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Abstract

Throughput Analysis of White Space Network Simulation in NS3

by Ponrajkumar S

Nowadays White space is one of the more focused areas in wireless networks. Lot of possibilities to use the TV white space for a secondary purpose in an effective manner with full protection to primary users. The Primary users are mainly TV transmitters and wireless microphones that operate on vacant TV bands. Spectrum sensing approach and database approach are well known mechanism to protect primary users. In this project Energy based spectrum sensing approach is implemented in the NS3 simulator to protect the primary users. In the results section throughput falling during the channel switch is calculated based on the simulation output.
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<td>CPE</td>
<td>Customer Premises Equipment (Subscriber Station)</td>
</tr>
<tr>
<td>BS</td>
<td>Base Station</td>
</tr>
<tr>
<td>TV</td>
<td>TeleVision</td>
</tr>
<tr>
<td>DS MAP</td>
<td>Down Stream MAP (DL MAP-DownLink MAP)</td>
</tr>
<tr>
<td>US MAP</td>
<td>Uplink Stream MAP (UL MAP-UpLink MAP)</td>
</tr>
<tr>
<td>DCD</td>
<td>Downlink Channel Descriptor Message</td>
</tr>
<tr>
<td>UCD</td>
<td>Uplink Channel Descriptor Message</td>
</tr>
<tr>
<td>UCS</td>
<td>Urgent Coexistence Situation</td>
</tr>
<tr>
<td>NS3</td>
<td>Network Simulator 3</td>
</tr>
<tr>
<td>UHF</td>
<td>Ultra High Frequency</td>
</tr>
<tr>
<td>VHF</td>
<td>Very High Frequency</td>
</tr>
<tr>
<td>ISM</td>
<td>Industrial, Scientific and Medical radio band</td>
</tr>
<tr>
<td>QP</td>
<td>Quiet Period</td>
</tr>
<tr>
<td>CBP</td>
<td>Coexistence Beacon Protocol</td>
</tr>
<tr>
<td>SCW</td>
<td>Self Coexistence Window</td>
</tr>
<tr>
<td>FCH</td>
<td>Frame Control Header</td>
</tr>
<tr>
<td>SCH</td>
<td>Superframe Control Header</td>
</tr>
<tr>
<td>OFDM</td>
<td>Orthogonal Frequency Division Multiplexing</td>
</tr>
<tr>
<td>OFDMA</td>
<td>Orthogonal Frequency Division Multiple Access</td>
</tr>
<tr>
<td>RTPS</td>
<td>Real Time Polling Service</td>
</tr>
<tr>
<td>QAM</td>
<td>Quadrature Amplitude Modulation</td>
</tr>
<tr>
<td>QPSK</td>
<td>Quadrature Phase Shift Keying</td>
</tr>
<tr>
<td>BPSK</td>
<td>Binary Phase Shift Keying</td>
</tr>
<tr>
<td>TTG</td>
<td>Transmit/Receive Transition Gap</td>
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<tr>
<td>RTG</td>
<td>Receive/Transmit Transition Gap</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
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<tr>
<td>MAC</td>
<td>Media Access Control</td>
</tr>
<tr>
<td>SNR</td>
<td>Signal to Noise Ratio</td>
</tr>
<tr>
<td>DSA</td>
<td>Dynamic Service Addition</td>
</tr>
<tr>
<td>DSC</td>
<td>Dynamic Service Change</td>
</tr>
<tr>
<td>DSD</td>
<td>Dynamic Service Deletion</td>
</tr>
<tr>
<td>UDP</td>
<td>User Datagram Protocol</td>
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<tr>
<td>IP</td>
<td>Internet Protocol</td>
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Chapter 1

Introduction

Connecting each and every place in the world to internet by cables is highly costly. Internet providers show little to no interest in connecting rural area, especially in developing countries like India. Efforts could be made to bring such areas under wireless coverage in a cost effective manner. Wireless coverage can extend from few meters to over a few kilometers. Lower bands like VHF and UHF are good candidates for long distance coverage due to their propagation capabilities.

The TV space band ranges from 54 MHz to 862 MHz. However, in India the entire TV band is not allocated to TV operators. Chunks of bands from 54 MHz to 862 MHz are given to TV operators[2]. The primary allocated bands are listed in table 1.1 and rest of the Bands are used for radio signal transmission and so on. Currently Doordarshan is the only channel operating in the above specified TV bands. It has been found that lot of TV white space is available in India.

<table>
<thead>
<tr>
<th>Band</th>
<th>Frequency Range</th>
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<tbody>
<tr>
<td>VHF-I</td>
<td>54 MHz - 86 MHz</td>
</tr>
<tr>
<td>VHF-III</td>
<td>174 MHz - 230 MHz</td>
</tr>
<tr>
<td>UHF-IV</td>
<td>470 MHz - 590 MHz</td>
</tr>
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</table>

Table 1.1: Allocation of TV Bands

Currently TV Bands are used for licensed operation or primary operation only. Unlicensed users are not allowed to use the TV Bands. Though this lower band has good propagation, unlicensed users can’t use it directly. Protection of Primary operation is highly important.

Deploying the white space networks is a costly undertaking and the local government has to be convinced of the benefits derived from its deployment. Testing and analyzing white space networks in live settings has a high risk of affecting the TV user’s. A better
way is to simulate white space networks in a simulator and analyze how this secondary system performs. **NS3** is the most used open source simulators and thus we will also use the same.

