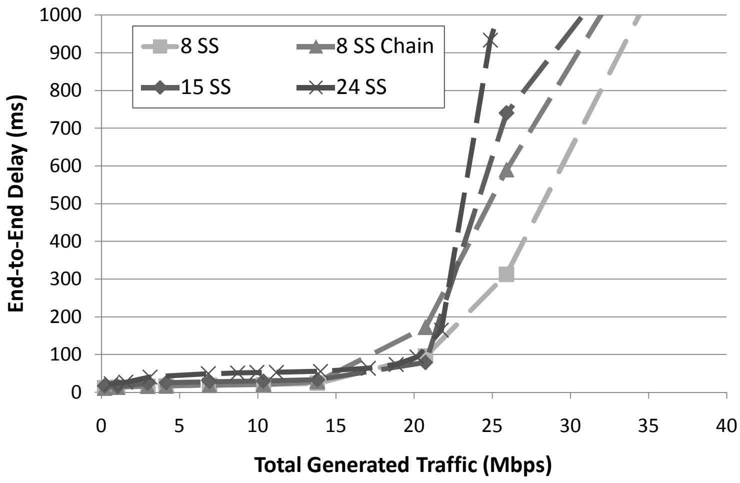


(b) HFS throughput

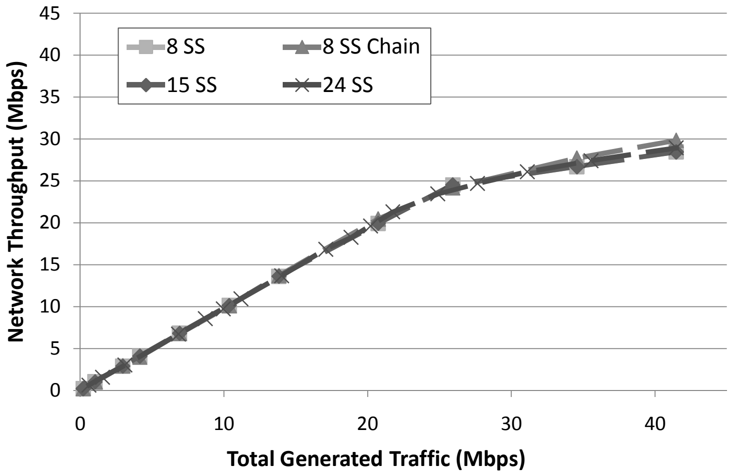


(c) HFS packet drop

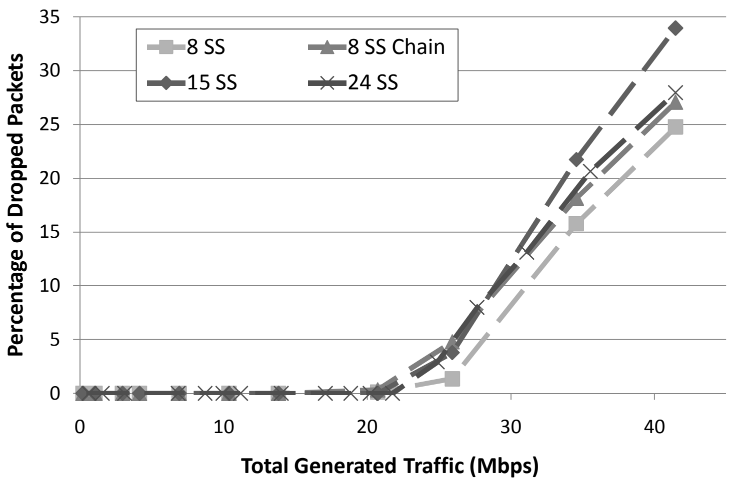
Figure 6.5. HFS performance in various topologies



