The SRAWAN MAC Protocol to Support Real-Time Services in Long Distance 802.11 Networks

by

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Abstract

The wireless communications market has grown rapidly since the introduction of 802.11 wireless local area networking (WLAN) standards in the 1990s. The 802.11 MAC was designed to be used in an indoor environment like small offices, home environment. It is based on CSMA/CA (carrier sense multiple access with collision avoidance) where flows cannot be guaranteed quality of service. The 802.11e provides QoS mechanisms to 802.11 WLANs to support bandwidth-sensitive applications such as voice and video. Despite, it was not tested well in long distance links. The challenge of using 802.11 hardware beyond its intended use, has shown in Digital Gangetic Plains project by forming long distance links using high gain antennas which spread the signal for tens of kilometers. Due to contention based channel access, huge round trip time in long distance links and hidden node problem, the 802.11 MAC protocol does not work well in long distance networks. In this thesis work, we try to overcome the above all mentioned problems by coming up with new MAC protocol to operate on point-to-multipoint long distance links.

We have designed, implemented and evaluated the new MAC protocol SRAWAN (Sectorized Rural Area Wireless Access Network) that gives better performance and QoS compared to the 802.11 MAC. The significant challenge here is while preserving the cost benefits of off the shelf 802.11 hardware, we need to implement new MAC protocol on top of the existing Atheros hardware. This we have done by taking the advantage of flexibilities provided by Atheros Madwifi driver of AR5212 chipsets. Outdoor experimental results shown that SRAWAN outperformed CSMA/CA by more than 40% for point-to-multipoint long distance links. We have implemented a fair scheduling among different flows by using the WFQ (Weighted Fair Queuing) scheduling discipline on top of the SRAWAN MAC protocol. This report also presents the performance evaluation of a WFQ scheduling scheme on SRAWAN MAC and shows that it provides guaranteed services. Experimental results shown better throughput results and also given quality of service for guaranteed bandwidth services when compared to very inefficient round-robin (RR) scheduling discipline or normal 802.11. WFQ scheduling algorithm also provides many more VoIP sessions(Ex: For a GSM6.10 codec, 802.11b provides 40 conversations) when compared with normal 802.11 MAC(11 conversations for same settings).

Acknowledgments

I would like to express my deep sense of gratitude to Dr. Bhaskaran Raman for his invaluable help and guidance during the course of this thesis. I am grateful to him for constantly encouraging me and for giving me new ideas during various phases of this project.

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Narasimha Reddy Puli
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Certificate

This is to certify that the work contained in the thesis entitled *"The SRAWAN MAC Protocol to Support Real-Time Services in Long Distance 802.11 Networks"*, by *Narasimha Reddy Puli*, has been carried out under my supervision and that this work has not been submitted elsewhere for a degree.

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Chapter 1

Introduction

802.11 [3] was originally developed for indoor purposes where multiple wireless nodes connect through an Access Point(AP) in their vicinity to a Wired LAN/Internet. 802.11 wirelesss technology has shown rapid growth since its inception in 1994. 802.11 WiFi has been accepted as a last-hop wireless solution in corporate environments and as well as home networks. Due to widespread acceptance of WiFi technology, open/inter-operable standard and competitive mass production of chipsets, the equipment and chip-sets cost has come down drastically (approx. costs: \$25-30 (chipset), \$120-700(Access point), \$60-110 (PCMCIA card) [1]). The indoor 802.11 WiFi technology has been used in long distance networks using high gain directional/sectored antennas like in [**?**] and [8]. The network models here in the consideration are point-to-multipoint long-distance links, envisioned to provide low-cost Internet connectivity to rural villages [1].

There has been a steady exponential growth of cellular networks and Internet for past one and half decades. The study of this growth by ITU [2] has shown that the growth of these technologies in the developing world is more lagging than in the developed world. And many kinds of studies by [2] have also shown that density of landline telephone network, cellular networks and Internet users is more in developed world than developing world. As the majority of developing world population is in rural areas, for example in India rural population constitutes 74% [1], hence the low tele-density in our country. Huge deployment costs of wired internet/cellular technologies and low population density of rural areas has made the use of these technologies non-viable in rural areas.

Digital Gangetic Plains (DGP) [8] project is an attempt to bring Internet and telephone networks to rural villages at a very low-cost compared to existing technologies. A large test-bed of about 10-15 nodes shown in Figure 1.1 spans several tens of kilometers, was built in the DGP project.

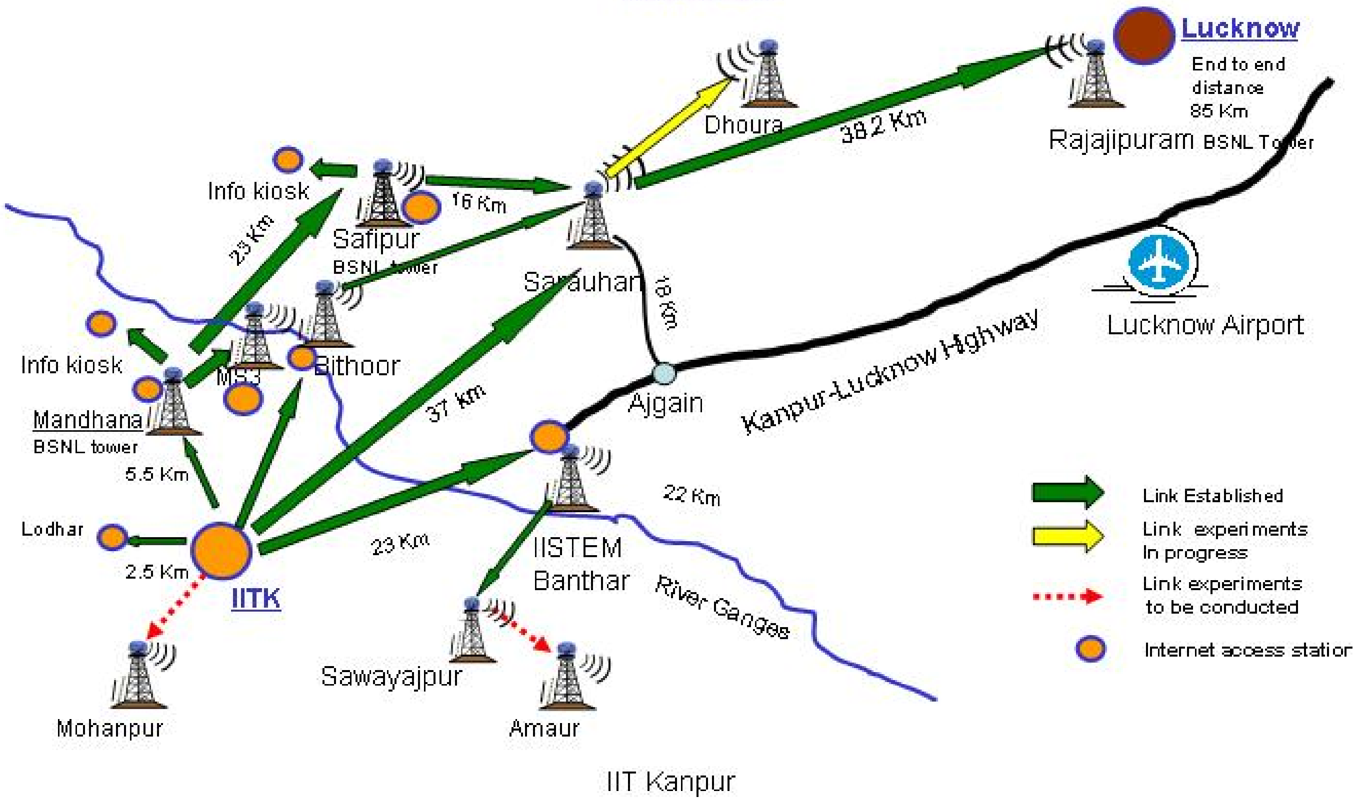


Figure 1.1: Hidden node problem in a Point to Multipoint network

Several operational and research challenges were tackled in this project. An experimental VoIP service was provided in a village (Sarauhan visible in Figure 1.1 which don't have a telephone to this day. DGP project has shown that low-cost 802.11 hardware can be used to establish long distance links which spread over tens of kilometers. But 802.11 MAC is a carrier sense multiple access with collision avoidance (CSMA/CA) based protocol and was designed to resolve contention in indoor environment where a small number of wireless nodes share a single channel. This contention based channel access mechanism is inefficient in long distance 802.11 WiFi networks. This is because of huge round-trip delay (air propagation delay is major part), increase of ack timeout and slot time to long distance point- to-point links [1]. Interference also reduces the efficiency of long-distance wireless links much further, because with increase in interference packet loss increases and so the propagation delay comes into picture many times.

In case of the network model we are considering (point to multipoint (P2MP)) hidden node problem causes interference which is shown in Figure 1.2. P2MP network is formed by placing a sectored antenna (or two directional antennas with a splitter) at node A and directional antennas at node C and A. While C is transmitting to A, B which cannot overhear the conversation from B to C, tries to transmit to A at the same time. And if the transmit power of antenna at node B is much more than the transmit power of antenna at node C this causes interference at node A and leads to packet collision.

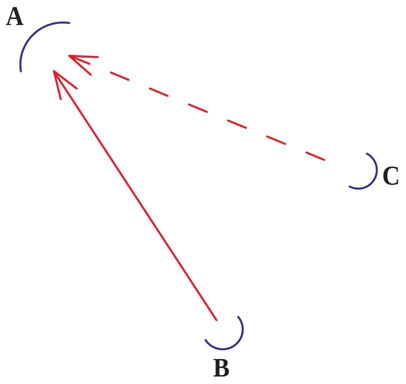


Figure 1.2: Hidden node problem in a Point to Multipoint network

Further, contention based protocols cannot provide guaranteed delay and/or bandwidth to real-time multimedia applications like voice, video, etc. With arbitrary contention, the throughput acheived is also variable with time. In order to provide guaranteed quality of service (QoS) to real-time services, generic contention based protocols are not suitable for the network models we are in consideration, since it contains arbitrary contention interval. A time division multiple access (TDMA) scheme is more appropriate to maximize the overall throughput of the network and also provides guaranteed bandwidth service and QoS to real-time services.

Problem Statement

The network model we are considering here is a point-to-multipoint (P2MP) network which is shown in Figure 1.3. P2MP network shown in Figure 1.3 has a landline connection to the central node called as Base station (BS) through which all the clients called Subscriber stations (SS) connect to this central node are provided Internet Connectivity. Sectorized antenna is placed on the tower of Base station node and Subscriber stations which are tens of kilometers apart form a wireless link with BS using directional antennas.

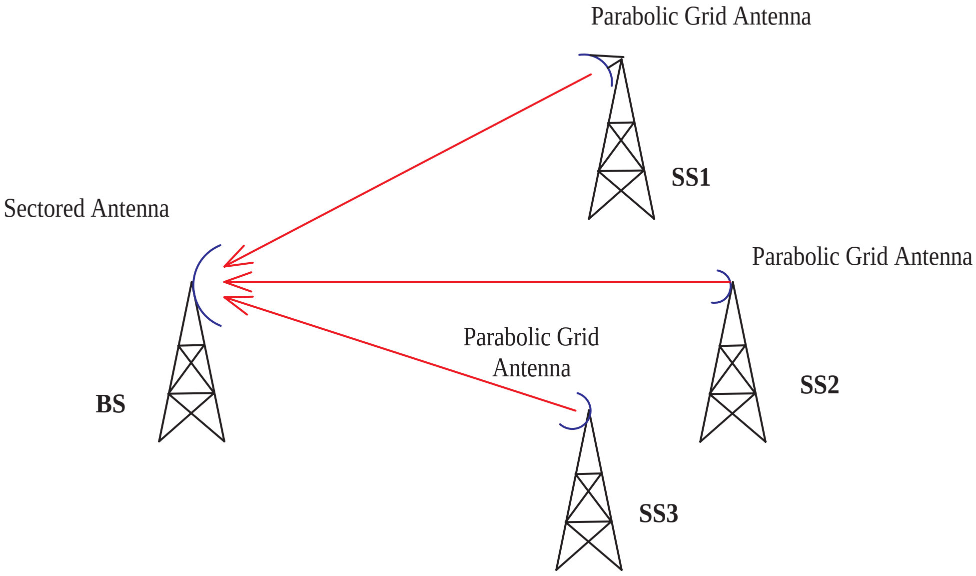


Figure 1.3: Network Model

Real-time multimedia applications like VoIP, Video by IP should be provided for above mentioned network model. Contention based protocols like 802.11a/b/g cannot solve the problem of hidden node problem at a cost of minimum overhead. In 802.11, VoIP performance is very poor in presence of coexisting traffic from other applications. Very few VoIP sessions can be supported due to various protocol overheads.