### 1.1 Problem Statement

There is lot of ongoing research going in this field. The highest priority in all of them is the protection of incumbents from secondary unlicensed operations. Next on their priority list is interference among the secondary operation, how the band can be used effectively. The other problems considered are using the spectrum sensing approach or database approach or both to detect primary users and other secondary users.

In this thesis we have deployed the NS3 simulation of TV white space network using energy based sensing. Security aspects of White Space Networks are not considered in this project. Only important and meaningful features of the standard have been implemented in simulator and so the standard has not been fully implemented in NS3.

#### 1.1.1 Motivation

Number of wireless devices are rapidly increasing at an exponential rate. This has resulted in increases in the use of unlicensed spectrum like ISM band. Unlicensed users have to share the bandwidth due to large user constraints. Another challenge is long distance transmission. As we know that lower bands have a good propagation model we can try and find out the possibility of using the lower band for unlicensed operation.

#### 1.1.2 Goals

- Create a Module that will be used to set up a white space network
- Generate simulation application with specific scenarios.
- Calculate throughput, number of packet drops based on the scenarios.

### 1.2 Contribution to NS3

Both 802.22 and WiMax standards use the same **Point to Multi Point Network (PMP)** architecture. But 802.22, also called WRAN standard, needs additional mechanisms and different packet headers to protect incumbents. Physical layer changes
and MAC layer changes are implemented in the WiMax module in order to protect the incumbents. Incumbent mechanism implemented based on the 802.22 standard documentation[1].

Additionally, existing WiMax module was unable to transmit large number of packets due to transmission time mismatch at precision level because of datarate conversion to symbols and usage of both slots and symbols in transmission timing calculation. We have fixed this problem too.

Major contributions of this project are introducing Quiet Period scheduling(QP), Self Coexistence Window(SCW through CBP packet), Channel switching with help of Urgent Coexistence Situation message (UCS) and channel switching Message, concept of backup channel, downlink and uplink scheduler allocation scheme, TV channel transmission detection with help of TV spectrum model[3], changing MAC layer header packets from WiMax.

The rest of this thesis is organized as follows, we present an overview of 802.22 - White Space Network in chapter 2, in Chapter 3 we discuss the simulator implementation, simulation results are shown in chapter 4 and finally conclusions are drawn along with suggested future work.
Chapter 2

Overview of 802.22 - TV White Space Networks

2.1 What is WhiteSpace

White space is the unused spectrum in any spectrum band. TV white space is the unused spectrum in the TV bands, that is UHF and VHF bands. TV white space is getting a lot of attention because of its propagation characteristics. Due to low frequency spectrum in TV bands, wireless devices can transmit for longer distances compared to other bands. Connecting rural areas by wire is costly and not much profitable to the vendors. So wireless devices can transmit the packets to rural area by using this TV white space band for a fraction of the cost.

2.1.1 Super Frame Structure

Super frame is aggregation of 16 frames. Representation of Super frame is shown in Figure 2.1. Super frame will have Super frame Control Header SCH in the first frame.

2.1.2 Frame Structure

Super frame is concatenation of 16 frames. Except Superframe Control Header SCH in frame zero, other fields are same in all frames including the first frame. Frame fields are shown in Figure 2.2
2.2 Type of Users

2.2.1 Primary Users

Primary users are mainly TV operators. TV operators hold a license for operating in a particular TV channel band in that geographical area. No disturbance to TV signals is allowed. TV operators operate in different band in different areas. So the TV band allocation is not static. Other primary operators in the UHF and VHF bands are radio operators, wireless mic etc.

2.2.2 Secondary users

Secondary users are not license holders for the TV Bands. Secondary Users should guarantee that they cause no interference to TV users and other primary users. TV Band is entirely dynamic and a lot of white space is available. In order to use the unused TV bands, Secondary users should be able to detect it correctly. So secondary users requires hardware, software drivers and cognitive radio to operate in the white
space. Secondary users should be able to change the operating frequency after finding the TV signal in the same channel where it is operating.

### 2.3 Methodologies for Detecting available Spectrum

TV bands are not used fully. TV operators operate in different TV bands in different places and in different time hence the White space network is dynamic. Primary users are license holders for the TV bands. If TV band is been identified as free, then secondary users can be allowed to operate. In order to identify the available bands mainly two types of approaches are followed, spectrum sensing approach and geolocation based database approach. These approaches are compared in detail in paper.[4]

#### 2.3.1 Spectrum Sensing Approach

If Secondary users are following the spectrum sensing approach, secondary users will scan for incumbents periodically. Standard and local government bodies will have the rules for time limit for detecting the incumbents. If incumbent is found, then channel switching time constraint also apply.[5].

#### 2.3.2 Geolocation Based Database Approach

In Database approach all the base stations are connected to centralized coordinator which is responsible for maintaining the incumbents and secondary users channel information. Based on the location it will search in the database for channels where there is absence of any incumbent. After that coordinator will return the available channels for secondary usage to Base Station. Location accuracy in Geo location based approach is important factor[6] because coordinator will give available channels in the particular geographical area only. It is described as easy to implement and difficult to follow. So it is considered as a short term solution.

### 2.4 Management Methodologies For Coexistence

#### 2.4.1 No Coexistence

Base station will operate independently without the coordination of other secondary cells. It will primarily focus on incumbent detection. If incumbent is not found in the
current channel, base station will start operating in the channel. This may lead to interference if more secondary cell users are trying to operate in the same channel.