(a) SFCFS ETE delay



(b) SFCFS throughput



(c) SFCFS packet drop

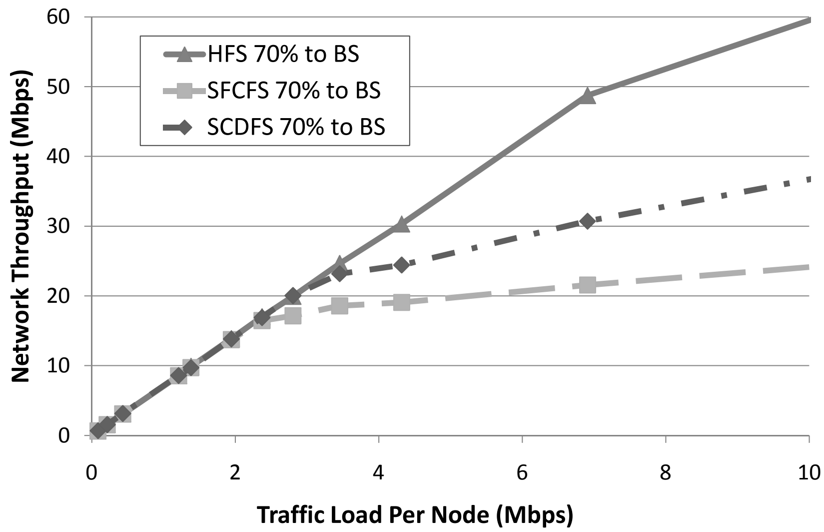
Figure 6.6. SFCFS performance in various topologies

ETE delay results of SFCFS experiments show that average delay values are better compared to the HFS method in lightly loaded scenarios. As the load increases unlike the HFS scheme, large networks start to suffer from more latency as shown in Figure 6.6(a) since CS cannot benefit from spatial reuse. In networks using SFCFS, the difference between 8 SS and 8 SS Chain topologies is more clear since concurrent transmissions are not allowed and 8 SS Chain introduces additional packets to be relayed generated by 4-hop SSs. Figure 6.6(b) shows that unlike the HFS, which exploits the spatial reuse as network gets larger, the achievable throughput in SFCFS is independent of the topology. The reason behind this behavior is in the standard CS definition, which states that only one node can transmit at a given time period, thus leading to similar throughput.

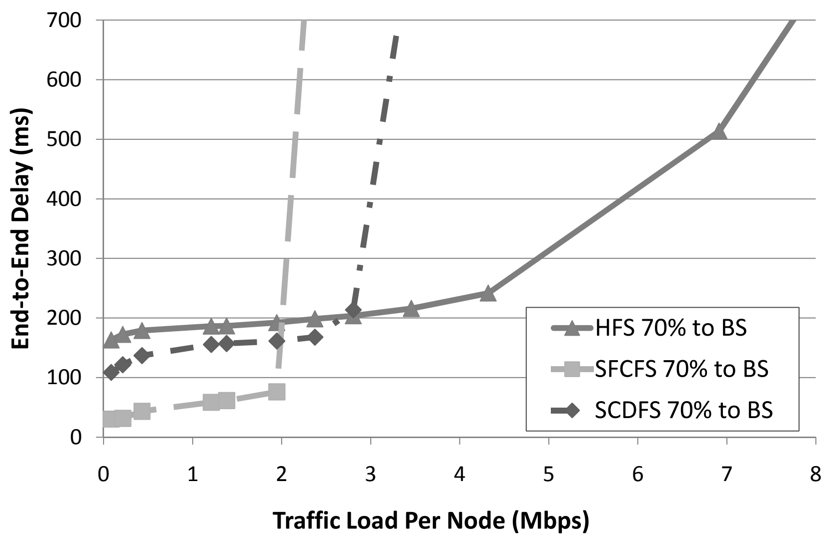
For all of the networks using SFCFS, packet drops start when generated traffic reaches 20 Mbps (Figure 6.6(c)). Beyond this point, in larger networks packet drop percentage rises faster compared to 8 SS topologies. Comparing both packet drop and throughput plots of SFCFS and HFS schemes, it is possible to deduce that for small networks they behave similarly. However, SFCFS has scalability problems limiting the performance as the topology gets larger.

