MH-WiFiRe: Multi-Hop Extension to WiFiRe

Dissertation

submitted in partial fulfillment of the requirements
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Master of Technology
by

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under the guidance of

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and
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Dissertation Approval Sheet

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MH-WiFiRe: Multi-Hop Extension to WiFiRe

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is approved for the degree of **Master of Technology**.

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CERTIFICATE OF COURSE WORK

This is to certify that **Mr. Kedar Rudre** was admitted to the candidacy of the M.Tech. Degree and has successfully completed all the courses required for the M.Tech. Programme. The details of the course work done are given below.

Sr.No.	Course No.	Course Name	Credits
		Semester 1 (Jul – Nov 2006)	
1.	IT634	Communication Networking	6
2.	IT619	Foundation Lab	8
3.	IT601	Mobile Computing	6
4.	HS699	Communication and Presentation Skills (P/NP)	4
3.	IT603	Database Management Systems	6
5.	IT623	Foundation course of IT - Part II	6
6.	IT653	Network Security	6
		Semester 2 (Jan – Apr 2007)	
7.	IT694	Seminar	4
8.	CS681	Performance Analysis of Computer Systems and Network	6
9.	HS701	Development, Technology and Global Order (Institute Elective)	6
10.	IT620	New Trends in IT (Sensor Networks)	6
11.	IT610	Quality of Service in Networks	6
		Semester 3 (Jul – Nov 2007)	
12.	CS601	Algorithms and Complexity	6
13.	CS601	Computer Networks (Audit)	6
		M.Tech. Project	
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15.	IT697	M.Tech. Project Stage - II (Jan 2008)	30
16.	IT698	M.Tech. Project Stage - III (Jul 2008)	42

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Abstract

Cost effectiveness is an important criterion for any technology/system to be successful in rural regions. *WiFiRe*: WiFi Rural Extension based on 802.11 provides low cost broadband Internet access for rural regions and supports real time traffic like VoIP and Video. WiFiRe assumes star topology with its cell covering a circular region of 15-20kms in radius. Due to its single hop nature, it suffers from drawbacks like line of sight requirement and fixed coverage area. In this project, we extend WiFiRe to multiple hops and present multi-hop WiFiRe architecture which alleviates the drawbacks of WiFiRe.

We first present different architectures for multi-hop WiFiRe and compare them on different dimensions important from the persepective of feasibility of the system in rural region. We also present detailed cost and coverage analysis for some of these architectures. On the basis of this comparative analysis, we select an architecture based on tree topology for further studies. Our next contribution is in providing detailed description of the MAC protocol for the multi-hop system. We consider TDMA based MAC protocol influenced by 2P. We present MAC level frame structure and further give detailed procedures required to perform tasks of the MAC protocol. To perform time slots allocation, we propose three different scheduling schemes. We then perform comparative analysis for these three scheduling schemes.

The next contribution of our project is a tool to evaluate the performance of the multi-hop WiFiRe system. We compare performance of our system for different codecs. We present delay analysis, coverage analysis and capacity analysis of the system. Through this analysis we show that its not only feasible to have multi-hop extension but its also possible to perform trade-off between coverage and number of VoIP calls supported. The trade-off depends on type of codec and scheduling scheme. The final contribution of the project is the future work that can be done in the same domain.

Contents

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Abbreviations and Notations

Abbreviations

AP	: Activity Phase
BE	: Best Effort
BS	: Base Station
BW	: Bandwidth
CSMA	: Carrier Sense Multiple Access
CSMA/CA	: Carrier Sense Multiple Access with Collision Avoidance
CTS	: Clear To Send
IP	: Internet Protocol
ID	: Identifier
LAN	: Local Area Network
LoS	: Line of Sight
MCN	: Multihop Cellular Network
MS	: Mobile Station
MAC	: Media Access Control
MAP	: Mobile Access Point
MH-WiFiRe	: Multi-hop WiFi Rural Extension
nrtPS	: Non-real time Polling Service
NAP	: No Activity Phase
PoP	: Point of Presence
PDU	: Protocol Data Unit
QoS	: Quality of Service
Rx	: Reception
RTS	: Request To Send
rtPS	: real time Polling Service
SCN	: Single hop Cellular Network
ST	: Subscriber Terminal
SIR	: Signal to Interference Ratio
Tx	: Transmission
TDMA	: Time Division Multiple Access

UL : Uplink
UP : Uplink Phase
UL-MAP : Up Link Slot Allocation Map
UL-TB : Upling Transport Block
VoIP : Voice over Internet Protocol
VN : Village Node
WAN : Wide Area Network
WiFi : Wireless Fidelity
WiFiRe : WiFi Rural Extension
WiMAX : Worldwide Interoperability for Microwave Access

Chapter 1

Introduction

1.1 Telecommunication Scenario of India

The past decade has witnessed *communication revolution* in the form of Cellular networks and Internet. But most of the development was limited to the the developed world or the urban part of the developing world. In India also, there was tremendous increase in the cellular phone and Internet users. The compound annual growth rate of cellular phones in India from 1995-2001 is nearly 110% [21], but in terms of absolute growth it is very less. The reason behind this is, development was restricted only to the urban part of India. There is still very little or no connectivity in rural India. The Cost factor associated with the deployment of wired infrastructure or broadband connectivity makes it unaffordable for rural India. The average income of rural India is very low and hence people of rural areas cannot afford such expensive technologies. Also, since the revenue earned from rural India is very less it is not an economically feasible solution to have wired or cellular networks till small villages. A typical Indian scenario is shown in Figure 1.1. In India, typically town places have Fiber point-of-presence(PoP) and are seperated by a distance of 30-40 Kms. Town places are surrounded by small villages with distance between them around 3-4 Kms.

Thus, the connectivity is there till town places or larger villages. It is required that this connectivity is extended till small villages which are surrounded near the town places. This problem of extending connectivity from town places or larger villages to small villages is often referred to as *Last Mile problem.* There exists many technologies/systems to address last mile problem. These alternatives are discussed in the next section.

1.1.1 Alternatives for the Last Mile

The major challenge in providing connectivity in rural India is cost. Any system/technology for providing connectivity in rural areas, will sustain only if it is affordable to the people.

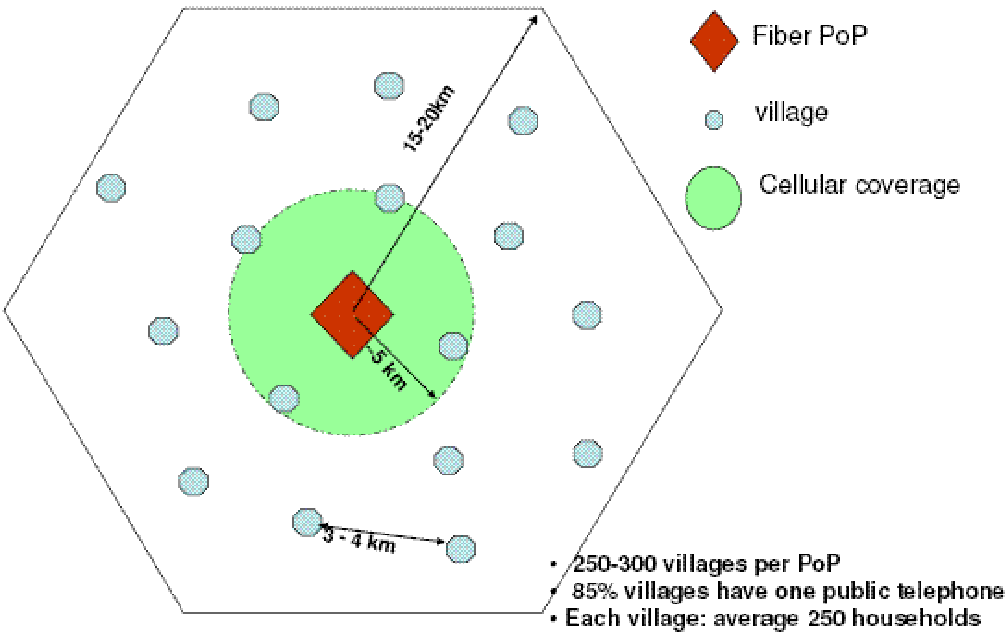

Figure 1.1: Typical Indian Scenario source:[25]

Considering low average income of rural people we will have to come up with a system that is cost effective. The different broadband wireless technologies that can be considered for last mile connectivity are:

- Cellular Networks (2G,3G).
- 802.16 WiMax
- 802.11b WiFi

Cellular technologies are fast and easy to deploy but its cost makes it unsuitable for rural networking. The present GSM technology even though cost-effective does not have long range and the bandwidth is limited. The CDMA 1X system is able to provide internet at 144kbps, thus it also fails to provide broadband access. The 3G technology has the ability to provide high BW applications, but presently, it is costly solution for rural areas. WiMax is a long range broadband(WAN) technology but it is not an affordable solution. Providers infrastructure required for WiMax and the WiMax terminals are expensive. As far as WiFi goes, it is easy to deploy, the devices cost low and are standardized, WiFi operates in license-free ISM band. Also recent deployments and study have shown that WiFi with some extension can provide voice services which are the most widely used applications in the rural area. All these features make WiFi the most cost-effective solution for Rural Networking.

There are many efforts [21][19][28][15][12] in the direction of using WiFi for rural connectivity. We discuss them breifly in chapter 2. Also in the next section we give

WiFi for Rural Extension (WiFiRe)[17] overview, which is a system designed with an aim of providing low cost connectivity in Rural area using WiFi. In this project we have extended WiFiRe, which is single hop star topology, to multiple hops alleviating some of its drawbacks.

1.2 WiFiRe Overview

WiFiRe[25] stands for WiFi for Rural Extension. WiFi (IEEE 802.11 [8]) is a LAN technology designed for short distance communication. The systems based on WiFi are cost-effective. But by making use of high gain directional antennas it is being practically demonstrated that we can use WiFi for establishing long distance point-to-point links [21]. The key idea in WiFiRe is to use low cost 802.11b PHY but replace the 802.11b MAC with something more appropriate for long distance communication. WiFiRe MAC is similar to IEEE 802.16d [9] (WiMax:Worldwide Interoperability for Microwave Access). The WiFiRe system is designed with a motivation towards its low cost application in rural India. Its goal is to provide low cost, long distance, broadband communication in rural India.

1.2.1 Architecture

As shown in Figure 1.2 WiFiRe architecture is based on star network topology, where Base Station(BS) is present at the fiber Point of Presence(PoP) and Subscriber Terminal (ST) in the villages nearby. BS has six or three sectorized antennas covering area of 15-20 kms. End-users are connected to STs with different LAN technologies [11]. STs communicate with BS through directional antennas which are mounted on a mast of 10m height. WiFiRe requires line of sight (LoS) communication between STs and BS. At BS, sectorized antennas are mounted on a transmission tower at a height of 40m to enable LoS communication. The WiFiRe system typically covers a circular region of 15kms to 20 kms, which is referred to as *cell*.

Its link layer is designed to provide long distance reliable communication, and supports service guarantee for real time and non-real time applications. WiFiRe uses time division duplex multisector TDM (TDD-MSTDM) MAC. Scheduling of slots is done so as to maximize simultaneous transmission in multiple sector while keeping co-channel interference within limit. Here we assume that scheduling is done in a Round Robin (RR) fashion, where each sector is scheduled one after another. For example, in Figure 1.2 in case of RR scheduling, STs in sector 1 will get scheduled first, followed by STs in sector 2 and then sector 3. Transmissions in the opposite sectors can be scheduled in parallel, hence sector 1 & sector 4; sector 2 & sector 5; and sector 3 & sector 6 will get scheduled in parallel.

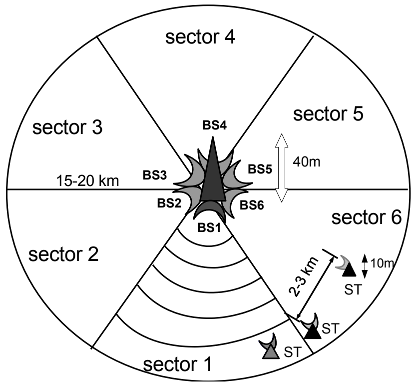

Figure 1.2: WiFiRe Architecture. Source[16]

1.2.2 Frame structure

In WiFiRe, being a TDMA based system, time is divided into frames and frames are further divided into slots. WiFiRe frame structure is shown in Figure 1.3. Frame duration depends on the VoIP packet generation period and slot duration depends on the VoIP packet size. In [25], frame duration is chosen as 10 ms and slot time in 32μsec. Figure 1.3 shows WiFiRe frame structure. Frame is partitioned into downlink (DL) and uplink (UL) segments. In DL segment we have transmission from BS to ST and in UL segement transmission takes place from STs to BS. These segments are seperatated by a guard band of 4.5 slots to account for propagation delays and transmitter-receiver turnaround. At the start of the frame we have beacon transmissions, which contains system information, control information and DL-MAP, UL-MAP. DL-MAP, UL-MAP specifies DL and UL slot allocations respectively.

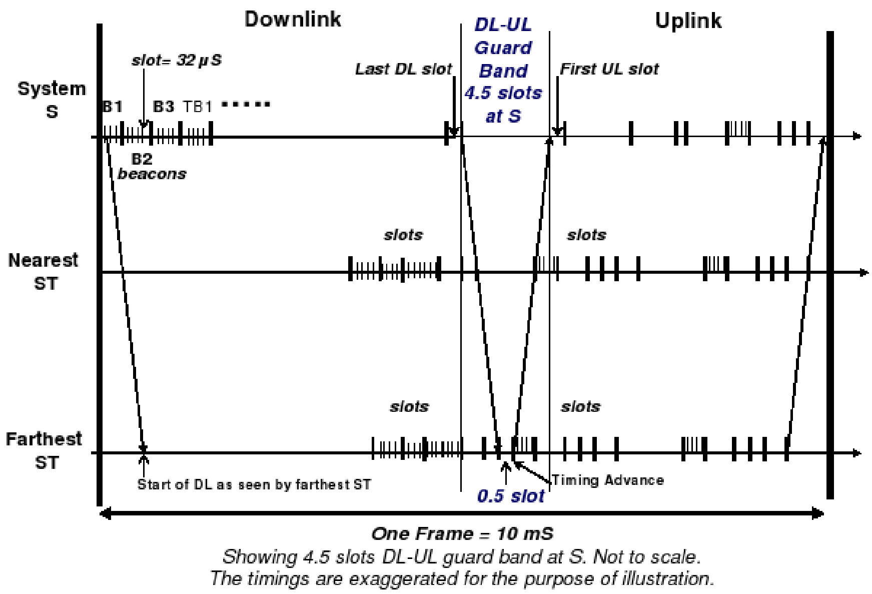

Figure 1.3: WiFiRe Frame. Source[17]

1.2.3 Limitations

As discussed earlier, WiFiRe assumes star topology, where STs and BS communicates over a single hop link. The single hop nature of WiFiRe, results into following limitations:

- Fixed Range:
  WiFiRe cell covers a circular range of 15-20 Kms in radius. Typically the distance between the two town places with Fiber PoP is 40-45 Kms, hence leaving 5-10 Kms of area with no coverage as shown in figure 1.4.

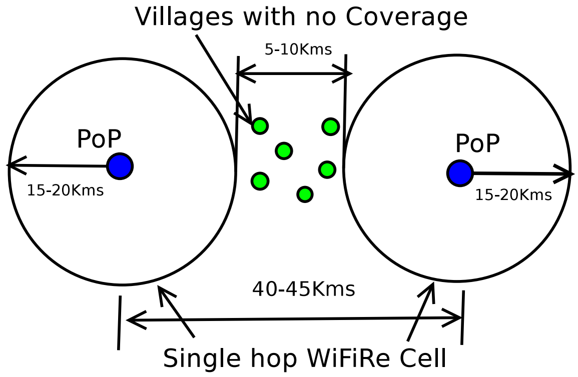

Figure 1.4: Fixed Range of WiFiRe

- Line of Sight requirement:
  In WiFiRe, STs communicates with BS using a directional antenna over a single hop directional link. This needs LoS communication. Hence ST will not be able to communicate with BS, if an obstacle is present as shown in figure1.5

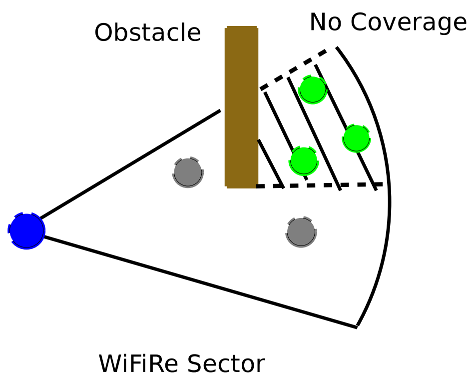

Figure 1.5: Line of Sight Requirement of WiFiRe

1.3 Problem Statement

As discussed in the previous section, the single hop nature of WiFiRe results into following drawbacks:

- Fixed Range
- Line of Sight requirement

The main aim of this project is to overcome these drawbacks by extending the WiFiRe architecture to multiple hops. The formal problem definition of our project is:

To Design a cost-effective multi-hop WiFiRe system which operates over a single wireless channel and alleviates the drawbacks of WiFiRe system

This will involve:

- Determining the Architecture of the multi-hop system:
  There will be various possible alternatives to extend the WiFiRe to multiple hops. We will have to look at these alternatives and select the architecture which best suits our requirements.
- Cost Analysis of the system:
  For any system to be implemented in rural India, it needs to be Cost effective. Hence, we will have to perform the cost analysis of the system, which will involve determining the best case and worst case cost of the system. Expected cost per village. Performing cost optimization etc.
- MAC Protocol details of the system:
  We will have to determine the structure of the frame, similar to WiFiRe, for the multi-hop system. Then we will have to give scheduling mechanism which is able to meet the QoS requirments of the traffic under consideration. Also we will have to explain the various steps involved in MAC protocol, starting from the registration of the ST to termination of the call.
- Analysis of the system:
  At the end we will have to present the performance analysis of the multi-hop WiFiRe system to show that multi-hop extension is feasible & practical and to answer some of the imporatant questions like number of VoIP calls supported per village, Amount of extension possible over WiFiRe. Performance analysis of different scheduling schemes etc.