2.4.2 Self Coexistence

Self coexistence mechanism will try to be aware of other secondary operations in the particular surrounding geographical location. If other secondary operations are detected, then it has to follow either spectrum etiquette or contention based approach. Because it will lead to lot of interference for both secondary user cells.

2.4.2.1 Spectrum Etiquette

Spectrum Etiquette will work if available channels are high compare to the number of secondary operations. Spectrum Etiquette will try to find full spectrum available channel. So Spectrum Etiquette will try to avoid sharing the spectrum with other secondary cell operations. If it is unable to find fully available channel, then the Base Station has to follow other mechanism like contention based approach or simply has to use the non error-free channel.

2.4.2.2 Contention Based Coexistence

Contention Based approach is needed when sufficient number of channels are not available for secondary operations. In this technique two or more secondary cells will have to share the common channel on a time basis. Frames in the super frame will be allocated as shown in the Figure 2.3

2.5 Quiet Period scheduling

As shown in Figure 2.4 two types of quiet period scheduling mechanism are available. Intra frame quiet period scheduling will do incumbent scanning within a frame for short time. If Energy based sensing approach is used, then minimum time of scanning will be 5 milli seconds\cite{1}. On the other hand inter frame quiet period scheduling approach will do scanning for 2 or 3 continuous frames. If incumbent presence is absorbed by subscriber station then it should report back to the Base station and follow channel switching mechanism if Base Station decides to switch current operating channel. If
incumbent is detected by Base Station, then BS will decide whether channel switching is required or not based on the power level and other features available.

2.6 Channel Switching Technique

Channel switching technique is discussed by assuming that only spectrum sensing approach is followed. Subscriber stations, also called Consumer Premises Equipment, follow different approach from Base station. Base station approach is explained in Figure 2.5 followed by subscriber station approach in Figure 2.6. Incumbent Detection Recovery Protocol (IDRP) is the protocol responsible for the channel switching technique.
2.6.1 Base Station Channel Switching Technique

![Diagram of Channel Switching Technique at Base Station]

Base station will receive incumbent notification if spectrum manager from base station or subscriber station found incumbent in the current sensing channel. After receiving the incumbent detection notification the base station will check whether the channel mentioned in the notification is for in-band or out-of-band channel. If it is out-of-band channel then it will update the backup/candidate channel list and notify the updates to subscriber station through Downlink Control Descriptor. Suppose the incumbent notification is for current operating channel then the base station will decide if channel switching for all nodes are required or not. If channel switching required for particular nodes, then those subscriber stations will be deregistered. If channel switching is required for all the subscriber stations then the base station will send the channel switching message. If Backup channels are available, then it will pickup the backup channel otherwise it will reinitialize the base station. If backup channel is available, then notify the channel switch to subscriber stations and wait for T56 time. Currently in the simulator T56 timer is set to one frame time. Then start operating in the first backup channel.
2.6.2 Subscriber Station Channel Switching Technique

Subscriber station will look for incumbent in the current sensing channel. If incumbent found in the current sensing channel and sensing channel is not operating channel, then subscriber station will send an unavailable backup channel list through measurement reply message in the uplink grant allocation. If incumbent found in the current operating channel, then it will notify the base station through UCS message in the uplink grant if uplink grant is allocated or in the UCS notification window. After sending the UCS message, subscriber station will wait for base station signal upto T59 timer (currently two frame times) to expire. Base station may send a yes/no reply for channel switch after receiving the incumbent notification. If T59 timer (2 frame times) has expired,
then the CPE will look for backup channels. If backup channel doesn’t exist, subscriber
station will start reinitialize. If backup channel exist, then it will switch to backup
channel and will look for base station signal. Subscriber can send a confirmation of
successful channel switch to base station.
Chapter 3

Simulator Implementation

3.1 Module Creation

We have created a new module called wireless-22 in NS3. This module has been created for adding the files that handle the physical and MAC layer functionalities of the 802.22 standard and also this module will have all the necessary functions to communicate to the upper layer network model. Steps on how to create a module in ns3 can be seen at the link in footnote\(^1\). In the following sections we will see the components of this module in more details.

3.2 Module Components

3.2.1 Bandwidth Manager

Bandwidth manager is for sending bandwidth request by subscriber stations, processing bandwidth request by base station and setting the subframe ratio. Bandwidth manager will give the allocation size of bandwidth request to the scheduler based on the selected service flow.

3.2.2 Base Station Link Manager

Base station link manager will process the ranging request from subscriber stations. Ranging request process is different for initial ranging and invited ranging. Ranging

\(^1\)https://www.nsnam.org/docs/manual/html/new-modules.html
response message is scheduled once ranging request is processed. This ranging request
should be received by Base station within the allotted ranging time and this is being
checked. Range response also have status. The status could be success, continue or
abort. If ranging response status is success, then the node is allowed for data transmis-
sion during it’s allocation in the uplink subframe. If ranging status is continue, then
corresponding subscriber will have to send ranging request again. If ranging status is
aborted, then it is not allowed to operate within the cell. Other than the ranging status
in the ranging response message, timing offset, frequency offset adjustment and power
level can be corrected by Base station according to the distance. In the NS3 simulator
currently constant values are used in the ranging response except ranging status.