6.2.2. Presence of Intranet Traffic

One of the major advantages using DS in the frame structure is the intranet traffic support. HFS method combines both SCDFS and SFDFS in which the SSs more than 2-hops away from the BS only transmit using DS, making it suitable for intranet transmissions. In this section, traffic generators are adjusted in such a way that specific percentage of generated packets are destined to 1-hop neighbors, and the rest of the packets are sent to the BS. Since SFCFS scheme lacks DS minislots in its data subframe, it needs to send packets first to the BS, from which the packet will be retransmitted to the destination node wasting many minislots. Since it is unfair to compare SFCFS and HFS in this case, SCDFS scheme is also tested, which has its fixed data subframe boundary according to the percentage of Internet and intranet traffic. This way the data subframe is utilized and SCDFS scheme will be more competitive.



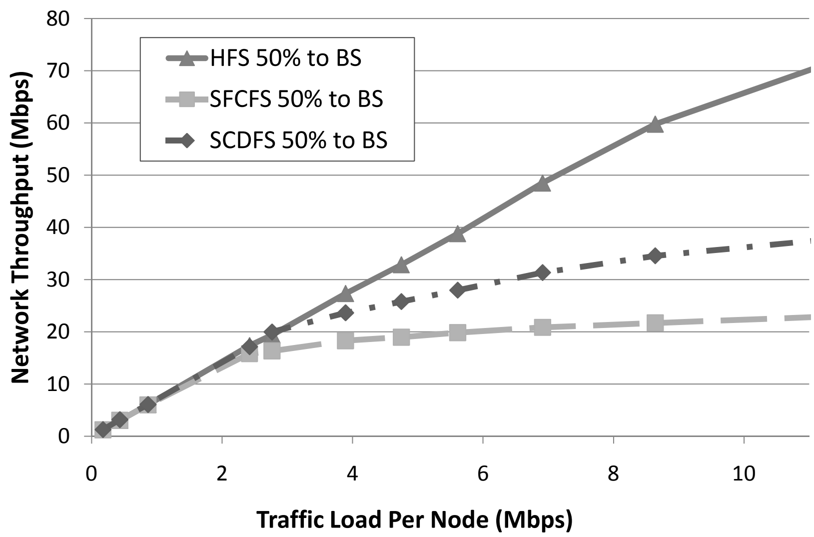
(a) Throughput 70 per cent to BS



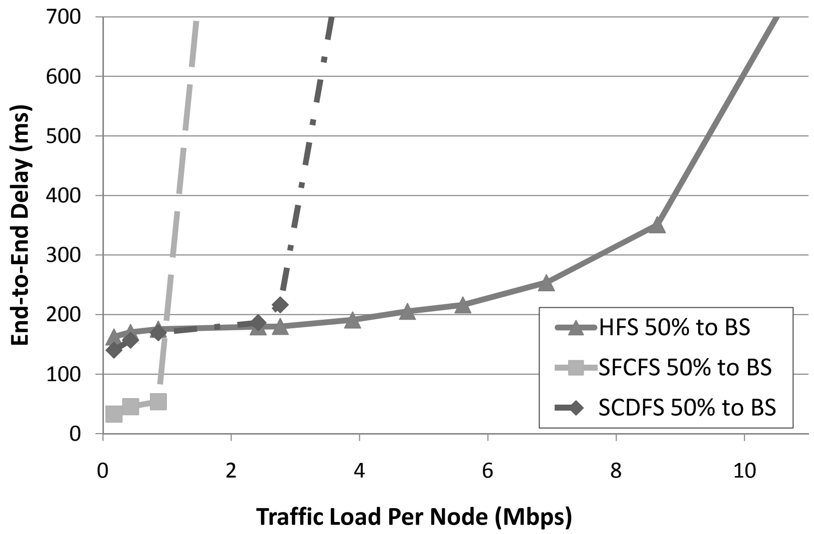
(b) End-to-end delay 70 per cent to BS

Figure 6.7. 70 per cent Internet, 30 per cent intranet traffic

Figure 6.7(a) and Figure 6.7(b) shows the performance of different frame structures working with 70 per cent Internet traffic. SFCFS fails first as expected since its frames does not have any minislots reserved for distributed traffic and packets destined to neighboring nodes need to be forwarded by the BS. As seen from the ETE delay graph, HFS method reaches 400 ms at 6 Mbps traffic load per node, corresponding to 42 Mbps total network throughput, which is significantly higher