1.4 Project Contributions

Contributions of our project are:

- Comparison of various multi-hop WiFiRe architectures.
- Cost analysis of the multi-hop WiFiRe system.

- Detailed description of the multi-hop WiFiRe architecture and MAC protocol.
- Three different scheduling techniques for the multi-hop WiFiRe and its comparative analysis.
- A tool to evaluate the performace of multi-hop WiFiRe system under different conditions.

1.5 Thesis Organization

The remaining of the thesis is organised as follows. In chapter 2, we will describe some of the previous work done in the area related to long distance wireless networks. In chapter 3, we will describe different architectures that we considered as an option for the multi-hop extension to the WiFiRe. In chapter 4, we perform cost analysis for the two most appropriate architectures to select the best architecture for the detailed study. In chapter 5, we will describe the multi-hop WiFiRe architecture in more detail. In chapter 6, we describe the various steps involved in MAC protocol in detail. In chapter 8, we will discuss three different schduling schemes and will present comparative analysis for the same.

Chapter 2

Related Work

There is lot of work already published in the area of multihop wireless networks and long distance networks. There are many implementations of Wireless Community Network all over the world. In this chapter we discuss some of the significant work done in this area.

2.1 Multihop Cellular Network

Ying-Dar Lin et al [18] provides a new architecture, Multihop Cellular Network(MCN), for wireless communication. This work is among the first few work done in the area of multihop communication over 802.11 wireless networks. The architecture tries to combine the features of conventional single hop cellular network and adhoc network.
In MCN, unlike Single hop cellular network(SCN) mobile station(MS) can communicate with each other directly. If the source and destination are in the same cell, other mobile stations can be used to relay packets to the destination, following a multi-hop path. If source and destination are not in the same cell then the packet is first send to the base station(BS), probably through intermediate mobile station and then the base station forwards it to the BS of the cell where destination resides. Packets are then forwarded to the destination MS either directly or through multi-hop path with intermediate MS routing the packet to the destination.

MCN provides better channel utilization, high throughput and range compared to SCN. But transmissions are omni-directional in nature and use CSMA/CA with RTS-CTS, which is not suitable for long distance wireless networks.[10]

2.2 2P MAC Protocol

Bhaskar et al [24] provides a new MAC protocol 2P, for long distance wireless networks as CSMA/CA is not suitable for it. 2P MAC is a TDMA-style protocol for mesh networks.

Even with the directional antennas, a node cannot receive and transmit simultaneously, since reception will face interference from the transmitting radio at that node. This is referred to as *Mix-Tx-Rx* [22]. Thus there is need of synchronous operation where the links at the node are all transmitting *(SynTx)* or all receiving.*(SynRx)*. In the 2P protocol, each node in the network simply switches between these two phases. When a node is in SynTx, its neighbors are in SynRx, and vice-versa. Thus in 2P we can have 100% utilization of the link, as the link is always active in one direction.

In rural scenario, the major traffic is expected to be generated by real time applications like VoIP and interactive videos. Especially VoIP is going to be the major source of revenue. But the paper[24] has not mentioned anything about time slot scheduling and channel allocation. Hence no analysis for the support of QoS for different types of real time traffic like VoIP calls, interactive videos etc. is given. 2P needs the underlying network topology to be bipartite and major of the traffic will be between nodes and the landline node. Hence , typically the resultant topology will be tree rooted at landline node. Now, considering Indian rural scenario[25] where we have town places(landline nodes) with fiber point of presence at a distance of 30-40 Kms surrounded by villages, with villages separated from each other by a distance of 3-4 Kms, the network topology will be a tree with large number of hops. At every hop, there will be some queuing and processing delay. Hence with a large number of hops it will be difficult to support the QoS required for the VoIP and interactive video traffic. Also for any architecture/technology to be successful in rural scenario it should be cost effective. But no costing analysis is provided in the paper. Thus in summary, [24] lacks network performance analysis and network infrastructure planning.

2.3 Cost Optimized topology Construction

Partha Dutta et al [15] present VillageNet, which is a wireless mesh network that aims to provide low-cost broadband Internet access for rural regions. The paper formally states routing and channel allocation problem, and cost optimized topology construction problem for long distance wireless mesh networks that uses 2P MAC protocol[24]. Paper also proves that Optimized topology construction problem in NP-hard. Thus paper tries to fill the void of [24], where no costing analysis is given.

But as described earlier, in Indian scenario a mesh network will result into a network topology with large number of hops, making it difficult to support the QoS required for the real time traffic like VoIP and interactive videos. Also the paper has not given any performance analysis for the long distance network. The authors have continued their work in [14], where they present first approximation algorithm with time complexity of O(log n) to solve the optimized topology construction problem.

In other literature realted to cost optimization Sayandeep Sen et al [26] have formulated network planning problem in terms of variables, constraints and optimization criteria. Constraints considered are throughput, power and interference. Variables to determined are network topology, tower heights, antennas types & orientation and transmit power. Objective is to optimize tower cost. They have considered this problem only for two hops trees. Authors consider throughput as constraint in the problem, but for real time traffic delay and jitter plays an important role but no analysis for the same is given. This may be because, authors have not considered any frame structure and time slot & channel allocation scheme.

Thus work in [14][15][26] is focussed on cost optimization and have not provided any performance analysis. Also no analysis is provided to show variation in cost of the system under different scenario. Worst and the best case for the network cost. What will be the estimated cost per village etc. Such detailed analysis related to cost is not covered in the above published literature.

2.4 WiLDNet

Rabin Patra et. al [19] present design, implementation and evaluation of WildNet, a system that address following problems in WiFi-based Long Distance (WiLD) networks:

- Shortcomings of 802.11 protocol which involves inappropriateness of CSMA/CA for long distance, 802.11 link-level recovery mechanism that results in low utilization and inter-link interference.
- High and variable loss rates in the underlying channel due to external factors.

Authors give a better implicit synchronization method that provides improvement over 2P in case of lossy environment. Unlike [24] the paper gives throughput and delay analysis but delay analysis is done only for single point-to-point long distance link. No analysis is given for end-to-end delay over multiple hops. Detailed frame structure is missing. Another important parameter to determine the utility of the system in rural area is maximum number of VoIP calls supported. But no analysis is provided in this respect. Also authors have not done anyanalysis on the budgeting of the system.

2.5 Community Network in Netherland

Rudi Van Drunen et al [28] have deployed Wireless Community Network (WCN) in Netherlands. The deployment is different from DGP and Ashwini [23] as it covers densely populated but small area. Its span is only about $25Km^2$. It uses 802.11b, hence CSMA/CA MAC which is not suitable for long distance wireless links. Authors have mainly discussed the deployment and issues in it and have not provided the performance analysis of the network. Even though authors have mentioned that various bandwidth and delay constraint applications like video server and gaming applications are supported but have not provided with the performance analysis of these applications.

2.6 FRACTEL

Fractel[12] considers rural wireless network having a combination of a) Long distance links, upto few kilometers b) Local access links upto 500 mts. Long distance links extends connectivity from a point of wired connectivity to a specific point in each village and local access links extends connectivity from this point to multiple nearby locations. Unlike [24][19][15][26], [12] gives slot and channel allocation algorithm. But the algorithm needs multiple channels and is applicable only for two hop trees. Authors have not presented any analysis for delay, throughput, maximum number of hops and connections supported for different real time traffic. Also the cost analysis of the system is not done.

Thus we see that most of the literature published till now lacks detailed analysis for the VoIP traffic, which is expected to be the dominant in case of rural scenario. This is mainly because, most of the system lack detailed explanation of the MAC protocol. No system has provided the detailed description of the frame structure and channel & slot allocation. Similarly we have some work done w.r.t. optimized topology construction problem. But still the detailed cost analysis is lacking. Questions like how cost will vary under different scenarios, whats the best case and worst case of the cost of the system, whats the approximate cost per village, how cost varies with the coverage etc. are not yet answered.

2.7 Applications in India

In this section we will present some of the applications of WiFi based long distance wireless networks in India. There are few wireless community networks being deployed to provide various services mainly to the rural community of India.

2.7.1 DakNet

DakNet[20] is a commercial wireless adhoc network, developed by MIT Media Lab that provides asynchronous digital connectivity. DakNet has been successfully deployed in remote parts of India and Cambodia. DakNet operation involves two steps. First, a vehicle equipped with Mobile Access Point(MAP) comes in the range of WiFi equipped village kiosk. Kiosk uploads and downloads the required data. Second, when MAP equipped vehicle comes in the range of an Internet access point, it automatically synchronizes the data from all the rural kiosks, using the Internet. DakNet is providing e-services like e-mail and voice mail in villages.

2.7.2 Akshay Network

Project Akshay[1] is implemented in Kerala to bridge the digital divide in the state. Its implemented on a pilot basis in Malappuram. Akshay Network is based on Wireless

Technologies and covers an area of 3,500+ sq. kms in Malappuram. Akshay network consists of two parts. First, Backbone Network whose throughput starts at 8 MBPS and additional backbones can be added for greater bandwidth. Second, Access Network which provides connectivity from backbone network to the subscribers. Point to multipoint radios are used, with last mile BW of 4 MBPS shared between subscribers. The network supports following Internet services:

- Broadband Internet Browsing.
- Voice Services
- Video Streaming: Supports initiatives like e-learning, e-health, e-governance.

Apart from the Internet based services, the network is also used for offering a number of Intranet-based solutions, especially in the education sector. Many programmes including local events, school festivals etc are broadcasting through Akshaya network. Tuitions for Public Service Examinations are also offered through the intranet solution

2.7.3 Arvind Eye Wireless

Intel and TIER group from UC Berkeley has deployed a long distance WiFi based network in southern part of India. The network connects the remote centers of Arvind eye hospitals to the main hospital using WiFi based long links. The network uses relay points to connect distant places which cannot be connected by a single point to point link. The network allows patients in the remote center to consult with the doctor sitting in the main hospital, without actually visiting the hospital. Deployment is being used on day-to-day basis.

Chapter 3

Architectures for MH-WiFiRe

This chapter starts with the requirements for a Good Multi-hop WiFiRe architecture. Then it discusses four possible architectures considered in this project for Multi-hop extension. The chapter concludes with the comparison of these architectures which helps in determining the pros and cons of the architectures.

3.1 Requirements of a Good Architecture

This section describes the requirements of a Good MH-WiFiRe Architecture. A good MH-WiFiRe architecture should meet following requirements:

1. Overcome drawbacks of WiFiRe:
   The Multihop architecture should overcome the Line of Sight requirement and Fixed Range drawbacks of WiFiRe.

2. Cost Effective:
   Any solution to be effective in Rural India needs to be cost efficient. Hence multihop extension to the WiFiRe should not come at high cost as it will not be affordable to the rural community.

3. Meet QoS requirements:
   The architecture should meet the QoS requirements of all the traffic that is expected on the networks. Presently, only VoIP traffic is considered.

4. More number of VoIP calls per Village:
   The architecture should not have more overhead and should try to use the available bandwidth to the maximum. Since here we consider only VoIP traffic the architecture should support maximum number of VoIP calls per village.

5. Minimum Changes in WiFiRe:
   The multihop extension should require no or very less modification to the original

WiFiRe system. The architecture and MAC of original WiFiRe should be maintained.

3.2 Three Hop Architecture

Three hop architecture have one or more complete WiFiRe cells in the Extended system. Each WiFiRe cell has its own System S' which controls the activities within its cell. The STs in the Extended WiFiRe cell send data to its corresponding secondary System which forwards it to the primary cell. The secondary system communicates to the primary system through a common ST which lies in the range of both primary as well as Extended cell. This ST is referred to as relay ST. The architecture with one Extended WiFiRe cell is shown in figure.3.1

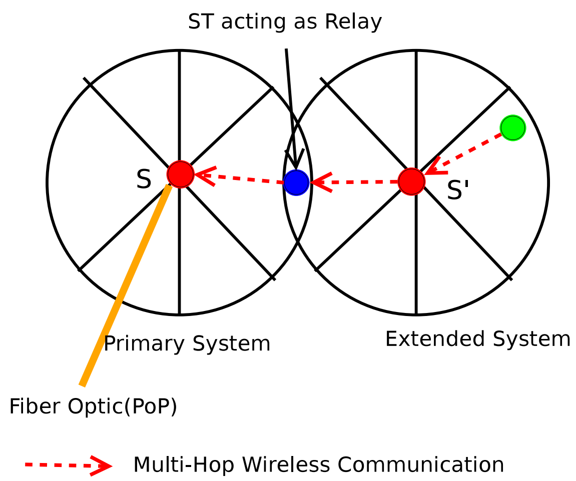

Figure 3.1: Three Hop ArchiThis section describes projects that replace 802.11 MAC with more efficient tecture

Thus the infrastrutural requirements for each extended cell are:

- One 40 mtr tower at the System.
- Six sector antennas, one for each sector.
- Mast and directional antenna at each secondary ST.

Thus infrastructure wise it is as costly as the original WiFiRe cell. The advantage of this architecture is the huge coverage area. We can have one Extended cell for each of the primary sector. These extended cells might overlap depending upon their size and placements. Assuming each cell make use of same frequency we will have to come up with a global scheduling of sectors, so that no two overlapping sectors transmits at the same time, making the system more complex.

3.3 Two Hop Architecture

In this architecture, like Three hop architecture we can have one or more WiFiRe cells in the secondary system. The difference in the two systems is that, primary system and the secondary system communicates directly over a point-to-point wireless link. There is no relay ST in between. Another difference is in the size of the cell. The architecture will have small WiFiRe cells because of the practical limitation of the length of long-distance point-to-point wireless link betwen secondary and the primary system. The architecture with one Extended WiFiRe cell is shown in Figure. 3.2

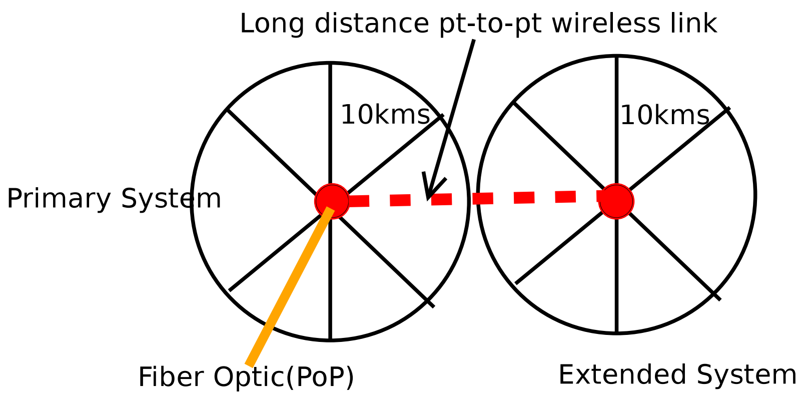

Figure 3.2: Two Hop Architecture

The infrastructural requirements are very much similar to Three hop architecture. Also there is possibility of overlapping sectors so we need global scheduling policy for the sectors, so that no two overlapping sectors transmit at the same time.

In both the above architectures we have complete WiFiRe cell in the secondary system. The circular shape of the cell results into some void areas where we have no connectivity. Thus the villages which lie in the void area will not have the connectivity.

3.4 Sectorized Architecture

This architecture extends the coverage area by 5-8 kms. Here we have relay STs at the boundary of the WiFiRe cell with sectorized antenna. The sectorized antenna extends the coverage area and the STs in the secondary system have directional antenna resulting into point-to-multipoint architecture. We can have multiple sectors at the relay ST, but his makes the system more complex as it may result into overlapping sectors and scheduling issues. Hence we assume only one sector per relay ST. We can have multiple relay STs within single primary sector. Figure 3.3 shows the example of this architecture with two relay STs.

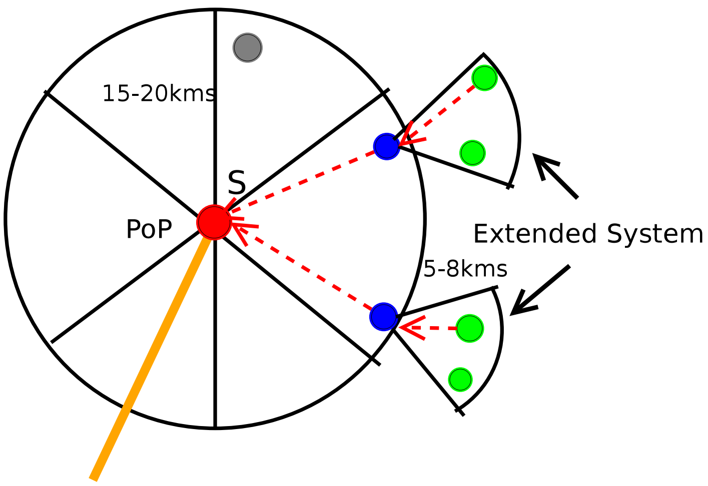

Figure 3.3: Sector Architecture

This architecture also results into void areas, but by carefully planning the placements of sectors we can reduce the void area.

3.5 Tree Based Architecture

This architecture adopts a Tree like structure. In all the above architectures we see that there is a relay ST which acts as connection point between primary and secondary system. Considering this fact, in this architecture we consider tree topology where relay ST is root of the tree. This architecture will usually require comparatively small distance links and is more efficient cost wise. This is explained in the subsequent chapters. In this architecture all the links are point-to-point links. Figure 3.4 shows typical example of Tree based architecture.