3.2.3 Subscriber Station Link Manager

This Link Manager is responsible for initial scanning, channel switch scanning, ranging
and UCS notification operations. During the start it will initiate the scanning to find
the Base Station’s frequency. After finding out the Base Station’s frequency, ranging
procedure is established. Once ranging is done, Link Manager will be sending UCS
notification message. UCS notification message is sent when TV signal is detected.
Whenever base station is changing the frequency after notifying the subscriber or after
time out, the subscriber will come to know that base station has moved to a different
channel. Now link manager will initiate the channel switching mechanism.

3.2.4 Connection Manager

There are seven different type of connections are considered. They are Broadcast, Initial
ranging, Basic, Primary, Transport, Multicast and Padding. Connection Manager has
connection identifier(CID) factory. CID factory is responsible for creating unique id for
each connection. The connection identifier is 2 bytes long. There are fixed identifiers
for broadcast(0xffff), initial ranging connection(0x0000) and padding(0xffffe). Rest of
the types have fixed range and they are Basic from 0x0001 to 0x5500, Primary from
0x5501 to 0xAA00, Transport from 0xAA01 to 0xfeff, Multicast from 0xff00 to 0xfffd.
Each connection will also have queue and serviceflow. Queue will have packets for
the particular connection. Whenever the scheduler is requesting Connection manager,
connection manager will check if that specific connection has packets and reply back,
also does defragmentation. Connection manager is a interface to queue and netdevice
for enqueueing and dequeuing the packets.
3.2.5 Downlink Scheduler

This scheduler is called by the Base station for scheduling the downlink sub frame. Scheduler will select the connection and will check for packets in the connection. If enough OFDM symbols are available to transmit the minimum required byte, then the packet will be scheduled. Only transport connection packets are fragmented if symbols are not sufficient to transmit the whole packet and rest of connection packets are not fragmented. Selection of connection will have the following order, Broadcast, Initial Ranging, Basic, Primary, and Service flow connections. If no sufficient symbols are left for the next packet, then the scheduler will stop scheduling: otherwise it continues until all the packets are scheduled from all the connections in the downlink sub frame. Bursts are added once all packets in the connection are scheduled or scheduler stops scheduling in between due to lack of sufficient symbols. Then the downlink burst is added at the end in the downlink burst list. This downlink burst list will be dequeued by sendburst method in base station to send the bursts during downlink sub frame time. Different kind of schedulers can be used depending upon the need. For example RTPS can be used for real time application. Currently simple scheduler is used that is first come first serve basis.

3.2.6 Uplink Scheduler

Base station will call uplink scheduler and uplink scheduler will schedule the uplink transmission in the uplink sub frame for subscriber station nodes. This uplink sub frame is further divided into four parts for different purpose of transmission. They are initial ranging interval, UCS interval, bandwidth request interval and regular grant for data transmission. Uplink scheduler will follow different kind of scheduling for OFDMA and OFDM. In OFDM only one node can send at any time and OFDM symbol will occupy the entire bandwidth whereas OFDMA will allow many nodes to transmit in parallel by allocating only unique part of the bandwidth to every transmitter. Currently OFDM is used in the simulator thus hereafter only OFDM is considered. Initial ranging interval is being used for sending the initial ranging packets by subscriber stations. Initial ranging interval is allocated periodically. Urgent Coexistence Situation (UCS) interval is being used for notifying the primary users transmission in the current channel. UCS interval is being allocated whenever quiet period is scheduled in the previous frame and also periodically. Scheduler will have the subscriber station’s record and its service flow. Bandwidth request interval is being used to send the bandwidth request for asking required bandwidth to send the regular transport packet. In the regular grant allocation is done such that maximum subscribers will get an opportunity to send transport packets.
Invited ranging followed by Service flow initialization is done when initial ranging status is continue. Invited ranging request and dynamic service flow requests are sent in regular interval. Once Invited ranging is done, then the ranging status will become successful. Once service flows have been added, then the subscriber can send higher layer data. If Service Data Unit is set in the service flow, then scheduler will allocate regular grant size to Service Data Unit(SDU). Scheduler will calculate the uplink allocation start time and keep scheduling from that point until all the uplink transmission is scheduled or uplink symbols are fully used. When the uplink sub frame scheduling is done, allocation information will be added in the ULMAP. Different kinds of uplink schedulers can be used for different kinds of application.

3.2.7 ServiceFlow

Service flow is created by service flow manager based on the request by netdevice. Service flow will be used to uniquely identity that which application is transmitting from whom and to whom. This service flow will have options for service data unit and maximum allowed grant size. It can be changed dynamically. So it is called dynamic service flow. Dynamic service flow can be added, modified and deleted based on the request from subscriber net device.