than 100 per cent Internet traffic case. SCDFS scheme performs better than SFCFS but still it has the limitations of the CS, thus failing at 3 Mbps traffic load per node. This is almost half of the throughout achieved by the HFS method. SFCFS scheme has the best ETE delay values until it fails since all allocations are done using CS.



(a) Throughput 50 per cent to BS



(b) End-to-end delay 50 per cent to BS

Figure 6.8. 50 per cent Internet, 50 per cent intranet traffic

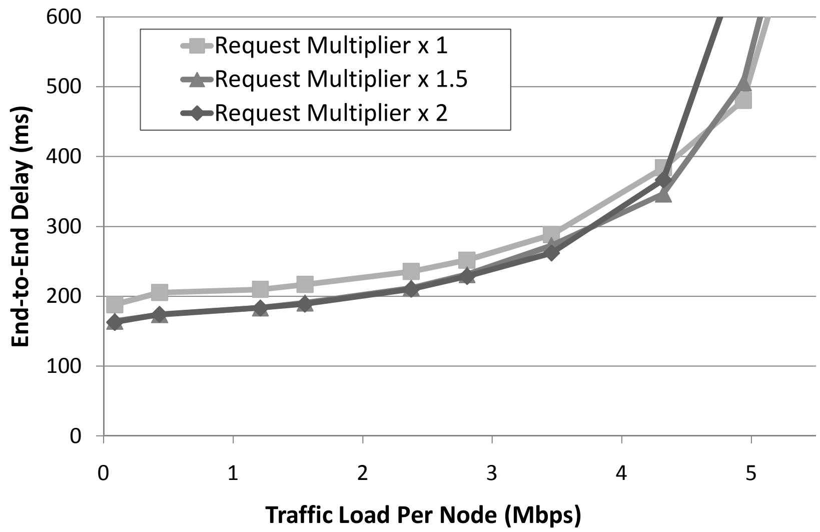
Second set of experiments are done using 50 per cent Internet traffic to observe an extreme case which is not very realistic. Compared to the 70 per cent Internet traffic experiment results, Figure 6.8(a) and Figure 6.8(b) show that the HFS method performs even better and fails at 9 Mbps traffic per node corresponding to total network throughput values over 60 Mbps. Performance of SCDFS remains the same around 3 Mbps since its CS and DS boundary is adjusted according to the percentage of intranet and Internet traffic. In this case, it uses 128 minislots for both CS and DS, which allows the SSs to utilize the data subframe evenly for the generated traffic. SFCFS performs worse since more distributed packets are required to be relayed by the BS.

The ETE delay values of HFS method when network is not congested seem to remain the same for both 50 per cent and 70 per cent Internet traffic cases, which is not the case for SCDFS scheme. As the amount of intranet traffic increases, the average ETE delay of SCDFS network increases and is equal to the HFS delay for 50 per cent Internet traffic case before the network starts to fail.