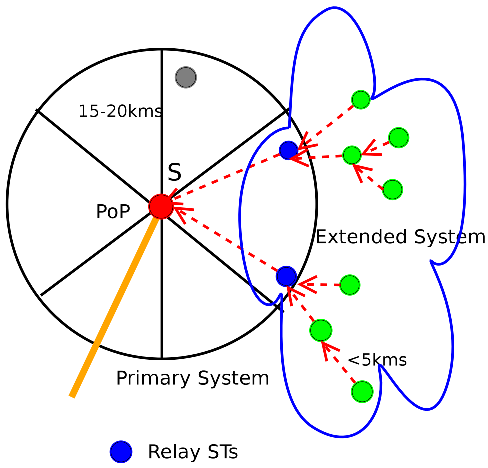

Figure 3.4: Tree Architecture

3.6 Comparison

The Table3.1 compares above described architectures on different parameters that helps us in deciding the the best suitable architecture for multihop extension.

Table 3.1: Comparison of MH-WiFiRe Architectures

Parameters	**ThreeHop**	**TwoHop**	**Sectorized**	**Tree Based**
Secondary System Coverage (in km^2)	707	628	160	160
Villages Covered	118	52	27	27
TotalCost	\$52 060	\$27 640	\$16 520	\$14 990
Cost/Village	\$441	\$531	\$612	\$555
PHY-OVERHEAD can be combined	No	No	No	Yes
Calls/Village	0.40	0.90	1.3	5
Requires LoS between Relay ST and Secondary ST	Yes	Yes	Yes	No
Presence of Voids	Yes	Yes	Yes	No
Complexity of the System	More	More	Less	Less
Overcomes Obstacles in the Primary Sector	No	No	Yes	Yes

Three hop and Two hop architecture provide more coverage area than sector and tree architecture. But considering a typical scenario of WiFiRe as shown in figure 4.2, Fiber Point-of-Presence are at a distance of 40-45 kms and hence typically only 5-10 kms of extension is required. For such extension tree and sector architectures are more suitable than the other two. Also the cost per village is less for three hop architecture, but the difference is not significant and overall the cost is not very high for all the architectures. Another important parameter is number of calls supported per village. Its less than one for both three hop and two hop architectures. Also its comparatively less for sector architecture, whereas for tree architecture its maximum and sufficient considering village scenario. Tree architecture is able to support more number of calls because it combines PHY-OVERHEAD, whereas other architectures cannot. The first three architectures requires LoS communication between Relay ST and Secondary ST because there exist a direct point-to-point wireless link between them, whereas in tree architecture there need not be a direct point-to-point wireless link between Relay ST and Secondary ST. Also there are no void areas in case of tree. Table 3.2 gives the best case infrastructural requirements for all the architectures. We see that all the architectures need at least one

40mtr tower except for Tree architecture. But tree architecture needs more directional antennas compared to others.

Table 3.2: Best Case Infrastructural Requirements

Infrastructure	**ThreeHop**	**TwoHop**	**Sectorized**	**Tree Based**
40m Towers	One	One	One	Zero
20m Masts per Village	One	One	One	One
Sectorized Antenna	Six	Six	One or More	Zero
Directional Antennas per Village	One	One	One	2(N-1)/N

Thus we see that three hop and two hop architectures do not really add more values through its huge coverage area. Typically we need to extend the WiFiRe by 5-8kms only. Also, three hop and two architectures cannot overcome the line of sight limitation (Figure 1.5) of the WiFiRe. Calls per village supported by these architectures is also less as they cover more number of villages with the BW limited by the underlying WiFiRe system. These limitations makes Three hop and two hop architectures unsuitable for the multi-hop extension. In the next chapter, we perform detail cost analysis of the remaining two architectures, that is tree and sector architecture, as Cost is a dominant factor in deciding the suitable architecture for rural area.

Chapter 4

Cost Analysis of Architectures

In this chapter, we first discuss some basics of long distance wireless links and towers, typical coverage requirements and best and worst case scenarios for Sectorized system. This is followed by cost analysis of Tree and Sector architecture.

4.1 Background

4.1.1 Long Distance Wireless Links

To establish a long distance wireless links its necessary to meet two requirements:

- Wireless Link Budget :
  A wireless link budget calculation totals the signal gains, substracts the signal losses over the wireless link and predicts whether the signal strength received at the receiver end is high enough for the link to work reliably [27]. For proper reception of the signal at the receiver end two conditions must be satisfied [22]:

  1. The signal level received at the receiver should be above certain threshold.
  2. The sinal should be above the interference by $SIR_{reqd.}$

  In this project, we have not considered Power constraints and Wireless Link Budget calculations. More details on the same can be obtained in [27] [22]

- Wireless Line-of-Sight [27] :
  It is common for wireless signal to experience attenuation and reflection or diffraction when it encounters an obstruction on its way. These obstructions are common in case of outdoor environment, hence to establish a long distance wireless link it is necessary to have wireless line-of-sight (LOS) path. It is a path with no obstruction to significantly block, reflect, diffract, absorb or attenuate the wireless signal. A wireless LOS path typically requires a visual LOS path plus additional path clearance to account for the spreading of the wireless signal. *Fresnel Zone* provides a

method to determine the amount of clearance a wirless link needs from an obstacle to establish a reliable link. The concept of fresnel zone is shown in Figure 4.1. Fresnel zone is calculated using following formula:

$$diam(ft.) = 72.1\sqrt{\frac{d1 * d2}{f * (d1 + d2)}} \quad (4.1)$$

where, $d1$,$d2$ are in miles and f is the frequency of the signal in GHz

At least 60% of the calculated Fresnel zone must be clear to avoid significant signal attenuation.

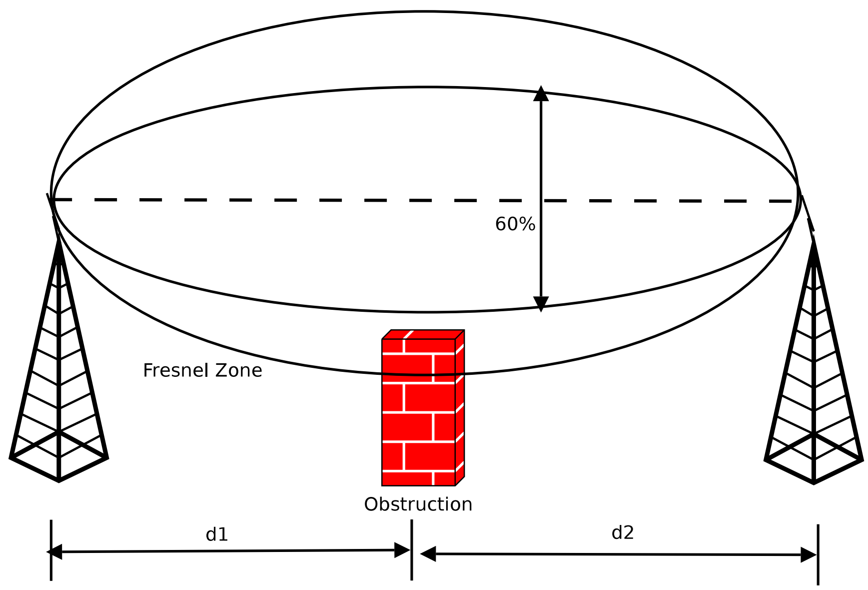

Figure 4.1: Fresnel Zone

In a village scenario common obstacles are bushes, farms, houses, trees and hills. Houses are not multi-storied and are usually not more than two-storied. Most of the trees have height of around 13-17 mtrs except some trees like Banyan tree, Pipal tree etc are usually large and have height of around 30mtrs[2]. Here we classify obstacles into three categories:

- Small Height Obstacles: Height of these obstacles is less than or equal to 17mtrs. For example, bushes, farms , houses, trees etc.
- Medium Height Obstacles: Height of these obstacles is greater than 17mtrs but less than or equal to 30mtrs. For example, large trees, small hills etc.
- Large Height Obstacles: Height of these obstacles is greater than 30mtrs. For example Hills, very large trees etc.

. As explained above to establish a link its necessary to overcome the obstacles. So antennas are mounted on a mounting structure of appropriate height. The commonly used mounting structures are:

- Poles: Poles are of 5-12 mtrs in height and are the cheapest among all.
- Masts: Mast are of 10-20mtrs in height and are cheap. Typically its cost is around $170.
- Towers: Towers are of 20-60mtrs in height and are most expensive. Among all the infrastructural requirements to establish a wireless link, tower is the most expensive component.

The terms "Mast" and "Tower" are often used interchangeably. However, in engineering terms, a tower is a self-supporting or cantilevered structure, while a mast is held up by stays or guys [3]. The cost of tower depends on its height. Table 4.1 gives cost of tower and mast w.r.t. the height [4].

Table 4.1: Cost of Towers/Masts

Item	Cost(approx. U.S.$)
Antenna Tower	
15m	$2,300
20m	$3,000
25m	$3,900
30m	$4,800
45m	$6,600
Antenna Mast	
10m	$85
15m	$130
20m	$170

The cost is almost constant till 20 mtrs, then there is a high rise in the cost after 20 mtrs after which the cost increases linearly with the height. From here onwards in the report, towers with height less than or equal to 20 mtrs will be referred as Mast to distinguish it from the Towers of height 30-40mtrs. Thus to have a cost effective system wireless links should be established with minimum number of Towers. To establish a long distance link with obstacle in between its more cost effective to use one large tower and one mast over using two towers of small height. This typical arrangement is shown in Figure 4.2. Following simple geometry of similar triangles, we get the following relationship between the height of Tower and the height of obstacle

$$H = 2h_o + (2FZ_R - h) \tag{4.2}$$

Thus we see that there is a linear relationship between height of the obstacle and height of the tower. The above relationship is plotted in Figure 4.3 considering FZ_R =5 mtrs and h = 20 mtrs. FZ_R = 5 mtrs implies, its a long distance link of length $\simeq$ 8 kms. We see that, for FZ_R = 5 mtrs, it is possible to establish a wireless link with mast at both end till the obstacle height is limited to 15 mtrs.

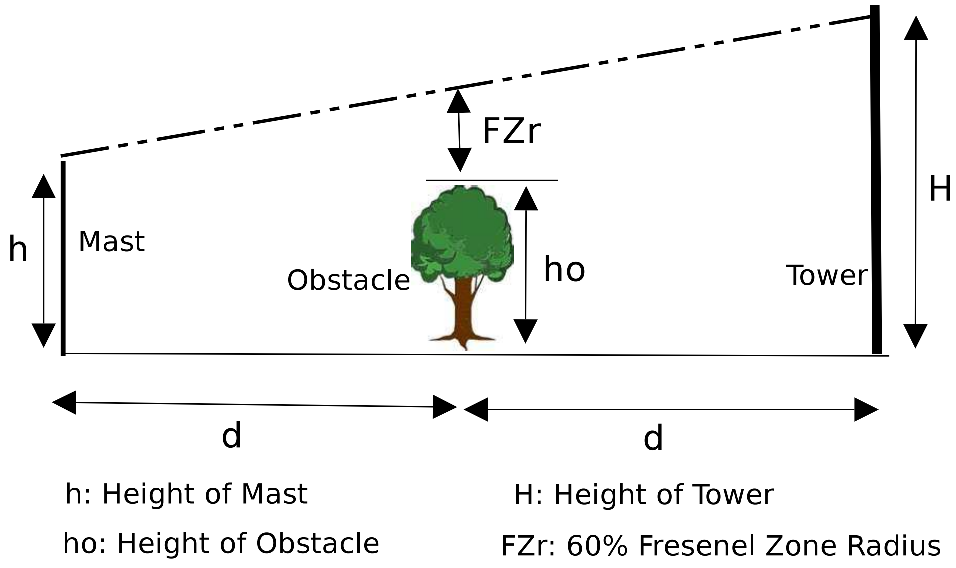

Figure 4.2: Long distance link

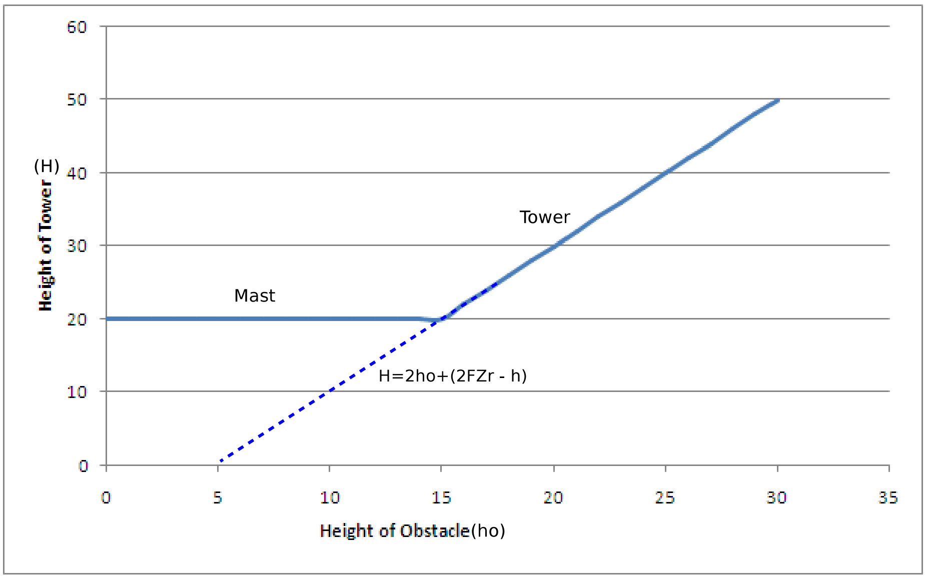

Figure 4.3: Tower Height required to establish a link

For a short distance wireless link of upto 4kms, for the 60% Fresnel clearance the radius comes to be 3.35 mtrs, hence the mast of 20mtrs at both end can overcome Small Height obstacles to establish a wireless link. To overcome Medium Height obstacles we will need tower at one end. For a long distance links of 8-10 kms, the required Fresnel radius for 60% clearance is about 5.5 mtrs. Also for such a long distance there are chances of terrain variation due to earth's curvature. To establish such a link we will need Tower at one end for Small height obstacles and to overcome Large obstacles we will need towers at both end. Its difficult to establish link with Large height obstacles for both small as well as long distance links. The above details are summarized in the Table 4.2

Table 4.2: Type of Links

Link Distance	Obstacle Type	Link Type
Short Link (<=4 kms)	Small (<=17 mtrs)	Mast-Mast
Short Link (<=4 kms)	Medium (>17&<=30 mtrs)	Tower-Mast
Short Link (<=4 kms)	Large (>30 mtrs)	Difficult to establish link
Long Link (8-10 kms)	Small (<=17 mtrs)	Tower-Mast
Long Link (8-10 kms)	Medium (>17&<=30 mtrs)	Tower-Tower
Long Link (8-10 kms)	Large(>30 mtrs)	Difficult to establish link

4.1.2 Typical WiFiRe Scenario

A typical WiFiRe scenario is described in Figure 1.4. From the figure it is clear that we need to extend the cell coverage by 5kms to 8kms. Typically the extended system should cover the area as shown in Figure 4.4.

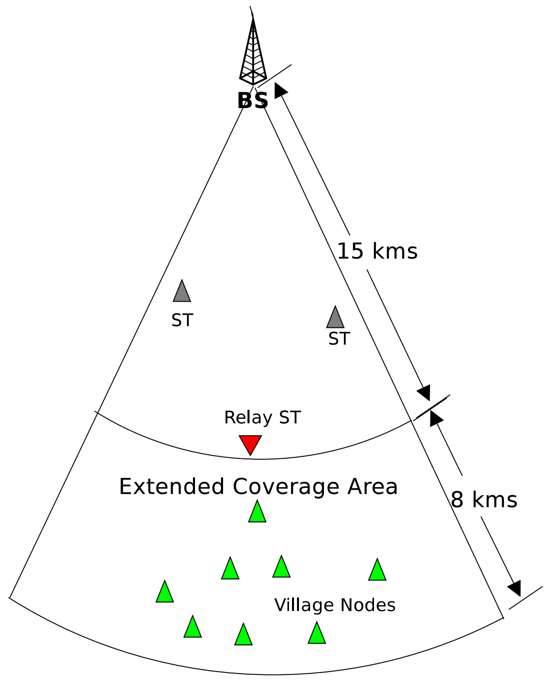

Figure 4.4: Coverage Required

The total extended coverage area comes to be 160 km^2. On an average there is one village every 6 km^2[13]. So expected number of villages in the extended coverage area are 27. Figures 4.5 and 4.6 show how Tree and Sector Architectures will typically extend the Primary system. Typically a link in a Sector architecture will be of 7-8 kms whereas in a

Tree architecture it will be 3-4 kms. Considering only small obstacles are present usually, sectorize system will need Tower at relay ST and mast at village nodes, whereas in case of tree architecture we can have mast at all sites. But if Medium height obstacles are present then we will need Tower-Mast setup for Tree architecture and Tower-Tower setup for Sectorized architecture.

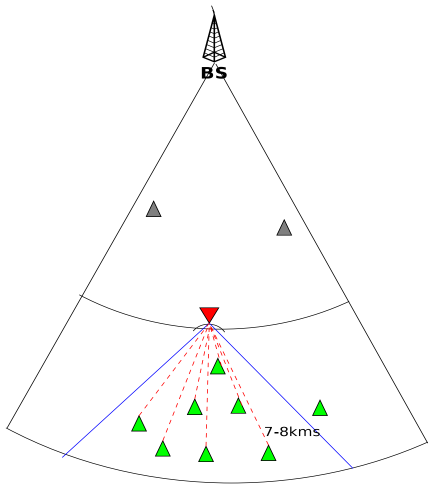

Figure 4.5: Sector Architecture

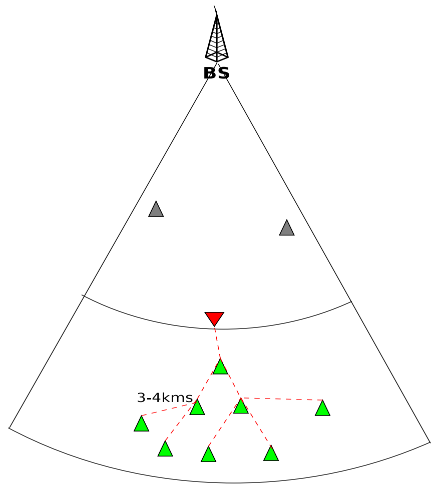

Figure 4.6: Tree Architecture

In a sectorize system its very unlikely that all the villages will get covered in a single sector. We will need multiple sectors to cover villages. Its also possible that some villages do not get covered at all due to presence of voids. Area covered by single sector depends on the beamwidth of the sector. The Table 4.3 gives various details for different beamwidth of sector. Area covered is calculated assuming coverage of 8kms and Number of sectors required is calculated assuming there is no sector overlapping and presence of voids. In reality, it is not possible to have complete coverage without sector overlapping or voids. If we try to achieve complete coverage then sectors will overlap increasing the complexity of the system. If we want non-overlapping sectors then the coverage will not be complete due to presence of void areas.