3.3 TV Spectrum Transmitter

TV transmitter will initiate the signal once the starting time is reached. During the initialization antenna type, phy layer, transmission power, transmission duration are set with appropriate given values. Isotropic antenna model is default antenna model. TV signal is sent continuously until transmission duration is completed. Channel bandwidth is 6 MHz and TV Band range is from 400 MHz to 700 MHz. Secondary users are the receiver here. At the receiver side noise exists initially and when TV signal is transmitted it will be added with noise and TV signal will be subtracted once the TV transmitter stop sending the TV signal in the current operating channel. TV signal presence was identified in adjacent channel by secondary users. Noise level is set to -120 dbm. During the quiet period sensing the presence of TV signal is set to true if power level of signal higher than -114 dBm[6]. The TV transmitter idea is from Benjamin TV spectrum model in NS3 and this work is been modified to operate with this module.[3]. Additional features such as multiple TV stations and each TV station using random frequency are implemented.
3.4 Physical Layer

Base station and subscriber station will forward down the burst with modulation type and direction. Direction could be either uplink or downlink. BPSK 1/2, QPSK 1/2, QPSK 3/4, QAM16 1/2, QAM16 3/4, QAM64 2/3, QAM64 3/4 are currently available modulation types. Other modulation types can be easily added. Table with coding rate(fec code), block size and bits per symbol is shown in 4.3. Total number of carriers is being set to 256 out of which 192 are data carriers. Default Cyclic Prefix is 1/4. Currently physical layer is converting the burst into number of blocks based on the modulation types. Block transmission time is calculated based on the modulation type. Physical layer will transmit the block during the block transmission time and followed by next block. Once all the blocks are transmitted the receiver will check if it has received all the blocks. If it has successfully received all the blocks, then the burst will be forwarded to MAC layer. Otherwise, the burst will be discarded. In case of during initial scanning, channel switching scanning [2.6], quiet period sensing [2.5], the subscriber station won’t transmit or forward the received bursts to upper layers.

Using IT++ a mathematical and signal processing library[8], the OFDM trace is generated for all modulation types. This generated trace file will have interval for each SNR and modulation type. If randomly generated value greater than the upper interval boundary, then no drop of block will happen. If randomly generated value lies within interval, then randomly blocks are dropped. If randomly generated value is lesser than lower boundary value, then block is dropped. Block error rate of 0.01 is set for the blocks in the physical layer.

3.5 OFDM Channel

All the device’s physical layer is attached to the single channel object component. Different propagation models are available in which one of them will be set. Currently available propagation models are

- RandomPropagation
- FriisPropagation
- LogDistancePropagation
- Cost231Propagation
- TwoRayGroundPropagation
• Okumura-Hata Propagation

Whenever the channel is called by transmitter it will check for the propagation model set. Based on the propagation model and mobility model it will calculate receiving power and delay to all the receivers. So each receiver will get the block after the calculated delay time with calculated receiving power.

3.6 NetDevice

NetDevice is responsible for forwarding the packet to upper layer and receiving the packet from upper layer. NetDevice is responsible for forwarding down the burst to physical layer and receiving the burst from physical layer. There are two types of NetDevice. They are Base station netdevice and subscriber station netdevice, for base station and subscriber station respectively. Common functionalities of both netdevice are receiving and forwarding the packets or burst. Base Station NetDevice alone is responsible for coordinating all the components. Base station netdevice is responsible for initiating channel switch, Quiet Period scheduling, Self Coexistence Window scheduling whenever the requirement is met. Subscriber station netdevice is responsible for managing the granted upstream and its own scheduling. It will initiate the scanning, channel switch scanning, invited ranging scanning, also setting up the service flow and incumbent scanning along with it’s link manager.
Chapter 4

SimulationResults

4.1 Scenario Setup

4.1.1 Propagation Model

Okumura Hata Propagation model is used and we will see why Okumura Hata propagation loss model is relevant here. TV band frequency range is set from 400 MHz to 700 MHz. Okumura Hata Propagation is the default propagation model. While doing experiment, the propagation model is set to Okumura Hata propagation model. Because Okumura Hata propagation loss model used to model open area path loss for distance greater than 1 Km and frequencies ranging from 150 MHz to 2.0 GHz. It has options for environment and city size. Environment can be urban, suburban or open areas and city size can be small, medium and large.

4.1.2 Mobility Model

NS3 has options for mobility model, they are: constant position mobility model, constant acceleration, constant velocity model, random way point mobility model, random walk 2d mobilitiy model, random direction 2d mobility model, steady state random direction 2d mobility model, Gaussian markov mobility model and Hierarchy mobility model. Out of which constant position mobility model, random walk 2d point and random way point mobility model have been tested and our module is working fine with these mobility models. In experiments Constant position model is used. Nodes are set to operate from few meters to 10 kilo meters from base station.
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<table>
<thead>
<tr>
<th>Variables</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bandwidth</td>
<td>6,7,8 MHz</td>
</tr>
<tr>
<td>Frequency range</td>
<td>54 to 862 MHz</td>
</tr>
<tr>
<td>Transmission Power</td>
<td>4W</td>
</tr>
<tr>
<td>Total number of carriers</td>
<td>256 (FFT)</td>
</tr>
<tr>
<td>Data carriers</td>
<td>192</td>
</tr>
<tr>
<td>pilot carriers and guard carriers</td>
<td>64</td>
</tr>
</tbody>
</table>

Table 4.1: Simulation Parameters

4.1.3 Simulation Parameters

All the major variables used in simulation are shown in table 4.1. All time intervals and constraints for MAC layer control messages are shown in table 4.2 for base station and subscriber stations respectively. This time interval are referenced for synchronization lost of downlink and uplink control messages by subscriber stations. Base station will not exceed the bounded time to make sure the subscriber stations are getting all the MAC layer control messages periodically.