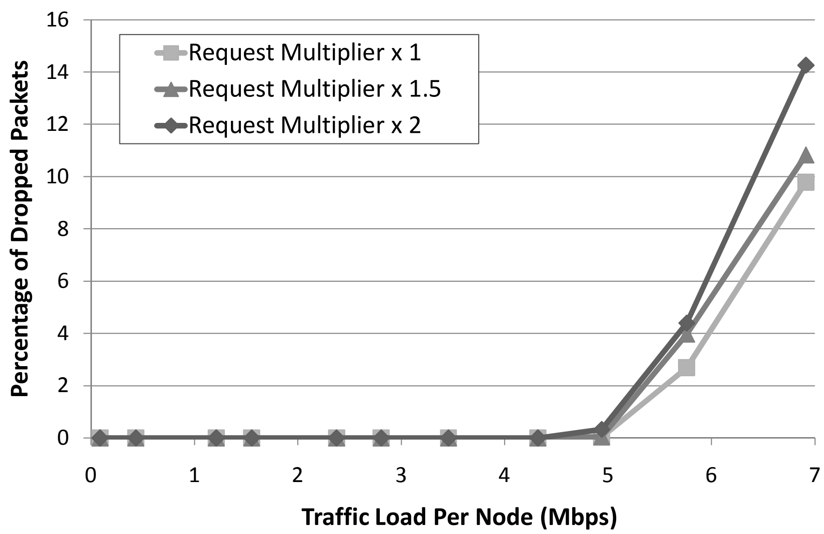
6.2.3. Effect of Distributed Request Multiplier

According to the DS algorithm implemented in NEMMS, SSs make their link based requests by checking their corresponding queues. This request initiates the three-way handshake procedure and requires 3 DSCH message exchanges between the requester and the granter node. Since all distributed allocations are done this way, SSs need to wait for the whole three-way handshake cycle, introducing significant delay. HFS uses the distributed request multiplier parameter in order to request some additional resources, which will be used for transmitting data packets arriving during the three-way handshake procedure.

As seen in Figure 6.9(a) both multipliers 1.5 and two provide around 15 per cent improvement in latency compared to the simple request mechanism. The downside of increasing the request multiplier is granting extra minislots, which will not be used if expected traffic does not arrive. Therefore, in bursty traffic conditions there are unavoidable waste of resources. Figure 6.9(b) shows the packet drops of networks using different request multipliers. The network using two as the request multiplier fails slightly early because of the extra grants given, followed by networks using multipliers 1.5 and one. Since there is not much of a difference in ETE delay values of scenarios using 1.5 and two multipliers, 1.5 is selected to be the default value for distributed request multiplier parameter in all simulations.



