Implementation of WiFiRe Model in OPNET

A WiMAX-like MAC over WiFi PHY

Dissertation

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by

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Dissertation Approval Sheet

This is to certify that the dissertation entitled

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A WiMAX-like MAC over WiFi PHY

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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. Anirudha Bodhankar** 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 2004)	
1.	IT601	Mobile Computing	6
2.	HS699	Communication and Presentation Skills (P/NP)	4
3.	IT603	Data Base Management Systems	6
4.	IT619	IT Foundation Laboratory	10
5.	IT623	Foundation course of IT - Part II	6
6.	IT694	Seminar	4
		Semester 2 (Jan – Apr 2005)	
7.	CS686	Object Oriented Systems	6
8.	EE701	Introduction to MEMS (Institute Elective)	6
9.	IT610	Quality of Service in Networks	6
10.	IT628	Data Mining	6
11.	IT680	Systems Lab.	6
		Semester 3 (Jul – Nov 2005)	
12.	CS601	Algorithms and Complexity (Audit)	-
13.	CS681	Performance Evaluation of Computer Systems and Networks	6
		M.Tech. Project	
14.	IT696	M.Tech. Project Stage - I (Jul 2005)	18
15.	IT697	M.Tech. Project Stage - II (Jan 2006)	30
16.	IT698	M.Tech. Project Stage - III (Jul 2006)	42

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Abstract

The 802.11(WiFi) family of wireless communication is extremely popular for indoor wireless networking. The chipsets are designed so that PHY and MAC layers are separate and they are available off-the-shelf at low cost. Also it operates in 2.5GHz ISM band which is license free spectrum avoiding licensing cost, hence is an attractive option for long range communication in rural areas of developing countries.

However many problem occur when using 802.11 for outdoor long range (15-20 Km) communication. The DCF mode does not support any quality of service, while PCF is not suitable for large number of stations and long distance. The MAC is based on CSMA/CA and is not efficient when the number of stations increases. Hence it is necessary to redesign MAC while retaining the PHY. One approach for this is WiFiRe

WiFiRe replaces the MAC of 802.11 with the MAC similar to that of 802.16 MAC which is suitable for long range communication. It also uses directional antennas and is meant for a star topology. WiFiRe MAC at the Base Station is multi-sector MAC which controls more than one 802.11 directional PHY.

The goal of this project is to implement the WiFiRe model in OPNET and analyse its performance. The code developed is to be such that, it can be easily extended to a real implementation.

Contents

List of Figures

Chapter 1

Introduction

1.1 Background

Deploying cellular networks or wired networks in rural areas in India is not a feasible solution because high cost of deployment. So the option that WiFiRe [2] proposes is the 802.11 family of wireless technologies. This is possible because of structure of Indian rural area, where there are very few high rise buildings in the terrain for several kilometres. With widespread acceptance of the technology, open/inter-operable standard, and competitive mass production, the equipment and chip sets are inexpensive. But, it has been found that the IEEE 802.11b MAC layer is not suitable for long-range outdoor communication network, especially for voice traffic. The DCF (Distributed Coordination Function) mechanism in 802.11b MAC layer does not provide any delay guarantees, while the PCF(Point Coordination Function) mechanism becomes inefficient with increase in number of stations and distance. In addition to this, in order to operate over long distances, the 802.11b MAC would require significantly longer slot times, further reducing its efficiency. WiFiRe employs a mechanism similar to the IEEE 802.16 MAC layer.

1.2 WiFiRe Approach

The main design goal of WiFiRe[2] is to enable the development of low-cost hardware and network operations for outdoor communications in a rural area. This is possible because:

- WiFiRe system avoids frequency licensing costs by operating in the unlicensed 2.4 GHz frequency band
- WiFiRe uses the IEEE 802.11b PHY for its physical layer, due to the low cost and

easy availability of IEEE 802.11b PHY chipsets.

WiFiRe employs the DSSS based IEEE 802.11b PHY layer as the physical layer module for RF control. This 802.11b PHY system is for operation in the 2.4 GHz band and designed for a wireless LAN with 1 Mbps, 2 Mbps and 11 Mbps data payload communication capability. The PHY has a processing gain of at least 10 dB and uses different baseband modulations to provide the various data rates. The typical transmission reach of this 802.11b PHY is 300 meters. However, WiFiRe extends the transmission range to 15-20 Kilometres, by using

- A deployment strategy based on sectorized/directional antennas
- MAC based on IEEE 802.16 MAC layer

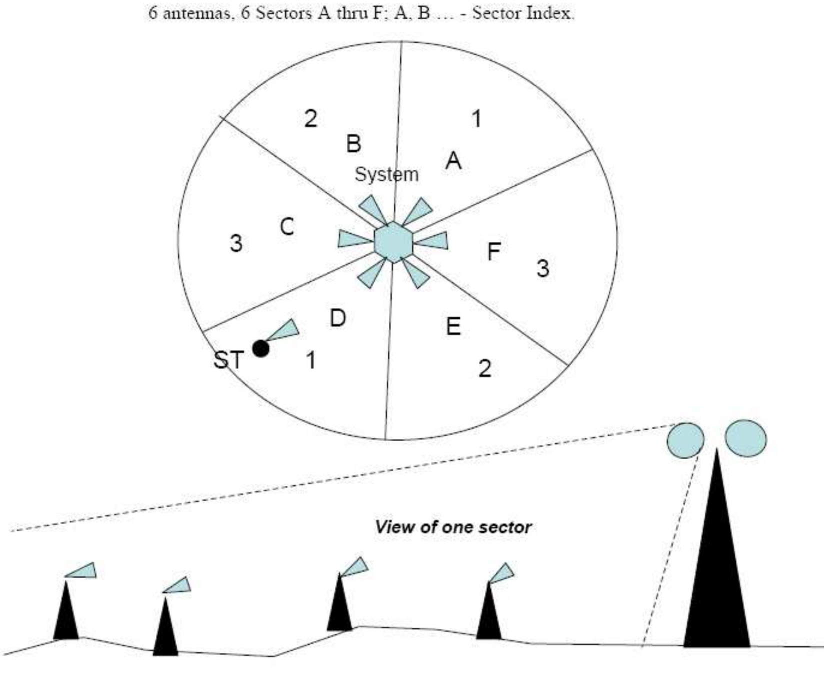

Figure 1.1: WiFiRe Network Topology

In order to operate in outdoors with a reach of 15 to 20 Kilometres, using the DSSS based 802.11b PHY, WiFiRe recommends a star network topology using directional antennas with a) appropriate transmission power b) adequate height of transmitter and receiver for Line of Sight (LoS) connectivity. Figure 1.1 depicts the use of directional antennas. The system consist of a set of directional antennas mounted on a transmission tower. Such a configuration would increase the reach of the 802.11b PHY to an outdoor rural scenario.

1.3 Problem Definition

1. Understand functioning of WiFiRe protocol and its performance.
2. Develop simulation model which can be be used preliminary to the implementation.

1.4 Solution Strategy

1. Build a simulation model in OPNET.
2. Perform Experiments.

1.5 Contributions of this Project

The significant contributions of this work are:

1. Developing simulation model of WiFiRe in OPNET
2. Performing preliminary performance study
3. First step towards implementation of WiFiRe : It helped in identifying some protocol deficiencies in earlier drafts of the WiFiRe.
4. Minor improvements in the scheduling strategy

Chapter 2

Literature Survey

2.1 802.11b (Wi-Fi)

An overview of the IEEE 802.11b Wireless Lan (Wi-Fi) is presented in the following section. The description reflects the various significant aspects of the standard's PHY and MAC layers.

2.1.1 MAC Layer

The 802.11 MAC, popularly known as WiFi provides two basic forms of channel access: Distributed Coordination Function (DCF), and Point Coordination Function (PCF). DCF is the most commonly used channel access mechanism which uses the Carrier Sense Multiple Access with collision avoidance (CSMA/CA) primitives. PCF is the centralised channel arbitration method based on polling approach. DCF is mandatory part of the standard, while PCF is optional.

In DCF method, each station senses the channel for a fixed duration called Distributed InterFrame Space (DIFS). If the channel is idle for DIFS, then a random back-off value is selected. The back-off value is decremented by one in each slot till the channel continues to remain idle. Each station independently selects the back-off value from a range, Congestion Window (0,CW-1). When the back-off reaches zero the station starts transmission of data. For stations whose back-off count has not reached zero, the countdown is frozen and they go into carrier sense phase waiting for the channel to be idle again for DIFS duration. After DIFS, the station which has had a successful transmission chooses a new random back-off value, while the others continue from the back-off value which was frozen earlier. For each data packet transmitted, the destination sends a positive acknowledgement at the MAC layer, after waiting for Short InterFrame Space (SIFS) duration. The duration of SIFS is shorter than DIFS. It is possible that the back-off counter reaches zero for more that two stations at the same time, resulting in collision of data. Absence of acknowledgement is used to detect collisions. In this case, the stations which are involved in the collision increase the range of Congestion Window using binary exponential back-off procedure. The minimum value of CW is CWmin for the first attempt. In subsequent attempts after collision, CW is doubled till it reaches CWmax.

The above mechanism of DCF is the basic DATA-ACK transmission of data. To avoid collisions due to hidden nodes and exposed nodes in the network, the procedure is extended by inclusion of a Request to Send (RTS) and Clear to Send (CTS) packets for a RTS-CTS-DATA-ACK communication. This is also known as Virtual Carrier Sense. RTS is sent by the transmitting node, and if the receiving node is willing to receive the data, it replies with a CTS packet. There is waiting period of SIFS between each packet to allow the transceivers at the stations to switch from transmitting mode to receiving mode and vice-versa. Both the RTS and CTS packets contain expected duration of the data transfer. All nodes which overhear the RTS and CTS packets remain idle for the duration of the data transfer, hence allowing data packets to be transmitted without collisions.