In this thesis work, we try to overcome all the above mentioned problems by coming up with new MAC protocol based on TDMA mechanism to operate in a P2MP network. This report essentially presents design, implementation, performance evaluation and analysis of TDMA-TDD based MAC that yields better results compared to normal 802.11 MAC. The

TDMA MAC design called SRAWAN (Sectorized Rural Area Wireless Access Network) is based on WiMAX MAC [4]. The challenge here is to intelligently select the minimal functionality from WiMAX in designing TDMA MAC and implement on top of the 802.11 PHY which is a very low-cost solution. In order to support QoS to real-time services, one of the best fair scheduling algorithms called *weighted fair queuing* (WFQ) is implemented on top of the SRAWAN MAC. Here is the list of significant questions that this thesis work tries to answer:

- How to implement totally new MAC protocol on top of off-the-shelf 802.11 to preserve the cost benefit?
- How does SRAWAN MAC behave in outdoor settings?
- How is tight time synchronization achieved between BS and SSs?
- What are the minimal functionalities to be picked up from WiMAX in designing SRAWAN that suits the requirement?
- Given a 802.16/802.11 implementation, how well does VoIP/Video/FTP traffic perform in such a setting?
- How many VoIP connections can SRAWAN/Bharani support?
- How well does WFQ perform in terms of delay experienced by the VoIP connections, in the presence of HTTP/FTP conncetions?
- What is effect of protocol overhead on the VoIP delay?
- How well does video perform in terms of delay with WFQ scheduling for uplink? How does this compare with the performance on the downlink?
- How does SRAWAN MAC perform in comparison with CSMA/CA?

Related work

Prior work related to QoS for real-time services is described in the following three subsections, then the problem statement of our thesis work is explained in detail.

Point Coordinated Function (PCF)[7]:

802.11 standard defines the PCF as an optional access mechanism, which enables the transmission of time-sensitive information [7]. In PCF, a point coordinator within the access point controls which stations can transmit during any give period of time. The point coordinator will step through all stations operating in PCF mode and poll them one at a time within a time period called as contention free period. For example, the point coordinator may first poll station A, and during a specific period of time station A can transmit data frames during which no other station can send anything. The point coordinator will then poll the next station and continue down the polling list, while letting each station to have a chance to send data. Thus, PCF is a contention-free protocol and enables stations to transmit data frames synchronously, with regular time delays between data frame transmissions. This makes it possible to more effectively support information flows, such as video and control mechanisms, having stiffer synchronization requirements.

Some of the disadvantages of using PCF are 1) To our knowledge the only access point that supports PCF is AOpen's WarpLink AOI-706 [7]. Most vendors like Cisco, Proxim access points do not support PCF. 2) The 802.11 standard is fairly vague in defining portions of the PCF protocol. As a result, you'd probably need to use the same vendor for the access points and radio cards to make it work properly. The Wi-Fi Alliance does not include PCF functionality in their interoperability standard. 3) Polling time of stations with empty queue is wasted unnecessarily.

802.11e MAC

IEEE 802.11e standard defines QoS mechanisms for 802.11 MAC that gives support to QoS-sensitive applications such as voice and video. 802.11e introduces two new protocols EDCF and HCF which are QoS enhancements of DCF and PCF access methods. EDCF does not solve the hidden node problem. 802.11e queues different priority level traffics into different hardware queues and the scheduler selects the packet from the high priority queue then transmits the packet from next highest priority queue. 802.11e standard is not implemented in many vendor chipsets. Implementation results of 802.11e performance analysis are not available and is not tested in real-time long distance wireless networks.

The Master-Slave protocol

Venkat in his thesis work [2] implemented a PCF like functionality in 802.11b at the driver level to support real-time multimedia streams in point-to-multipoint networks. This is a master-slave protocol where a central node called Master controls all the nodes called slaves in its network. Master decides the uplink time slots for slaves to transmit. Master-Slave protocol is different from PCF in the kind of operation, PCF operates in the Network interface card (NIC)whereas this protocol operates at the driver level giving more flexibility for implementing packet aggregation and various other schemes [**?**]. This thesis work has the following disadvantages in context of long distance point-to-multipoint networks: 1) Implementing PCF mode at driver level to suppress the behaviour of underlying DCF incurs lot of overhead (Ex. processing overhead) which is not suitable for providing Internet connectivity. 2) Due to high processing overheads delay-jitter values might be more and may not suit well for delay-intolerant VoIP kind of services. 3) Wastage of Bandwidth as, time slots remain unused when a polled slave has empty queue to transmit. 4) Protocol does not differentiate or prioritize between real-time and non-real time traffics. 5) Scalability issues are not addressed, experiments were conducted with a maximum of two VoIP slaves.

WiMAX

WiMAX is “a standards-based technology enabling the delivery of last mile wireless broadband access as an alternative to cable and DSL”[12]. WiMAX was formed in April 2001 to promote conformance and interoperability of the standard IEEE 802.16. The 802.16 MAC was designed specifically for the PMP wireless access environment. The IEEE 802.16 media access controller (MAC) is significantly different from that of IEEE 802.11 Wi-Fi MAC. In Wi-Fi, the MAC uses contention accessall subscriber stations wishing to pass data through an access point are competing for the AP’s attention on a random basis. This can cause distant nodes from the AP to be repeatedly interrupted by less sensitive, closer nodes, greatly reducing their throughput. And this makes services, such as VoIP or IPTV which depend on a determined level of quality of service (QoS) difficult to maintain for large numbers of users.

In contrast, the 802.16 MAC is a scheduling MAC where the subscriber station only has to compete once (for initial entry into the network). After that it is allocated a time slot by the base station. The time slot can enlarge and constrict, but it remains assigned to the subscriber station meaning that other subscribers are not supposed to use it but take their turn. The scheduling algorithm also allows the base station to control Quality of Service by balancing the assignments among the needs of the subscriber stations. The WiMAX hardware is too costly and WiMAX has too many functionalities which are not required in the scenario of providing Internet connectivity to rural villages.

Approach

In order to implement this SRAWAN MAC at the driver level , we have done modifications to Atheros driver Madwifi [11] on AR5212 Atheros chipsets (Ubiquiti SR2 and CM9 cards [?] which uses the same 802.11 PHY. To achieve this implementation we have exploited the flexibilities provided by Atheros HAL (Hardware Abstraction Layer) like disabling immediate MAC level acknowledgements, disabling RTS/CTS, disabling exponential backoff, disabling virtual carrier sensing(NAV) and disabling physical carrier sensing(CCA).

Assumptions

The following assumptions were made in this thesis work:

- All the nodes in the network are stationary
- The network is of 1-hop
- The communication from landline node to any of the remaining nodes is point to multipoint.
- Assumed that the traffic carried by the flows are already classified.

Summary of the results

The performance evaluation of SRAWAN MAC has shown significant overall throughput performance improvement of 40% in comparison with CSMA/CA due to lack of contention overhead, interference unlike in CSMA/CA. The theoretical calculations of VoIP capacity analysis have shown huge improvement of around 200% for 802.11bPHY and around 85% for 802.11a PHY in terms of maximum number of VoIP conversations. WFQ Scheduling algorithm on top of SRAWAN MAC has provided fair scheduling for all kinds of traffic. WFQ scheduling has shown that TCP traffic and VoIP traffic can coexist harmoniously.

Organization of the report

The thesis report is organized as follows. Chapter 2 gives a detailed description of SRAWAN MAC design and implementation. This chapter also presents theoretical estimate of throughput performance calculations of SRAWAN MAC. It also contains the theoretical calculations of VoIP capacity analysis for SRAWAN and 802.11b/a MACs. Then it is followed by the description and the effect of scheduling algorithm on top of the SRAWAN to support QoS for real-time traffic in Chapter 3. Chapter 4 describes the performance evaluation and analysis of the SRAWAN MAC. This chapter shows various experimental results that were conducted in outdoor for SRAWAN MAC and various experimental results that were conducted in indoor for WFQ - SRAWAN scheduling scheme. Performance comparison analysis is also presented in this chapter 4. Chapter 5 concludes the thesis report by summarizing the work done and gives ideas for future work in extending SRAWAN MAC to work in multi-sector networks.

Chapter 2

SRAWAN: Design and Implementation

SRAWAN (Sectorized Rural Area Wireless Access Network) is a TDMA MAC similar to 802.16 MAC designed to provide rural Internet connectivity. This was initiated through a project from a company called Zazu Networks, Bangalore. A novel idea of implementing a totally new MAC at driver level on existing off-the-shelf 802.11 hardware is achieved through this project. The MAC is designed for a point-to-multipoint long distance wireless network topogoly described clearly in network model section. This was designed combinedly by Dr. Bhaskaran Raman, the author and Pavan Kumar Surishetty in Indian Institute of Technology, Kanpur. This chapter is organized as follows. The chapter starts with design goals of this new TDMA MAC in section 2.1. Later section 2.2 is about the description of the architecture, frame structure and functional specifications of the MAC. Subsequently section 3 explains the implementation challenges and decisions taken while incorporating this MAC on 802.11 hardware are also clearly explained in this chapter. The chapter ends with the theoretical bandwidth calculations of SRAWAN MAC for all the three 802.11a/b/g PHYs in section 2.4.

2.1 Design goals

The goals of designing this new MAC protocol are listed as follows.

1. Provide low-cost Internet connectivity to rural villages through long distance wireless links that span tens of kilometers

2. Aimed to achieve better throughput efficiency than the normal 802.11

3. Provide tele-medicine, tele-education and tele-communication services to rural villages through the support of real-time services like *Voice over IP*(VoIP) and *Video over IP* applications

4. Standardize the TDMA MAC that can be implemented on 802.11 hardware.

2.2 Architecture

SRAWAN is designed for a point-to-multipoint network model as shown in the Figure 2.1. There are two kinds of entities in this network model called as Base station (BS) and Subscriber station (SS). These entities are static. BS is a centralized node which acts as a single point of control of the whole network. Generally BS is placed somewhere in city or town because this is the only entity in the network provided landline Internet connection. SSs are the client nodes placed in different villages obtain the Internet connection through BS. SSs and BS communicate through long distance wireless links using high-gain directional antennas. BS is equipped with either sector/omni-directional antenna to cover client nodes in its region. SS is equipped with a parabolic grid directional antenna facing towards the direction of BS.

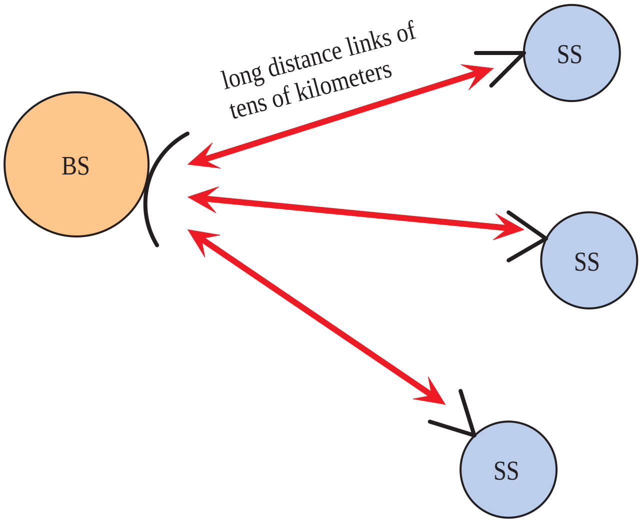


Figure 2.1: A point-to-mulitpoint system

BS decides when the SSs and BS should use the shared single channel. It is done through a *time division multiple access* (TDMA) mechanism. TDMA is used to share the same frequency channel among all the SSs and the BS by dividing it into different timeslots. The scheduler at BS allocates these timeslots for all SSs and BS using a centralized scheduling algorithm and broadcasts the scheduled timeslots to all the SSs in its region. SSs take this information and transmit/receive at their scheduled timeslots. The radio signals of uplink and downlink transmissions are separated through a *time division duplexing* (TDD) channel access method. In order to react correctly to the scheduled timeslots, all the SSs should be in tight time synchronization with BS. SRAWAN can also be called as simplified version of WiMAX, because most of the functionalities are picked up from WiMAX. As the design goals of SRAWAN are minimal and should work with off-the-shelf 802.11 hardware, it does not support all the complex functionalies(Ex.Mesh network model, FDD channel access method, Frequency range of 10-66GHz and so on).

2.2.1 Communication process

This subsection briefly describes about how BS and SS behave on booting up and progress further until they establish a connection between them to perform data exchange as shown in Figure 2.2. This communication procedure is explaned clearly with all the management messages transmitted in section 2.3.2 once the frame structure description is completed.