(a) HFS ETE delay

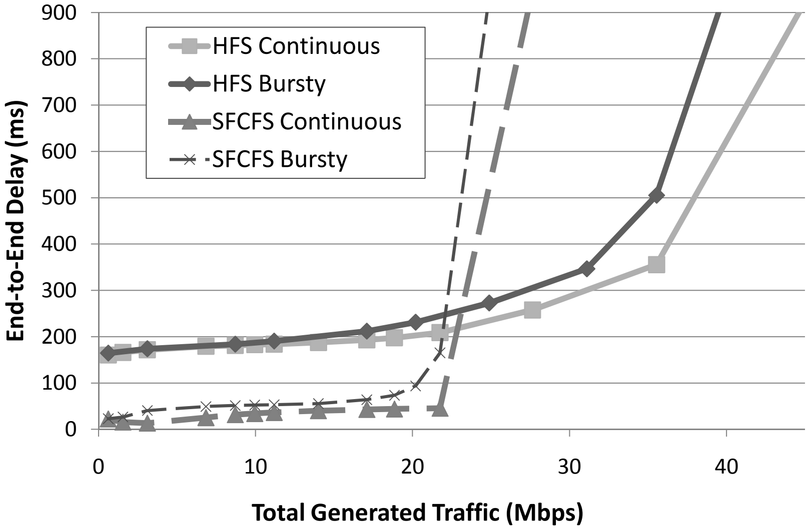


(b) HFS packet drop

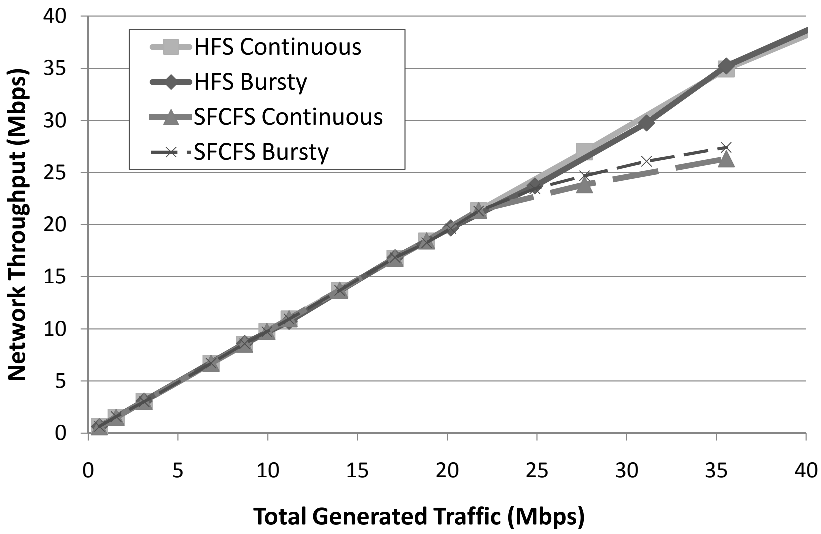
Figure 6.9. Effect of DS Request Multiplier on HFS performance

6.2.4. Continuous vs Bursty Traffic

As stated in Table 4.1, CS is more suitable for consistent continuous traffic because of the centralized control message sequences whereas DS is more suitable for bursty traffic conditions since it has fast connection setup times. Since the HFS method uses both CS and DS mechanisms some experiments are done in this section to observe its behavior under bursty and continuous traffic types.