Table 4.3: Antennas with different Beamwidths

Beamwidth	**Area covered by one sector**	**#Sectors for complete coverage**
30°	16.75 km^2	10
60°	33.5 km^2	5
120°	67 km^2	3

Thus the best case, with respect to the coverage, for the sectorized system is when all the villages gets covered in a single sector, whereas the worst case occurs when we need maximum number of sectors to have complete coverage.

4.2 Cost Comparison of Architectures

Cost is an important factor in determining the most suitable architecture for Multi-hop extension. This section provides cost analysis of Tree and Sector Architecture. The cost of the two architectures is compared on different basis. First, cost is compared assuming infrastructural requirement for best and worst case.. Then cost compared with respect to the coverage provided by the architecture. And at the end the expected costs of two architecture using a probabilistic model is compared.

4.2.1 Coverage Analysis

As described in the last section, the best case of sectoized system, with respect to coverage, occurs when all the villages are covered by single sector. And the worst case occurs when we need all the sectors. The typical scenario described in figure 4.4 is considered and beam-width of the sectorized antenna is assumed to be 60°. The number of villages in the extended system are assumed to be 25. Here in case of sectorized architecture we have assumed that only small obstacles are present and hence we need towers only at Relay STs, which has sectorized antenna. Tree architecture will need tower in case there are medium height obstacles between a link. Figure 4.7 compares the cost of Sectorized and Tree Architecture under different scenario.

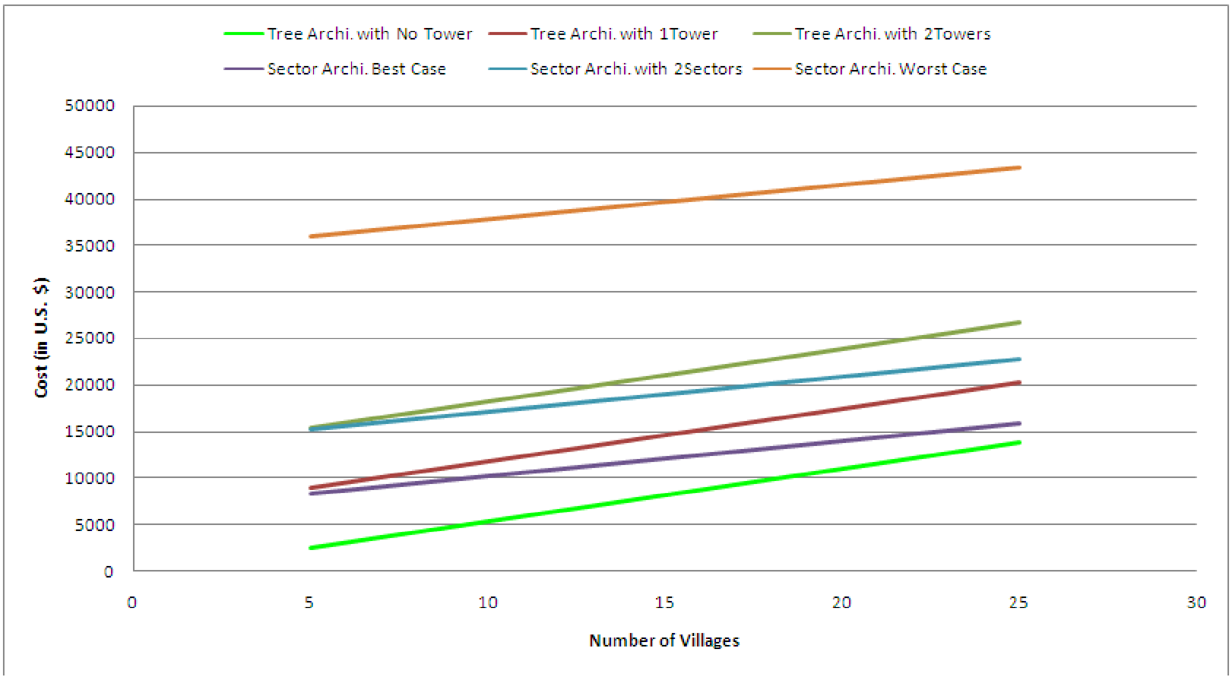

Figure 4.7: Cost Comparison of Sector and Tree Architecture

Figure 4.7 shows that the cost of the system varies linearly with the number of villages. The rise in the cost of the system with number of villages is more in case of Tree architecture. This is because the per node infrastructural cost, assuming same mounting structure is used in the village for both the architecture, is more in case of Tree because Tree architecture needs two additional directional antennas for every new village whereas sector architecture needs only one directional antenna. But if only small height obstacles are there then Tree architecture is possible with all Mast and no tower. Whereas in case of Sectorized architecture at least one tower will be required. Cost of best case sectorized architecture is U.S.$15 780, whereas cost of tree architecture with no tower is U.S.$13 850. Because of the tower, even the cost of the best case of the sectorized architecture is 14% more than the tree architecture with no tower for 25 villages. But if equal number of towers are needed in both the architectures then the Sectorized architecture is more cost efficient than the tree architecture. For example, cost of tree architecture is U.S.$20 280, which is 22% more costlier than sectorized architecture with one tower

Typically, chances of having medium or large obstacle in a rural scenario is less. Usually there will be small obstacles and flat terrain. If the villages are equally distributed in the extended coverage area, then it is not possible to cover all the villages in a single sector. Typically there will be 5 villages in the sectorized area covered by 60° beamwidth sector antenna. The Figure 4.8 shows how cost varies for two architectures with the coverage. Here its assumed that only small obstacles are there hence its possible to construct a tree architecture without a tower and sectorized architecture with only one tower per sector. On an average, cost of Sectorized architecture increases at a rate of U.S.$1735 per village whereas of tree architecture its only U.S$ 554, that is about three times more.

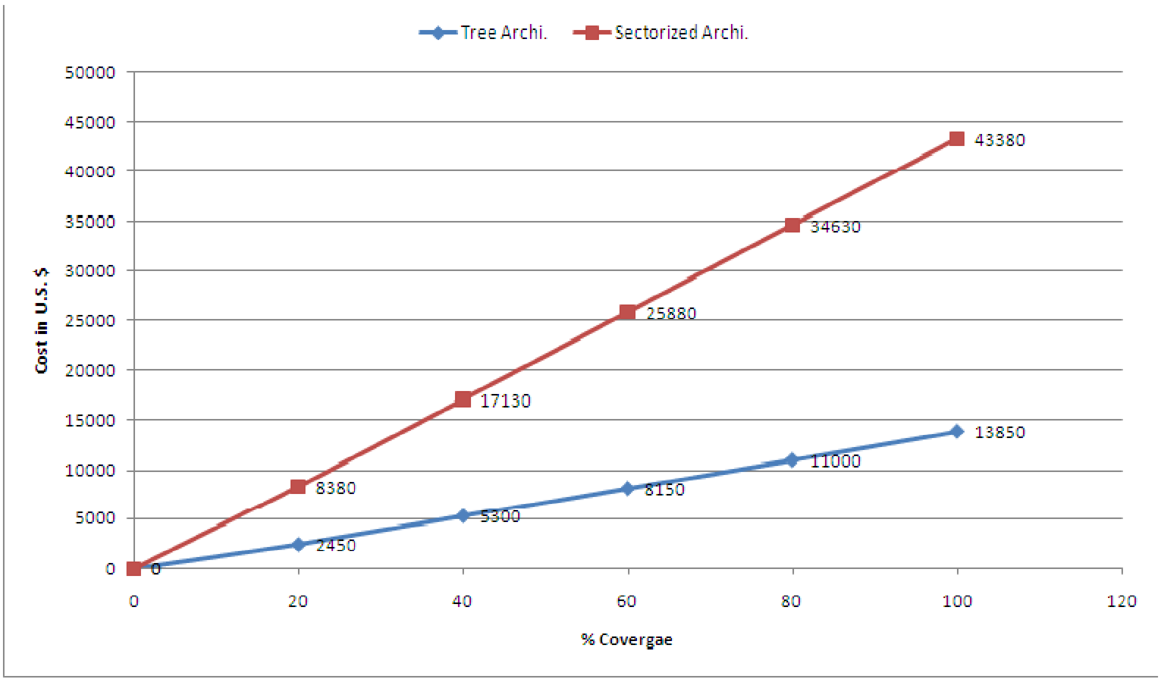

Figure 4.8: Cost comparison with Coverage

Thus from Figure 4.8 its clear that considering typical rural scenario, where mostly we have small obstacles and very less terrain variation, the tree architecture is more cost efficient than the sectorized architecture.

4.2.2 Probabilistic Cost Model

This section gives the probabilistic model for the two architectures, and then compares the expected cost of the two architecture based on the model. The calculations are done with an assumption that there are 25 villages. The cost of the system is mainly dominated by the tower cost and the tower requirement depends on the obstacles. Mounting structures used for establishing a link depends on the type of the obstacle present between the link and the link distance. This is shown in Table 4.2. In this probabilistic model we consider only two types of obstacles, Small height obstacles and Medium height obstacles. We consider following two probabilities as given:
p: Probability that there is a small height obstacle between a link.
q: Probability that there is a medium height obstacle between a link.
Now small height obstacles, like trees, one or two storied buildings are more commonly found in rural areas than medium obstacles like large trees, hills etc. hence $p > q$. Large value of p implies that there are more trees and small buildings, similarly large value of q implies more medium height obstacles. Thus in a hilly area, values of p and q will be large and it will be small in case of plane terrain. In case of tree architecture, links will be of small distance hence we can have mast-mast link even in the presence of small obstacle but for medium height obstacle we will need Tower-mast link. Whereas in case of sector architecture, typically links are long distance and hence will need tower-mast link with small obstacle and tower-tower link in case of medium obstacle. If no obstacle is present then we can have mast-mast link. Here for analysis purpose we assume only single sector. Also its assumed that in case of tree architecture every VN has two potential uplink successors.

For sectorized architecture to have no tower, we should not have any obstacle, medium as well as small, between all the N point-to-multipoint links between Relay ST and secondary STs. Thus probability of *No Tower* in Sector Architecture will be,
P(*No tower in sector architecture*)=P(*No small obstacles*)* P(*No medium obstacles*)

$$P(\textit{No tower in sector architecture}) = (1-q)^n(1-p)^n \tag{4.3}$$

Similarly, for tree architecture to have no tower we should not have medium obstacle between both the potential uplinks for all the nodes. Thus probability of *No Tower* in Tree Architecture will be,

$$P(\textit{No tower in tree architecture}) = (1-q^2)^n \tag{4.4}$$

Figure 4.9 plots the above probabilities for different values of p and q. In the figure4.9 P(Obstacle1)=p and P(Obstacle2)=q.

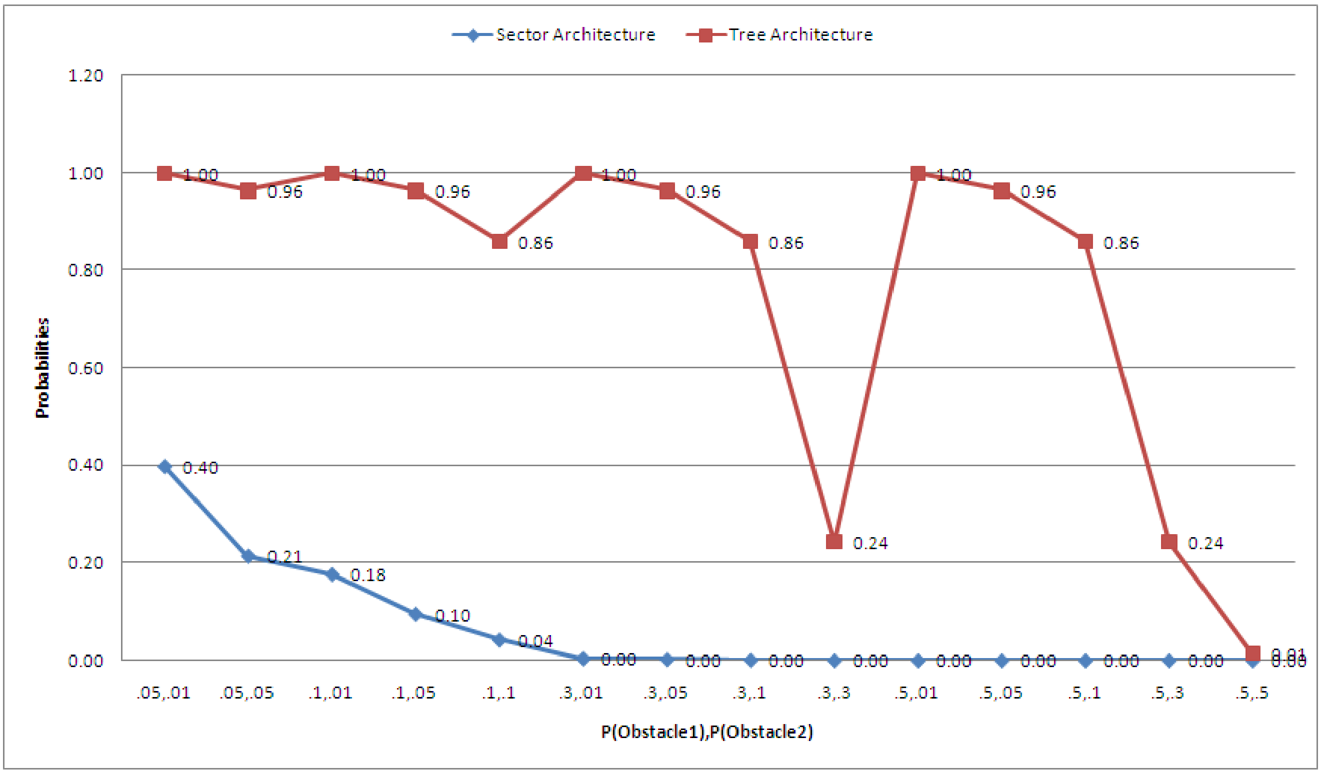

Figure 4.9: No Tower Probability

From Figure 4.9 it is clear that probability of No Tower is very less in case of sector architecture and is close to one in most of the scenarios in case of tree architecture. Probability of tower in case of tree architecture in not dependent on small obstacle probability, p. It increases with the probability of Medium obstacle. The expected cost of the system can be determined once the probability for the different number of towers is known.

- Sectorized Architecture:

$$P(No\ tower) = (1-q)^n(1-p)^n \tag{4.5}$$

A tower will be required if there is at least one small obstacle between the N point-to-multipoint link AND no medium height obstacle. Hence
P(*One tower*)= P(*1 or more Small obstacles*) * P(*0 Medium obstacles*)

$$P(One\ tower) = [1-(1-p)^n] * (1-q)^{n-1} \tag{4.6}$$

Now, x towers will be required if there are $x-1$ medium height obstacles between N point-to-multipoint links. Thus

P(x $towers$)= P($x-1$ $medium$ $obstacles$)

$$P(x\ towers) = \binom{n-1}{x-1} q^{x-1}(1-q)^{n-x} \tag{4.7}$$

- Tree Architecture:

$$P(No\ tower) = (1-q^2)^n \tag{4.8}$$

Now x towers will be required if we have x such VNs, where there is a medium height obstacle in the path of its both the uplink successors.

$$P(x\ towers) = \binom{n}{x} (q^2)^x(1-q^2)^{n-x} \tag{4.9}$$

Figure 4.10 shows the expected cost of the system for 10 villages under different terrain conditions. Following probabilities of obstacles are assumed for different types of terrain:
Plane terrain : $p = 0.05; q = 0.01$
Normal Terrain : $p = 0.1; q = 0.05$
Hilly Terrain : $p = 0.5; q = 0.3$

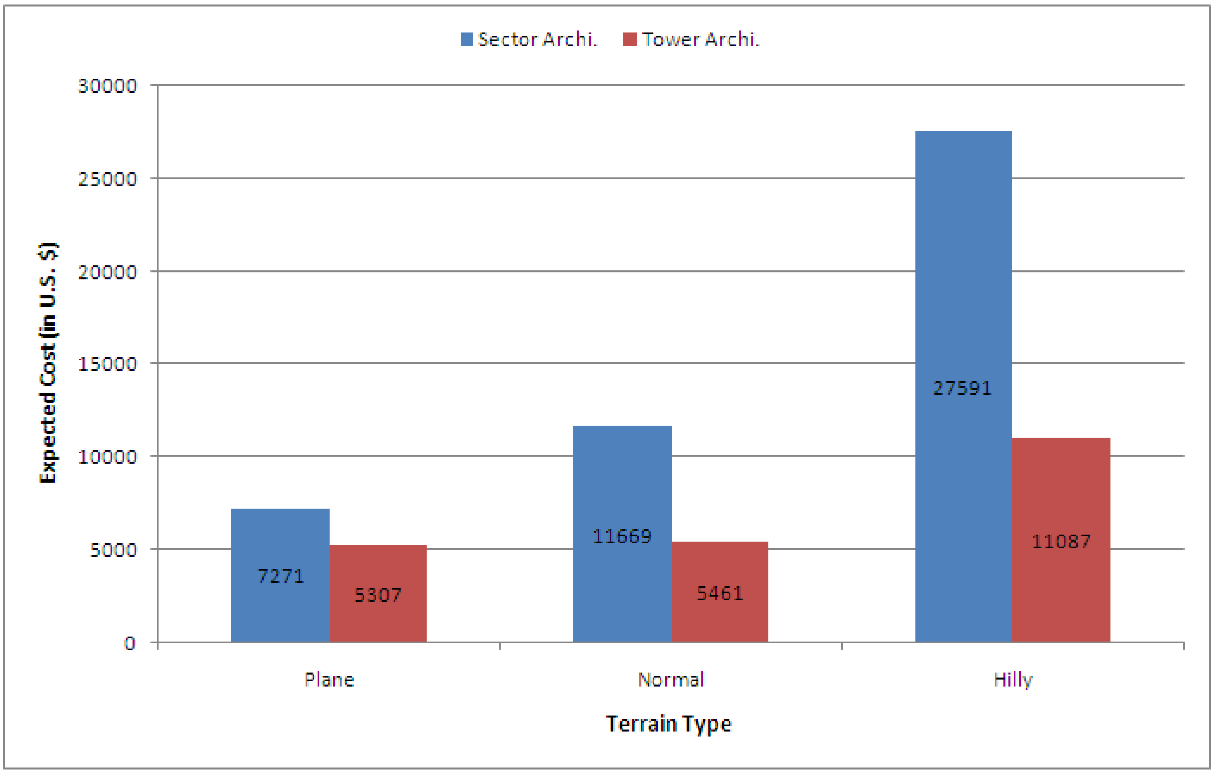

Figure 4.10: Expected Cost of the System

From the figure 4.10 its clear that the cost of Tree architecture is less than the cost of sector architecture. Also the difference between the cost increases as the terrain contains more obstacles. For example, in case of plane terrain expected cost of sector architecture is 37% more than the tree architecture with an absolute difference in the cost equal to U.S.$1964. Whereas in case of hilly terrain, sector architecture is 150% more costlier than tree architecture with an absolute difference of U.S$ 16 504.