2.1.2 Physical Layer

Depending on the current infrastructure and the distance between the sender and receiver 802.11b system offers 11, 5.5 , 2 or 1 Mbit/s. Maximum user data rate is approximately 6 Mbit/s. The lower data rates 1 and 2 Mbit/s use the 11 bit Barker sequence and DBPSK or DQPSK, respectively. The new data rates 5.5 and 11 Mbit/s, use 8-chip complementary code keying (CCK).

The standard defines several packet formats for the physical layer. The mandatory format interoperates with the original versions of 802.11. The optional versions provide a more efficient data transfer due to shorter headers/different coding schemes and can co-exist with other 802.11 versions. However, the standard states that control all frames shall be transmitted at one of the basic rates, so they will be understood by all stations in BSs

2.2 Overview of 802.16

An overview of the IEEE 802.16 Wireless MAN air interface is presented in the following section. The description reflects the various significant aspects of the standard's PHY and MAC layers. The standard is designed for use in a point-to-multipoint network topology where a base station (BS) transmits to multiple subscriber stations (SS) in a cellular coverage area. The latest standard also covers Mesh Topology.

2.2.1 Medium Access Control Layer

The MAC layer controls medium access on the uplink channel using a DAMA TDMA system. On the downlink, the BS transmits to the subscriber stations using time division multiplexing (TDM). The subscriber stations use TDMA on the uplink and transmit to the BS in their allotted time slots.

Each SS is periodically granted transmission opportunities by the BS. The BS accepts bandwidth requests from the SSs and grants them time-slots on the uplink channel. These grants are made based on the service agreements, which are negotiated during connection setup. The BS may also provisions certain time slots on the uplink that are available to all SSs for contention. The SSs may use these slots to transfer data or to request for dedicated transmission opportunities.

The standard uses frame sizes of 0.5, 1 or 2 ms. The uplink channel is divided into a stream of mini-slots. The system divides time into physical slots (PS), each with duration of four modulation symbols. A mini-slot comprises two PSs. A subscriber station that desires to transmit on the uplink requests transmission opportunities in units of mini-slots. The BS accepts requests over a period of time and creates an allocation map (MAP) message describing the channel allocation for a certain period into the future called the MAP time. The MAP is then broadcast on the downlink to all subscriber stations. In addition to dedicated transmission opportunities for individual subscriber stations, a MAP message may allocate a certain number of open slots for contention based transmission. These transmission opportunities are prone to collisions. Collisions are resolved using the binary exponential algorithm.

The downlink frame is shown in Figure 2.1 The frame starts with a frame control section that contains the downlink MAP (DL-MAP) for the current downlink frame as

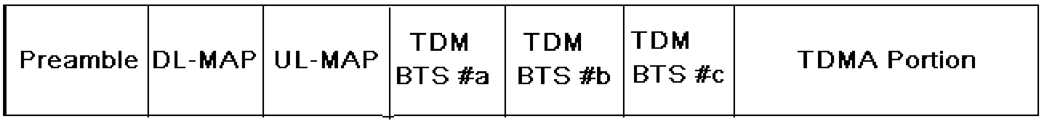

Figure 2.1: Downlink Frame Structure

well as the uplink MAP (UL-MAP) for a frame in future. The DL-MAP informs all SSs when to listen for transmissions destined for them in the current frame. The UL-MAP informs SSs of their transmission opportunities as a response to their dynamic bandwidth requests, or on the basis of service agreements.

The downlink frame typically contains a TDM portion immediately following the uplink and downlink MAPs. This TDM portion carries downlink data for a SS using a negotiated burst profile identified by the Downlink Interval Usage Code (DIUC). The TDM portion may optionally be followed by a TDMA portion to allow better support for half-duplex SSs.

The allocation MAP comprises Information Elements (IEs) that define the usage of particular time slots in the uplink. The IEEE 802.16 standard defines different IEs for different purposes. Request IEs define uplink intervals that can be used by SSs to request the BS for transmission opportunities. Initial maintenance IEs specify when new SSs may enter the network. Station maintenance IEs specify time intervals when SSs may perform ranging and power control. Data grant burst type IEs specify when SSs may transmit protocol data units (PDUs) on the uplink channel.

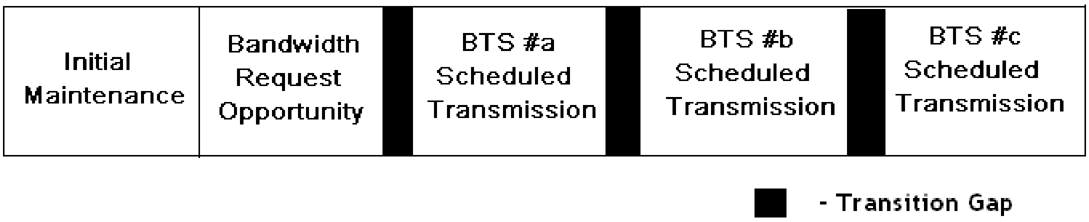

Figure 2.2: Uplink Frame Structure

The uplink frame (Figure 2.2)comprises transmissions from different SSs based on the decision of the BS uplink scheduler as indicated in the UL-MAP. The scheduler may also provision time for initial maintenance and bandwidth requests in any given frame. This information is conveyed to the SSs by the corresponding IEs in the UL-MAP. The uplink frame also contains guard times in the form of SS Transition Gaps. These gaps are used by the BS to re-synchronise to different SS transmissions.

2.2.2 Physical Layer

The IEEE 802.16 PHY systems operates in the range of 10 to 66 GHz. Line-of-sight propagation paths are a practical necessity in such systems. The standard specifies single-carrier modulation schemes with FEC. The air interface supports both FDD and TDD operation modes.

The standard supports three different modulation schemes. It supports higher order 16-QAM and 64-QAM schemes to maximise link throughput and also supports QPSK for robustness and reliability. While both QPSK and 16-QAM are mandatory on the downlink, the uplink need support only QPSK.

2.2.3 Scheduling Service Classes

The IEEE 802.16 MAC defines various scheduling service classes. Subscriber stations can establish connections using the scheduling service class most suitable for the application in use. Each SS negotiates its service agreements with the BS during connection setup. The BS uses these scheduling classes while allocating uplink bandwidth for the SSs. The scheduling service classes defined in IEEE 802.16 are Unsolicited Grant Service (USG), Real-Time Polling Service (rtPS), Non-Real-Time Polling Service (nrtPS), and Best Effort (BE) Service.

USG pre-allocates periodic transmission opportunities to the SSs. This eliminates the overhead involved in the bandwidth request-grant process. The grant size is a system parameter negotiated at connection setup and is a part of the service agreements. Real-Time Polling Service ensures that SSs get periodic bandwidth request opportunities. The SSs can then request bandwidth from the BS. This service permits the SSs to transmit without contending for the uplink channel and is ideal for applications that periodically generate variable sized packets. It targets applications such as voice over Internet Protocol (VoIP),streaming audio and streaming video. Non-Real-Time Polling Service is designed for applications that need high bandwidth connections and are not delay sensitive, for example, bulk file transfers. Best Effort service targets best effort traffic where no throughput or delay guarantees are necessary. Here, the SSs are required to contend for transmission opportunities. The availability of contention opportunities is not guaranteed. The IEEE 802.16 MAC also provides support for fragmentation and concatenation.

2.2.4 Radio Link Control

In addition to performing the traditional functions, such as power control and ranging, the RLC is responsible for transitioning from one PHY scheme to another. Combinations of PHY modulation and FEC schemes used between the BS and SSs are termed as downlink or uplink burst profiles depending on the direction of flow. In IEEE 802.16, burst profiles are identified using Downlink Interval Usage Code (DIUC) and Uplink Interval Usage Code (UIUC). The RLC is capable of switching between different PHY burst profiles on a per-frame and per-SS basis. The SSs use preset downlink burst proles during connection setup.Thereafter, the BS and the SSs continuously negotiate uplink and downlink burst profiles in an effort to optimise network performance.

2.3 WiFiRe MAC design

The WiFiRe MAC layer is designed for use with directional antennas for enhancing the reach of 802.11b PHY in rural scenario. The radiation patterns of directional antennas for a transmitter gives rise to sectorized coverage areas as depicted in figure 2.3. Typically multiple sectorized antennas are required to cover an area that an omni-directional would have covered otherwise. System uses multiple sectorized antennas not only for longer reach but also for complete coverage around transmitting point/tower. As a result, the MAC layer is a multi-sector MAC requiring a functionality that can control all antennas simultaneously.