(a) Delay vs offered traffic



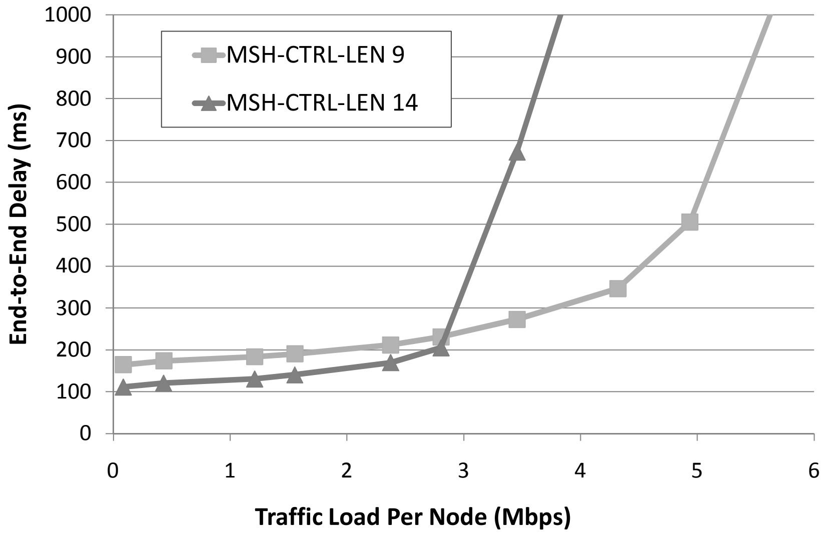
(b) Throughput vs offered traffic

Figure 6.10. Effect of continuous vs bursty traffic

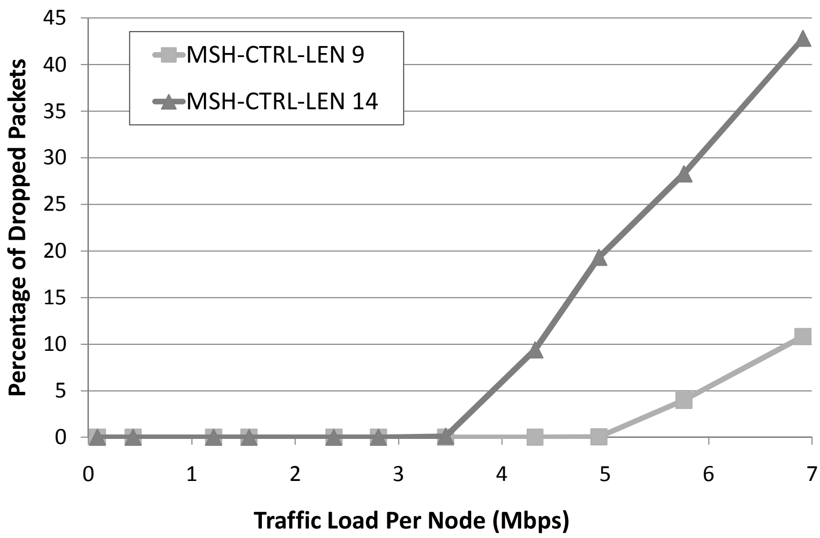
HFS behaves similarly under both traffic conditions as seen in Figure 6.10(a) and Figure 6.10(b). ETE delay performance of HFS experiments start to differ as the network gets congested but for light and moderately loaded scenarios identical results are obtained. On the contrary, SFCFS scheme shows slight difference in both ETE delay and throughput graphs. When traffic generation is bursty the SFCFS network reaches the latency limit at slightly lower introduced traffic compared to the continuous packet generation. Therefore, the HFS method is more stable under various traffic conditions.

6.2.5. Effect of Control Subframe Size

MSH-CTRL-LEN is an important parameter for both CS and DS mechanisms since it directly effects the length of scheduling cycles and data subframe size as addressed in [17]. MSH-CTRL-LEN is a 4-bit parameter and can take values between one to 16. As this parameter gets larger, more TOs are reserved for scheduling messages, which use the most robust modulation coding (using more resources). This shortens the scheduling message exchange times but since the frame size remains the same the additional TOs are taken from the data subframe.



(a) Effect of MSH-CTRL-LEN on delay



(b) Packet drop for various MSH-CTRL-LEN

Figure 6.11. Effect of MSH-CTRL-LEN parameter on network performance

MSH-CTRL-LEN should be selected with caution considering the frame duration since OFDM symbols per minislot (s) value is derived using this parameter. Transmissions should be done using a whole number of OFDM symbols so there can be a lot of resources wasted due to rounding. s is expected to decrease as MSH-CTRL-LEN gets larger since the data subframe gets smaller.

$$s = \left\lfloor \frac{\left\lfloor \frac{T_{fr}}{T_{sym}} \right\rfloor - MSH\,CTRL\,LEN \cdot 7}{256} \right\rfloor \tag{6.1}$$

Equation 6.1 gives the value of s, where T_{fr} is the frame duration and T_{sym} is the OFDM symbol duration. For $T_{fr} = 10\,ms$ and MSH-CTRL-LEN = 9 TOs value of s is found to be three whereas using 14 TOs results in s equal to two. The latter case is a good example of the addressed rounding problem ($\lfloor 2.87 \rfloor = 2$) since in each minislot 0.87 OFDM symbol duration is wasted. This sums up to 223 OFDM symbols in a frame, wasting around 27 per cent of the total frame duration.

Since more TOs are reserved for scheduling messages in each frame using MSH-CTRL-LEN equal to 14, ETE delay decreases significantly as shown in Figure 6.11(a). HFS scheme requires more DSCH messages, so the 14 TOs are split as three being reserved for centralized and 11 TOs reserved for distributed messaging. On the other hand, the mentioned rounding problem limits the total achievable throughput dramatically causing packet drops to start at 3.5 Mbps traffic load per node (Figure 6.11(b)).