4.3 Conclusions

Both Tree as well as Sector architecture are suitable for extending the WiFiRe to multi-hop. Which architecture to use largely depends on the scenario. But considering general scenarios, we see that tree architecture offers following benefits over sector architecture.

- Cost Effective: Sector architecture will usually require more number of towers compared to tree and hence the cost of tree architecture is less than the sector architecture. In case of normal terrain the expected cost of sector architecture is 2.1 times of tree architecure.

- More number of calls supported: Since the tree architecture combines the PHY-OVERHEAD it is able to support more number of calls per village compared to the sector architecture. For example for G.729 codec, with 10 msec frame size and all calls from secondary system sectorized architecture supports 1.3 calls per villages, which are significantly less than 5 calls/village supported by tree architecture.

- No Voids: In sector architecture its possible that certain villages may not get connectivity because they may lie in the void areas. But tree architecture do not have void areas.

Considering the benefits offered by the tree architecture over sector, we decided to select tree architecture for detailed studies. In the subsequent chapters we study the tree architectures in detail, present MAC protocol details and also explain few scheduling schemes.

Chapter 5

Tree Based MH-WiFiRe Architecture

This chapters describes Tree Architecture for MH-WiFiRe in detail as this is the architecture chosen for detail study and analysis in the project. From now onwards every mention of MH-WiFiRe Architecture refers to the Tree Architecture. Reference to any other MH-WiFiRe architecture will be mentioned explicitly.

5.1 Overview

Figure 5.1 shows different components of MH-WiFiRe. This section describes these components and other terms which will be used in the report.

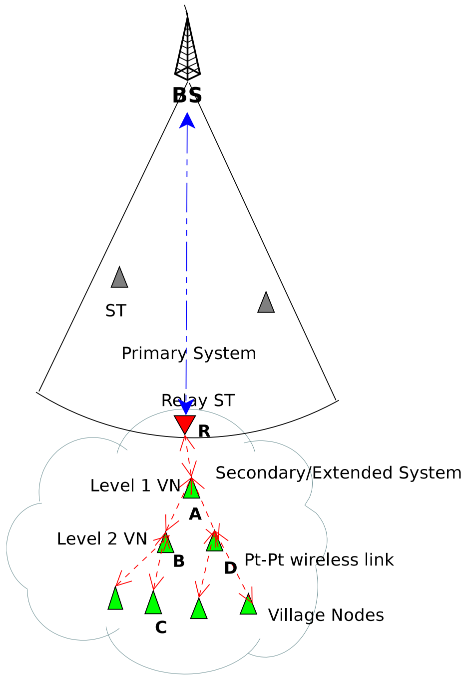

Figure 5.1: MHWiFiRe Architecture

- **Base Station and STs**: BS and STs belong to the primary system. BS uses a sectorized antenna .BS is like a gateway and is connected to the external world through high speed wired connection. STs are connected to the BS over a directional wireless link. ST is a user premise network equipment. We usually have one ST per village. All the traffic from a village goes through the ST.

- **Relay ST**: Relay ST belongs to both Primary system as well as secondary system. It acts like connection point for the primary and the secondary system. It keeps track of the VNs that come under it and controls the scheduling of data in the secondary system. Every VN needs to register to the Relay ST. It forwards the traffic from the VNs to the BS and vice-versa. It also processes the control information received from the VN like registration request, connection establishment/ termination request etc. Thus Relay ST performs a role for the secondary system similar to what the BS plays for the primary WiFiRe system. This makes the secondary system independent of the Primary system. The BS is not aware of the existence of the extended system. For BS all the calls coming from the extended system appears to be coming from the Relay ST.

- **Village Node**: The STs in the extended system are referred as Village Nodes(VN). Village nodes unlike STs are also responsible for the relaying of data of other VNs. VNs maintain some forwarding information so that they correctly forward the data. The village nodes form a tree topology with Relay ST as the root. Relay ST is at level 0, hence village nodes directly connected to the relay ST are level1 VNs and so on. For example in the figure 5.1 VN A, B and C are Level1, Level2 and Level 3 VNs respectively.

- **Downlink and Uplink Successor**: The downlink successor of a VN are the ones which are directly connected to the VN and are one level below in the tree. For example, VN B & D are downlink successor of A and VN A is downlink successor of R. Thus a VN have zero or more downlink successor. Similarly uplink successor of a VN is a node which is directly connected to the VN and is one level up in the tree. For example, VN B is uplink successor of VN C, and VN B is uplink successor of VN A.

5.2 Assumptions

This section describes the assumptions made in designing the MH-WiFiRe system.

- Round Robin Scheduling:
  Underlying primary WiFiRe system uses round robin scheduling of sectors in the Uplink Phase. In round robin scheduling all the STs in sector1 & sector4 are scheduled first, followed by STs of sector2 & sector5 and then sector3 & sector6. This assumption is made to keep the scheduling in MH-WiFiRe simple. Scheduling based on interference matrix can also be handled but is not looked into in present project.

- Synchronized Village Nodes:
  VNs are synchronized and hence can detect the slot boundaries accurately. Every VN synchronises to its uplink successor in a similar fashion as in WiFiRe STs synchronises with BS. The details of synchronization is not covered in the present project.

- Only VoIP traffic:
  Presently MH-WiFiRe supports only VoIP traffic, that is, it only supports Unsolicited Grant Service. Support for other types of services that is rtPS, nrTPS and BE is not provided. WiFiRe is a system build for Rural areas where major Internet traffic will be VoIP calls.

- Equal number of UL and DL slots:
  Since only VoIP traffic is considered, primary WiFiRe frame will have equal number of UL and DL slots.

- No interfering point-to-point links :
  All point-to-point wireless communications operate without interfering with any other point-to-point communication.

- Reliable system:
  System is assumed to be reliable and hence no mechanism to handle link failure, node failure or any other type of failure of the system is provided in the current project.

5.3 Frame Structure

This section describes the frame structure for the MH-WiFiRe system. As mentioned is section 3.1, one of the requirement of a MH-WiFiRe system is to have least possible changes in the underlying WiFiRe. Considering the same, the MH-WiFiRe do not need any changes in the WiFiRe frame structure. Underlying primary system continues to use the same frame structure. The secondary system will have its own frame structure, and this mapping of frame structure will be done by Relay ST, which lies in both, primary as well as in secondary system. Relay ST receives beacon which contains UL-MAP and DL-MAP for the primary system. The Relay ST forwards this to all the VNs which calculates a global transmission schedule. The transmission schedule depends on the Primary WiFiRe frame, and hence the structure of Secondary frame depends on the primary WiFiRe scheduling. This mapping of Primary frame to Secondary frame is explained later in this section.

Now as shown in Figure 5.2, the WiFiRe frame has beacon transmission at the start. There are 3 beacons each of 6 slots. Thus first 18 slots are used for beacon transmission. Following beacon transmission there is Downlink Transport block(DL-TB). The data is transmitted in the downlink direction from BS to STs in DL-TB. Then there is guard band followed by uplink transmission. Assuming Round Robin scheduling of sectors we will have three divisions in the uplink and downlink phase, one for each sector. Figure 5.2 shows the simplified version of the WiFiRe frame.

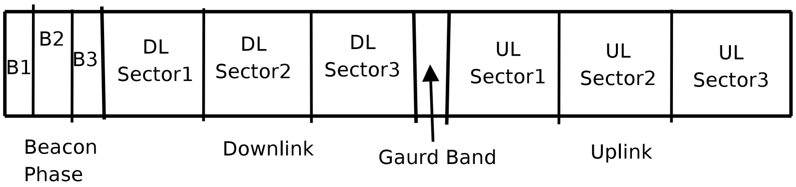

Figure 5.2: Simplified WiFiRe Frame

A ST in the WiFiRe cell is in one of the three phases.

- **Transmitting**: ST is in transmitting phase when it is sending data to the BS, in the uplink slots.
- **Receiving**: ST is in receiving phase, when the data send by BS is reachable at the ST, that is ST is in receiving phase for all the downlink slots, when the sector in which it is located is scheduled for the downlink transmission, even though it may not be actually receiving the data.
- **Idle**: ST is in idle phase when it is not in Transmitting phase or Receiving phase. That is, ST is in idle phase when its sector is not scheduled for the downlink transmission or when its uplink slots are not scheduled.

As Relay ST is like any other ST in the primary system, at any given time, it is also in one of three phases as described above. A relay ST cannot transmit or receive data to/from the secondary system when it is in receiving phase as this communication will interfere with the downlink transmission from the BS, as both the communications operates on the same channel. Similarly ST cannot receive data from the secondary system when it is in transmitting mode as it will result into Tx-Rx interference [24].

Thus a relay ST can Receive data from the secondary system when it is in Idle phase and can Transmit data to the secondary system when it is in idle phase or in transmitting phase. Thus when Relay ST is in

- Idle Phase, it can receive as well transmit data from/to secondary system
- Transmiting Phase, it can only transmit data to secondary system
- Receiving Phase, it can neither transmit nor receive data from the secondary system.

These different phases of relay ST gets mapped to the frame structure of the extended system as shown in figure 5.3. The figure shows the mapping between the WiFiRe frame and the corresponding MH-WiFiRe frame. The meaning of different phases is explained below. The frame assumes that the relay ST is in 2nd sector.

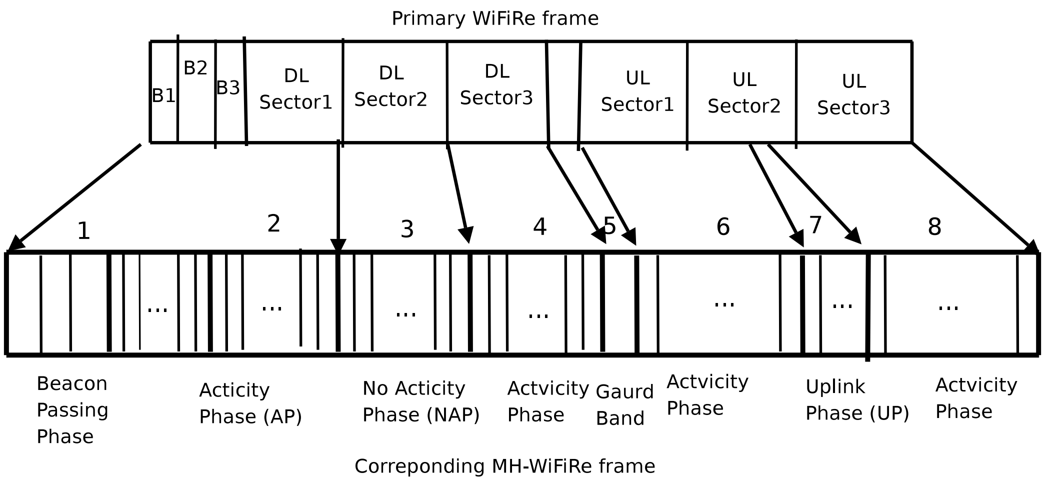

Figure 5.3: MHWiFiRe Frame

- **Beacon phase**: In this phase the relay ST receives beacon from the BS. Relay ST forwards the beacon to the Level1 VNs in the secondary system. The level1 VNs forwards the beacon to its downlink successors. This process of forwarding beacons to the downlink successor continues till the VNs at the leaf level receives the beacon. Upon receiving the beacon every VN determines the frame structure from the DL-MAP and UL-MAP present in it. Thus all VNs come up with the same frame structure.

- **Activity Phase(AP)**: This phase corresponds to the Idle phase of relay ST in the Primary system. Hence both Transmission(Tx) as well as Reception(Rx) is possible at Relay ST. Here transmission means transmission of data from relay ST to the secondary system and reception means reception of data at relay ST from the secondary system. When relay ST is transmitting data to the secondary system it is said to be in Tx mode and when it is receiving data from the secondary system it is said to be in Rx mode.

- **No Activity phase(NAP)**: This phase corresponds to the Reception phase of relay ST in the Primary system. Hence no activity w.r.t to the secondary system is possible at relay ST. Relay ST can neither be in Tx mode nor in Rx mode.

- **Uplink Phase(UP)**: This phase corresponds to the Transmitting phase of relay ST in the primary system. In this phase relay ST can only be in Tx mode, that is, it can only transmit data to the secondary system but cannot receive data from it.

The actual position and duration of these phases will vary with the location of the relay ST and DL-MAP & UL-MAP of the primary system.

5.4 MAC Protocol Overview

The MAC mechanism is TDMA based similar to WiFiRe. As shown in figure 5.3 the frame is divided into time slots. Each frame is partitioned into different phases as explained above. All the transmission happens over a point-to-point wireless link.

Relay ST forwards the beacon received from the BS to its downlink successor which in turn forwards it to their downlink successors. This process continues till all the VNs get the beacon. After getting the beacon, VN determines the frame structure following the mapping explained above. Hence all the VNs come up with a global scheduling scheme as it is derived from the common input(DL-MAP and UL-MAP) and same scheduling algorithm.

Every VN is assigned a unique 2 byte Village Node ID(VN-ID) similar to ST-ID in WiFiRe. All VNs are registered to Relay ST and BS in unaware of the presence of the extended system. When a VN want to establish a VoIP call, it sends a call establishment request to the Relay ST. Relay ST forwards this request, with some modification to BS. For BS it appears that the call establishment request has come from Relay ST. If BS accepts the call then Relay ST sends the call acceptance response back to VN. Upon receiving call acceptance response VN starts sending VoIP packets according to the scheduling scheme. These packets are routed through Relay ST. Every intermediate VN forwards the packets of its downlink successor to appropriate uplink successor. For this purpose, every VN maintains a forwarding information. Once the call is done, VN sends a call termination request to BS. These steps are classified into different phases and are explained in detail in Chapter 5.

5.5 Advantages over WiFiRe

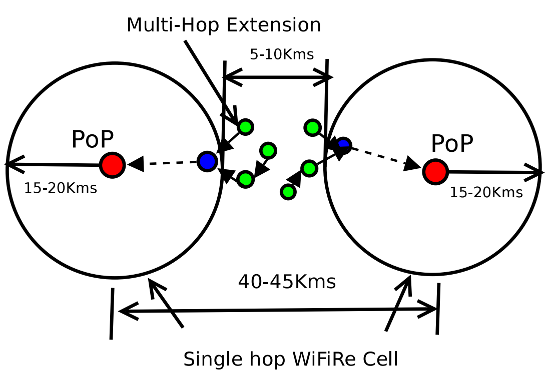

Figure 5.4: Fixed Range

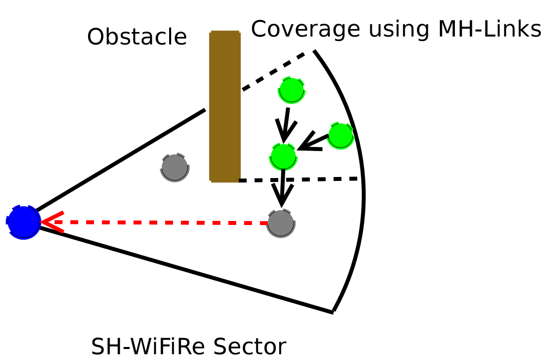

Figure 5.5: LoS requirement

The MH-WiFiRe overcomes the Line Of Sight and Limited Range problem of the WiFiRe system. Figures 1.4 and 1.5 describes typical scenarios under which WiFiRe fails to provide complete connectivity. In this section we present how MH-WiFiRe system can overcome these drawbacks. Figures 5.4 and 5.5 shows the MH-WiFiRe system in the same scenarios.

Villages which lie outside WiFiRe cell, form a tree topology rooted at ST lying in the range of WiFiRe cell. This is shown in Figure 5.4. As discussed above, we call this ST as relay ST and villages lying outside the WiFiRe cell as VNs. VNs send data to relay ST over multiple hops, which forwards it to BS. Similarly, in case of obstacles as shown in Figure 5.5, villages which are not in direct line of sight of the BS, forms a tree structure with root of the tree as one of the ST which directly communicates with the BS. This ST acts as relay ST and forwards the traffic of the villages not in range due to obstacle.