All the sectors in a multiple antenna configuration continue to use the same frequency channel. As a result, transmission by one antenna will interfere with that of an adjacent sector. On the other hand, depending on antenna models and transmission power level, opposite sectors may be completely free from interference with respect to each other. In any case, in order to avoid interference conflicts, the MAC layer needs to co-ordinate the

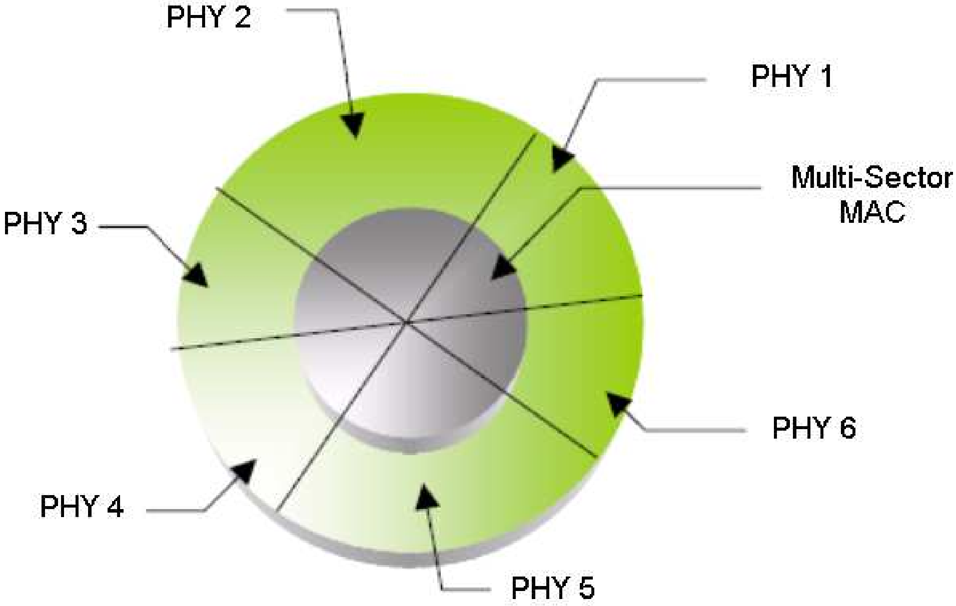

Figure 2.3: A Multi-Sector MAC controlling multiple sector

transmission between the antennas.

In a multi-sector system, each antenna is controlled by an 802.11b PHY. The MAC layer sits on top of all of these 802.11b PHY(s). From the perspective of the MAC, each PHY (hence each BS antenna) is addressable and identifiable. Thus a single MAC controls more than one PHY and is responsible for scheduling MAC messages appropriately, while resolving possible transmission conflict from the perspective of receivers. The MAC layer uses TDD in uplink and down link directions to avoid conflict between interfering antennas.

This aspect of sectorization of coverage area while using the same frequency channel for all the sector antennas is a key feature of the system. It not only impacts the design of the MAC protocol between transmitter and receiver(s) but also the scheduling policies and the system performance.

2.4 Related Literature

[3] Discusses various issues in using 802.11 family of wireless technologies for long distance transmission in rural environment, such as quality of 802.11 PHY performance outdoors,

range extension, spectral vs. cost efficiency, cost of building towers. It gives the details of the 802.11 based mesh networks deployed in the Digital Gangetic Plains Project providing voice and data service to villages. [4] and [5] discusses the issues in using CSMA/CA in networks including long distance links. CSMA/CA is designed to resolve contention in indoor environment. It is inefficient in long distance point-to-point links, They designed a new MAC for mesh networks synTX/synRX, which in the context of our problem translates to saying that the antennas at the base station should be either all be in transmit mode or all in the receive mode and the transmissions should satisfy some power relations.

Deploying long distance 802.11 mesh network is not scalable.

- As the number of nodes increase the number of antennas at the BS also increases.
- With too many hops reliability is problem.

[6] Talks about how the inexplicitly specified parameters of 802.11 can be exploited to increase the range up to 6 Km. But it doesn't achieve a good throughput.

In next chapter we will give brief introduction to OPNET simulator.

Chapter 3

Choice of Simulator

3.1 QualNet

Initially we started with QualNet[7] since partial implementation of WiMAX was available in QualNet [8]. But the implementation was for Base Station with one omni-directional antenna. QualNet specification says that it has support for directional antennas. The antenna pattern has to be specified in three dimension(3D) using angle θ (theta) and angle ϕ (phi) as follows shown in figure 3.1

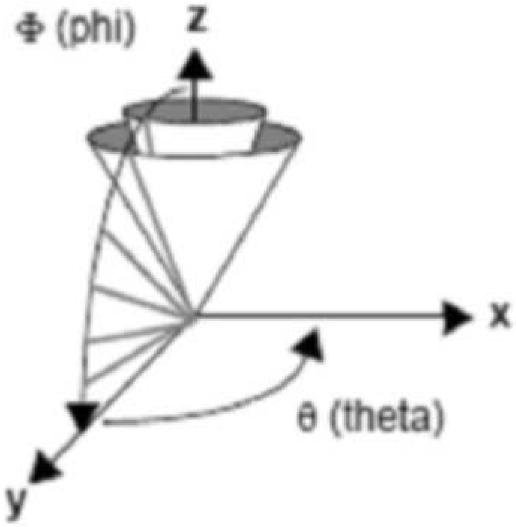

Figure 3.1: Describing antenna pattern using Φ and Θ

Here ϕ varies from 0^o to 180^o and θ varies from 0^o to 360^o degree. For each value of ϕ there are 360 values of θ. These values has to be specified in an ASCII file. Specifying antenna pattern in QualNet is tedious. QualNet provides directional antenna support only at the receiver end not at transmitter.At transmitter QualNet supports only Omnidirectional antennas.

3.2 OPNET

3.2.1 We chose OPNET because

- OPNET[9] provides directional antenna support both at transmitter and receiver.
- It provides graphical editor for creating antenna patterns
- In November OPNET released the WiMAX(MAC) patch,which we could refer to for our implementation.

3.3 OPNET Overview

3.3.1 Pipeline Stages in OPNET

Since wireless is basically a broadcast medium, a single transmission can affect many receivers simultaneously. Received signal strength at each receiver depends on many factors such as transmitted signal power, distance between transmitter and receiver environment noise etc. So each receiver may receive the transmitted signal differently. The timing of signal reaching the receivers also varies. Hence separate pipeline must be executed for each eligible receiver.
The radio transceiver pipeline consist of total fourteen stages most of which must be executed on per receiver basis. All of the pipeline stages can be modified. Below is description of each stage :

1. **Receiver Group**

   Each transmitter maintains its own list of *receiver group* which are possible candidates of receiving transmission from the object. The purpose is to create an initial receiver group for each transmitter channel. The kernel evaluates each receiver against the transmitter in order to create the receiver group for the transmitter channel.

Next stages in the pipeline are evaluated for only those receivers which are in *receiver group* of the transmitter. Less the number of receivers in the receiver group less time it takes for simulation. API is provided to add and remove receivers to and from the receiver group. However the network conditions change during simulation, it's hard to decide which receiver to include in the receiver channel group. Possible reasons for not including a receiver channel in the receiver group is

- Distinct frequency bands
- Physical separation: This is implemented in 802.11 where if the distance between the transmitter and the receiver is more than $300m$, receiver is not included in transmitter's *receiver group*.

2. **Transmission Delay**

   This stage is executed once for every transmission. It calculates the total time taken to transmit a packet. This is the only stage which is evaluated only once irrespective of number of receivers in the *receiver group*. The result from this stage is used to schedule end of transmission event at the transmitter module. When this event is generated the transmitter schedules transmission of a new packet if any, else the transmitter becomes idle. Result from this stage is also used with result from *propagation stage* in order to schedule reception of a packet at the receiver.

3. **Closure**

   This stage is invoked once for each receiver channel in the receiver group. The goal of this stage is to determine if the transmitted signal can physically attain the candidate receiver channel and affect it in any way. Thus, this stage applies to interfering transmissions (such as jamming) as well as to desired ones. Generally, the computations performed by this stage are based mostly on physical considerations, such as occlusion by obstacles and/or the surface of the earth. It returns a *boolean* value. It returns TRUE If closure can be established between transmitter and receiver and signal contact between transmitter and receiver is possible. If it returns FALSE signal contact between the transmitter and receiver is not possible and no further stage is evaluated for the transmitter and receiver pair.

4. **Channel Match**

This stage is invoked for every receiver channel that satisfies the link closure stage. The purpose of this stage is to classify the current transmission for a particular receiver channel as follows:

- **Valid** Transmissions in this category are considered compatible with the receiver channel. The packet may be accepted and forwarded to next modules for further processing.
- **Noise :** In this class the data can not be received at the receiver but the transmission can generate the interference at the receiver.
- **Ignore** Transmissions in this class does not affect the receiver channel in any way and hence can be ignored. Further pipeline stages are suspended for the current transmission.

5. **Transmitter Antenna Gain**

   This is the fifth stage of the transceiver pipeline. Transmission antenna gain is calculated for all receivers that are classified *noise* or *valid* by the *channel match* stage. It is calculated using the vector between the transmitter and receiver. Transmitter antenna *gain* calculated by this stage is used by *power model.*

6. **Propagation Delay** Propagation Delay is the time taken bay the packet signal to travel from source to destination. It depends on the distance between the transmitter and receiver. *propagation delay* is calculated for every receiver that is classified *noise* or *valid* by the *channel match* stage. *propagation delay* with *transmission delay* is used to schedule the packet arrival event at the receiver.

7. **Receiver Antenna Gain**

   This is first stage at the receiver and seventh stage of the pipeline. *receiver antenna gain* is calculated at each receiver depending on the vector leading from receiver to transmitter. This is used in calculation of *received power* in *power model.*

8. **Receiver Power**

   Received Power is calculated for each eligible destination channel at the receiver. The purpose of this stage is to calculate the received power of arriving packet's signal (in watts). For the packets that are classified as *valid*, the received power is an indication of how accurately receiver can capture the information in packet. The stage is executed also for the packets classified as *noise*, this is useful in calculating relative strength of *valid* packets to *noise*.

Computation of received power depends on many factors like transmission power, distance separating transmitter and receiver, transmission frequency, transmitter and receiver antenna gain.

9. **Interference Noise**

   This stage is executed only in two circumstances: The packet is *valid* and arrives at the destination while another packet is being received; the packet is being received while another (*valid/noise*) arrives. The purpose of this stage is to account for the transmissions that arrive at the receiver concurrently. The value is stored only for the valid packets. The result can be shared by pipeline of two packets if both are valid packets.