From the time BS boots up, it broadcasts the beacon packets informing the network about its presence. These beacon packets are sent into air periodically and continued for the whole period of BS running. Once an SS boots up, it scans for beacon packets in all the channels until it identifies any beacon with specified format. Once after identifying the BS (through beacon packet) in its coverage area, SS tries to communicate with BS in order to enter into the network of the BS. In its first phase of communication with the BS, SS tries to synchronize its clock with the BS clock. In WiMAX[10], this phase of operation BS sends the information about frequency, power and timing adjustments for SS in order to transmit SS in BS specified frequency, at minimum transmit power being in sync with BS. So, this phase is named as *ranging.* SS after being in time synchronization with BS, tries to register to this network. This phase of SS registering for BS network is called *registration.* In order to establish a new connection, SS should be already registered to that BS. Data exchange between SS and BS is done through a notion of *connection.* A single SS can establish more than one connection (each service flow can be carried by a

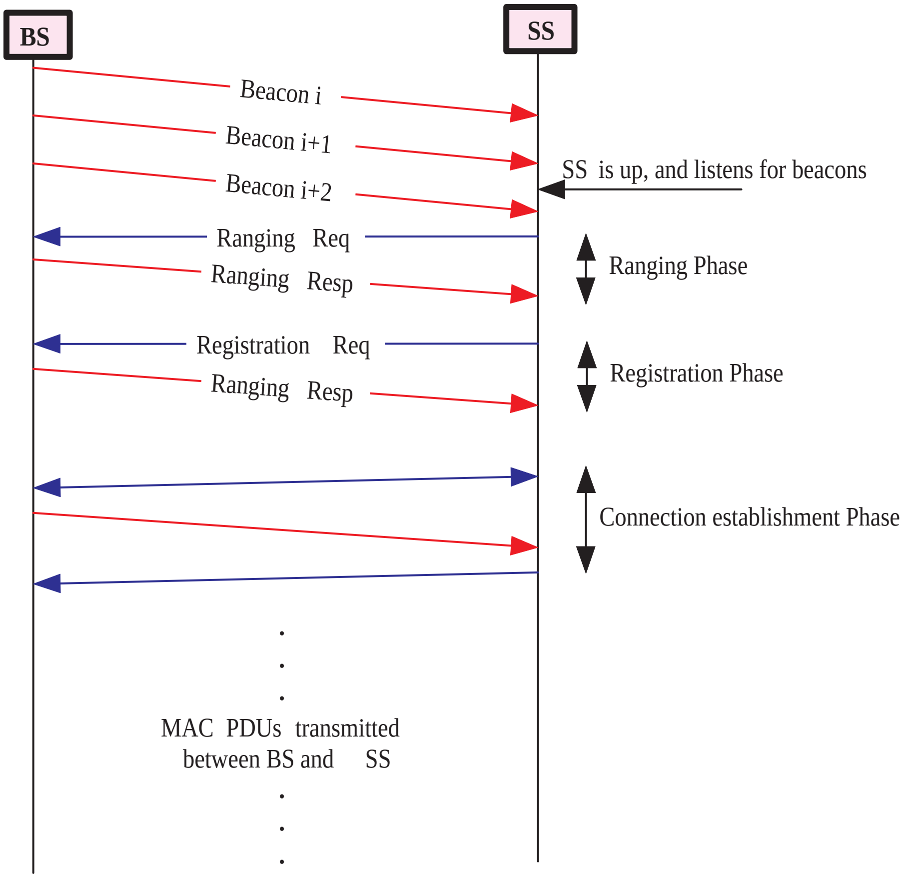


Figure 2.2: Communication process between BS and SS

different connection) with BS at the discretion of BS. Any SS in order to enter into the network of BS has to go through all the above management phases.

2.3 Frame Structure and Functional Description

2.3.1 Frame Structure

Frame structure during which the entities (BS and SS) in the network of the SRAWAN MAC exchange messages is shown in Figure 2.3. The frame is divided into *downlink* (DL) and *uplink* (UL) subframes. DL subframe is the period during which the packets are transmitted from BS to SS direction and UL subframe is the duration of packets transmitted from SS to BS direction. Both the subframes have specific formats. DL subframe starts with a beacon packet to inform the presence of BS in its coverage region. This beacon is broadcasted at minimum data rate so that these messages can cover a large area of region. This beacon packet contains the BS information like BSSID as an identifier of the network. The immediate next downlink transmission after beacon in DL subframe is the UL frame control information called as *frame control header* (FCH). The various control fields in FCH are *DL channel descriptor* (DCD), *UL channel descriptor* (UCD) and ULMAP described as follows.

- **DCD** contains the characteristics of the downlink physical channel information.
- **UCD** gives information about the characteristics of uplink physical channel and few other uplink parameters related to contention intervals bounds. The various fields in UCD are *minimum ranging contention window*(Rang_CwMin), *maximum ranging contention window*(Rang_CwMax), *minimum bandwidth request contention window*(Band_CwMin) and *maximum bandwidth request contention window*(Band_CwMax).
- **ULMAP** contains two or more entries of uplink channel access allocations to SS. UL scheduler at BS allocates UL timeslots to various SSs for their UL transmission of data/management packets. The two UL allocations that always exist in every ULMAP are initial ranging timeslots and bandwidth request timeslots. Initial ranging contention slots are used by SSs while joining the BS network. Bandwidth request contention slots are used for establishing new connection and to request the bandwidth demands.

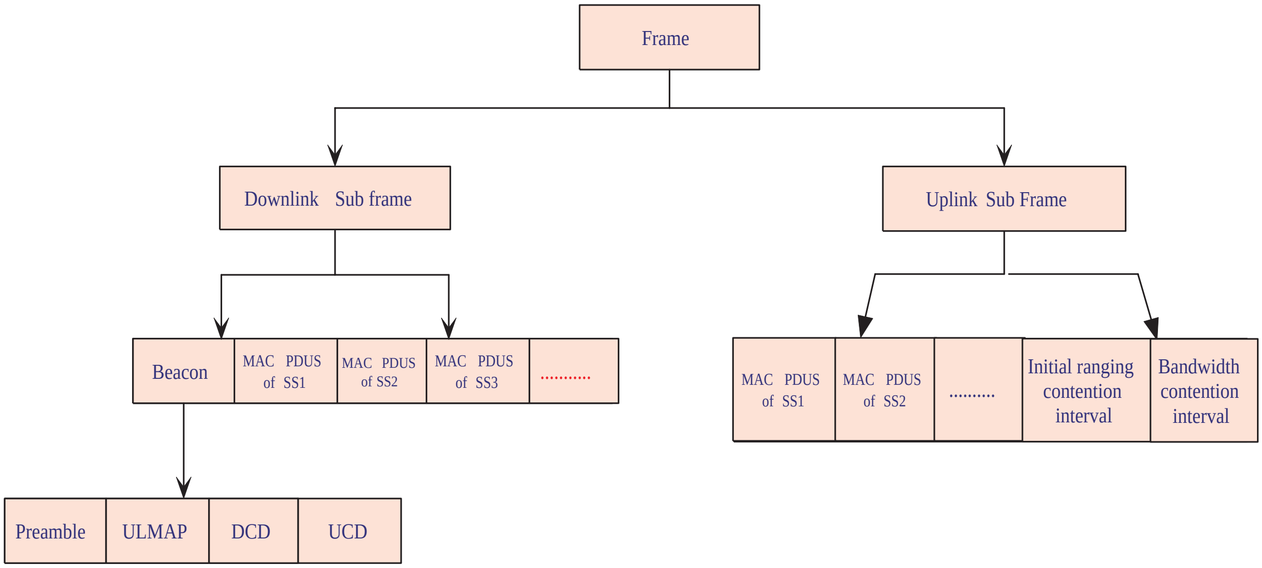


Figure 2.3: SRAWAN Frame structure

In WiMAX these fields of FCH are sent as separate messages, but here in SRAWAN, we encapsulate all these fields into beacon payload because, beacon is also broadcasted periodically and header overhead can be reduced by doing this. Beacon packets are followed by one or more MAC PDUs destined to individual SSs. These MAC PDUs include the management messages and data packets. The BS does not inform SSs about the DL traffic apriori as in WiMAX using downlink map (DLMAP) frame control field. In WiMAX, the DLMAP contains the control information of downlink slots during which packets transmitted by BS are destined to individual SSs. SS use this DLMAP information and sleep for an interval during which downlink packets are not destined to this SS to save the power in the DL. If we use this DLMAP in SRAWAN MAC, SSs go to sleep mode and wakeup at their time slot intervals. Due to these shifts from sleep mode to wakeup and so on SS might drift its clock and can go out of sync with BS. As we are not concerned much about power saving SRAWAN do not have this DLMAP control information in FCH. So, SSs have to wakeup all the time of operation and check all the packets in DL whether any packet is destined for it or not. Similarly in UL subframe also SS can go to sleep mode for the interval during which SS is not given UL slots. But here we are not much interested in power saving, SS is wakeup all the times during UL subframe also. Here ends the transmission of DL subframe after which UL subframe starts with a gap of guard time.

This gap is to prevent the packet collisions between downlink and uplink transmissions.

UL subframe consists of one or more UL MAC PDUs followed by initial ranging contention interval and bandwidth request contention interval (the reason behind this order is explained in implementation section 1.4). Initial ranging contention interval is the period during which SSs (that have just come up) contend to send the ranging request message to BS in order to timely synchronize with BS. Bandwidth request contention interval is the period during which registered SSs request for a new connection or established connections can request their bandwidth requirements to BS. The ranging, connection request and data slots may be present in any given frame, may consist of any number of slots, may appear in any order at the discretion of the BS uplink scheduler. These details are indicated in each frame by the ULMAP. An SS may transmit more than one MAC PDU if the BS allocates enough time slots for it in the ULMAP. In implementation SSs and BS may not be in tight time synchronization at required granularity. So non-ideal synchronization of clocks between BS and SS and non-availability of ideal timer interrupts, SSs might start their transmissions little earlier or little after the exact timeslots. Due to this, packet collisions might occur. This can be prevented by maintaining a gap between two different SSs' UL transmissions called as *guard time*. Guard times are maintained at different points in UL subframe as shown in Figure 2.4. The various points of guard time are

- Between end of DL subframe and start of UL subframe
- Between two SS UL transmissions
- Between initial ranging contention interval and bandwidth contention interval slots
- And also between two frames

MAC Protocol data unit format

The SRAWAN MAC PDU format for non-ARQed connections is as shown in Figure 2.5. It uses the 802.11 PHY for physical character encoding and also SRAWAN uses the whole 802.11 MAC header as it is along with a SRAWAN MAC header. The description of fields in SRAWAN MAC header shown in Figure **??** is as follows.

- *HT* stands for Header Type and shall be set to 0 [Note: WiMAX also allows HT=1 which denotes a bandwidth request header; this may be defined in the future for SRAWAN]

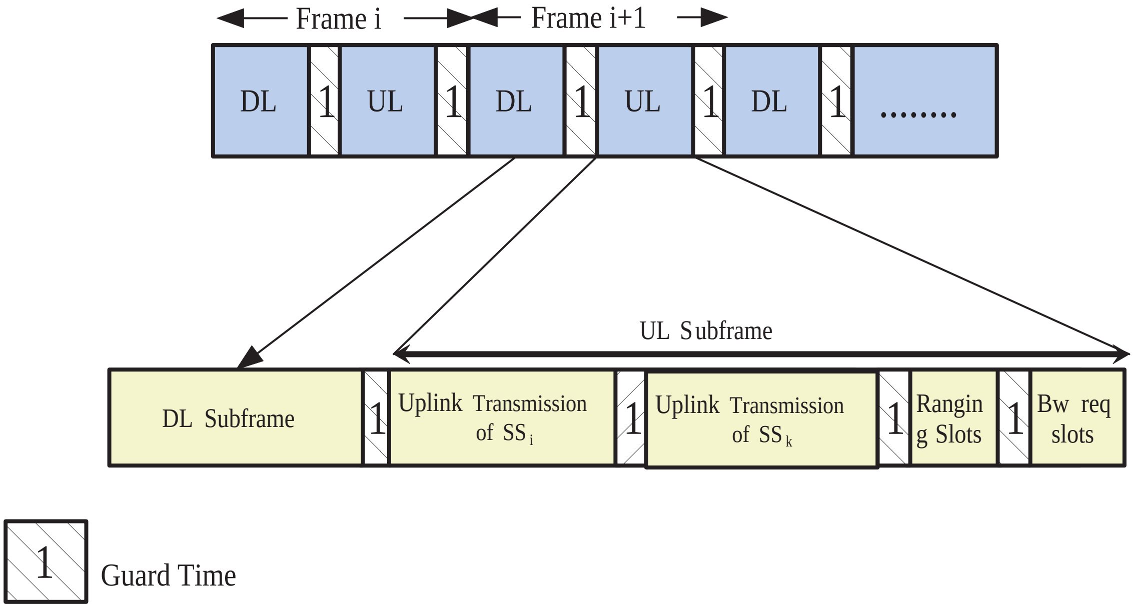


Figure 2.4: Guard times at various points in the frame structure

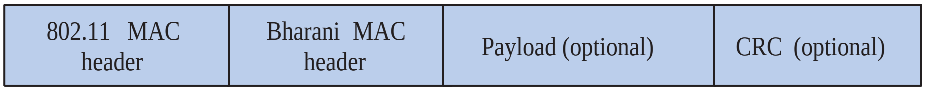


Figure 2.5: MAC PDU format

- *EC* denotes EncryptionControl. EC=1 if and only if payload is encrypted.
- The *Type* field has 6 bits:
  - Bit5(MSB): Is mesh subheader present? Always 0 for SRAWAN
  - Bit4: ARQ feedback payload present? Always 0 for SRAWAN
  - Bit3: Extended type: not relevant for SRAWAN, always 0
  - Bit2: Fragmentation subheader present? Always 0 for SRAWAN
  - Bit1: Packing subheader present? (only relevant bit for SRAWAN)
  - Bit0(LSB): Not relevant for SRAWAN, always 0
- *CI* stands for CRC Indicator; this is always 1 for SRAWAN
- *EKS* is Encryption Key Sequence: the index of the 802.1x key and Initialization Vector used to encrypt the payload (check 802.1x and revisit). This field is relevant only when EC=1 (PDU encryption is enabled).
- *LEN* is the MAC PDU length, including the header and CRC
- *Seq* is the 8-bit sequence number of the MAC PDU (for ARQ purposes)
- *CID* is the connectionID to which the MAC PDU belongs
- *Rsv* denotes reserved fields; they are always 0 for SRAWAN
- *SACK Map* is the SelectiveACKnowledgement map. It has 16 bits. Suppose the value of the ACKSEQ field is N. Bit0 (LSB) of the SACK map denotes whether or not sequence N+1 has been received. Bit1 denotes whether or not sequence N+2 has been received, and so on. Note that the sequence number additions above are all modulo 64.
- *ACK SEQ* is the next insequence expected MAC PDU sequence number in the reverse direction of the connection.
- *HCS* is the Header Check Sequence; this shall be similar to the WiMAX HCS, except that the rest of the fields (SEQ, ACK SEQ, and SACK Map) shall also be included in the computation.