Chapter 6

MH-WiFiRe MAC Protocol

This chapter describes the MH-WiFiRe MAC protocol in detail. The details of the MAC protocol have been classified into various steps, which are described below in detail.

6.1 Initial Setup

During the deployment of the sub-system first VNs and relays STs needs to be configured. Every village node in the sub-system have 48-bit universal MAC address, which defines the village node uniquely. Each village node will maintain its uplink successor and downlink successors. In tree topology the node will have exactly one uplink successor and zero or more downlink successors.

Whenever a new village node is deployed following things are required to be done.

- Assigning unique village node IDs. This is optional as we can use universally unique MAC address as IDs

- Initializing uplink and downlink successors of a village node.

- Orienting uplink and downlink antennas to point to the uplink and downlink successors respectively.

- Determining the VN's position w.r.t. Relay ST, that is, how many hops is it away from the Relay ST.

- Synchronization of the node with its uplink successor. Here its assumed that synchronization is done similar to WiFiRe and hence details of the same have not been covered.

As described earlier relay ST is the one which accumulates the traffic from/to the sub-system and forwards it to the BS/village node. It thus acts as the central point for the sub-system. During setup it is required to perform the following initializations at the relay ST.

- A unique identifier if the relay ST is newly installed.
- Initializing downlink successors.

6.2 Registration

As described in section 3.1, a good multihop architecture should be transparent to the underlying WiFiRe system. Hence the underlying WiFiRe system is not aware of the existence of the village nodes. Also to perform minimum modification to the existing WiFiRe, we continue to use the same generic MAC header and the MAC PDU format. It is the job of the relay STs to maintain the details about its respective village nodes. Hence every village node registers itself with the relay ST.

The detailed explanation for the registration process is given below.

1. Once the initial setup of the village node is done, it constructs Registration Request(RegR) PDU. The format of the RegR PDU is :

   <u>*Registration Request*</u>
   MAC generic Header: with type field=0xYY
   Village Node MAC Address: 6 byte

2. After construction of the Registration Request PDU, the VN waits for the transmission opportunity. The village node determines its transmission slot from the global schedule that it calculates from the beacon forwarded to it by the uplink successor. At its corresponding transmission slot it transmits the Registration Request PDU(RegR), which travels through one or more hops to reach to the Relay ST.

3. As the registration request travels through the multiple hops, at each hop the VN make a note of the Registration Request. Each intermediate node keeps track of the MAC address of the VN which generated the RegR and the downlink successor from which it received the request. This information is maintained in a table called *Outstanding Registration Request Table.*

4. Upon receiving the RegR PDU, the relay ST extracts the MAC address of the VN and assigns a unique 16-bit Village Node ID (VN ID) to the VN. It makes an entry into the *MAC address table*, which contains the MAC addresses and the corresponding VN IDs of all the VNs that come under the relay ST. Thus *MAC address table* maintains mapping between VN ID and the MAC address of the VN. VN ID is similar to the primary CID used by the WiFiRe system.

5. After making an entry in the MAC address table the relay ST constructs Registration Response (RegRe) PDU. The format of the RegRe PDU is.

Registration Response
MAC generic Header: with type field=0xYY
Village Node MAC Address: 6 byte
Village Node ID: 2 byte.

6. Once the RegRe PDU is constructed, Relay ST transmits it to the downlink successor from which it received the corresponding RegR PDU. Each intermediate VN upon receiving the RegRe PDU extracts the MAC address and the VN ID. It deletes the entry corresponding to the MAC address from the *Outstanding Registration Request Table.*

   To maintain forwarding information each VN has one *Reachability Table* which keeps track of all the nodes which are reachable through this node in the downlink direction and the corresponding next hop downlink successor. When a VN receives RegRe PDU, it makes an entry in the *Reachability Table.* The *Reachability Table* should contain following minimum information, <Village Node ID>,<Next Downlink Successor>. Village node ID is obtained from the RegRe and the Next Downlink Successor from the entry in the *Outstanding Registration Request Table.*

7. Registration phase completes when the RegRe message reaches to the VN which initiated the registration request. The village node extracts the VN ID which is used by the VN for any further communication with the Relay ST.

6.3 Call Establishment

Once the VN has registered itself with the relay ST, it can request for a call establishment. This phase can be termed as Call Establishment phase. In this phase the VN interested in establishing a VoIP call sends the request to the Relay ST. Relay ST forwards this request to the BS. For the BS it appears that as if the request has come from the relay ST. If the relay ST gets a positive response from the BS, then it forwards the positive connection establishment response to the VN. The detailed explanation of the connection establishment phase is given below.

1. A VN wishing to establish a VoIP connection sends a Service Addition Request (SAReq) to the relay ST. The SAReq PDU has the following format:

   Service Addition Request
   MAC generic Header: with type field=0xYY
   Village Node ID: 2 byte.

2. When the SAReq reaches to the relay ST, the relay ST constructs a Dynamic Service Addition Request with its own specification and sends it to the BS. If the relay

ST gets back the response, it creates a Service Addition Response (SARes) PDU, which has the following format:

Service Addition Response
MAC generic Header: with type field=0xYY
Village Node ID: 2 byte.
Data CID: 2 byte.

Village node ID is the ID of the VN that requested for the Call establishment. Data CID is the connection identifier returned by the BS, in response to the service addition request. This Data CID is used for the further VoIP packet exchanges.

3. After constructing the SARes relay ST transmits it to the corresponding VN. As this SARes travels through intermediate VNs, each node makes an entry in the *Forwarding Table*. Forwarding Table is used by the intermediated node to forward the VoIP packets of that connection to the appropriate downlink successor. The forwarding table at minimum should contain following entries, <Data CID>,<Next Downlink Successor>.

   When an intermediate VN receives SARes PDU, it extracts the destination VN ID from the PDU and determines the next downlink successor from the reachability table. Then it makes an entry in the Forwarding Table. There are two main reasons for maintaining Data CID and not the VN ID.

   - There might be more that one VoIP connections from the same VN. In this case, the only way to identify which packet belongs to which connection is through the Data CID, as Data CID is unique for every connection.
   - If we will maintain the forwarding information in terms of Data CID then there will be no need to perform any changes in the VoIP packets received from the primary WiFiRe system. The relay ST and all the intermediate VN will only require to forward the VoIP packets based on the Data CID. This reduces the processing delay at the node.

Thus for BS it appears that the call is initiated by the Relay ST. The Relay ST at a time can request only for one call establishment. Till the response for the same is not received or timeout occurs, relay ST cannot send another call establishment request to BS as there is no way to determine for which call request the response is received. Thus in case relay ST receives a request for call establishment when there is already one request under process then it enques the call establishment request and forwards it once the under process request is done.

6.4 Call Termination

This phase can also be termed as Connection Termination phase. In this phase the entity wishing to terminate the VoIP call can send the Service Deletion Request. The steps involved in Call Termination phase are:

1. A VN wishing to terminate the VoIP connection sends a Service Deletion Request(SDReq) PDU to Relay ST. The SDReq PDU has the following Structure:

   Service Deletion Request
   MAC Generic Header: with type field=0xYY
   Data CID: 2 bytes.

   Data CID is data connection ID for the connection that is being terminated.

2. When Relay ST receives SDReq, it constructs Dynamic Service Deletion Request and sends it to the BS. When the relay ST gets back the Dynamic Service Deletion Response(DSD-Resp) from BS, it constructs Service Deletion Response(SDRes), having following format:

   Service Deletion Response
   MAC Generic Header: with type field=0xYY
   Data CID: 2 bytes.
   Data CID is data connection ID for the connection being terminated.

3. As the SDRes Travels over a multiple hop path, all the intermediate nodes removes the entry for the corresponding connection from the *Forwarding Table*.

4. The BS may unilaterally decide to terminate a connection. In this case it simply sends a DSD-Req to the Relay ST. Relay ST constructs SDReq PDU and sends it to the the VN. VN responds to this message with SDRes to the Relay ST. Relay ST upon receiving the SDRes creates corresponding DSD-Res and sends it to the BS.

In this chapter we discussed various tasks involved in MH-WiFiRe MAC. The procedures and various messages involved are similar to WiFiRe MAC and hence will require minimal changes. Another important taks to be perfomed at MAC layer is scheduling of data slots. In the next chapter we present three scheduling techniques for the same.

Chapter 7

Scheduling in MHWiFiRe

In Chapter 5 and Chapter 6 we presented the MH-WiFiRe architecture and MH-WiFiRe MAC protocol respectively. Now this chapter will talk about Scheduling in MH-WiFiRe. All the VNs follow same Scheduling scheme so as to come up with a Global schedule. The MH-WiFiRe is a TDMA based system, where time is divided into frames and frames are divided into slots similar to WiFiRe. The job of scheduling algorithm is to decide which nodes can transmit in a given slot. The goals of a scheduling algorithm are:

- Meet the QoS requirements of the VoIP calls.
- Maximizing throughput by parallel transmission.
- Supporting maximum number of users/Calls.
- Less control overhead.

There are many scheduling schemes in the literature. The scheduling schemes mentioned here are influenced by 2P protocol[24]. According to 2P scheduling scheme any node at a given time can only be in two phase/mode, either Transmitting (Tx) or receiving (Rx). When one node is in Tx mode its neighbors are in Rx mode and vice-versa. Thus when relay ST is in Tx mode the Level1 VNs are in Rx mode and Level2 VNs are in Tx mode and so on. Thus all the VNs at even level are in the same mode as that of relay ST and VNs at odd levels are in opposite mode as shown in figure 7.

Thus the job of the scheduling algorithm is to schedule the mode of the relay ST for all the slots of the frame. The modes of the other VNs gets automatically fixed, as shown in figure 7. From here onwards whenever its mentioned schedule Tx or Rx mode/slot, it means schedule Tx or Rx mode/slot for relay ST. Modes of other VNs gets decided upon their position relative to the relay ST.

As described in chapter 5, the frame is partitioned into different phases, Activity Phase(AP), No activity phase(NAP) and Tx/Uplink Phase (UP). Relay ST can only be in Tx mode in UP and there cannot be any activity during NAP. Strictly speaking, in NAP there cannot be any activity at the relay ST, but its possible to have reception

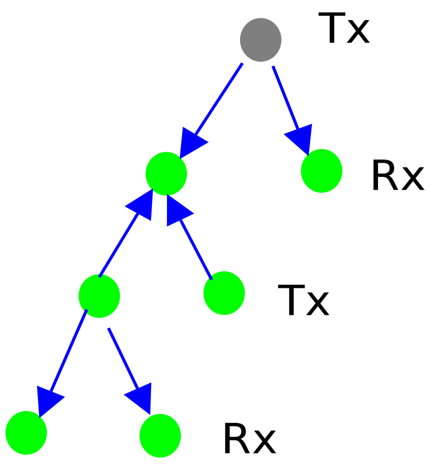

Figure 7.1: Relay ST in Tx mode

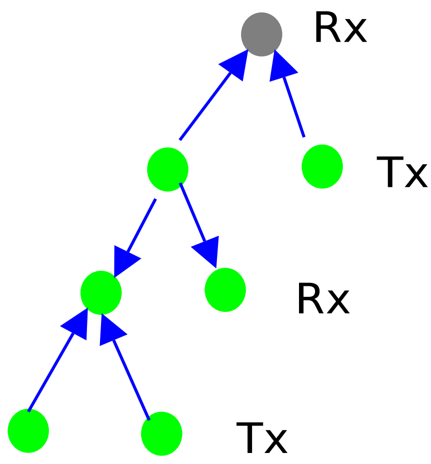

Figure 7.2: Relay ST in Rx mode

Figure 7.3: Applicability of 2P to MH-WiFiRe

and transmission at other VNs such that it do not interfere with the communication at the relay ST. But for simplification purpose, no activity is considered at other VNs also during NAP. Thus the job of scheduling algorithm reduces to schedule the slots in AP with a constraint that number of Tx slots are equal to Rx slots, that is, slot in the AP must be divided into TX and Rx mode such that we have equal number of Tx and Rx slots.

Let, AP_slots = The #slots in the AP.
UP_slots = The #slots in the UP.
Rx_slots = #slots in which relay ST is in Rx mode
Tx_slots = #slots in which relay ST is in Tx mode
Tx_slots_prime = #slots in Tx mode slots in AP

Now, the constraint is Tx_slot=Rx_slot and
Total slots with some activity = AP_slots+UP_slots
Thus, Rx_slots = Tx_slots=(AP_slots+UP_slots)/2
Tx_slots_prime = Tx_slots-UP_slots.

Reason for selecting a protocol similar to 2P :

- It is suitable for tree like structure, where graph is always going to be bi-partite.
- Maximum possible throughput as all the links are active at a given time, either in downlink direction or uplink direction.
- Equal number of transmission and reception opportunities at any node as required in case of VoIP traffic.
- Simple to implement.

7.1 Simple Scheduling Scheme

Before proceeding to the actual scheduling scheme lets first simplify the MH-WiFiRe frame structure to make the description and analysis of scheduling algorithm simple. The frame consists of three phase as show in step1 of the figure 7.4 but there is nothing to schedule in NAP and guard band. So as shown in figure 7.4 (step 2) we can simply ignore that part. Now without loss of generality we can assume that frame ends with UP (step 3) for the purpose of analysis. Next combine all the APs into one, thus only two parts are left now, UP and AP.(step4).

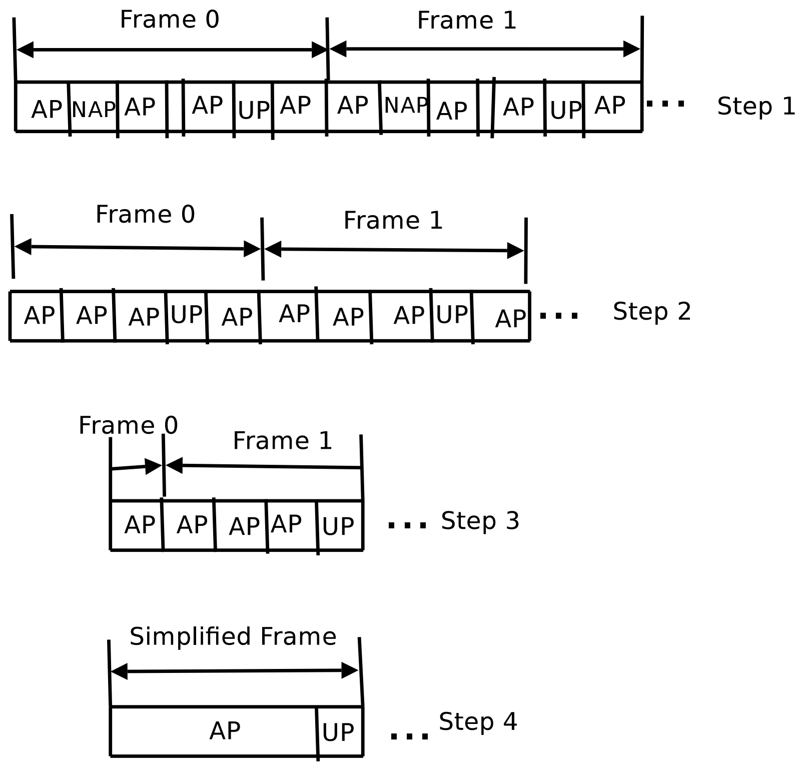

Figure 7.4: Simplified Frame for Analysis

The most simplistic scheduling scheme will be to schedule all the Rx_slot followed by Tx_slots. Thus first Rx_slots in AP will be in Rx mode and remaining Tx_slots_prime will be in Tx mode. All the slots in UP will be in Tx mode. This is shown in figure 7.5.

Thus in a simple scheduling scheme we have Rx slots followed by Tx slots in a frame. Lets call it as cycle. Cycle is defined as:

A group of consecutive slots, which contains one or more Tx slots followed by one or more Rx slots or vice-versa.

The significance of cycle is that a packet is expected to move by two hops in one cycle as shown in figure 7.6. In worst case the VoIP packet of every connection should at least move by ONE hop, assuming every connection has given a slot in a cycle.

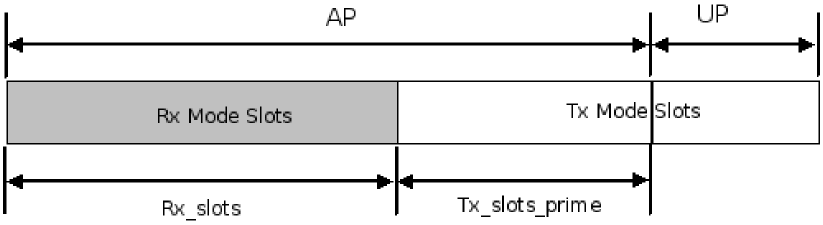

Figure 7.5: Simple Scheduling Policy

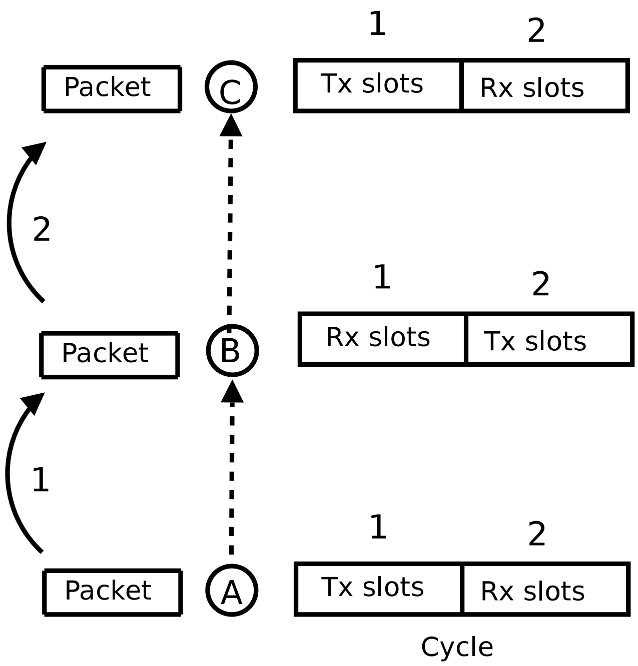

Figure 7.6: Significance of cycle

Thus in case of simple scheduling scheme, every VoIP packet will experience a delay of one frame time at every hop. The frame time of MH-WiFiRe is same as WiFiRe and till now its assumed to be 10msec. Also the slot time considered in 32μ Sec. Both the frame time and the slot time are not fixed in WiFiRe. It depends on the type of Codec. Only constraint is that every VoIP connection gets a slot at regular interval which is less than or equal to the interval at which the VoIP packets are generated.