10. **Background Noise**

    The purpose of this stage is to represent the effect of all noise sources except for other concurrently arriving transmissions (because these are accounted for by the *interference noise* stage). The expected result is the sum of the power (in watts) of other noise sources, measured at the receiver's location and in the receiver channel's band. Typical background noise sources include thermal or galactic noise, emissions from neighbouring electronics, and otherwise unmodeled radio transmissions (such as commercial radio, amateur radio, or television, depending on frequency).

11. **Signal-to-Noise Ratio**

    This stage executed for a valid packet for following three conditions:

    - The packet arrives at its destination channel.
    - The packet is already being received and another packet (valid or invalid) arrives.
    - The packet is already being received and another packet (valid or invalid) completes reception.

    The purpose of SNR stage is to compute the current average power SNR for the arriving packet. This calculation is usually based on values obtained during earlier stages, including received power, background noise, and interference noise. The

SNR of the packet is important in determining receiver's ability to correctly receive the packet's content. The result computed by this stage is used by the Kernel to update standard output results of receiver channels and usually also by later stages of the pipeline.

12. **Bit Error Rate**
    BER stage is executed for all the valid packets for which SNR stage is executed. The purpose of the BER stage is to derive the probability of bit errors during the past interval of constant SNR. This is not the empirical rate of bit errors, but the expected rate, usually based on the SNR. In general, the bit error rate provided by this stage is also a function of the type of modulation used for the transmitted signal.

13. **Error Allocation**
    The purpose of the error allocation stage is to estimate the number of bit errors in a packet segment where the bit error probability has been calculated and is constant. This segment might be the entire packet, if no changes in bit error probability occur over the course of the packet's reception. Bit error count estimation is usually based on the bit error probability (obtained from stage 11) and the length of the affected segment.

14. **Error Collection**
    Error correction stage is invoked when a packet completes reception. This stage determines acceptance of packet. This is usually dependent upon whether the packet has experienced collisions or not, this result computed in the error allocation stage, and the ability of the receiver to correct the errors affecting the packet (hence the name of the stage). Based on the determination of this stage, the Kernel will either destroy the packet, or allow it to proceed into the destination node. In addition, this result affects error and throughput results collected for the receiver channel.

Chapter 4

Modelling WiFiRe in OPNET

4.1 Overview of Model in OPNET

Figure 4.1 shows the block diagram of the System. It consists of two parts, Base Station (BS) and the Subscriber Station (SS). The BS consists of BS data classifier, BS traffic shaper, Packet queues, BS Scheduler, BE Bandwidth request generator, and Bandwidth request queues. The SS consists of SS data classifier, SS traffic shaper, Packet queues, BE Bandwidth request generator, and SS uplink scheduler.

WiFiRe is a connection oriented MAC. Each incoming packet is mapped to a connection, which is indexed by Connection Identifier (CID). The packet enters the MAC at the *classifier*(BS Data Classifier or SS Data Classifier). The classifier directs the packets from the higher layer to one of the outgoing connections. Different classifiers can be defined at each node.

The packets received from the Uplink Channel can be either Data packets, Best Effort Bandwidth (BE BW) Request packets, or Control packets. The Data packets are sent to the upper layers for further processing. The BE BW request packets are queued according to the CID of the connection in the BE BW request queues. Control packets are passed to the BS Scheduler.

The packets received from the Downlink Channel can be either Data packets or Control packets. The data packets are sent to the upper layers for further processing. The control packets are either MAPs or Dynamic Service Addition (DSA) response messages. The control packets are sent to the SS Uplink Scheduler for further processing.

- **BE BW Request Generator**

  It generates BW request for BE flow, if BE queue has packets to send. At BS, BE

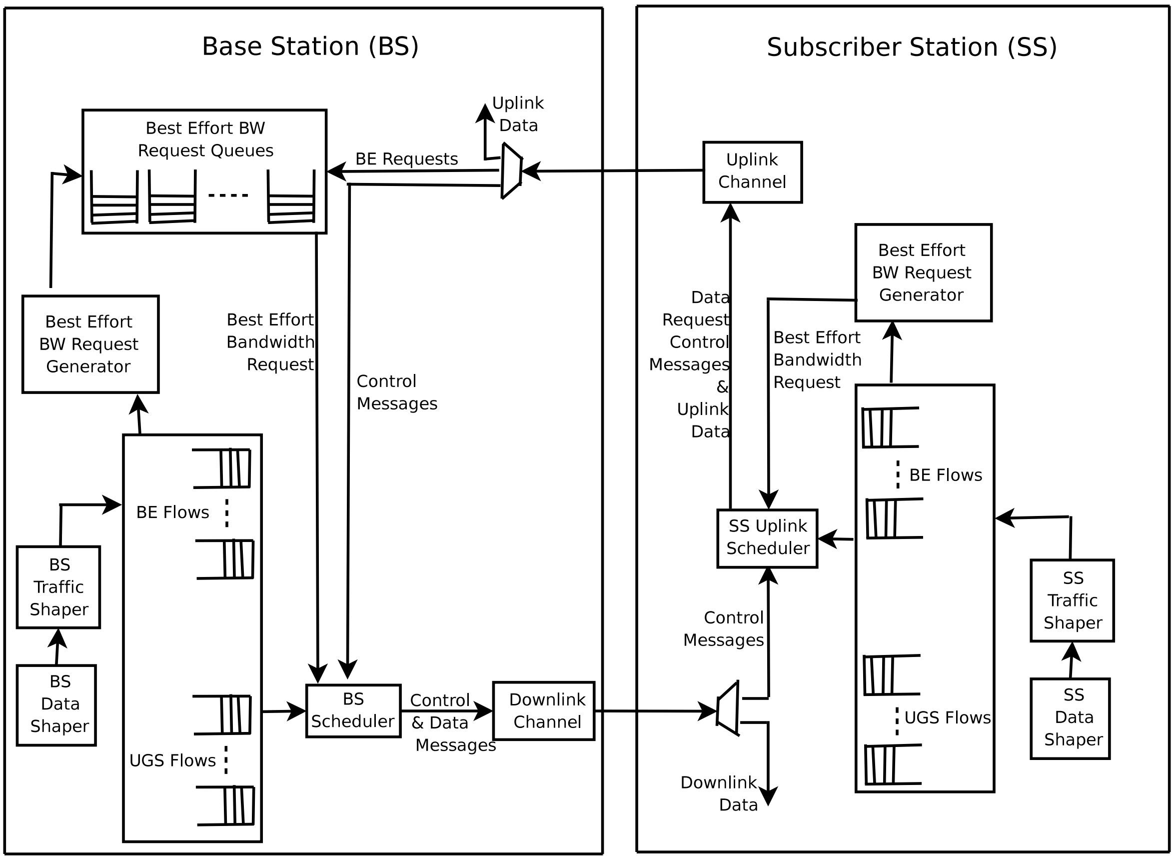

Figure 4.1: Block diagram of the system

BW Requests are directly enqueued in the BW Request queues. But at SS BE BW Requests are transmitted over the *uplink channel* during Contention Slots.

- **SS Uplink Scheduler**

  It performs multiple functions.

  - On arrival of map, it schedules transmission of uplink data.
  - In contention slots, it schedules transmission of BE BW Requests.
  - Schedules transmission of other control messages like DSA Requests.

- **BS Scheduler**

  The design of BS Scheduler is explained in chapter 5. BS Scheduler prepares MAPs and transmits MAPs on downlink channel. It also schedules transmission of downlink data on downlink channel.

4.2 Assumptions

In the implementation of current model, following assumptions are made.

1. All the SS and BS start at the same time. No ranging is performed. BS after becoming ready, starts transmitting MAPs. Each SS receives the MAPs and, it associates with the BS antenna from which it receives maximum power. Each SS informs BS about the BS antenna if it is associated with and sends the interference matrix to BS which is used by *scheduler*.

2. The structure of DSA messages is defined but, DSA messages are exchanged before the simulation starts.

3. DSC messages are not supported.

4.3 MAC State Diagrams

Figure 4.2 shows the state diagram of the MAC. It shows the states that are common to both BS and SS. The description of each state is given below in pseudo C code.

In Init state all variables are initialised. MAC and IP addresses are obtained.

A given node can be either a SS or BS. BS_ROLE defines whether a given node is SS or BS. Depending on value of BS_ROLE corresponding process is invoked. When a process is invoked, the control is passed to the invoked process. The invoked process is termed as child of the process that invoked it. Control returns to the parent process once the child gets blocked.