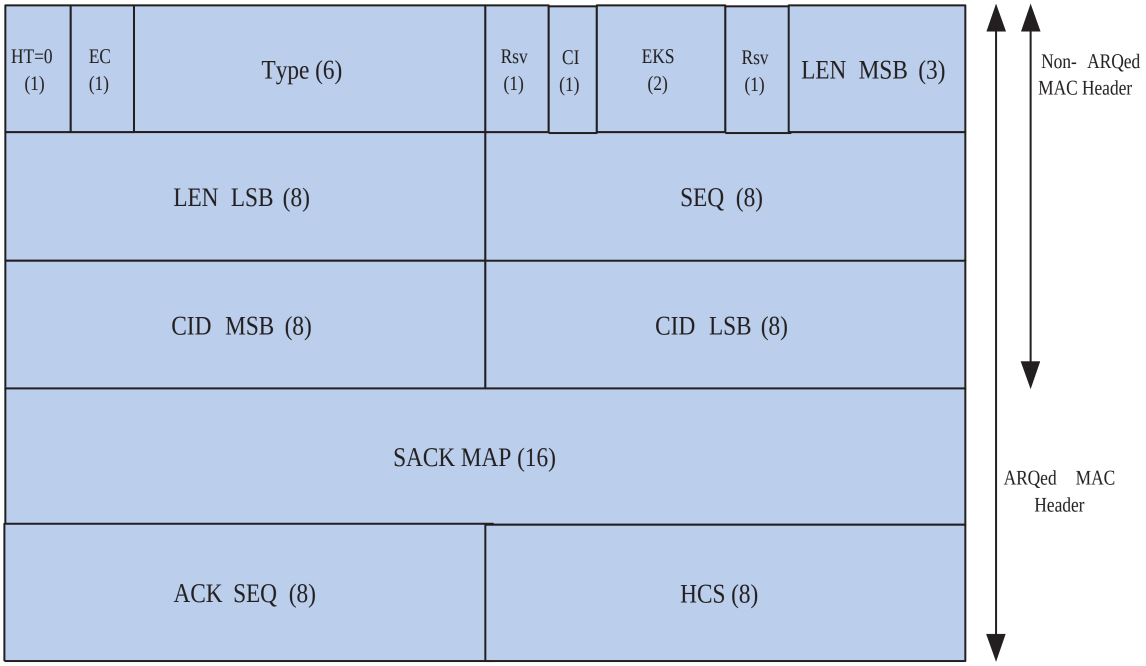


Figure 2.6: SRAWAN MAC header format

2.3.2 Functional description

This subsection describes the various phases that the entities in the network go through in order to enter into the network and perform data exchange. It also describes the various management messages that are exchanged in each phase of operation. First let us start discussing about the various phases that BS goes through. BS on booting up goes to run state and is remained in that state for all the times. In this phase of operation it broadcasts the periodic beacons with control information like network identifier (BSSID), UCD and ULMAP which are clearly explained in section 2.3.1. The next few sections will elucidate the various management phases that SS go through to enter into the network of BS for data exchange. The activity diagram of SS phase transitions is shown in Figure 2.7.

1. **Downlink Synchronization** [10]: On booting up, SS wishes to search for any BS network running in its region It enters into DL synchronization state as shown in Figure 2.7 and scans in all the channels available for a beacon packet with a specific format of preamble. Once SS finds a beacon packet of any BS, it extracts the control information fields (BSSID, Rang_CwMin, Rang_CwMax, timestamp) that are

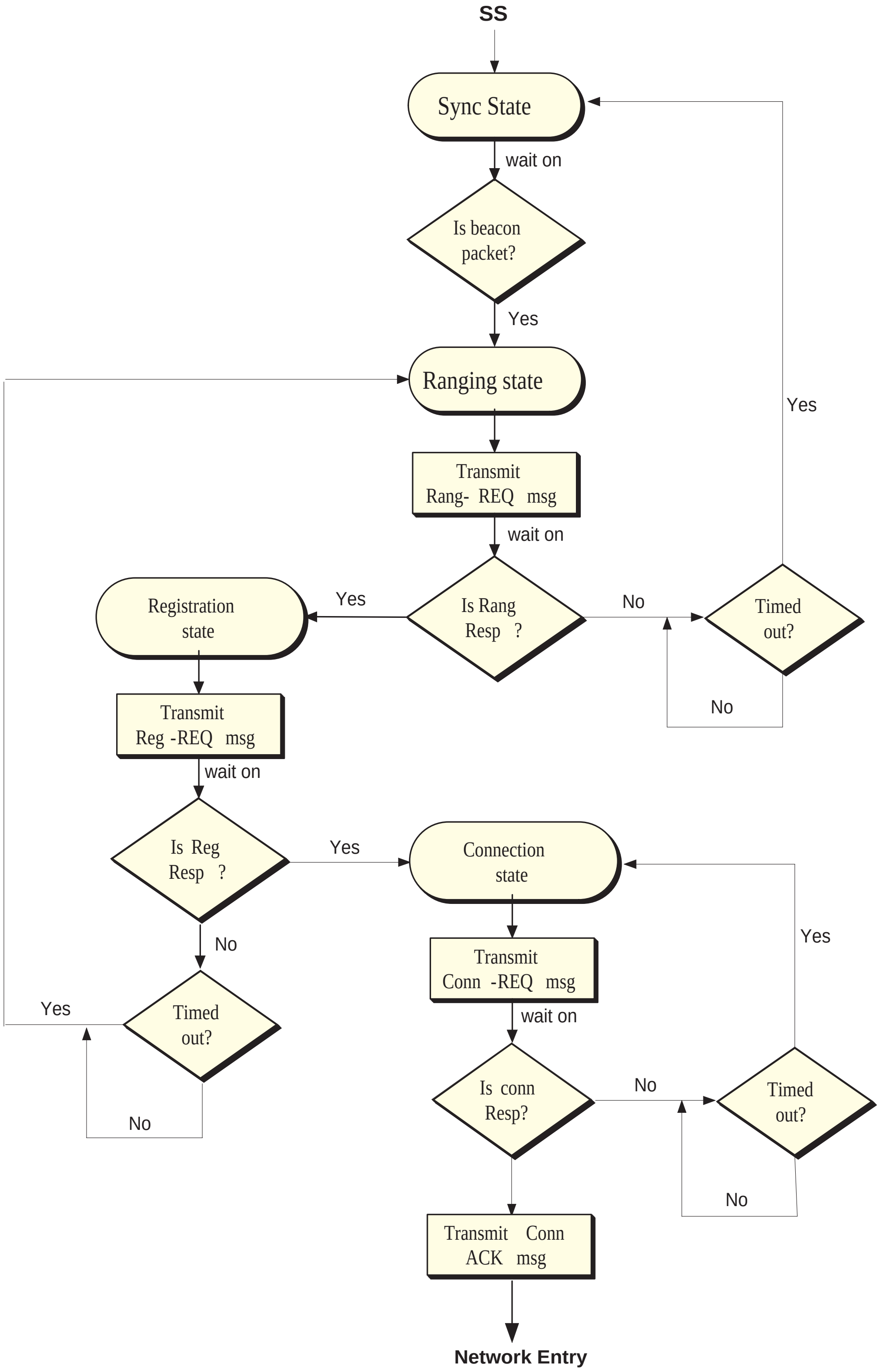


Figure 2.7: Network entry process of SS

required from the beacon payload and stores them to communicate with the BS in the initial ranging procedure.

2. **Ranging**: Ranging is the process through which the SS does the power and timings adjustments with the information obtained from the BS. Unlike 802.16, SRAWAN does not concern about the transmit power adjustments. The SS is configured with a frequency and transmit power value prior to booting. SS performs only time synchronization with the BS by sychronizing the clock of SS to BS's clock. Timing synchronizatoin is more important because this protocol should work for long distance links which are tens of kilometers apart (RF propagation delay can be in the order of 50-100 microseconds and also the processing delay at BS and SS is of the order of 100 microseconds). Uplink Ranging consists of two procedures: *initial ranging* and *periodic ranging*. Initial ranging allows an SS joining the network to acquire correct transmission parameters, such as time offset and transmit power level, so that the SS can communicate with the BS. Following initial ranging, periodic ranging allows the SS to adjust transmission parameters so that the SS can maintain uplink communications with the BS. An SS after extracting the control information from the initial beacon packet, enters into ranging phase. It uses the BSSID to specify the network to which it would like to enter and $Rang_CwMin/Rang_CwMax$ to randomly select the time slot in initial ranging contention interval to transmit the initial ranging request (iRang_Req) message. It also uses the timestamp in clock synchronization process. The SS extracts the initial ranging contention interval bounds by processing the ULMAP. It backoffs for a random number (bounded between Rang_CwMin and Rang_CwMax values) of timeslots in initial ranging contention interval and transmits the iRang_Req message. If it does not receive the ranging response back within the timeout period, the ranging request message is sent again with an incremented backoff period. This is continued until backoff period reaches its maximum allowed value, Rang_CwMax. BS after receiving a ranging request message from SS replies back with ranging response message(Rang_Resp) with mainly the following information in its payload.

    - Primary connection ID (CID) assigned by BS, used for identification SS to BS in all except one (periodic ranging request message) management messages exhanged in various management phases.

- Basic connection ID assigned by BS used as an identification of SS in periodic ranging messages. BS allocates slots for SS periodic ranging message with this ID.
- Clock adjustment information to SS calculated by BS through the parameters from SS in its ranging request message.

Time synchronization of SS with BS: The synchronization process of SS's clock with BS clock is explained in Figure **??**. Assume that T_{ss} is the current clock of SS. After receiving the first beacon, SS extracts the timestamp T_{stamp} from the beacon payload and sets its clock to this timestamp (at this point of time T_{ss} becomes T_{stamp}). The T_{stamp} in beacon payload was inserted by BS just before propagating into air. So the SS's clock is now slow by air propagation delay, d amount. The subscriber station sends the timestamp T_{stamp} value extracted from beacon and the time gap between the beacon reception and transmission of iRang_Req message. This time gap, T_{gap} is obtained by taking out the T_{stamp} from SS's current timestamp, T_{ss}.

After receiving the iRang_Req message from SS, BS will wait for the next downlink subframe to send the Rang_Resp. In the mean time BS takes the timestamp and time gap values from iRang_Req to calculate the air propagation delay between BS and SS as follows. The timestamp read from iRang_Req is the time at which the BS transmitted the iRang_Req. So the difference between BS's current clock (time at which Rang_Resp is received), T_{bs} and sum of two values ($T_{stamp} + T_{gap}$ read from iRang_Req gives the round trip time between BS and SS.

- Round trip time between BS and SS, RTT = $T_{bs} - T_{gap}$
- Propagation delay between BS and SS, d = RTT/2

The BS includes this RTT/2 value in the payload of Rang_Resp which is transmitted in next downlink frame. The SS then corrects its clock by incrementing its clock with this RTT/2 value becomes $T_{ss} + RTT/2$. The Rang_Resp encapsulates the following other information in its payload. SS MAC address, the $T_{stamp}+T_{gap}$ (which is nothing but the timestamp of SS at the time of transmission of iRang_Req) value, basic CID and primary CID (newly generated for this SS).

The SS after receiving the Rang_Resp first extracts the timestamp field in its payload. This timestamp is verified whether it is same as the timestamp value of SS at the

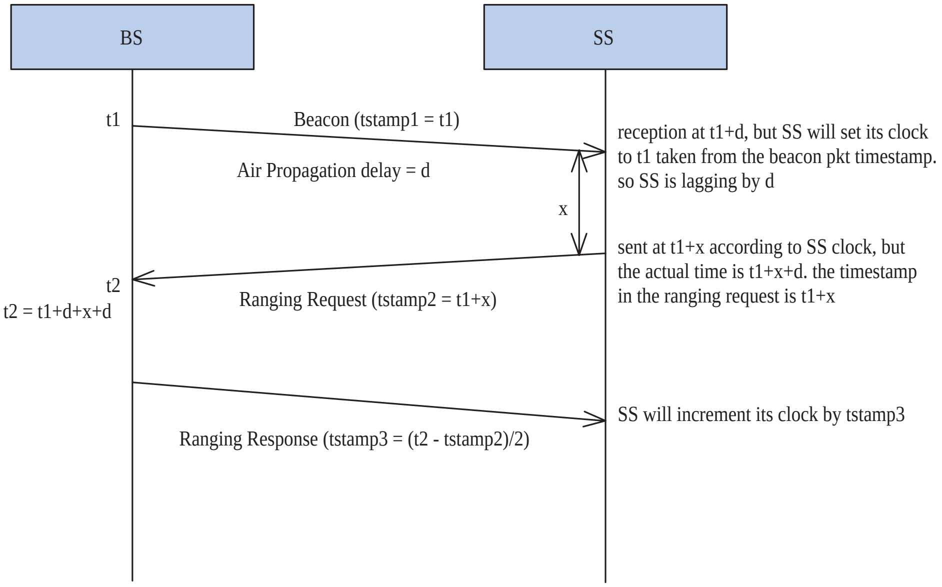


Figure 2.8: Time synchronization during Ranging

time of transmission of iRang_Req message. This verification is to confirm that this Rang_Resp message is generated for the last transmitted iRang_Resp message. If the verification is failed, it rejects the Rang_Resp message to go further forward. Instead if verification is successful, it extracts the other fields(Primary CID, Basic CID, clock adjustment value) from the Rang_Resp message and adjusts its clock by adding the clock adjustment value to its current clock.