4.1.3.1 OFDM Symbol Time Calculation:

NFFT = 256
Sampling Frequency = 8/7 * 6 MHz = 6857142.86
Physical Slot Duration = 4 / Sampling Frequency = 5.833333333e-7 seconds
Physical Slots Per Frame = Frame Duration / Physical Slot Duration = 17142
Subcarrier Spacing = Sampling Frequency / Nfft = (6*8/7)e6 /256 = 26785
Useful symbol time = 1 / SubcarrierSpacing = 0.00003733432
Cyclic prefix time = useful symbol time/4 = 0.00000933358
OFDM symbol duration = useful symbol time + cyclic prefix time = 0.0000466679
physical slots per symbol = symbolDuration / physical slot duration = 80
Symbols Per Frame = FrameDuration / symbolDuration = 215

One frame duration time is 10ms. 215 OFDM symbols are there in one frame. So one OFDM symbol time is 10/215=0.046 ms (leaving Transmit Receive Transition Gap TTG and RTG Receive Transmit Transition Gap, cyclic prefix modes)
<table>
<thead>
<tr>
<th>Entity</th>
<th>Name</th>
<th>Description</th>
<th>Time (second)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base Station</td>
<td>Initial ranging interval</td>
<td>Time between Initial Ranging regions assigned by the BS</td>
<td>.05</td>
</tr>
<tr>
<td>Base Station</td>
<td>DCD interval</td>
<td>Time between transmission of DCD messages</td>
<td>3</td>
</tr>
<tr>
<td>Base Station</td>
<td>UCD interval</td>
<td>Time between transmission of UCD messages</td>
<td>3</td>
</tr>
<tr>
<td>Base Station</td>
<td>Serviceflow ack timeout</td>
<td>wait after sending service flow response</td>
<td>0.05</td>
</tr>
<tr>
<td>Subscriber station</td>
<td>Dlmap interval T56</td>
<td>Time since last received DL-MAP message before downlink synchronization is considered lost</td>
<td>0.5</td>
</tr>
<tr>
<td>Subscriber station</td>
<td>Ulmap interval</td>
<td>Time since last received UL-MAP before uplink synchronization is considered lost</td>
<td>0.5</td>
</tr>
<tr>
<td>Subscriber station</td>
<td>DCD interval</td>
<td>Maximum time between transmission of DCD messages</td>
<td>10</td>
</tr>
<tr>
<td>Subscriber station</td>
<td>UCD interval</td>
<td>Maximum time between transmission of UCD messages</td>
<td>10</td>
</tr>
<tr>
<td>Subscriber station</td>
<td>DCD timeout</td>
<td>Wait for DCD timeout</td>
<td>50</td>
</tr>
<tr>
<td>Subscriber station</td>
<td>UCD timeout</td>
<td>Maximum time between transmission of UCD messages</td>
<td>50</td>
</tr>
<tr>
<td>Subscriber station</td>
<td>ranging wait timeout</td>
<td>Wait for broadcast ranging timeout, i.e., wait for initial ranging opportunity</td>
<td>0.2</td>
</tr>
<tr>
<td>Subscriber station</td>
<td>ranging response T3</td>
<td>ranging Response reception timeout following the transmission of a ranging request</td>
<td>0.2</td>
</tr>
<tr>
<td>Subscriber station</td>
<td>service flow response timeout T7</td>
<td>wait for DSA/DSC/DSD Response timeout</td>
<td>1</td>
</tr>
<tr>
<td>Subscriber station</td>
<td>ss wait for bs signal T20</td>
<td>Time the SS searches for SCH or CBP on a given channel.</td>
<td>.04</td>
</tr>
</tbody>
</table>

Table 4.2: Timers on MAC control messages
4.2 Experiment Results

4.2.1 Scenarios

In all case scenarios, modulation type is set to QAM64 with 3/4 error rate. Simulation application is set to run up to 70 seconds in all cases. TV signal is start sending signal either from 15th second or 16th second. TV transmitter will stop sending the signal after completion of 30 seconds transmit duration.

1. Simulation Validation - Single cell one transmission without any interference

In order to validate the module added to the simulator, throughput of one cell doing one transmission without any interference is calculated. Full bandwidth grant is given to find the throughput and checked against theoretical throughput. UDP client will transmit a packet of 1024 bytes every 0.1 milliseconds. Here Throughput is calculated at UDP level. Theoretical throughput calculation is shown in the table 4.4 and simulator output for this scenario is shown in the diagram 4.1. Actual throughput is matching the theoretical throughput approximately in some cases and is slightly lesser in remaining cases. Because of mac layer padding and fragmentation due to symbol overhead, theoretical throughput is not achieved fully.

2. Single cell with one transmission considering block error rate without TV signal
In this scenario single cell is handling one transmission without TV interference is considered. Burst error rate loss is activated. Theoretical throughput of this single cell with one transmission is shown in the diagram 4.2. IT++[8] a signal processing open source software is used to generate OFDM modulation trace. This trace file is producing block error rate model. Additionally, SNR value based dropping mechanism is implemented. When SNR value is high, the probability of dropping the block is lesser compare to low SNR value. Also, Lower modulation exception is made from SNR based dropping. Because for lower modulation less SNR value is sufficient. Based on the packet drops, block error rate is matching approximately 1%.