Listing 4.1: Invoke Corresponding Process

```
/**********Invoke corresponding process**********/
//BS_ROLE is TRUE if the node is a Base Station.
if (BS_ROLE == TRUE)
    invoke (bs_control)
else
    invoke (ss_contol)
```

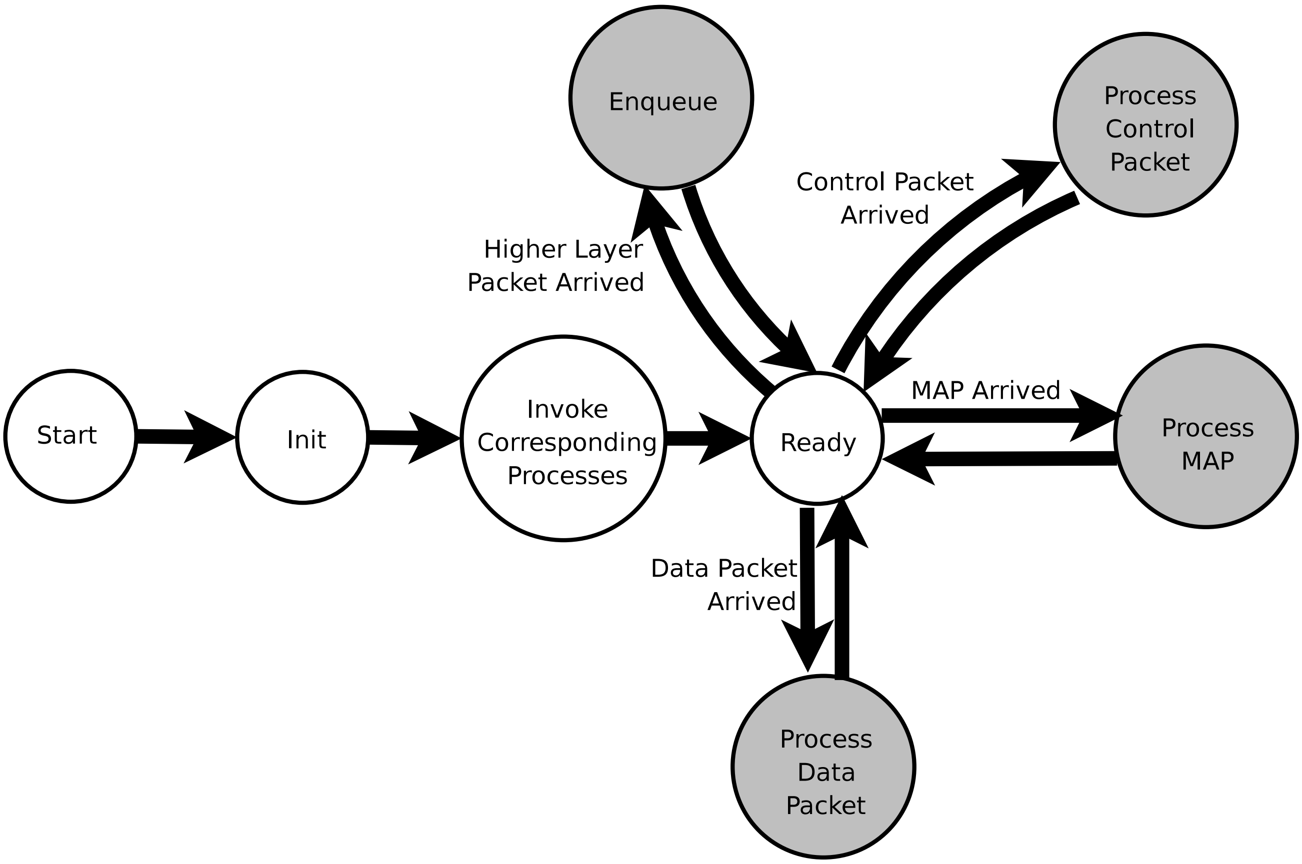

Figure 4.2: MAC State Diagram

System then enters the *Ready* state and waits for the events.

When MAC receives packet from higher layer, it makes transition to *Enqueue* state. Each incoming higher layer packet is mapped to one of outgoing connection, identified by a CID. A CID has a queue associated with it. The packet which does not match any condition specified in classifier is inserted in default BE connection queue.

Listing 4.2: Enqueue

```
/**********Enqueue**********/
//packet contains, packet received from higher layer
cid = classify_packet(packet)

/*INVALID(cid) returns TRUE if cid is NULL, else it
    returns FALSE*/
if(INVALID(cid))
```

```
    insert_packet(default_queue , packet)
else
    queue = get_queue(cid)
    insert_packet(queue, packet)
```

When control packet arrives from the lower layer, child process is invoked and the packet is passed to child process. Control returns to the parent process once the child gets blocked.

Listing 4.3: Process Control Packet

```
/**********Process Control Packet**********/
//control packets are processed by BS and SS processes
if (BS_ROLE == TRUE)
    pass_packet (bs_control)
else
    pass_packet (ss_contol)
```

MAP is processed in similar way at both BS and SS. When MAP arrives, node checks each map element in the map. If the CID in map element belongs to node, the information in map element is used to schedule transmission by the node. The map element contains following fields.

- CID
- Start Slot (Slot number at which transmission should start)
- Number of Slots (Number of slots alloted for transmission)

Listing 4.4: Process Map

```
/**********Process Map***********/
for each map_element
    cid = get_cid(map_element)
    //exists(cid) returns TRUE if cid belongs to the
```

```
    //current node.
    if (!exists(cid))
        next
    //get the packet queue corresponding to the cid
    queue = get_queue(cid)
    slots_allocated = get_slots(map_element)

    do
        head_pk_size = get_pk_size(queue, 1);
        if (slots_allocated < (head_pk_size + TX_OVERHEAD)
            break;
        packet = remove_pk(queue,1)
        schedule_pk(packet)
        slots_allocated -= (head_pk_size + TX_OVERHEAD)
    while(1)

    if (slots_allocatted > MIN_TX_QUANTITY)
        packet =remove_pk_part(queue, 1, slots_allocated-
            TX_OVERHEAD)
        schedule_pk_part(packet)
```

When MAC receives data packet form PHY, it is passed to the higher layer for further processing.

Listing 4.5: Process Data Packet

```
/**********Process Data Packet**********/
get_ip_packets(packet)
{
    while(ip_pk = get_packet(packet) )
        if(COMPLETE(ip_pk))
            send_pk_to_upper_layer(ip_pk)
        else
```

```
            compl_pk = insert_packet_seg_queue(q, packet)
        /*if inserting the packet segement in q forms
        a complete packet then insert_packet_seg_queue
        returns the packet. Else returns NIL*/
    if (compl_pk != NIL)
        send_pk_to_upper_layer(compl_pk)
}

cid = get_cid(packet)
if (INVALID(cid))
    drop_packet(packet)
    exit
get_ip_packets(packet)
```

4.4 Base Station State Diagram

Figure 4.3 shows the state diagram of a BS. The description of states is given below in pseudo C code.

Init state initialises all the variables specific to BS. It also places(directs) the antennas (six in current implementation) at the BS.

Listing 4.6: Init State

```
/**********Init**********/
initialize_variables() //Initializes all the variables
place_antennas(); //place all the antennas
```

The BW Request is inserted in BE BW Request queue, identified by CID.

Listing 4.7: Process BW Request

```
/**********BW Request Process**********/
//BW requests come only from the BE flows
```

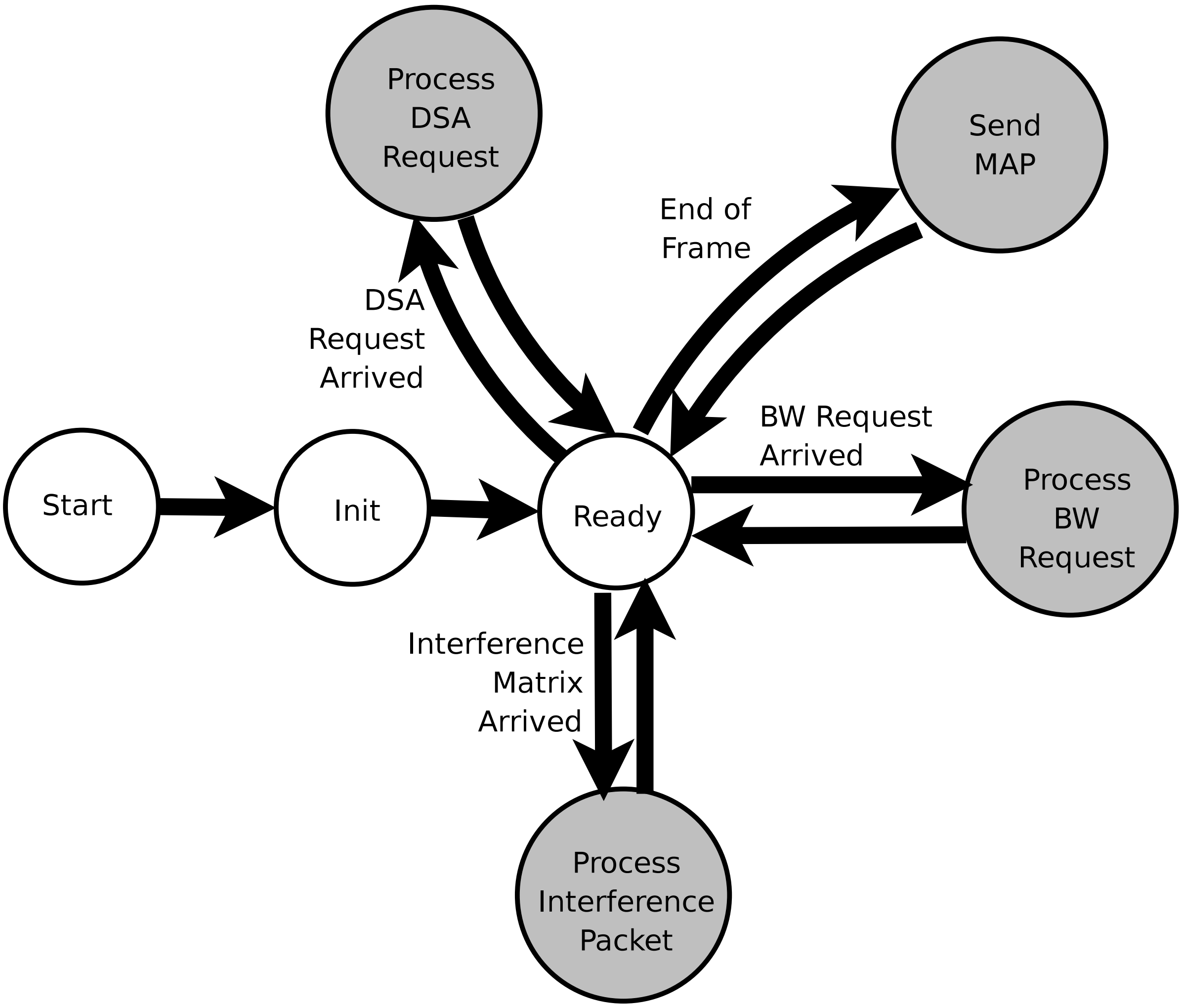

Figure 4.3: State Diagram of Base Station)

```
cid = get_cid(packet)
if (!exists(cid))
   exit
//enque bw request in a queue
queue = get_queue(cid)
enqueue(queue,bw_req)
```