6.2.6. Effect of Constant Exponent Parameter

Constant exponent parameter is set to four in the WiMAX standard but as addressed in [15] it should have smaller values for faster response times during the three-way handshake procedure. Therefore, HFS scheme sets this parameter to one for most of the experiments in this section. The ETE delay improvement gained by this modification can be seen from Figure 6.12. For lightly loaded cases delay values are similar since DSCH messaging delay is not so effective under low traffic conditions but as the traffic load increases, *Constant Exponent 4* scenario starts to suffer more delay.

This is because of the extensive hold-off periods of DSCH transmissions, which needs to be shortened for more dynamic scheduling.

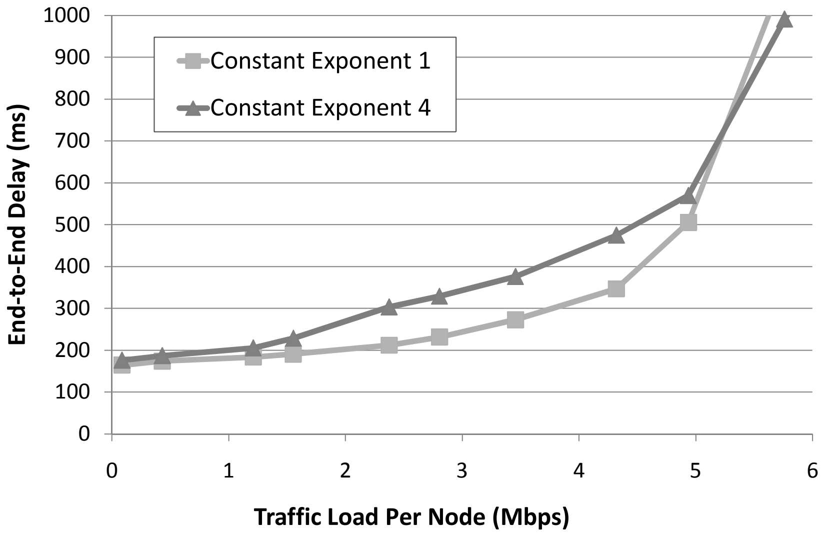


Figure 6.12. Effect of Constant Exponent values on HFS performance

7. CONCLUSIONS

Standard frame structures and scheduling guidelines defined for the WiMAX Mesh mode lead to significant performance limitations caused by: lack of spatial reuse in CS, the fixed data subframe boundary in CS/DS, and high latency cost of multi-hop transmissions in DS schemes. In this study a *Hybrid Frame Structure* method is introduced to overcome these problems and to improve the network performance by differentiating the data subframe scheduling according to the hop count of SSs. The HFS method utilizes the SCDFS and SFDFS defined in the standard in order to combine the spatial reuse property of DS and low latency transmissions of CS.

Performance evaluations are done in several topologies, testing various system parameters for scenarios using mostly Internet traffic to be more realistic. Results show that even for 100 per cent Internet traffic scenarios HFS outperforms the SFCFS considering maximum achievable throughput values within acceptable latency limits. In the presence of intranet traffic HFS performs significantly better since SSs having hop count more than one only use DS, which is actually designed for intranet traffic. On the other hand, the average ETE delay values of networks using HFS method is rather high compared to the standard frame structures. Although average latency is high in HFS, results show that 1-hop and 2-hop SSs have low latencies but SSs further away than 2-hops start to experience high ETE delay values for Internet traffic, especially when network is in a congested state.

As future work the CS limit, which is used as 1-hop SSs in HFS, can be increased according to the expected type of traffic in the network to use more of CS data allocations. Also more improved DS algorithms and HOE selection schemes can be developed to improve high latency of multihop DS transmissions.

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