3. **Single cell with five transmission considering block error rate without TV signal**

In this scenario single cell is handling five transmissions without TV interference is considered. Burst error rate loss is activated. Theoretical throughput of this single cell with five transmissions is shown in the diagram 4.3. IT++ a signal processing open source software is used to generate OFDM modulation trace. This trace file is producing block error rate values for given SNR. This SNR value is higher, than no block will be dropped. If SNR value is low, definitely the block will be dropped. If SNR value is in between, block will be dropped according to the IT++ probability. Additionally, same SNR value based dropping mechanism is used here.
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4. Five cells each with five transmission with block error rate without TV signal

In this scenario five cells are handling five transmissions each without TV interference is considered. Burst error rate loss is activated. Theoretical throughput of this single cell with five transmissions is shown in the diagram 4.4 and simulation...
throughput is shown 4.4. IT++ error model and SNR value based dropping mechanism is used. Currently each cell is operating in different frequency. Collision helper has to be implemented in order to set the same channel for multiple cells.

5. Single cell with one transmission considering block error rate and TV signal
With Block error rate, TV transmitter is operating in the same channel in this scenario. When TV channel start operating, the noise to secondary node is TV signal. Otherwise, the floor noise is the default noise here. Because, the TV signal presence has higher dbm value (-110 dbm) than the floor noise value (-131 db). So floor noise value become negligible in this case. Here no backup channel is considered. TV transmitter start sending TV signals from 15th second in the same operating channel. After finding the TV signal presence, the base station is switching the channel. Here average number of times channel switching case is considered by setting the operating channel 150 MHz away from the current operating channel. Throughput for this case is shown in figure 4.5.

6. Single cell with five transmission considering TV signal, block error rate
Single cell up to five transmission with TV, Block error rate
Single cell with five transmission with TV signal presence and other noise presence is the setup here. Throughput of this setup is shown in the diagram 4.6. Same setup compare to previous case except number of subscribers in the cell is five.

![Figure 4.5: Single cell with one transmission - TV signal, block error rate considered](image-url)
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7. Multiple cells each with five transmission - with TV, Block error rate

Multiple cells (five) operating in different frequencies with block error rate. So

![Diagram](image.png)

**Figure 4.6:** Single cell with five transmission - TV signal, block error rate considered

![Diagram](image.png)

**Figure 4.7:** Five cells with five transmission with TV, Block error rate

for each base station, TV transmitter is been set in the same frequency in which corresponding base station is operating. Throughput for this scenario is shown in 4.7
8. **Single cell with one transmission - considering TV signal, block error rate, backup channel** With Block error rate, TV signal are also operating in the same channel in this scenario. Currently backup channel mechanism is not implemented. In the simulator it is set that both base station and subscriber station will have backup channel. So when TV signal is detected, backup channel will be set to operating channel. Throughput for this case is shown in figure 4.8.

9. **Single cell with five transmission - considering TV signal, block error rate, backup channel**
   
   Same backup channels set for all subscriber stations and base station. So every subscriber station will switch to same backup channel when TV signal is been sensed. Block error rate loss is also activated. Throughput falling for this scenario is shown 4.9

10. **Multiple cell up to five transmission considering TV signal, block error rate**

    Same Five cells each with single base station and ten subscriber stations are considered here. Each base station is having five flows of transmission. TV interference is considered by setting TV transmitter channel, secondary users channel same. Block error rate is also set active. Data rate drop during the channel switching is calculated and shown in the figure 4.10.
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Throughput of QAM64_3/4 for 1 cell with 5 flows with Block Error Rate, TV signal and Backup Channel

Figure 4.9: single cell up to five transmission with backup channel - considering TV signal, block error rate

Throughput of QAM64_3/4 for 5 cells each with 5 flows with Block Error Rate, TV signal, backup channel

Figure 4.10: Multiple cell up to five transmission with backup channel - considering TV signal, block error rate
Chapter 4. Simulation Results: Scenario Setup with Case Scenarios, Experimental Results

<table>
<thead>
<tr>
<th>ModulationType</th>
<th>CodingRate</th>
<th>CodedBlockSize</th>
<th>UsefulBlockSize</th>
<th>BitsPerSymbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>BPSK</td>
<td>1/2</td>
<td>24</td>
<td>12</td>
<td>1</td>
</tr>
<tr>
<td>QPSK</td>
<td>1/2</td>
<td>48</td>
<td>24</td>
<td>2</td>
</tr>
<tr>
<td>QPSK</td>
<td>3/4</td>
<td>48</td>
<td>36</td>
<td>2</td>
</tr>
<tr>
<td>QAM16</td>
<td>1/2</td>
<td>96</td>
<td>48</td>
<td>4</td>
</tr>
<tr>
<td>QAM16</td>
<td>3/4</td>
<td>96</td>
<td>72</td>
<td>4</td>
</tr>
<tr>
<td>QAM64</td>
<td>2/3</td>
<td>144</td>
<td>96</td>
<td>6</td>
</tr>
<tr>
<td>QAM64</td>
<td>3/4</td>
<td>144</td>
<td>108</td>
<td>6</td>
</tr>
</tbody>
</table>

Table 4.3: Block Size and Bits Per Symbol for Modulation Types

4.3 Theoretical Throughput Calculation

UDP client is transmitting packet and the other end UDP server is receiving it. In MAC layer packets are added into burst and when the transmission allocation start, MAC layer net device will forward the burst to physical layer. Physical layer will break the burst into blocks and start transmitting through the channel. This block size is different for different modulation types. The block size for each modulation is shown in the table 4.3. Bursts are divided into blocks and one block contains 108 bytes if QAM64 3/4 is used.