Listing 4.8: Process DSA Request

```
/**********DSA Request Process**********/
//total_slots_per_frame  is total number of slots in a
```

```
frame
/*total_slots_per_frame_free is total number of slots in frame
  free currently */
//data_rate is data_rate of the channel
service_flow_type = get_ service_flow_type(packet)
service_flow_direction = get_ service_flow_direction (packet)
if (service_flow_type == BEST_EFFORT)
    cid = generate_cid(cid)
    if (service_flow_direction == DOWNLINK)
        create_queue(cid)
        //creates a queue which can be accessed using the cid
    else
        send_dsp_resp(true,cid)
if (service_flow_type == UGS)
    bw_request = get_datarate(packet)
    //(bw_request is in bytes/sec)
    avg_sdu_size = get_avg_sdu_size(packet)
    bw_request = bw_request + TX_OVERHEAD_BYTES * avg_sdu_size
    bw_request = convet_into_slots(bw_request)
    bw_request_per_frame = bw_request/total_slots_per_frame
                                        *data_rate
    //admit_flow() is function of admission control.
    if(admit_flow(bw_request_per_frame))
        //admit the flow
        cid = generate_cid(cid);
        if (service_flow_direction == DOWNLINK)
            create_queue(cid)
```

```
        else
            send_dsp_resp(true,cid);
    else
        send_dsp_resp(false.-1);
```

On arrival of Interference Matrix at BS, Association Matrix, Interference Matrix and Conditional matrix are updated at the BS. The definition of Interference Matrix, Association Matrix and Conditional Matrix is given in chapter 5

Listing 4.9: Process Interference Matrix

```
/**********Process Interference Matrix**********/
calculate_association_matrix()
calculate_interference_matrix()
calculate_conditional_matix()
```

At end of each frame BS sends MAP, and schedules transmission of next MAP.

Listing 4.10: Send Map

```
/**********Send MAP**********/
map = create_map();
send_map(map)
```

4.5 Subscriber Station State Diagram

SS is simple as compared to BS. Figure 4.4 shows the state diagram of a SS. The description of states is given below in pseudo C code.

When SS is invoked it initialises all variables typical to SS. It also directs the antenna towards the BS.

Listing 4.11: Init State

```
/**********Init**********/
```

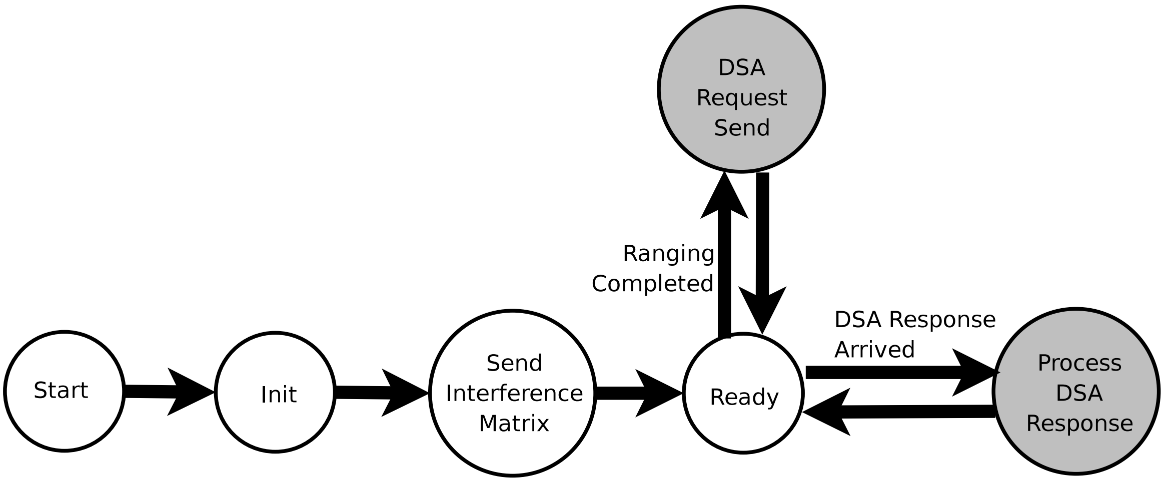

Figure 4.4: State Diagram of the Subscriber station

```
initialize_variables() //Initializes all the variables
place_antenna(); //place antennas
```

SS calculates power it receives from different BS antennas each time it receives packet. Whenever there is change in power level SS receives from any BS antenna it notifies BS about it.

Listing 4.12: Send Interference Matrix

```
/**********Send Interference Matrix**********/
//intr_matrix[] contains power reseived from all BS
    antennas.
rec_power= get_rec_power()
if (change(rec_power))
    send (intr_matrix)
```

Before simulation starts SS registers all the flows at BS.

Listing 4.13: DSA Request Send

```
/**********DSA Request Send**********/
for each flow
    generate_DSA_request()
```

```
    send_DSA_request()
```

Listing 4.14: Process DSA Response

```
/**********DSA Response process**********/
response get_rerponse(packet)
if(response == TRUE)
    create_queue(cid)
```

Next chapter discusses the design of Scheduler at the BS.

Chapter 5

Scheduler

In order to test the model implementation and the performance, we need to also implement scheduler at the BS. We have implemented Greedy Heuristic Scheduler [1].

5.1 Interference Pattern

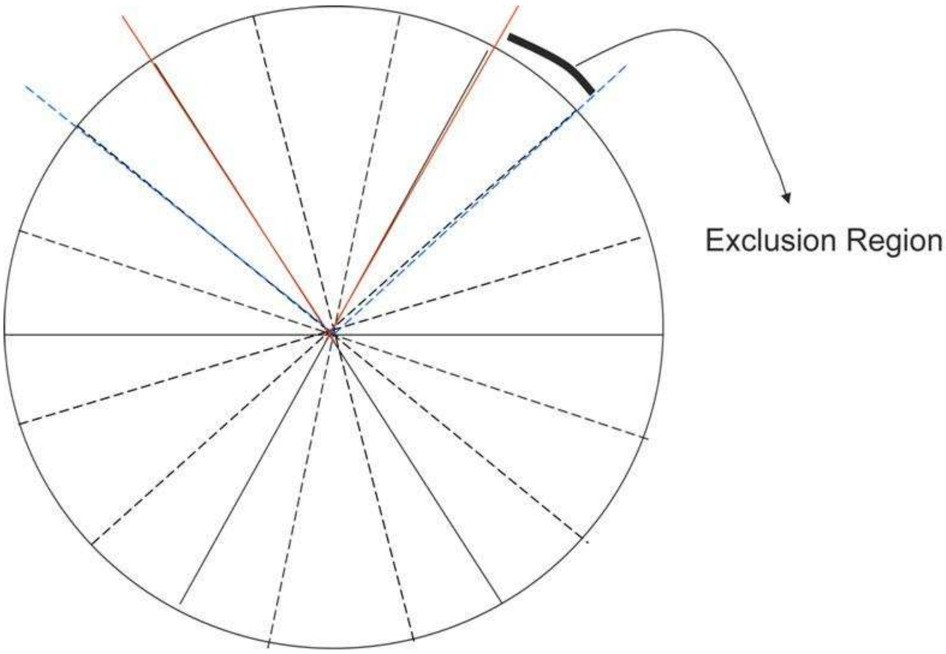

Figure 5.1: A antenna coverage and interference pattern for a six sector partitioned cell

Figure 5.1 shows typical view of a System (S) with 6 BS antennas. Each BS has a sectorized antenna (60^o) associated with it. The antennas at SS will be narrow beam directional antennas. At S all the BS antennas will be placed very close to each other. Because of side and back lobes of a sectorized antenna, if one BS antenna is transmitting it will interfere with the reception of nearby BS antenna in the same system. So the BS antennas at System S are either all transmitting or all receiving. The region covered by solid (red) lines shows the communication range of the BS antenna and forms the sector of the BS antenna. The region covered by dotted (blue) lines on either side of the sector shows the exclusion (taboo) region of the antenna. All the SSs in a sector will associate with the antenna serving that sector. Depending on interference The transmission in one sector may prohibit transmission between some BS-SS pairs in the nearby sector.

5.2 Greedy Heuristic Scheduler [1]

5.2.1 Notation and Terminology

- number of BS antennas at S (n):. For the setup we are using, the number of BS antennas are 6. This number varies depending on density of SSs in the region. Increasing the number of BS antennas at S increases the capacity of system up to a limit.

- number of SSs (m) : The number of SS in a sector j is denoted by m_j and number of SSs in exclusion region in clockwise previous sector by m_{j-} .Similarly we define m_{j+}.

- Association Matrix (A): Association matrix is an m x n matrix where each row corresponds to a SS and each column corresponds to BS antenna. The $(i,j)^{th}$ element of the matrix A is 1 if i^{th} SS i is associated with j^{th} BS antenna. SS i is associated with BS antenna j when power received by i from the packet sent by j is greater than some specified *communication threshold*. Otherwise it is 0

- Exclusion Matrix (I): Exclusion matrix is a m x n matrix, where m is number of SS and n is number of BS antennas. The $(i,j)^{th}$ element of matrix I is 1 if power received by i from the packet sent by j is greater then some specified *interference threshold* . Other wise its 0

- Activation vector(u): Activation vector is a 1 x n matrix where i^{th} element denotes which SS in sector i is active. All active SSs may be either transmitting or receiving.