3. **Registration**: After successful completion of initial ranging the SS registers with the network as shown in network entry diagram. Through Registration SS informs the BS that it is entering the BS's set of SSs serviced. In order to establish one or more connections for SS, it is required prior to register to BS. The SS sends a registration request message to the BS, and the BS sends a registration response to the SS. The registration request message uses primary CID in the generic mac header. BS identifies that this registration request is transmitted by the SS using SSs primary CID allocated which was assinged by BS.

In the next immediate frame of reception of ranging request message from SS, BS allocates uplink time slots for that particular SS to transmit registration request message. If the SS sends a registration request, then the BS will send a registration response in next immediate frame after which the SS can establish connections for data exchange. Instead the SS does not send a registration request in the uplink slots alloted frame, BS allocates uplink slots for registration request from SS after a timeout period, during which the BS did not receive any registration request from the SS. The timer is reset after allocating uplink slots. Like this BS allocates uplinks slots to the SS for a maximum of NUM_RETRANSMISSIONS times for a registration request message. If the SS does not send registration request message even after allocating uplink slots for 4 more times, BS clears the information of the SS and CIDs allocated to the SS. SS has to start again from ranging phase in order to enter into registration phase.

4. **Connection formation**: After registration, the SS can request for any number of further connections. SS can request for a new connection at any time after completion of registration. So, as the BS does not know when to allocate uplink slots for connection request for SSs. The bandwidth contention slots in the uplink subframe are used to transmit the connection request messages. Connection phase exchanges the information regarding the connection capabilities and the requirements for the connection. The information includes the type of service flow to be provided, QoS parameters required for the service flow, whether packing is to be enabled and if ARQ (Automatic Repeat Request)is to be enabled or not. Some of the QoS parameters of the service flow are the minimum reserved bandwidth, packet size indicator (whether SDU size is fixed or variable useful in packing) and the periodic interval (for real-time service flows like voice). SRAWAN supports all the types of scheduling services grouped mainly into four categories in 802.16. These categories are *Unsolicated Grant Service*(UGS), *Real-time Polling Service*(RTPS), *Non-real time Polling Service*(N-RTPS) and *Best Effort*(BE) traffic which are defined in below.

   When an SS want to establish a new connection, it sends a connection request message using the primary CID in bandwidth contention interval. The SS maintains a timer for connection response message to be received. On receiving this request message, the BS checks whether the new connection with the required quality of service parameters can be provided or not and also verify whether the requested capabilities like packing, ARQ can be provided on the BS side. In the next immediate DL subframe the BS transmits a connection response message with information like connection ID and confirmation of this new connection. If the BS can accomodate this new connection, it also allocates uplink slots in the same frame of connection response message for SS to send connection acknowledgement. SS transmits the connection acknowledgement in the uplink slots provided using connection ID. So connection establishment is a 3-way handshake similar to that in TCP. An SS can form more than one connection with the BS by requesting a new connection for every different service flow.

A connection is bidirectional and is identified by a connection ID. The same CID is used for communication from BS to SS, as well as from SS to BS. In the case of multiple connections between an SS and a BS, SRAWAN does not specify how traffic may be split across the various connections. There are two possible ways of filtering the traffic to different connections. First one is by considering P2MP network as a routed layer-3 network. Then BS or SS may present each of the connections as a separate interface to the routing layer. In such a case, the installation of routing entries will automatically define which packets go on which connection. An alternate possibility arises when the point-to-multipoint setup is considered as a bridged layer-2 LAN segment. Then the BS or SS may present each of the SRAWAN connections as a separate port to the bridging layer. In this scenario, the forwarding entries in the bridged network would define which packets are sent on which connection.

Scheduling services [4] : Scheduling services represent the data handling mechanisms supported by the MAC scheduler for data transport on a connection. Each connection is associated with a scheduling service type. Each scheduling service is associated with a set of QoS parameters which quantify aspects of its behavior. The four services are supported described below

- **UGS** supports real-time multimedia streams consisting of fixed-size data packets that are issued at periodic intervals. Generally used voice codecs (Ex. GSM6.10, G.710) generates packets of this kind of service, where the codecs generate fixed size packets at periodic interval. The QoS service flow parameters required for this scheduling service are minimum reserved bandwidth, periodic interval, tolerated jitter and packet size.
- **rtPS** supports real-time data streams consisting of variable-sized data packets that are issued at periodic intervals. *Moving Pictures Experts Group* (MPEG)

video codec generates variable size packets at regular intervals. This sheduling service flow type requires minimum Reserved bandwidth, periodic interval QoS parameters.

- **n-rtPS** supports delay tolerant data streams that generate variable-size data packets for which a minimum reserved bandwidth is required, Ex: FTP traffic. The QoS service flow parameters required are minimum reserved bandwidth and traffic priority. Traffic priority is used for priority among n-rtPS services.
- **BE** supports kinds of traffic for which no minimal-level bandwidth is required. So this service can be provided slots based on the availability. No mandatory QoS requirements are there for BE service. But, in order to implement the WFQ scheduling scheme BE services are also given minimum reserved bandwidth parameter which is taken as weight in scheduling.

5. **Authentication and Security**: SRAWAN does not define any new authentication or security mechanism. 802.1x authentication and security mechanisms are used in the point-to-multipoint setup, just as in a 802.11 infrastructure mode of deployment. SRAWAN does not impose any restrictions on data send in the packets (payload can contain anything) and also how to send the packets (packet payload can be encrypted). It only restricts when to send a packet. 802.1x authentication and security mechanisms rely on exchange of challenge-response messages and it does not lay any restrictions on when to send a response for a challenge (but the response should come in a limited period of time). So 802.1x security mechanisms can be used in SRAWAN for authentication and security. Primary CID can be used in exchange of messages in this phase.

6. **Packing**: The overhead of PHY preamble and MAC headers can be reduced by packing multiple MAC SDUs of a connection into a single PDU (provided the PDU size is less than Maximum Transmit Unit size). Packing significantly improves the throughput efficiency. If each SDU is sent separately, a lot of overhead is incurred due to PHY preamble and MAC headers for each SDU. If packing is used for fixed size SDUs, the packing headers are reduced further in which only one packing subheader is used for all the SDUs packed into a PDU as shown in Figure 2.9. But, in variable size SDU packing, each SDU has a packing subheader as shown in Figure 2.10.

   However, SRAWAN does not define MAC level fragmentation. This is because frag-

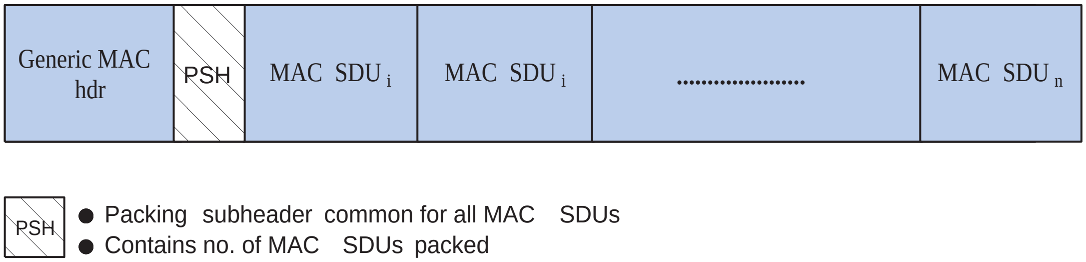


Figure 2.9: Packing format of fixed size SDUs

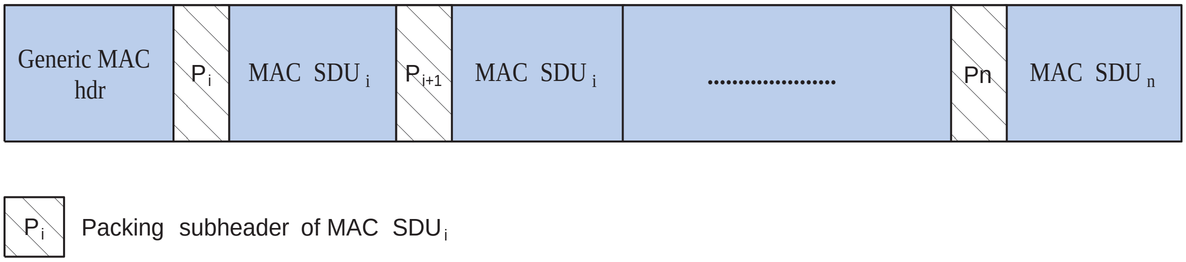


Figure 2.10: Packing format of variable size SDUs

mentation functionality is provided at IP layer which can be used by just specifying the maximum transfer unit (MTU). SRAWAN also defines concatenation of multiple MAC PDUs (belonging to same or different CIDs) each with a different PHY into a MAC PDU with asingle PHY layer overhead. This is similar to the concatenation in WiMAX. The MAC PDU format of concatenating multiple MAC PDUs belonging to different CIDs is shown in Figure 2.11

7. **Automatic Repeat reQuest (ARQ)**: This link layer protocol also provide reliable data transmission by retransmits of link layer frames. The SRAWAN MAC follows a selective ARQ mechanism with cumulative acknowlegement. SRAWAN

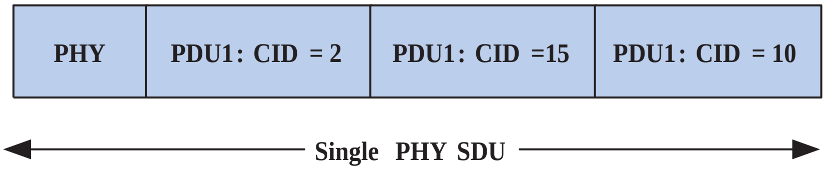


Figure 2.11: Concatenation of multiple MAC PDUs

uses a perconnection ARQ similar to WiMAX. But, it does not use the same complex ARQ mechanism like in WiMAX. SRAWAN significantly reduces the complexity of WiMAX ARQ mechanisms. ARQ state machine is maintained on both BS and SS for each ARQed connection. SRAWAN uses retransmissions at the granularity of MAC PDUs. This implies that every MAC PDU needs to have an independent CRC. Every MAC PDU has a 8-bit sequence number for ARQ purposes. A window based ARQ with selectiveACKs is used in SRAWAN. The maximum number of non-acknowledged packets that can be transmitted in sequence (which is nothing but a window size) are 16 (1/4th of the sequencen umber space). That is, there can be a maximum difference of 16 in the sequence numbers of the PDU to be sent and the last acknowledged PDU. Once sender receives a negative acknowledgement about a packet, it retransmit that packet for a maximum of 4 times. The receiver shall wait for a maximum of 4 tries of the sender, after which it shall assume that the PDU has been lost, and shall proceed as though the PDU has been received and sent up the network stack. The fields (SEQ, ACK SEQ and SACK MAP) used for ARQ mechanism are explained in detail in section 2.3.1.

2.3.3 Summary of the MAC Management Messages

SRAWAN MAC management messages are exchanged in the management phases and while periodic ranging. During all these exchanges, each of these messages use either primary CID or basic CID. This subsection gives an overview of all the management messages exchange and the also tells about the CID used for identification of these messages.

1. **Beacon**: Frame is started with this packet broadcasted by the BS on broadcast connection. This contains BSSID timestamp, DCD (contains BSSID), UCD (contains contention window bounds for contention intervals) and ULMAP which defines the uplink timeslots for various SSs in the subsequent. Broadcast CID is used for beacon packets

2. **Ranging Request**: This management message is transmitted by SS while initial ranging procedure or periodic ranging procedure to be in time synchronization with BS. Primary CID is used for initial ranging request and basic CID is used in periodic ranging request message.

3. **Ranging Response**: The BS respond to the SS initial ranging request with a ranging response which contains an SS MAC address, basic CID, primary CID and clock adjustment value. Both the messages are sent on initial ranging CID. All periodic ranging requests and their responses are sent on basic CID.
4. **Registration Request**: The SS after synchronizing its clock with BS, tries to register to the BS network using this message. This message is sent using primary CID
5. **Registration Response**: BS on receiving the registration request from some BS which has gone through ranging process confirms about the SS's registration into its list of SSs. This message is also sent using primary CID.
6. **Connection Request**, **Response** and **Acknowledgement**: These messages are used for the creation of a new connection in order start exchange of data between SS and BS.

2.3.4 Limitations of the scope of SRAWAN

The following issues are out of scope of SRAWAN specification

- What is the optimal scheduling of downlink and uplink subframes in order to achieve efficiency of two totally opposing performance metrics (throughput and delay)
- How the various SS may be placed or directed (to reduce interference)
- What the transmit powers of the BS and SS may be (again, to reduce interference)
- How various BS may operate in physical proximity of one another (they may use various frequencies of operation, or may adjust their transmit power to allow such operation)

2.4 Implementation details and Performance Estimation

This section describes how we solved the implementation challenges in building the SRAWAN MAC on top of Atheros AR5212 chipset of 802.11 hardware. This also describes various features incorporated in the SRAWAN. Parallely it describes the features enabled or disabled in Atheoros driver (MADWIFI: Multiband Atheoros Driver for WiFi) in this process of building SRAWAN MAC. We exploit the flexibilities of hardware abstraction layer (HAL) in Atheros AR5212 chipsets to enable or disable features of hardware.