4.3.1 Data Rate

Physical Layer Data rate is calculated based on the below formula.

\[
\text{Phy. Layer Data Rate} = \frac{\text{No. of Data Carriers} \times \text{Coding Rate} \times \text{Bits Per OFDM Symbol}}{\text{OFDM Symbol Time}}
\]

For Example, calculation for QPSK with code rate 1/2

\[
\frac{192 \times 0.5 \times 2}{0.000046} = 4.173 \text{Mbps}
\]

calculation for QAM64 with code rate 5/6

\[
\frac{192 \times 5/6 \times 6}{0.000046} = 20.86 \text{Mbps}
\]

Similarly, throughput in higher layer calculated based on the below description.
MAC layer throughput calculation:

1. Normally two fifth of the total symbols in a frame are given to downlink, two fifth of the symbols are in a frame given to uplink and rest of them for self coexistence window.

2. In case of intra frame quiet period scheduling one fourth of the total symbols are in a frame given to downlink, one fourth of the total symbols are in a frame given to uplink. In simulation program for every 16th frame intra frame quiet period scheduling is assigned. So an average of 82 symbols are alloted for uplink transmission.

3. Around average of 68 out of 82 OFDM symbols used to carry the higher layer data. Rest of the symbols in uplink subframe is allocated for transmitting the MAC control messages ranging message, bandwidth request message, service flow request message, Urgent coexistence message and invited ranging message.

4. Additionally, OFDM symbol padding and fragmentation header overhead is also has to be considered.

\[
MAC \text{ layer throughput} = \frac{68 \times \text{physical layer rate}}{215}
\]

IP layer throughput calculation: Packet size is 1044. Useful data from/to transport layer is 1024 bytes and IP Header is 20 bytes.

\[
IP \text{ layer throughput} = \frac{1024 \times MAC \text{ layer throughput}}{1044}
\]

UDP layer throughput calculation: UDP header data is 8 bytes and useful data is 1012 bytes

\[
UDP \text{ throughput} = \frac{1012 \times MAC \text{ layer throughput}}{1044} = \frac{1012 \times IP \text{ layer throughput}}{1024}
\]

4.4 Throughput comparison

If Backup Channels is been considered, then service interrupt is lesser. Otherwise, channel switching will take time up to 2 or 3 seconds depends upon the total channels considered. This can be seen clearly in the throughput graph results 4.2.
Chapter 4. *Simulation Results: Scenario Setup with Case Scenarios, Experimental Results*

<table>
<thead>
<tr>
<th>Modulation</th>
<th>Coding Rate</th>
<th>Physical Layer Data Rate (Mbps)</th>
<th>MAC Layer Data Rate (Mbps)</th>
<th>IP Layer Data Rate (Mbps)</th>
<th>UDP Data Rate (Mbps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>QPSK</td>
<td>1/2</td>
<td>4.17</td>
<td>1.31</td>
<td>1.26</td>
<td>1.24</td>
</tr>
<tr>
<td>QPSK</td>
<td>2/3</td>
<td>5.56</td>
<td>1.75</td>
<td>1.68</td>
<td>1.65</td>
</tr>
<tr>
<td>QPSK</td>
<td>3/4</td>
<td>6.26</td>
<td>1.97</td>
<td>1.89</td>
<td>1.86</td>
</tr>
<tr>
<td>QPSK</td>
<td>5/6</td>
<td>6.95</td>
<td>2.20</td>
<td>2.11</td>
<td>2.08</td>
</tr>
<tr>
<td>QAM16</td>
<td>1/2</td>
<td>8.35</td>
<td>2.64</td>
<td>2.54</td>
<td>2.50</td>
</tr>
<tr>
<td>QAM16</td>
<td>2/3</td>
<td>11.34</td>
<td>3.58</td>
<td>3.44</td>
<td>3.39</td>
</tr>
<tr>
<td>QAM16</td>
<td>3/4</td>
<td>12.52</td>
<td>3.95</td>
<td>3.80</td>
<td>3.75</td>
</tr>
<tr>
<td>QAM16</td>
<td>5/6</td>
<td>13.91</td>
<td>4.40</td>
<td>4.23</td>
<td>4.17</td>
</tr>
<tr>
<td>QAM64</td>
<td>1/2</td>
<td>12.52</td>
<td>3.95</td>
<td>3.80</td>
<td>3.75</td>
</tr>
<tr>
<td>QAM64</td>
<td>2/3</td>
<td>16.69</td>
<td>5.28</td>
<td>5.08</td>
<td>5.01</td>
</tr>
<tr>
<td>QAM64</td>
<td>3/4</td>
<td>18.78</td>
<td>5.93</td>
<td>5.71</td>
<td>5.62</td>
</tr>
<tr>
<td>QAM64</td>
<td>5/6</td>
<td>20.86</td>
<td>6.60</td>
<td>6.35</td>
<td>6.25</td>
</tr>
</tbody>
</table>

Table 4.4: Theoretical Data Rate for Modulation Types in All Layers
Chapter 5

Conclusion and Future Work

Simulation of White Space Network is implemented in NS3 simulator considering important aspects of 802.22. This work can be extended to add remaining aspects of 802.22 like aggregating channels, inter cell interference, OFDM to OFDMA conversion. White space network could be replacement for long distance transmission by wires. This technique can be used for rural area connection where lot of white space is available. Including the trace file results from field experiment into simulator will give lot of interesting analysis results. White space network can act as a backhaul for other networks. This white space concept can be extended to other bands like radar with some minimal changes.
Bibliography