- Maximal Activation Vector (U) : If no more SS in an *activation vector* can be activated without causing interference to some other transmissions scheduled in the same vector then this activation vector is maximal.

- Schedule (S): Schedules consist of SSs that are active at any given time.
- Interfering Links $\iota(S)$ This is set of SSs that can interfere with the links in S.
- UGS Grants (q) : q is m x 1 matrix. Where each row specifies the UGS grants for the corresponding SS.

5.2.2 Example

To explain the notations above consider the following example

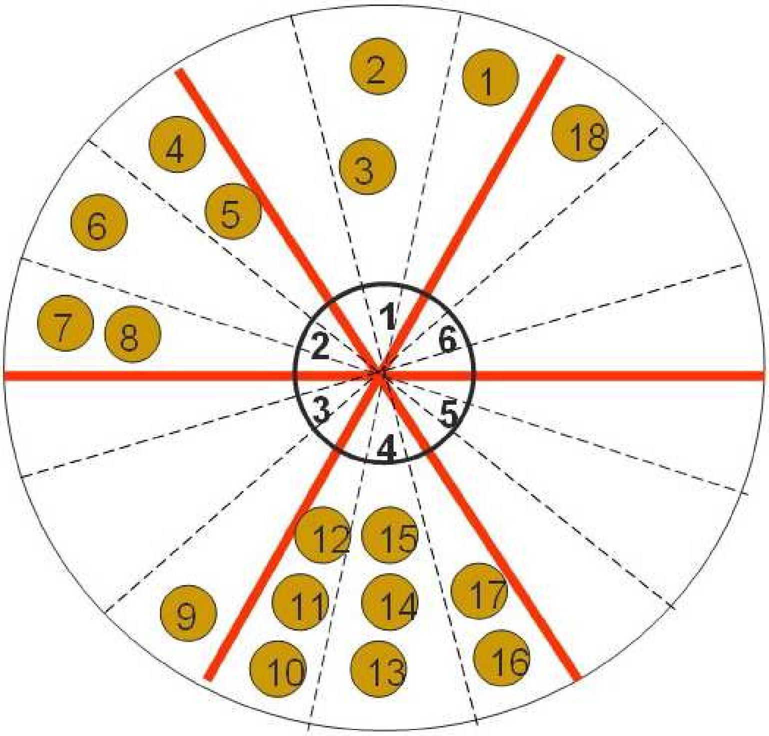

Figure 5.2: Example scenario of the system

The association matrix A and Interference matrix I for figure 5.2 is:

$$A = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \end{bmatrix} .I = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 1 & 0 & 0 & 0 \\ 0 & 1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 1 & 1 & 0 \\ 1 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

5.3 Scheduling Uplink flows

A heuristic greedy scheduling algorithm is suggested by [1]. Here the optimisation parameter is the UGS grant size of a SS. The SSs are scheduled such that the SS with greater UGS grant always gets preference over other SS and is scheduled first. Create an activation vector u that includes maximum UGS grant. Now activate another SS whose UGS grant is maximum among those SSs which are not interfering with the current SSs in activation set. This goes on till maximal activation is formed. Once, one of the SS completes transmission, remove that SS from the activation vector and select another SS whose UGS grant is maximum among those who do not interfere with any transmission from SS currently in the activation vector. Repeat this till the maximal activation vector is formed. Repeat the above steps till every station's UGS grant is not processed.

Algorithm 1 Greedy Heuristic algorithm for Uplink Scheduling taken from [1]

```
INPUT m : number of SSs
n :number of BS antennas
Activation Vector A(m,n)
Interference Vector I(m,n)
UGS grant matrix q(m,1)
//q contains UGS request size of all the SSs in slots.
OUTPUT Schedule S
1: Initially, slot index $k = 0$. Let SS $i$ be such that
       $q_{ki} = \max_{l=1 \dots m} \{q_{kl}\}$
   i.e. The SS with longest UGS grant at the beginning of slot $k$ is $i$. Create activation vector $\mathbf{u}$ with link $i$ activated. i.e. $u = \{i\}$
2: Let SS $j$ be such that
       $q_{kj} = \max_{l} \{q_{kl} : l \ni \iota(u)\}$
   $j$ is such that it is maximum among interfering SSs. activate $j$ find new $\iota(u)$.
3: Let
       $n = \{q_{kl} : \min_{l=1,\dots,m} (q_{kl}, l \in u)\}$
   i.e. $n$ is the minimum number of slots required for the first SS in u to complete its transmission. Use u in the schedule from $k$th to $(k+1)th$ slot.
       $q_{k+n,i} = \begin{cases} q_{k,i} - n & for \quad i \in u \\ q_{k,i} & for \quad i \ni u \end{cases}$
   and $k = K + n$. i.e. slot index advances by n, and the queue length for the SSs ate the begingin of $(k+n)th$slot is $n$ less
4: At the end of $k + nth$ slot,
       $u = u - \{l : q_{kl} = min(q_{kl}, l \in u)\}$
   i.e., remove those SSs that have completed their UGS grants from activation vector.
5: Go back to step 3 and from maximal activation vector including u. Continue above procedure until all the SSs are not serviced
6: Once UGS grants are serviced we serve the BE flows in similar way.
```

5.4 Preprocessing

We extend the Greedy Heuristic Scheduling algorithm for faster implementation by doing preprocessing. we group together the nodes, exhibiting similar characteristics. We represent the group as a single node.

5.4.1 Notation and Terminology

- Conditional matrix C : It is a m x m matrix such that
  C(i,j) = 1 if i=j
  C(i,j) = 1 if I and j can not be serviced simultaneously
  C(i,j) = 0 else where.

Conditional matrix for the figure 5.2 is as follows

$$C = \begin{bmatrix}
1 & 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\
1 & 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\
1 & 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\
1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 1 & 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 1 & 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 0 \\
1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1
\end{bmatrix}$$

The matrix is symmetric. One can notice that few rows in the matrix are identical. These rows corresponds to the nodes having similar characteristics like nodes associated with same antenna, nodes in exclusion region of the same antenna. The idea is to combine these rows and form new row, which means represent the set of nodes exhibiting similar characteristics with one node. The UGS grant of this representative node is sum of UGS grant of all nodes it is representing. In the example given 7 such representative nodes can be found, as follows

$a = \{1, 2, 3\}$
$b = \{4, 5\}$
$c = \{6\}$
$d = \{7, 8\}$
$e = \{9\}$
$f = \{10, 11, 12, 13, 14, 15, 16, 17\}$
$g = \{18\}$

The conditional matrix now reduces to

$$C = \begin{bmatrix} 1 & 1 & 0 & 0 & 0 & 0 & 1 \\ 1 & 1 & 1 & 1 & 0 & 0 & 0 \\ 0 & 1 & 1 & 1 & 0 & 0 & 0 \\ 0 & 1 & 1 & 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 1 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 & 1 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

There is not much difference between uplink and downlink scheduling. But in downlink we can take advantage of the fact that only one station is transmitting. And since it is a broadcast medium we can combine multiple UGS grants to save PHY overhead. With the preprocessing that we applied long burst of continuous transmission from the same BS are possible.

In this chapter we described the design of Scheduler at the BS [1]. We also proposed an extension to the scheduling algorithm, for faster computation of schedule.

In next chapter we check the validity of the implemented model by performing some simulation experiments.

Chapter 6

Simulation Setup

6.1 Simulation Setup

Following parameters need to be specified when setting up simulation.

1. Classifier Definition
2. Service Class Definition
3. Packet interarrival time (exponential distribution)
4. Packet size (Uniform Distribution)

6.2 Scenario

Figure 6.1 shows the scenario of simulation setup. Simulation consist of one BS, surrounded by 16 SS, which are placed randomly around the BS. Each SS has 4 flows registered at the BS: one UGS downlink flow, one UGS uplink flow, one BE downlink flow and one BE uplink flow.

Figure 6.2 shows how throughput of system varies with increasing load. Initially throughtput of system increases with increase in load. After some load threshold the throughput reaches the saturation point. For the given scenario achievable throughput is 25 Mbps.

Figure 6.3 shows the delay faced by packets from UGS flows for throughput. The point upto which UGS flows adhere to the aggreement, delay is less and constant. but with increase in load beyond a threshold results in longer delayes for UGS flow packets.

Figure 6.4 shows delay faced by packets from BE flows for given throughput.