The whole implementation can be described as three parts: Transmit path (Tx), Receive path (Rx) and other features common to transmit and receive path. First let us start discussing the features common to both and paths

1. **Common features**

    - Introduced two new modes of operation called as BS and SS in the *MADWIFI* driver which have their own state machine that goes through the various phases as explained in the section 2.3.2. The driver functionality of already existing modes like STA, AP and Monitor are not disturbed such that these modes of operation can also work without any deviations. So, totally the driver supports five modes of operation. The reason for implementing this is that SRAWAN is envisaged to work in a multi-sector network.
    - The unit of time in which the BS and the SS communicate is called timeslot, 10 microseconds in our implementation.
    - High Resolution timers are needed in order to synchronize the SSs and the BS as accurate as possible. In order to implement these we have used AR5212 hardware interrupts which can be generated to a microsecond granularity level.
    - The whole 802.11 MAC header is used as it is and SRAWAN MAC header is encapsulated between MAC payload and 802.11 MAC header. The reasons behind this are as follows. In 802.11, the packets are filtered based on BSSID is incorporated in hardware. So we want to use this functionality which is done much more faster than implementing this feature in driver. In order to this packet filtering functionality which is incorporated in hardware, we need to be in compliant with 802.11 MAC header.
    - The rate control module is incorporated into SRAWAN implementation. The proprietary rate control module is used at BS to get the rate at which SS should transmit its uplink packets.
    - ARQ mechanism is incorporated in SRAWAN MAC for retransmission of negative acknowledged packets. We build a selective ARQ with cumulative ac-

knowledgements. All the SSs and the BS maintain both the sender and receiver windows for each connection. The sender buffers the packets until their acknowledgements have reached or their maximum retransmissions are completed. The maximum number of times a packet is retransmitted is 4.

2. **Transmit path features**

   - Whenever a frame is ready in a queue to transmit into air using CSMA/CA, the queue control unit implemented in hardware gives control of frame to *DCF control unit* (DCU) which is also implemented in hardware in AR5212. The DCU is the unit which randomly chooses a backoff period and senses the availability of the physical channel (called as clear channel assessment(CCA)). Once the channel is free it decrements the backoff counter for duration of free channel until zero. Once this counter has reached zero,it propagates the packet into air after DIFS (DCF Interface Frame Space) amount of gap. But in our MAC protocol, BS schedules all the entities in its network when to transmits their share of packets. So, no entity is required to sense whether is channel is free or not. This is the reason why we tried to disable the clear channel assessment feature in hardware. But we are not fully successful in disabling this feature. However, by increasing the CCA threshold to a value where the hardware ignores any energy in the channel. In the same way, backoff contention mechanism is also not need in our TDMA MAC design, so we also disable the backoff feature by setting some hardware register bit through HAL. And also DIFS space is also nullified by setting the DIFS hardware register to zero.

   - In order to prevent the hidden node problem in CSMA/CA mechanism, virtual carrier sensing is incorporated in 802.11. If the virtual carrier sensing is enabled, whenever a sender wants to transmit, it first checks the NAV (Network Allocation Vector) to confirm when the channel becomes free. Once the channel is free it sends an RTS (Ready to Send) packet to receiver saying about that it want to use the radio channel for a specified amount of time. The receiver confirms about the channel is ready or not by sending CTS (Clear to Send) packet. Others who listen to the CTS update their NAVs. As SRAWAN is a TDMA MAC, it does not have this hidden node problem. So, the virtual carrier sensing (NAV) feature and RTS/CTS exchanges are disabled successfully.

3. **Receive path features**

    - On filtering the packet based on BSSID in CSMA/CA, if the packet is destined to this node it immediately does the CRC checking. If the verification result is correct after a SIFS (Short Inter-Frame Space) space it replies back with an immediate acknowledgement. As the frame structure is timely divided between the entities in the network, the possibility of collisions is very less. So, we are not interested in these immediate acknowledgements as in CSMA/CA.
    - Hence, we disabled immediate acknowledgements by setting the corresponding flags in a hardware register. The SIFS space is also nullified in the similar way.

4. **Few other implementation details**

    - As mentioned in design of SRAWAN, in our implementation SS does not scan all the available channels to choose among the BSs running in its region. SSs are configured to a specific channel
    - All the entities in the network transmit at thier maximum power levels.
    - Beacon packets are transmitted at minimum transmit rate possible in PHY (Ex. 1Mbps in 802.11b and 6Mbps in 802.11a/g). This is to ensure that farther SSs can also hear to beacons.
    - Our MAC supports all the 4 kinds of scheduling services that are classified in 802.16 as UGS, rtPS, n-rtPS and BE. In order to support this feature, each connection maintains its own packets in a separate software queue.

5. **Scheduling**: In the first phase of implementation, we used round-robin scheme of scheduling the connections at BS. Each connection is given fixed number (500usecs for each connection because MTU size of MAC PDU should be able to transmit at lower tx rates) of uplink slots in a round-robin fashion. If all the connections are not given slots in the same frame, next frame starts giving uplink slots from the connection stopped in earlier frame. During the downlink, the BS will schedule the packets in a round robin way described as follws. If a connection has packets to send, one packet is trasmitted and next connection is choosen. This is continued until either any more packet cannot be accomodated in downlink subframe or queues of all the connections are empty. This is very inefficient way of scheduling. In this

RR-scheme additional bandwidth requests are of no use. Real-time services cannot be provided guaranteed delay and or bandwidth bounds using this RR-scheme. VoIP traffic performance goes down in the presence of other applications traffic. In the second phase of implementation, we used *Weighted Fair Queueing* (WFQ) scheme of scheduling the connections at BS described in detail in section 3. This scheduling scheme provides QoS to all the kinds of scheduling services that are briefed in section connection formation. This WFQ scheme also enables any kind of traffic to co-exist harmoniously with their required service quality.

2.4.1 Theoretical throughput performance estimation

Here in this subsection we will do the theoretical calculations of maximum throughput that can be achieved by *Bharani* implementation for all the three 802.11a/b/g PHYs

- Frame duration in our implementation is fixed and is 10msec. There is a trade-off between throughput and response delay with the frame duration. With large frame duration, the overall throughput increases due to overhead including less number of times in a period, but the response time increases because of increase in gap between start UL subframe and next DL subframe or vice versa. With small frame duration, the overhead of ranging, bandwidth contention, guard times and beacon packets are included more number of times compared with the case of large frame duration, hence the overall throughput goes down. But as the gap between start of UL subframe and next DL subframe or vice versa is decreased, the response delay decreases. The optimal frame duration can be obtained by testing the throughput-delay values at various frame duration values and selecting the one at which desired throughput-delay performance is required.

- Downlink : Uplink - Any ratio of DL and UL does not effect overall throughput that can be achieved. But as we are concerned about the support of maximum number of VoIP conversations which consist almost equal amount of data exchange on both sides, both the durations are of equal size. So DL:UL = 1:1

  Downlink duration = 5msec (includes beacon time, data transmission time and guard time between DL and UL subframes)

  Uplink duration = 5msec (includes data transmission time, one or more guard times between uplink transmissions of different connections, guard time between UL data slots and initial ranging interval, guard time between initial ranging contention interval and bandwidth request contention interval, guard time between bandwidth contention interval and next frame, initial ranging contention interval and lastly bandwidth contention interval)

- Time slot size - 10 microseconds, ULMAP allocation is given in time slot units.

- Data transmission times in both DL and UL are obtained by first calculating incurred overheads in both DL and UL subframes and then taking them out from respective subframe durations.

- DL data transmission time:

  Beacon transmission time - beacons are transmitted with lowest rate possible 1Mbps with long preamble in 802.11b and 6Mbps in 802.11g/a.

  Guard time between DL subframe and UL subframe is 200usecs

  In 802.11b transmission time = ≅700usecs $(192 + (26 + 6 + 30) * 8)$

  In 802.11g/a transmission time = ≅110usecs $(20 + (26 + 6 + 30) * 8/6)$

  So, in 802.11b the DL data transmission time is = ≅4.1 msec $(5000usecs - (700 + 200)usecs)$

- UL data transmission time:

  Initial Ranging contention slots = 200usecs, because the ranging request message can be sent at any rate between 2Mbps to 54Mbps. The maximum transmission time of this message is when it is transmitted at 2Mbps is ≅200usecs.

  Bandwidth request contention slots = 200 usecs, because of the same reason mentioned above.

  Guard time between above two contention slots = 200usecs

  Guard time between UL data transmission and Initial ranging contention interval = 200usecs

  Guard time between bandwidth contention interval and next frame = 200usecs

  If there are more than one SS uplink transmissions, there exists guard time of 200usesc between contiguous two transmissions.

Assuming only one SS uplink data transmission (for maximum throughput estimation) the UL data transmission time for all three 802.11a/b/g = ≅4msecs ($5000 usecs - 5 * 200 usecs$), 400 timeslots

- Let us calculate the throughput values for DL and UL individually
- With an MTU size of 1500bytes, the size of MAC PDU in SRAWAN MAC will be = $1500+26+6+8 = 1540$ bytes (26 bytes of 802.11 MAC header, 6 bytes of SRAWAN MAC header and 8 bytes of LLC header)
- Assumption of all the packets of same size(MTU) is made. In maximum throughput calculations the transmit rate of 802.11b is 11Mbps and for 802.11g/a is 54Mbps

1. **802.11b**
    - MAC PDU (of MTU size) transmission time at 11Mbps = $96 + 1540 * 8/11$ = 1216usecs, 122 timeslots
    - So, in a DL data transmission time of 4.1msecs maximum of 3 MAC PDUs can be transmitted ($3 * 1216 = 3648 usecs$)
    - similarly in an UL data transmission time of 4msecs(400 timeslots), maximum of 3 MAC PDUs can be transmitted (3 * 122 = 366 timeslots)
    - So maximum number of MAC PDUs in both DL and UL is 6 ($3 + 3$)
    - The overall throughput that can be acheived at the MAC layer is $6 * 1540/10 MBps = 7.39 Mbps$
    - Effective throughput at the transport layer is $6 * (1540 - 26 - 6 - 20 - 8 - 8) * 8/10 MBps = 7.07 Mbps$ (20 bytes of ethernet header and 8 bytes of UDP header)
    - With MTU size of 1500bytes, approximately 450usecs of downlink subframe and 350usecs of uplink subframe are left unused. This is due to the case that one more MTU size MAC PDU cannot be accomodated in times left. So, let us see the effect of reduced MTU size (1000 bytes).
    - MAC PDU (MTU size of 950bytes) transmission time at 11Mbps = $96 + 990 * 8/11$ = 816usecs which is nothing but 82 timeslots
    - So, Maximum number of MAC PDUs transmitted in a DL data transmission time of 4.1msecs ($4100/816 \cong 5$)

  - similarly in an UL data transmission time of 4msecs(400 timeslots), maximum of 5 MAC PDUs can be transmitted (5 * 82 = 410 timeslots)
  - So maximum number of MAC PDUs in both DL and UL is 10 $(5+5)$
  - The overall throughput that can be acheived at the MAC layer is $10*990*8/10MBps = 7.92Mbps$
  - Effective throughput at the transport layer is $10*(990-26-6-20-8-8)*8/10MBps = 7.38Mbps$ (20 bytes of ethernet header and 8 bytes of UDP header)
  - Time taken for transmission of 1010 byte packet at 11 Mbps $= 1010*8/11$ usec $=$ 1098 usec

2. **802.11a/g**: PHY overhead is 20usecs [6], maximum data rate is 54Mbps
  - MAC PDU (of MTU size) transmission time at 11Mbps $= 20+1540*8/54$ $=$ 248usecs, 25 timeslots
  - So, in a DL data transmission time of 4.1msecs maximum of 16 MAC PDUs can be transmitted (4100/248)
  - similarly in an UL data transmission time of 4msecs(400 timeslots), maximum of 16 MAC PDUs can be transmitted $(400/25 = 16)$
  - So maximum number of MAC PDUs in both DL and UL is 32 $(16+16)$
  - The overall throughput that can be acheived at the MAC layer is $32*1540/10MBps = 39.42Mbps$
  - Effective throughput at the transport layer is $32*(1540-26-6-20-8-8)*8/10MBps = 37.68Mbps$ (20 bytes of ethernet header and 8 bytes of UDP header)
  - With MTU size of 1500bytes, approximately 132usecs of downlink subframe and 32usecs of uplink subframe are left unused. This is due to the case that one more MTU size MAC PDU cannot be accomodated in times left. So, let us see the effect of increase in MTU size to 2000 bytes.
  - MAC PDU (MTU size of 2000bytes) transmission time at 54Mbps $= 20+2040*8/54 = 320$usecs which is nothing but 32 timeslots
  - So, Maximum number of MAC PDUs transmitted in a DL data transmission time of 4.1msecs ($4100/320 \cong 13$)

- similarly in an UL data transmission time of 4msecs(400 timeslots), maximum of 12 MAC PDUs can be transmitted ($400/32 = 12$)
- So maximum number of MAC PDUs in both DL and UL is 10 ($13 + 12$)
- The overall throughput that can be acheived at the MAC layer is $25 * 2040 * 8/10MBps = 40.8Mbps$
- Effective throughput at the transport layer is $25 * (2040 - 26 - 6 - 20 - 8 - 8) * 8/10MBps = 39.44Mbps$ (20 bytes of ethernet header and 8 bytes of UDP header)

The throughput performance estimations for 802.11a/b/g at different MTU sizes is shown in Table 2.1.