7.1.1 Terms and Definitions

Before moving ahead with the analysis of scheduling scheme, lets define few terms and relationships that are used for the analysis.

- Frame Parameters:
  - Transmission Rate: Its the bit-rate at which the data is transmitted. For eg. for 802.11b it can 11Mbps to 1Mbps

  - Frame Size: The duration of the Frame, it will be usually expressed in msec.
  - Slot Time: The duration of one Slot and is expressed in μ Sec.
  - Frame Overhead: These are the number of Overhead slots in a frame. It includes Beacon Phase and Guard Band.

- VoIP Parameters:
  - Codec: An audio codec is a hardware device or a computer program that compresses/decompresses digital audio data according to a given audio file format or streaming audio format. The term codec is a combination of 'coder-decoder'. The object of a codec algorithm is to represent the high-fidelity audio signal with minimum number of bits while retaining the quality. Here only software codecs are referred.[5]
  - VoIP Periodicity: The periodicity at which the VoIP packets are generated.
  - Tolerable VoIP Delay: Its the maximum End-to-End delay that a VoIP packet can experience so as to get an acceptable VoIP quality. Its usually 150-200 msec.
  - VoIP Packet Size: The size of the VoIP packet generated. (In bytes)
  - Coder Delay: Coder delay is the time taken by the digital signal processor (DSP) to compress a block of PCM samples. This is also called processing delay .
  - Packetization Delay: Packetization delay is the time taken to fill a packet payload with encoded/compressed speech.[6]
  - VoIP Delay: End-to-End delay experienced by the VoIP packet. It includes Fix delay + Variable Delay. The components that contributes to fix delay are, Coder Delay, Packetization Delay and Network Delay. The Variable component includes the queing delay that a packet experiences in the MH-WiFiRe system.

The frame size depends on the VoIP Periodicity. Assuming every VoIP call gets only one slot in a frame, the size of frame should be less than or equal to VoIP periodicity. One slot carries one VoIP packet, hence duration of the slots depends on the transmission rate and VoIP packet size.

7.1.2 Analysis

In this section we will analyze the Scheduling scheme for different codecs. The details of the different codecs are given in Table 7.1.[6][7]

For any scheduling scheme its important that it meets the End-to-end delay requirements of the VoIP call and is able to support maximum number of simultaneous calls.

Table 7.1: Details of different Codec

Codec & Bit Rate	Voice Payload Size	Packet generation Interval	Coder Delay	Packetization Delay
G.711 (64 Kbps)	160 Bytes	20 ms	10 ms	20 ms
G.729 (8 Kbps)	20 Bytes	20 ms	10 ms	20 ms
G.723.1 (6.3 Kbps)	24 Bytes	30 ms	20 ms	24 ms
G.723.1 (5.3 Kbps)	20 Bytes	30 ms	20 ms	30 ms
G.726 (24 Kbps)	60 Bytes	20 ms	10 ms	20 ms
G.728 (16 Kbps)	60 Bytes	30 ms	-	-

Every packet experiences a delay of one frame size at every node. Thus end-to-end delay experienced by a packet is function of Frame size and number of Hops. Similarly number of simultaneous VoIP calls will depend on the number of slots available for the transmission. Figure 7.7 shows relationship between delay and number of hops for different codecs. Here we have ignored the propogation delay, as it is negligible compared to other delays. The delay experienced is linearly related to the number of hops. The increase in the delay at every hop depends on the frame size. The frame size here is equal to the packet generation interval, with every connection getting one slot in every frame. We see that, codecs G.711, G.729 and G.726 experience same delay (20 msec per hop) as all the three codecs have equal coder delay, packetization delay and packet generation interval. Whereas in case of other three codecs, delay increases more rapidly, 10msec more at every hop, due difference in the frame size.

For a acceptable VoIP call quality, the delay experienced by VoIP packet should be less than tolerable VoIP delay. Hence maximum number of hops gets limited by the Tolerable VoIP delay. Figure 7.8 shows maximum number of hops possible for different codecs for different Tolerable VoIP delay. According to the IETF standard, tolerable end-to-end VoIP delay should not be more than 150 ms. Figure 7.8 show that for 150 ms of Tolerable VoIP delay some codecs are not even able to support more than 1 hop, beating the purpose of multi-hop. Hence its required to come up with some scheme to reduce the queing delay and increase the maximum number of hops possible.

The other important parameter is maximum number of Simultaneous calls possible for different codecs. This is with an assumption that all the calls are from Secondary system and there is no call from the Primary ST. This is shown in Figure 7.9. We see

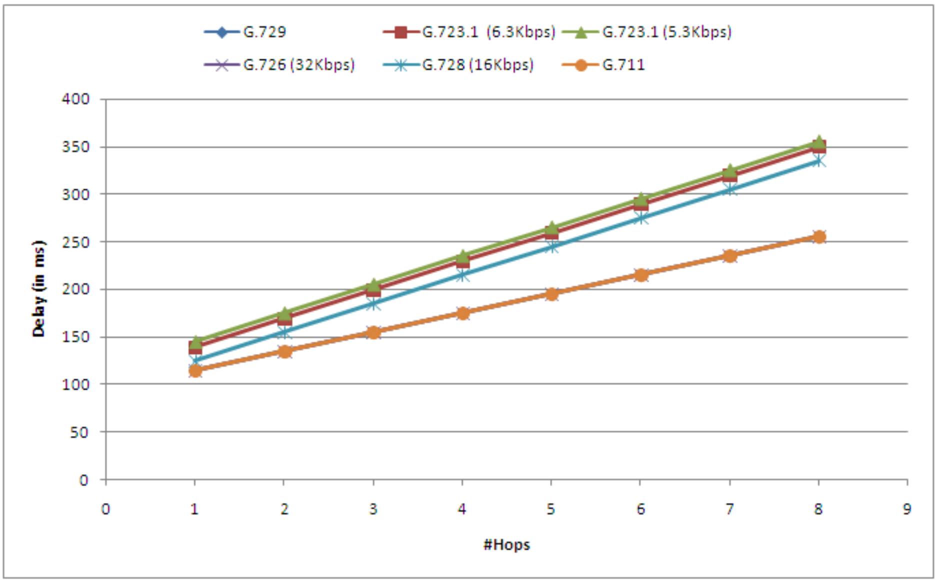

Figure 7.7: Delay experienced in Simple scheduling w.r.t Hops

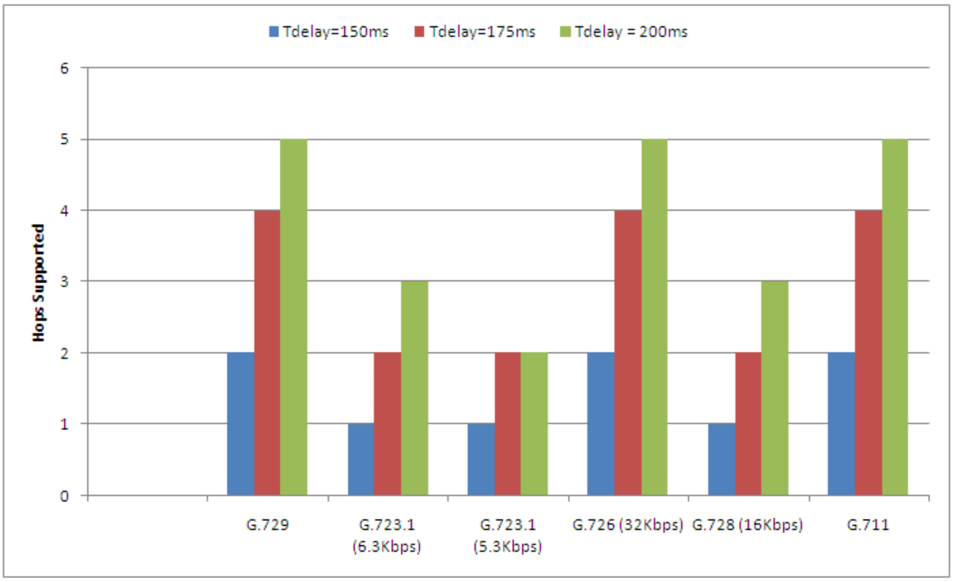

Figure 7.8: Number of Hops supported by different codec for different Tolerable Delays

that number of simultaneous calls supported by most of the codecs are more than 5 per villages, assuming there are 27 villages in the extended system, but the number of hops supported are very less. For example, both the G.723.1 codecs are able to support more than 7 calls per village, but with only 1 hop. Whereas, codecs G.726 and G.711 are able to support two hops but with 1 or 2 calls per village. Thus a scheme is required which will allow trade-off between max number of hops and simultaneous calls. There are two such schemes described in the next section.

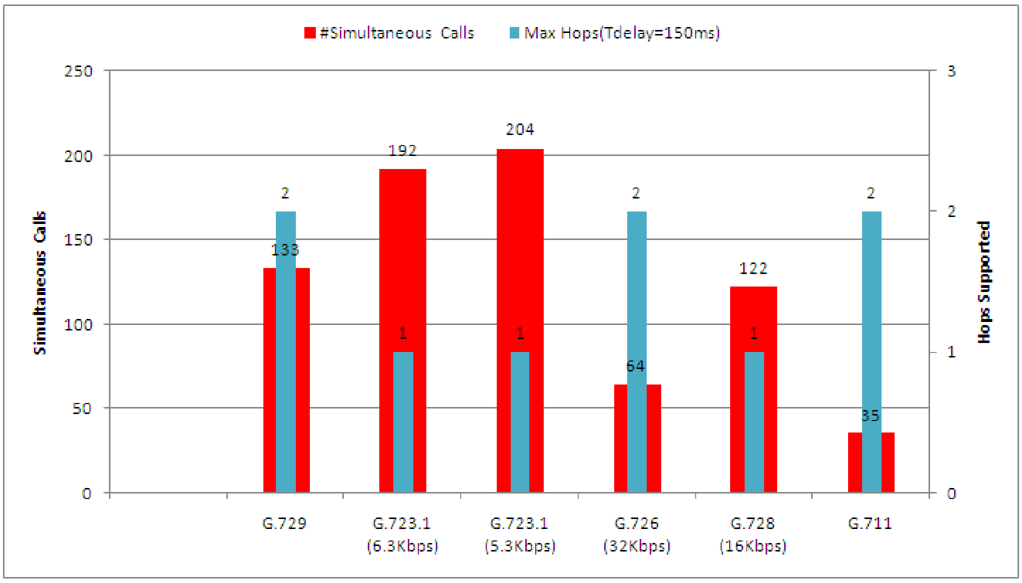

Figure 7.9: Simultaneous Calls and hops supported by different codecs

7.2 Other Scheduling Schemes

This section describes two scheduling schemes which allow us to perform trade-off between max number of hops and Simultaneous calls. The first scheme requires changes in the Frame size of the primary WiFiRe frame whereas in second scheme, changes are restricted to only secondary Frame.

7.2.1 Scheduling using Sub-frame

This scheme requires changes in the Frame size of the Primary WiFiRe. The queing delay experienced by a packet at every hop is equal to one frame size. Thus queing delay can be reduce by reducing the frame size itself (Assuming every VoIP call gets one slot in a frame). This will reduce the number of slots in a frame and hence will decrease the number of calls possible. But queing delay will decrease, supporting more number of hops. Example of this is show in Figure 7.10 where a given frame is divided into two frames.

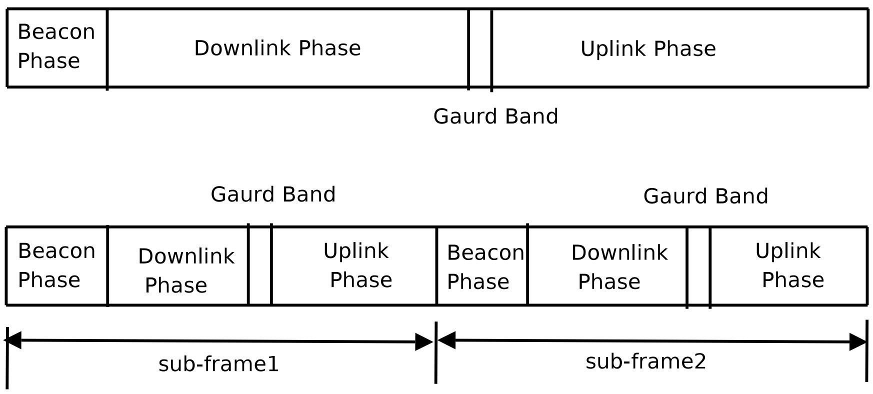

Figure 7.10: Division of frame to sub-frames

7.2.2 Scheduling using Cycle

This scheme do not require any changes in the primary WiFiRe frame. This scheme also reduces queing delay to decrease the overall end-to-end delay and hence support more number of hops. But in this scheme instead of reducing the Primary WiFiRe frame size, the MH-WiFiRe frame is divided into more number of cycles, instead of dividing it into only one cycle as done by the simple scheduling scheme. Thus instead of having all Rx slots followed by Tx slots in a frame, we have more such cycles of Rx-Tx, with every VoIP call getting one slot in every cycle. Figure 7.11 gives an example with two cycles. Every cycle involves two Tx-Rx switching overheads which is not more than 2-3 slots.

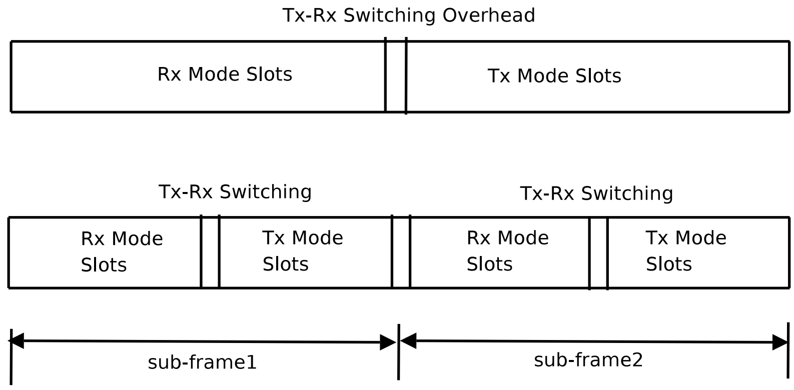

Figure 7.11: Division of frame to Cycle

In the next two subsections we performs comparison of two schemes. First, some graphical results are given to compare the two schemes, followed by a qualitative analysis.

7.2.3 Graphical Analysis

This section gives how Max number of hops supported and Simultaneous Calls possible varies with number of cycles/frames for three different codecs. Figures 7.12 7.13 gives this analysis for G.729 Codec and G.728 codec resepectively. As expected, with the increase in the number of Sub-frames and Cycles, Max number of hops that can be supported increases at the cost of decrease in the Simultaneous Calls. For example for G.729 (Figure 7.12), with six cycles/sub-frame in one primary WiFiRe frame, the number of hops increases to 18 for sub-frame and to 12 for cycle scheme. Whereas number of calls decreases to 11 for sub-frame and to 23 for cycle scheme.

Now one should select a scheme which is able to support maximum number of Simultaneous calls for the required number of Maximum hops support. Now typically for most of the practical purposes 3-4 hops are enough for the tree architecture to cover the required area. Considering this, for G.729 its better to use cycle scheme. For G.728 both the schemes perform equally. Figure 7.14 shows same analysis for G.723.1(6.3 Kbps) codec.

Here we see that its better to use sub-frame scheme as it provides more number of simultaneous calls for a given maximum number of hops. Assuming we need to support 4 hop architecture, the Table 7.2 gives Simultaneous calls supported by different codecs. This allows us to select the proper scheme. For a particular number of cycles/sub-frames, the sub-frame scheme supports more number of hops than cycle scheme, but at the same time supports less number of simultaneous calls than cycle scheme. For example, in case of G.729 for 3 cycles/sub-frames, cycle scheme supports 50 simultaneous calls whereas sub-frame supports only 33. But this has got no significance as what matters is end-to-end delay and not number of cycles or sub-frames.