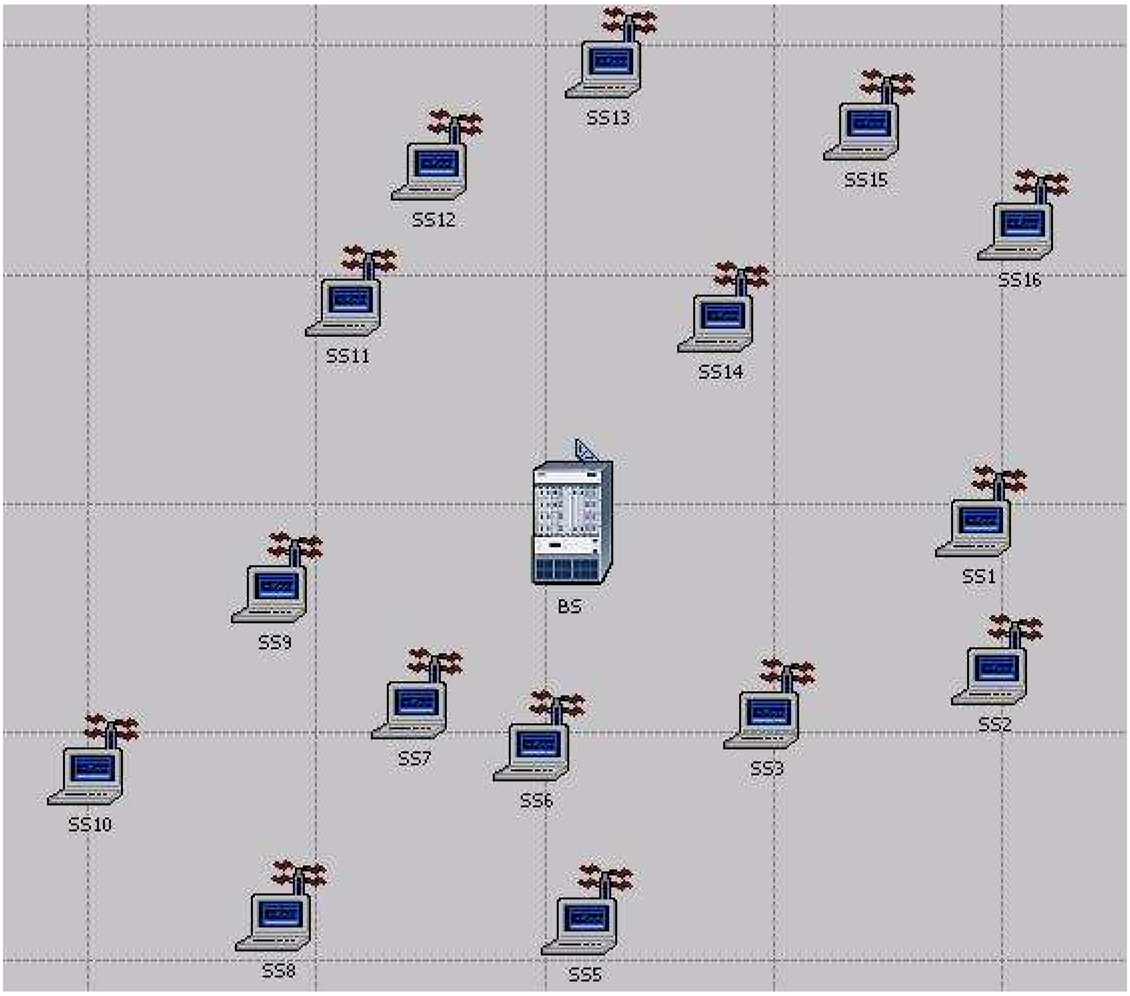

Figure 6.1: Scenario of simulation setup. The unit is in 5km.

The Behavious observed in ghraphs is close to that expected by simple theoritical analysis. Thus we believe that our implementation to perform correctly in other scenarios.

Due to lack of time we have been unable to perform detailed simulations to throughly analysethe performance of WiFiRe in various scenarios.

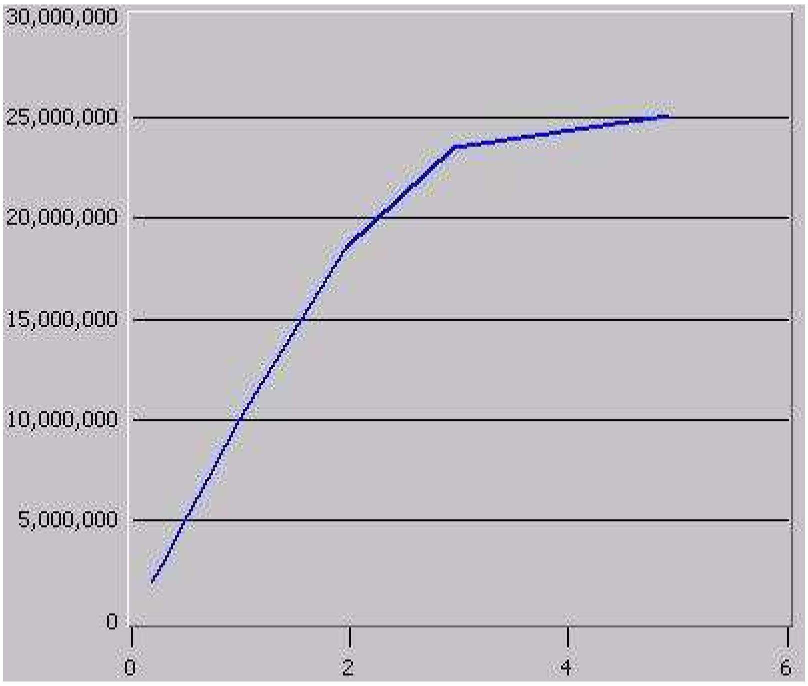

Figure 6.2: Throughput vs Load. Y-axis is in bps, X-axis in 10Mbps

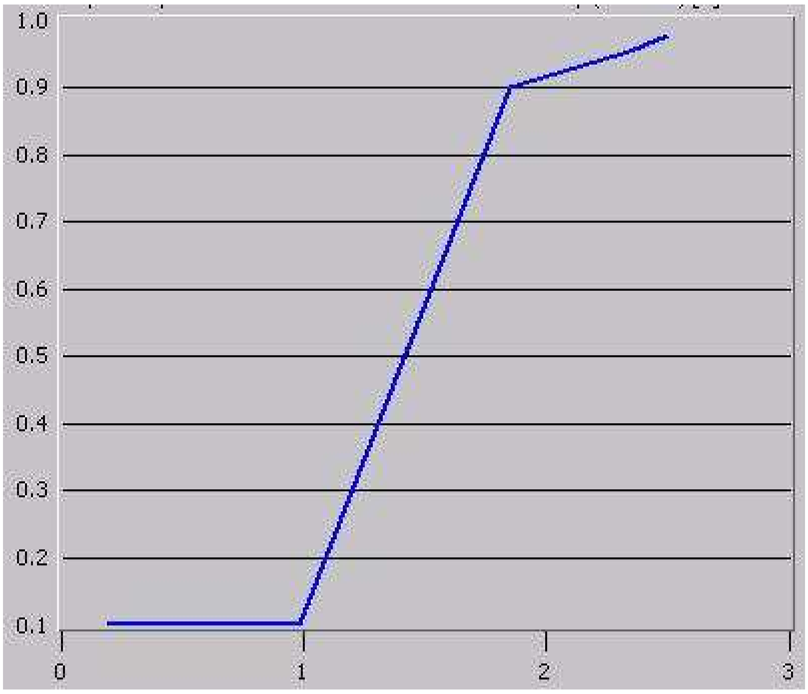

Figure 6.3: Throughput vs Delay of UGS flows. Y-axis is in seconds, X-axis in 10Mbps

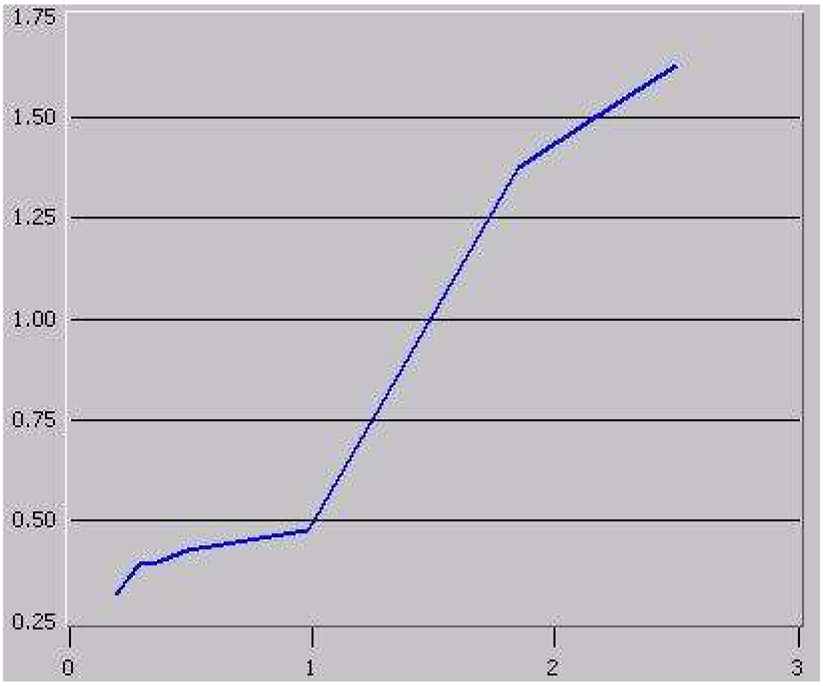

Figure 6.4: Throughput vs Delay of BE flows. Y-axis is in seconds, X-axis in 10Mbps

Chapter 7

Conclusion

We have implemented WiFiRe model in OPNET and checked its correctness by simulation results. Using WiFiRe we are able estblish communication links over long distance of upto 20 Km with good throughput.

7.1 Future Work

Experiments performed just support the validity of WiFiRe model implemented in OPNET. More experiments need to be performed in order to check performance of WiFiRe. The throughput of system is dependant on the simulation scenario. Maximum achievable throughput is different in different scenario.

While implementing the WiFiRe model, we relaxed few specifications such as Ranging, DSC messages etc. These specifications need to be implemented in order to understand the full functioning of WiFiRe. We also haven't implemented the extension of Greedy Heuristic Algorithm.

We believe that most of the code written for opnet model for WiFiRe can be easily extended for real implementation.

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Anirudha Bodhankar
I. I. T. Bombay
July 17th, 2006