MTU Size (bytes)	SRAWAN MAC throughput with 802.11b PHY	Effective TCP throughput with 802.11b PHY	SRAWAN MAC throughput with 802.11a/g PHY	Effective TCP throughput with 802.11a/g PHY
950	7.92 Mbps	7.38 Mbps	38.02 Mbps	35.4 Mbps
1500	7.39 Mbps	7.07 Mbps	39.42 Mbps	37.68 Mbps
2000	6.53 Mbps	6.31	40.8 Mbps	39.44 Mbps

Table 2.1: MAC and TCP layer throughput estimations using SRAWAN MAC

2.4.2 Theoretical VoIP Capacity Estimation and Analysis

This subsection does theoretical calculations of maximum number of VoIP conversations that can be supported by SRAWAN in several cases with all the three 802.11 b/g/a PHYs individually. We then compare these results with VoIP capacity values of CSMA/CA. The different scenarios in which these calculations were done are:

1. **Case 1:** With guard time of 200usecs because of the time skew of around 150 - 200usecs in BS and SS clock

2. **Case 2:** Assuming tight time synchronization is achieved between BS and SS, we use a guard time of 50usecs and equal ratios of DL and UL subframes

1. **VoIP capacity estimation in case 1: Guard time of 200usecs**

- Frame duration, $frame\_len$ = 10msec, the reason for this value is described in section 2.4.1
- Downlink : Uplink = 1:1
- Downlink duration = 5msec (includes beacon time, data transmission time and guard time between DL and UL subframes (200usecs))
- Uplink duration = 5msec (includes data transmission time, one or more guard times between uplink transmissions of different connections, guard time between UL data slots and initial ranging interval (200usecs), guard time between initial ranging contention (200usecs) interval and initial ranging contention interval (200usecs))
- Time slot size - 10 microseconds, ULMAP allocation is given in time slot units.
- The maximum transmit rate of 802.11b is 11Mbps and for 802.11g/a is 54Mbps
- Data transmission time in DL subframe
  - In **802.11b** $DL\_SDU\_TRANS\_TIME$ = 4.1msecs (700usecs for beacon and 200usecs of Guard time)
  - In **802.11a/g** $DL\_SDU\_TRANS\_TIME$ = 4.69msecs (110usecs for beacon and 200usecs of Guard time)
- Data transmission time in UL subframe
  - With guard time of 200usecs, $UL\_SDU\_TRANS\_TIME$ with **802.11b** or **802.11a/g** is = 4.4msecs
- Let us calculate the VoIP packet transmission time, t:
- Assume $interval$ is the framing interval of voice codec, $frame\_len$ is the length of frame, $GUARD\_TIME$ is the guard time
- As UL includes guard time between two different SS UL transmissions, let us find the number of VoIP packets that can be transmitted in UL subframe.
- So, Number of conversations that can be carried out in a single frame, $N_f = = UL\_SDU\_TRANS\_TIME/(t + GUARD\_TIME)$
- The voice codecs generate packets at a periodic interval, so the maximum number of conversations that can be carried with a minimum delay is nothing but the product of N_f and the number of frames that can be accomodated in a inter-packet arrival gap.

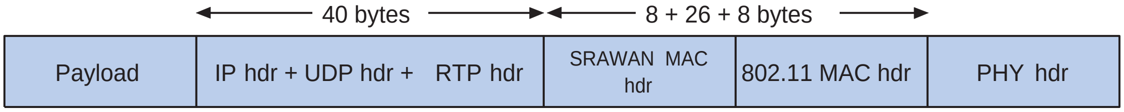


Figure 2.12: VoIP MAC PDU format in SRAWAN MAC

- $VoIP\_Capacity = N_f * (interval/frame\_len)$
- VoIP packet format is shown in Figure 2.12

  For a GSM.610 voice codec using 802.11b PHY

  - GSM 6.10 Codec parameters $interval$ = 20msecs, payload = 33 bytes is shown in Table 2.2
  - VoIP Packet transmission time, $t = (33+40+42)*8/11+96 \cong 180usecs, 18timeslots$
  - $N_f = UL\_DATA\_TIME/(t + GUARD\_TIME) = 440timeslots/(18 + 20)timeslots \cong 11.6$
  - $VoIP\_Capacity = N_f*interval/frame\_len = 11.6*20/10 = 23.2conversations$

  For a GSM.610 voice codec using 802.11a/g PHY

  - Maximum transmit rate is 54Mbps and PHY overhead is 20usecs
  - VoIP Packet transmission time, $t = (33+40+42)*8/54+20 \cong 37usecs, 4timeslots$
  - $N_f = UL\_DATA\_TIME/(t+GUARD\_TIME) = 440timeslots/(4+20)timeslots \cong 18.3$
  - $VoIP\_Capacity = N_f*interval/frame\_len = 18.3*20/10 = 36.6conversations$
- The VoIP capacity of SRAWAN for all the codecs in Table 2.2 and the performance(in terms of maximum no. of VoIP conversations) improvement with CSMA/CA using 802.11b PHY and guard time of 200usecs is shown in Table 2.3

  The Table 2.3 describes that using 802.11b PHY, there is an average improvement of 98% in maximum number of VoIP conversations in SRAWAN MAC when compared with CSMA/CA
- The VoIP capacity of SRAWAN for all the codecs in Table 2.2 and the performance(in terms of maximum no. of VoIP conversations) improvement with CSMA/CA using 802.11a/g PHY and guard time of 200usecs is shown in Table 2.4

Codec	**GSM 6.10**	**G.711**	**G.723.1**	**G.726-32**	**G.729**
Bit rate (Kbps)	13.2	64	5.3/6.3	32	8
Framing interval (ms)	20	20	30	20	10
Payload (Bytes)	33	160	20/24	80	10
Packets /sec	50	50	33	50	50*

Table 2.2: Attributes of commonly used CODECS

Codec	**Ordinary 802.11 VoIP capacity**	**SRAWAN VoIP Capacity**	**Percentage Improvement**
GSM 6.10	11.2	23.2	107%
G. 711	10.2	19.4	90%
G. 723.1	17.2	35.7	107%
G. 726 - 32	10.8	21.4	98%
G. 729	11.4	23.8	108%

Table 2.3: SRAWAN VoIP capacity comparison with CSMA/CA in 802.11b with guard time of 200usecs

Codec	**Ordinary 802.11 VoIP capacity**	**SRAWAN VoIP Capacity**	**Percentage Improvement**
GSM 6.10	56.4	38.3	-32%
G. 711	51	35.2	-31%
G. 723.1	86.1	57.4	-33%
G. 726 - 32	54.3	36.7	-32%
G. 729	57	38.3	-33%

Table 2.4: SRAWAN VoIP capacity comparison with CSMA/CA in 802.11a/g with guard time of 200usecs

The Table 2.4 describes that using 802.11g/a PHYs, the VoIP capacity has come down by an average of 33% when compared to CSMA/CA. The reason behind this is described as follows. At 54Mbps more number of VoIP packets can be accomodated in given UL data frame. But due to large guard time of 200usecs between each VoIP packet transmission, the maximum number of VoIP packets in an UL subframe are restricted to be less and hence the VoIP capacity came down.

2. **VoIP capacity estimation in case 2: Guard time of 50usecs**

- Data transmission time in DL subframe
  - In **802.11b** $DL\_SDU\_TRANS\_TIME$ = 4.25msecs (700usecs for beacon and 50usecs of guard time)
  - In **802.11a/g** $DL\_SDU\_TRANS\_TIME$ = 4.84msecs (110usecs for beacon and 50usecs of Guard time)
- Data transmission time in UL subframe
  - With guard time of 50usecs, $UL\_SDU\_TRANS\_TIME$ in **802.11b** or **802.11a/g** is = 4.85msecs

  For a GSM.610 voice codec using 802.11b PHY

  - GSM 6.10 Codec parameters $interval$ = 20msecs, payload = 33 bytes is shown in Table 2.2
  - VoIP Packet transmission time, $t = (33{+}40{+}42){*}8/11{+}96 \cong 180 usecs, 18 timeslots$
  - $N_f = UL\_DATA\_TIME/(t + GUARD\_TIME) = 485 timeslots/(18 + 5) timeslots \cong 21.1$
  - $VoIP\_Capacity = N_f {*} interval/frame\_len = 21.1{*}20/10 = 42.2 conversations$

  For a GSM.610 voice codec using 802.11a/g PHY

  - Maximum transmit rate is 54Mbps and PHY overhead is 20usecs
  - VoIP Packet transmission time, $t = (33{+}40{+}42){*}8/54{+}20 \cong 37 usecs, 4 timeslots$
  - $N_f = UL\_DATA\_TIME/(t{+}GUARD\_TIME) = 485 timeslots/(4{+}5) timeslots \cong 53.3$
  - $VoIP\_Capacity = N_f {*} interval/frame\_len = 53.3{*}20/10 = 107.7 conversations$

- The VoIP capacity of SRAWAN for all the codecs in Table 2.2 and the performance(in terms of maximum no. of VoIP conversations) improvement with CSMA/CA using 802.11b PHY and guard time of 50usecs is shown in Table 2.5

Codec	**Ordinary 802.11 VoIP capacity**	**SRAWAN VoIP Capacity**	**Percentage Improvement**
GSM 6.10	11.2	44.1	294%
G. 711	10.2	30.3	197%
G. 723.1	17.2	66.1	285%
G. 726 - 32	10.8	37.3	245%
G. 729	11.4	44.1	287%

Table 2.5: SRAWAN VoIP capacity comparison with CSMA/CA in 802.11b with guard time of 50usecs

The Table 2.5 describes that using 802.11b PHY, there is an huge improvement of around 250% in maximum number of VoIP conversations in SRAWAN MAC when compared with CSMA/CA

- The VoIP capacity of SRAWAN for all the codecs in Table 2.2 and the performance(in terms of maximum no. of VoIP conversations) improvement with CSMA/CA using 802.11a/g PHY and guard time of 50usecs is shown in Table 2.6

Codec	**Ordinary 802.11 VoIP capacity**	**SRAWAN VoIP Capacity**	**Percentage Improvement**
GSM 6.10	56.4	121.3	115%
G. 711	51	97	90%
G. 723.1	86.1	181.9	111%
G. 726 - 32	54.3	107.8	98%
G. 729	57	121.3	113%

Table 2.6: SRAWAN VoIP capacity comparison with CSMA/CA in 802.11a/g with guard time of 50usecs

The Table 2.6 describes that using 802.11g/a PHYs and a smaller guard time, the VoIP capacity has huge improvement of average of 100% when compared to CSMA/CA. The reason behind this is every VoIP packet transmission has an additinal overhead of 50usecs of guard time which has reduced the overall guard time overhead in UL data frame and accomodated more number of VoIP sessions.

Chapter 3

Performance Evaluation and Analysis

In this chapter we describe the experimental performance analysis of SRAWAN MAC protocol using both *Round-Robin* and *Weighted Fair Queuing* packet scheduling algorithms by carrying various traffic flows of different service types. The various experimental observations identified while performing these experiments are also mentioned in this chapter. This chapter starts with listing all the hardware and software used in different experimental setups. Performance results of SRAWAN MAC with Round-Robin scheduler are described in the second section of this chapter. This section also shows the performance comparison of normal legacy 802.11 MAC and SRAWAN MAC with RR scheduling. Following section describes the performance results of WFQ scheduled SRAWAN MAC. This section also describes how well does WFQ performs in terms of delay experienced by the VoIP connections. WFQ scheduled SRAWAN MAC is evaluated by injecting various kinds of traffic like Voice/Video/FTP to evaluate how well does all these traffics co-exist. This section shows the performance values of WFQ in two settings: one is single connection per SS where it is tested till two SSs, and second one is multiple connection per SS setting. In this setting, each SS support multiple virtual connections to the BS. This chapter ends with experimental observations identified while doing various experiments in different scenarios.

3.1 Software and Hardware details

This section describes the software and hardware used in developing this protocol. Hardware section deals with detailed description of the hardware in terms of platform support, maximum transmit power, range values and so on.

3.1.1 Software:

- **Atheros Madwifi driver**
- **Linux Pebble Environment:** This is a somewhat minimal (more than 16 megs, less than 400 megs, designed to fit on a 128 meg CF card) Debian stripped distro aimed for use in wireless embedded devices. It's biggest advantage is that it mounts read-only. we don't have to worry as much about wearing down the compact flash or doing proper shutdowns. Even we can unplug and plug in as much as we want.