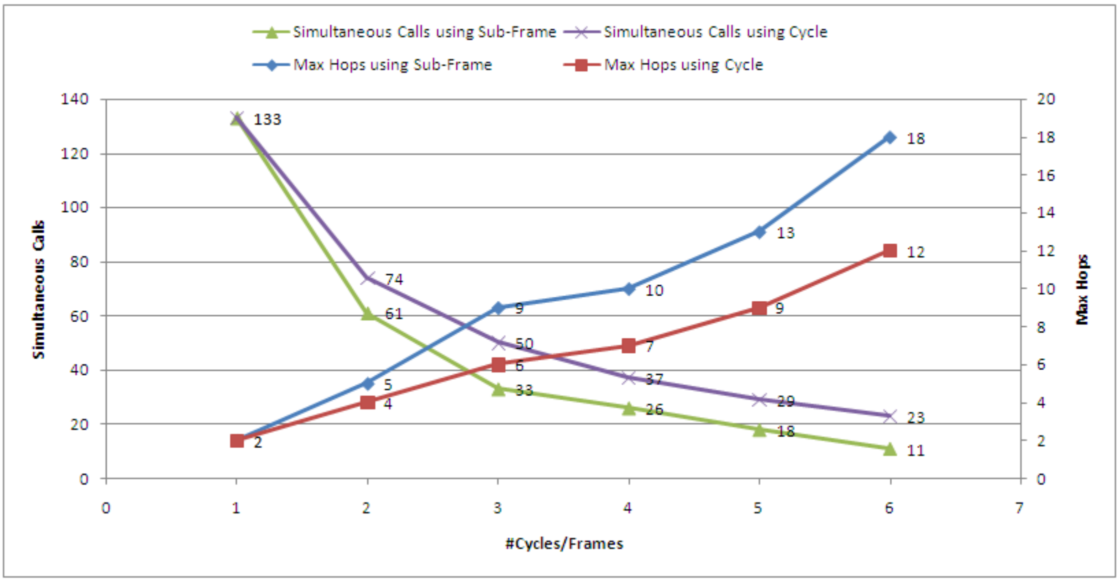

Figure 7.12: Performance of Sub-frame and Cycle scheme using G.729

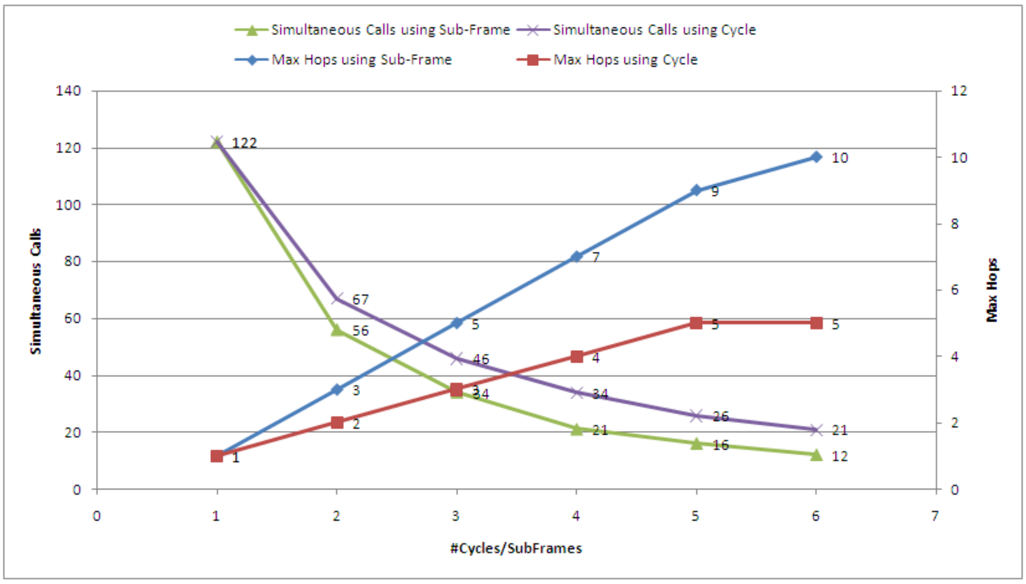

Figure 7.13: Performance of Sub-frame and Cycle scheme using G.728

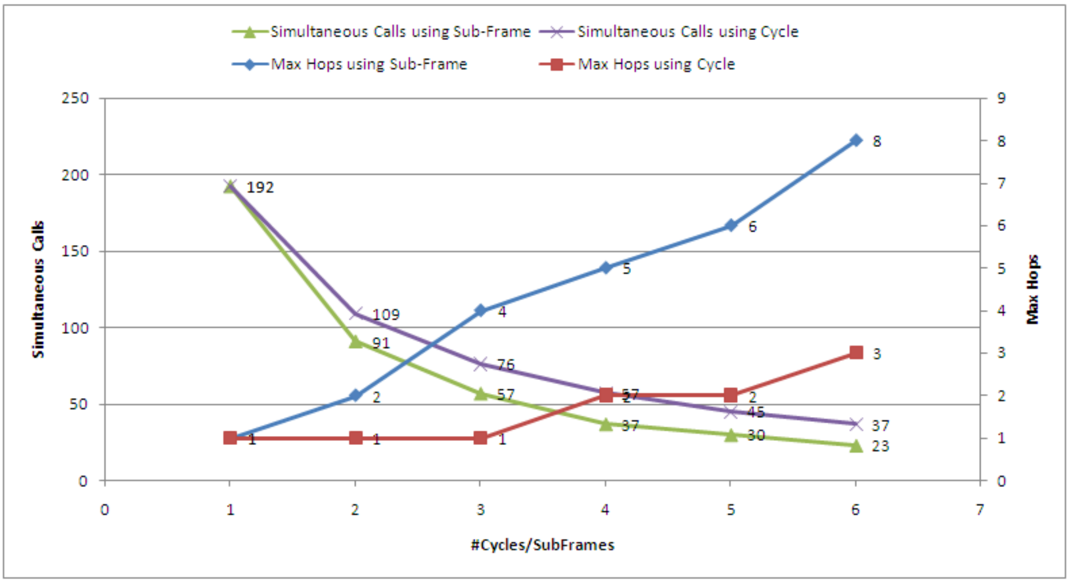

Figure 7.14: Performance of Sub-frame and Cycle scheme using G.723.1(6.3Kbps)

Table 7.2: Comparison of Cycle and Sub-frame scheme for different codecs

Codec	Hops Supported		Simultaneous Calls		Number of	
	Sub-frame	Cycle	Sub-frame	Cycle	Sub-frames	Cycles
G.711 (64 Kbps)	5	4	12	15	2	2
G.729 (8 Kbps)	5	4	61	74	2	2
G.723.1 (6.3Kbps)	4	-	57	-	3	-
G.723.1 (5.3Kbps)	4	-	40	-	4	-
G.726 (24 Kbps)	5	4	27	32	2	2
G.728 (16 Kbps)	5	4	34	34	3	4

The above analysis of the scheduling schemes shows that, both the schemes are equally good and the scheme to use largely depends on codec and other requirements like maximum required hops and calls per villages to be supported. But the comparative analysis of the two scheduling schemes that we have presented till now assumes that there are no calls from the Primary system. But in practice certain fraction of slots will be occupied by the calls from the STs present in the Primary sector. The calls from the primary system will increase the downlink period of the sector and hence will increase the No Activity Phase (NAP) of the secondary system. As a result number of slots available in the Activity phase will decrease, resulting into decrease in the number of calls.

Figure 7.15 shows, the effect of calls from the Primary system on number of calls possible from secondary system for both the scheduling schemes with G.729 codec and two calls and two subframes. As expected, number of calls supported from secondary system decreases for both the schemes. But decrease in case of subframe scheme is more steep as compared to cycle scheme. We see that, approximately for every 0.1 fraction of slot occupation by Primary calls, number of calls supported from Secondary system decreases by 14 in case of subframe scheme and decreases by 8 in case of Cycle scheme.

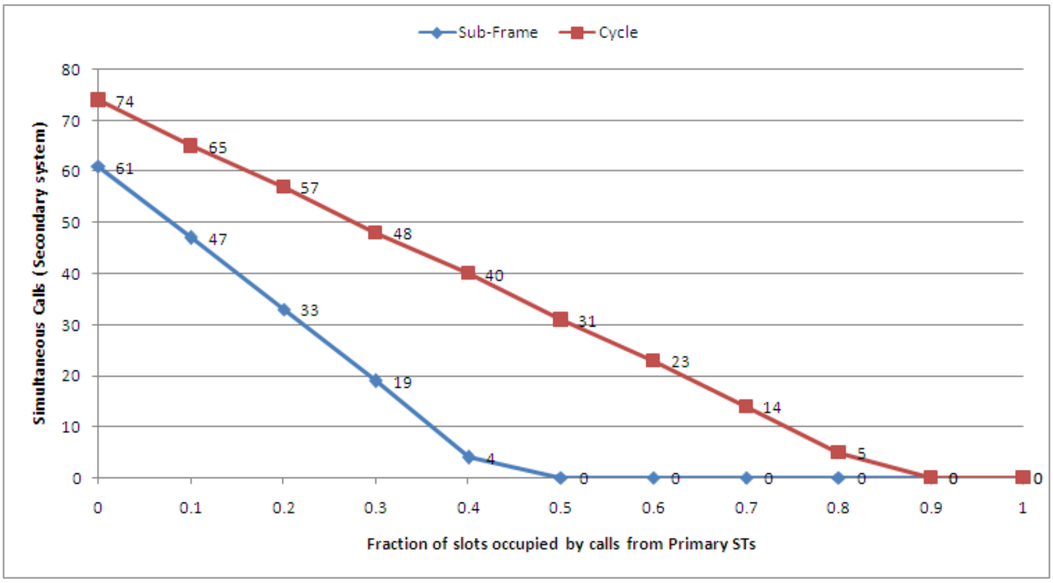

Figure 7.15: Calls from Secondary system w.r.t. fraction of slots occupied by Primary system

On the similar line, Figure 7.16 shows, the effect of number of Cycles/Subframe on calls from secondary system for both the scheduling schemes with G.728 codec. The number in the parentheses indicates the fraction of slots used by the calls from the primary system. We observe that calls supported from secondary system by sub-frame scheduling scheme decreases rapidly to zero with increase in number of sub-frames. Typically assuming uniform distribution of villages, we can expect 0.4 fraction of slots to be occupied by the calls from the STs of the primary system. Now from Figure 7.16, we can observe that for 0.4 fraction of slots for primary system, the number of simultaneous calls decreases from 69 to 3 for sub-frame scheme, whereas for cycle scheme it decreases to 36 calls. Thus there is 95% decrease in simultaneous calls for sub-frame scheme and 47% decrease for cycle scheme. Even though the decrease in case of cycle scheme is also significant, but still its able to support 1.3 calls per village.

Table 7.3 shows similar analysis as done in Table 7.2 for 4 hop tree, with an assumption that 40% of the slots are occpuied by the calls from the primary system. We can see that cycle scheme clearly outperforms sub-frame scheme, sub-frame scheme not even able to support a single call for four of the codecs.

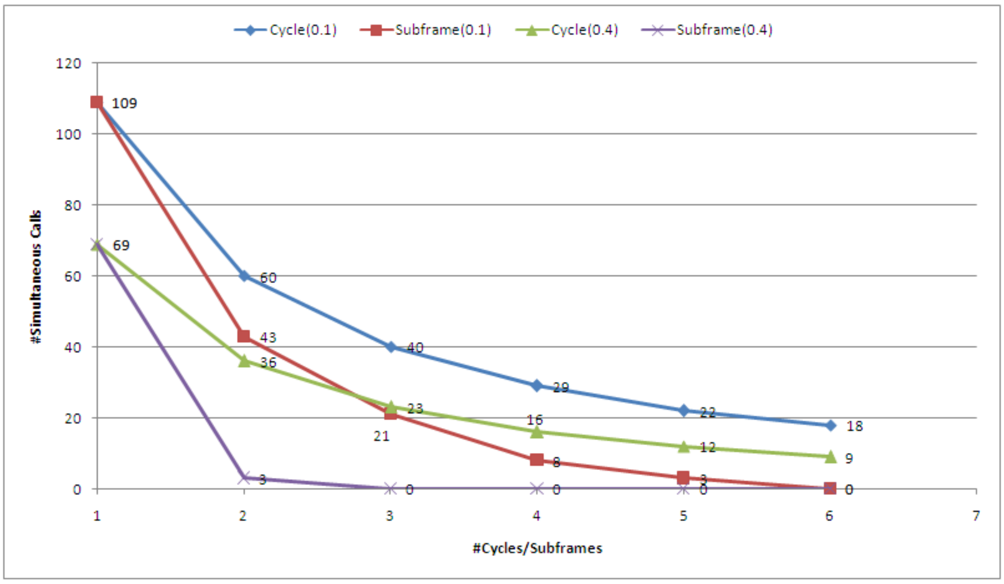

Figure 7.16: Calls from Secondary system w.r.t. number of Cycles/Subframes

The sharp decrease in case of sub-frame happens because, in case of cycle, NAP is present only once for every VoIP interval, whereas its repeated in every subframe for sub-frame scheduling. This is because, in case of sub-frame scheduling even the calls from the primary STs gets scheduled in every subframe. But there is no need to schedule these calls in every subframe as STs in the primary system are only one hop away from BS and hence do not experience huge delays. To avoid this from happening we need a complex scheduling scheme which will make sure that slots to Primary STs are allotted after proper interval. Using simple sub-frame scheduling scheme which allocates slots in every sub-frame to both Primary STs as well as Secondary VNs will make the sub-frame scheduling scheme ineffective.

7.2.4 Qualitative Analysis

Here we give qualitative pros and cons of the two schemes

- Sub-frame scheme requires changes in the primary WiFiRe frame, whereas in cycle scheme changes are done only in secondary MH-WiFire frame.
- Sub-frame scheme involves more overhead slots than cycle as every frame will have beacon phase, Guard band and also the downlink phase which corresponds to the NAP in MH-WiFiRe. Whereas in case of Cycle, the only overhead involve in Tx-Rx switching overhead which is typically not more than 2-3 slots.
- Delay is less in case of sub-frame as the hop from relay ST to BS also involves less delay. But in case of Cycle, delay in this hop is equal to the original WiFiRe frame size.

Table 7.3: Comparison of Cycle and Sub-frame schemes with 0.4 fraction of slots allotted to Primary system

Codec	Hops Supported		Simultaneous Calls		Number of	
	Sub-frame	Cycle	Sub-frame	Cycle	Sub-frames	Cycles
G.711 (64 Kbps)	5	4	0	4	2	2
G.729 (8 Kbps)	5	4	4	40	2	2
G.723.1 (6.3Kbps)	4	-	10	-	3	-
G.723.1 (5.3Kbps)	4	-	0	-	4	-
G.726 (24 Kbps)	5	4	0	15	2	2
G.728 (16 Kbps)	5	4	0	16	3	4

- Sub-frame mechanism is less flexible, suppose there is multi-hop extension in more than one sector then the frame size will get decided by the worst of two and hence may not be optimum for the other multi-hop extension. Whereas in case of cycle where changes are made only in secondary system, we can have different sizes of cycles for two multi-hop extensions.

- Simple Sub-frame scheme supports very less number of calls for more than one sub-frames when we have calls from primary system, making it less effective.

Thus which scheduling scheme to use depends on various factors like:

- Number of simultaneous calls supported for the required number of hops. This depends on the type of codec used and fraction of slots used by the calls from the primary system.

- Required Flexibility. Cycle architecture provides more flexibility as it allows to have different lengths of cycle for different multi-hop extensions. But this is not possible with the sub-frame scheme.

- Feasibility of changes in the Primary WiFiRe frame as sub-frame scheme requires changes in the size of the primary WiFiRe frame.

Chapter 8

Conclusions and Future Work

8.1 Conclusions

802.11 is a cost effective solution for providing connectivity in rural regions. WiFiRe is an attempt towards providing broadband Internet connectivity in rural area. But due to its single hop nature it suffers from drawbacks like line of sight requirement and fixed range. In this thesis we present architecture for multi-hop extension to WiFiRe and show that it is possible to support QoS required for VoIP traffic over multi-hop WiFiRe architecture. We explored various architectures for multi-hop extension and then selected Tree topology based architecture due to its suitability to our scenario, cost effectiveness and support for sufficient number of VoIP calls per village.

The architecture can easily support 2-3 hops typically required to extend the coverage area by 5-8 kms at an additional approx. cost of U.S.$ 550 per village. We have given detailed description of the MAC protocol for multi-hop WiFiRe, which includes design of MAC level frame structure and description of the various procedures required to accomplish the MAC level tasks. The MAC protocol is TDMA based and is similar to 2P. Further we have presented three different scheduling schemes, Simple scheduling scheme, Sub-frame based scheduling scheme and Cycle based scheduling scheme. Then we have compared them under different dimensions and scenarios. Unlike, simple scheduling scheme, sub-frame and cycle schemes allow to perform trade-off between number of simultaneous calls and maximum hops supported and perform equally well in a scenario where we have no calls from primary STs. But as the fraction of calls increases from the primary system, the cycle scheme outperforms sub-frame scheme.

For G.729 codec and 4-hop architecture, our MH-WiFiRe system supports 74 simultaneous calls, that is nearly 3 calls per village assuming 25 villages in the secondary system and no calls from the primary system. Considering more realistic situation, where 40% of the slots are used by calls from the secondary system, the MH-WiFiRe system supports 40 simultaneous calls that is 1.6 calls per village. This number appears small, but considering expected traffic from rural region this is sufficient. Also presently the calculations are done for 802.11b with 11Mbps data rate. If we use 802.11g or any other 802.11x having higher data rate then our architecture will support more number of calls. Thus our MH-WiFiRe architecture do not require any significant change in the underlying WiFiRe and can overcome limitations of WiFiRe, by providing required extension to the coverage and supports sufficient capacity required in case of rural scenario.

8.2 Future Work

- Supporting other types of flows:
  Presently architecture supports only VoIP traffic, which is an example of Unsolicited Grants Service (UGS). It needs to be extended to support other types of flows like real-time Polling Service (rtPS), non-real-time Polling Service (nrtPS) and Best-Effort services (BES).

- Transmission Power assignment problem:
  We have not considered power assignment problem in our thesis. We assume proper assignment of transmission power at every node required for successful transmission. The power assignment is an important constraint and can affect the structure of the topology.

- Scheduling based on Interference Matrix:
  Presently our system assumes Round Robin (RR) scheduling of primary WiFiRe sectors. More proper and efficient way of scheduling transmission of STs in primary WiFiRe is using Interference Matrix. We have designed the MH-WiFiRe frame structure w.r.t. the RR scheduling scheme. This will need some modification if the underlying WiFiRe schedules STs using Interference Matrix.

- Error handling:
  Presently our systems assumes robustness and hence errors like link failure or node failure are not handled. But in practice these errors will be encountered hence we need to design mechanism to handle these failures.

- Implementation of the Protocol:
  This is the most important next step in the project. In this thesis, we have presented the architecture and design of MH-WiFiRe system and have evaluated its performance using software tool developed by us. The next step in this direction would be to actually implement the MH-WiFiRe system over a hardware.

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