3.1.2 Hardware:

- WRAP [16] (Wireless Router Application Platform) Board used: WRAP.1C-1, 2LAN / 2Minipci model WRAP boards are used. There is a slot for compact flash card. Some of the specifications of this model WRAP board are:
  - CPU Speed: 233 MHz AMD Geode SC1100 CPU (fast 486 core)
  - DRAM: 64 or 128 MB SDRAM
  - Storage: Operating system and application stored on CompactFlash card (not included). All the experiments are done using only this model of WRAP boards.
- **Minipci Cards**: In our experiments we used three types of cards named as CM9, SR2 and SR5. As the transmit power and operating distance of these cards are very much important for 802.11 in an outdoor environment, card specifications are described below.
  1. **Winstron CM9[13]**
     - Supports *802.11 a/b/g PHY*
     - **Operation distance**(depend on antenna performance):
       802.11a
       Outdoor: 85m@54Mbps, 300m@6Mbps
       Indoor: 20m@54Mbps, 40m@6Mbps
       802.11b
       Outdoor:300m@11Mbps, 400m@1Mbps
       Indoor: 30m@11Mbps, 50m@1Mbps

802.11g
Outdoor: 80m@54Mbps, 300m@6Mbps
Indoor: 15m@54Mbps, 35m@6Mbps

- **Output Power:**
  802.11b
  18 dBm
  802.11g
  18dBm @6Mbps
  15dBm @54Mbps
  802.11a
  17dBm @6Mbps
  13dBm @54Mbps

2. **Ubiquiti SR2**[14]**:** The Super Range 2 (SR2) from UBiQUiTi Networks is a 802.11b/g mini-PCI card with patent-pending Super Range radio technology has been designed from the ground up specifically for outdoor wireless. The SR2 solves the problem of increasing 802.11 based outdoor wireless system perfromance without the increased system complexity, legal questions, added spurious emissions, and degraded receiver performance that accompany use of external bi-directional amplifiers.
   - **Features**
     * 400mW 802.11 b/g Power
     * -98dBm 802.11 RX sensitivity
     * Atheros 5004 chipset based
   - **Transmit power:**

Rate	Power
1-24 Mbps	26 dBm, +/- 1dB
36 Mbps	24 dBm, +/- 1dB
48 Mbps	22 dBm, +/- 1dB
54 Mbps	21 dBm, +/- 1dB

3. **Ubiquiti SR5[15]:** The world's first hi-performance 5GHz 802.11a mini-PCI module. Utilizing SuperRange technology, the SR5 exhibits improved output power and sensitivity over standard wireless cards. The SR5 is ideal for long distance bridging, hi-performance point-to-multipoint links, and mesh networking.
   - **Features** * 400mW 802.11a Power * -93dBm 802.11 RX sensitivity * Atheros 5004 chipset based * RoHS compliant
   - Specifications: Chipset
     Atheros AR5213 MAC/BB Atheros AR2112 ROC
   - **Transmit Power**

Rate	Power
6-24 Mbps	26 dBm, +/- 1dB
36 Mbps	24 dBm, +/- 1dB
48 Mbps	22 dBm, +/- 1dB
54 Mbps	21 dBm, +/- 1dB

- Laptops are used for developing the protocol and parallely tested with card bus adapters.
- PCMCIA cards
- External Antennae (3dB rubber duck omni-directional, 24dBi high gain directional/sectoral antennae)
- Pigtail MMCX/ULF
- Battery

3.2 Performance results of Round-Robin scheduled SRAWAN MAC

Round-Robin scheduled SRAWAN MAC is experimented in both indoors and outdoors across point-to-point and point-to-multipoint links. The experimental setup of these four combinations of experiments and their throughput performance measurements are shown in the following subsections. For all these experiments the implementation parameters of the protocol are as follows:

- Frame size: 10millisec
- Downlink Frame: 5millisec (includes beacon packet and guard time between downlink subframe and uplink subframe which is around 150microsec)
- Uplink Frame: 5millisec (includes ranging contention period of 200usecs, bandwidth contention period of 200usecs, guard time of 200usecs between ranging and bandwidth contention intervals and guard time of 200usecs between end of current uplink subframe and start of next downlink subframe)
- Uplink slots per SS in one round: 500usecs.

3.2.1 Indoor RR Results:

In indoor environment, experiments are conducted between WRAP boards at a distance apart of 5-10ft. Low gain 3dB rubber duck omni-directional antennae are used. ULF pigtails are used to form a link between minipci card and rubber duck antenna.

Point-to-Point Experiment:

The experimental setup of point-to-point network is shown in Figure 3.1. Two WRAP boards are used in this experiment, one as Base Station and the other as Subscriber Station. The results shown are taken using all three different (SR2/CM9/SR5) minipci cards at 54Mbps data rate with 11g PHY. So, with the hardware details mentioned in previous section, the transmit power of the CM9/SR2/SR5 cards at 54Mbps transmit rate is 20/20/13dBm respectively. The throughput performance results are shown in the Table 3.1. The signal strength values are also noted but not tabulated at this point of time. The throughput measurements are for UDP streams measured using *netperf*, a network performance analyser tool.

The experiment is performed as follows. *netserver* is started on both the BS and the SS. Then clients are started on both the ends using the client command:

```
$ >netperf -H hostname -t UDP_STREAM -l RUN_LENGTH
```

Similarly for the same point-to-point network using 11b/11a PHY, the throughput results are shown in Table 3.1.

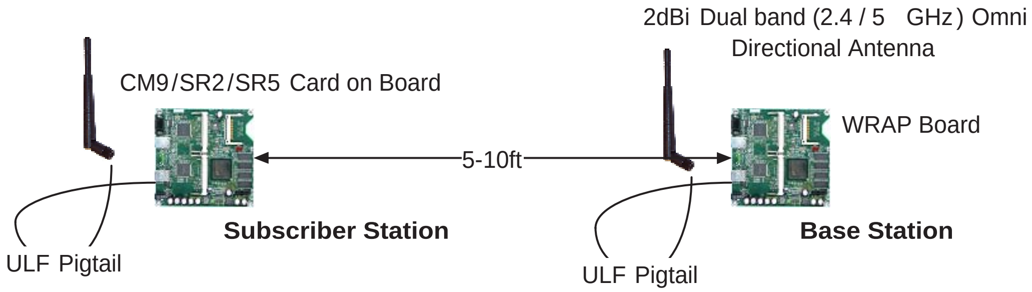


Figure 3.1: A point-to-mulitpoint system

PHY	Effective UDP throughput of SRAWAN MAC	Effectiev UDP Throughput in legacy 802.11 MAC
802.11b	7.92 Mbps	7.42 Mbps
802.11g	40.33(21.67, 18.66) Mbps	34 - 37 Mbps
802.11a	39.87(21.66, 18.21) Mbps	30 - 34 Mbps

Table 3.1: Point-to-Point Results in a RR scheduled SRAWAN MAC

Point-to-Multipoint Experiment:

The experimental setup of a point-to-multipoint network is shown in Figure 3.2. In this test case, three WRAP boards are used. One acts as a Base Station and other two as Subscriber Stations. In this setup also both the subscriber stations are placed 5-10ft distance apart from Base Station. The results shown are taken using all the three (CM9/SR2/SR5) minipci cards at 54Mbps data rate. So, the transmit power of the hardware is 20/20/13dBm respectively. The throughput performance results is shown in the Table 3.2. In this scenario also the performance measurements were done using *netperf* network analyser tool.

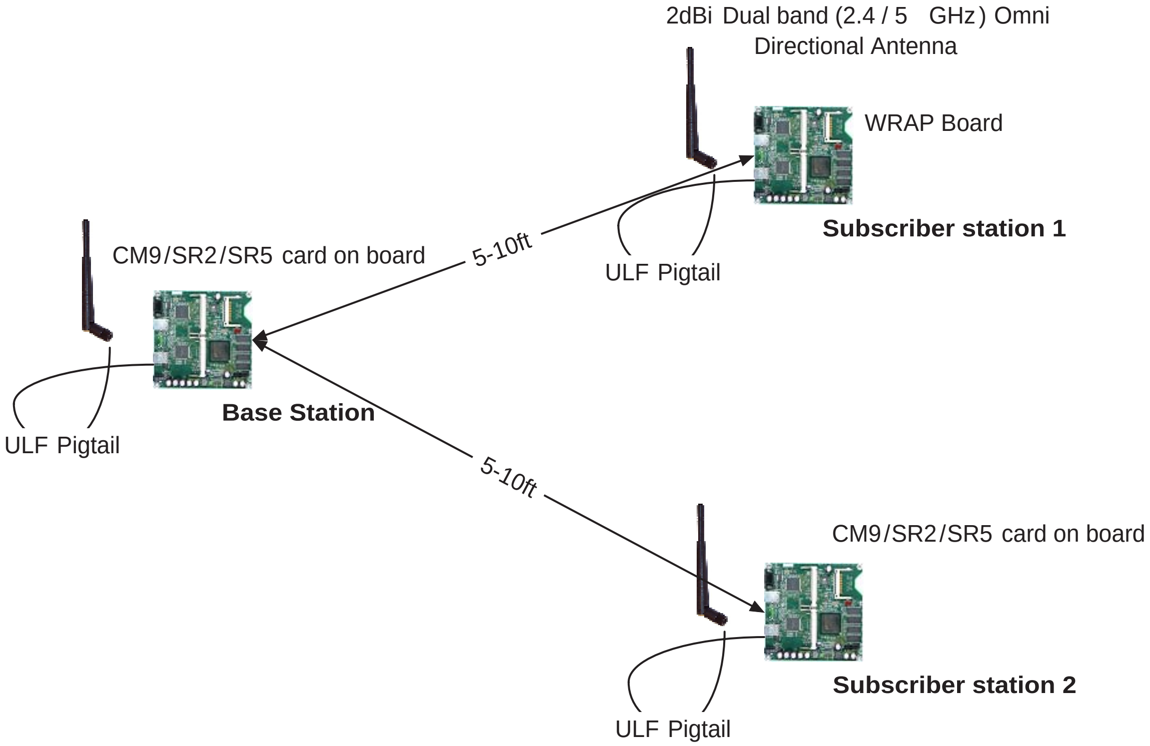


Figure 3.2: A point-to-multipoint test bed of RR-Scheduled SRAWAN MAC

The throughput performance is measured in point-to-multipoint setup as follows. Once SS1 and SS2 enters into the BS network, *netserver* is started on these three points and start netperf of UPD streams simultaneously for the same amount of time. Bidirectional Traaffic streams are run between BS-SS1 and BS-SS2 simultaneously, hence totally 4 streams of traffic running at the same time which are BS-SS1, SS1-BS, BS-SS2, SS2-BS. The throughput values at four points of measurements are as follows:

- **BS Readings:**

  Stream1 => BS-SS1 11.78Mbps

  Stream2 => BS-SS2 11.80Mbps

- **Readings at SS1:**

  Stream => SS1-BS 9.10Mbps

- **Readings at SS2:**

  Stream => SS2-BS 9.12Mbps

Hence the total bandwidth of SRAWAN MAC in a point-to-multipoint network of two SSs is 11.78 + 11.80 + 9.10 + 9.12 = 41.8Mbps.

This experiment is performed with above three mentioned minipci cards using 11g and 11b PHY. 11a results are also taken with SR5 and CM9 cards. All these results are shown in the Table 3.2.

PHY	Effective UDP throughput of SRAWAN MAC	Effective UDP Throughput in legacy 802.11 MAC
802.11b	5.70 (3.00, 2.70) Mbps	5.7 (3.2, 2.5) Mbps
802.11g	41.80 Mbps	33-36 Mbps
802.11a	41.81 Mbps	30-33 Mbps

Table 3.2: Point-to-Multipoint network performance of RR scheduled SRAWAN MAC with 2 SSs

3.2.2 Outdoor Experimental setup and results

In outdoor environment SRAWAN MAC is experimented in only 11b with a maximum data rate of 11Mbps. And also performance measurements were made only with SR2 cards in a point-to-point and point-to-multipoint networks.

Point-to-Point experiment:

In outdoor environment, SRAWAN MAC is experimented over 3.5Km point-to-point link between FBTop and Mohanpur. The experimental setup is shown in Figure 3.3. In this experiment, MMCX Male pigtails are used between the minipci and RF cable which goes till external antenna. The nodes on either end are equipped with high-gain parabolic grid antennae of 24dBi gain with a beam width of 8 degree. The antennae are placed on the towers of 33mts and 20mts so that the two antennae are in line of sight. As the experiment is conducted in 11b at 11Mbps, the output power of the hardware is 18dBm. Throughput measurements of SRAWAN MAC under this setup are shown in Table 3.3.

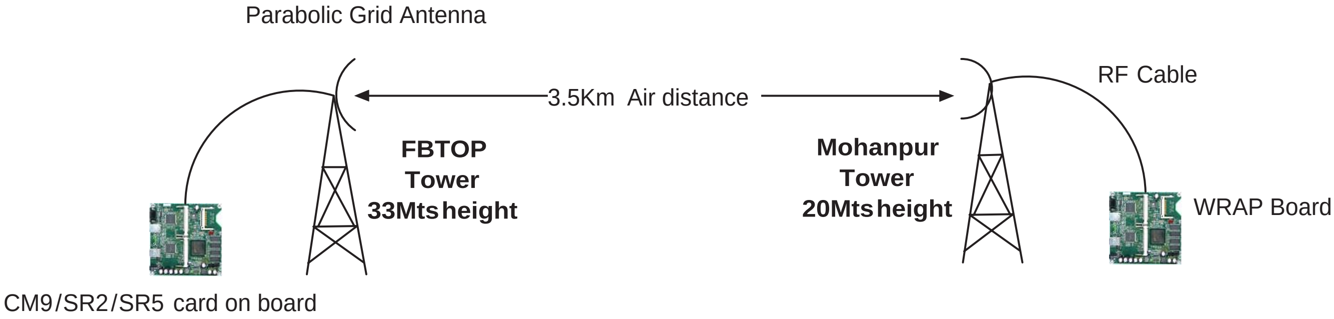


Figure 3.3: A point-to-multipoint outdoor test bed of RR-Scheduled SRAWAN MAC

Point-to-point throughput measurements has to be taken in many other cases like 11g/11a at different data rates using different minipci cards.

PHY	Effective TCP throughput of SRAWAN MAC	Effectiev TCP Throughput in legacy 802.11 MAC
802.11b	5.95 Mbps	7.42 Mbps

Table 3.3: Point-to-Point network performance of RR scheduled SRAWAN MAC in Outdoor environment

Point-to-Multipoint experiment:

Point-to-Multipoint experiment on SRAWAN MAC was experimented in Pavan's thesis [?]. Figure 3.4 shows the experimental setup which Pavan tested. This has same experimental setup as point-to-multipoint experiment in indoor environment, except that the WRAP boards are connected to high-gain sectoral/parabolic grid antennae placed on top of the towers which are quite distance apart in terms of Kms. The throughput performance of SRAWAN MAC under this setup is shown in Table 3.4

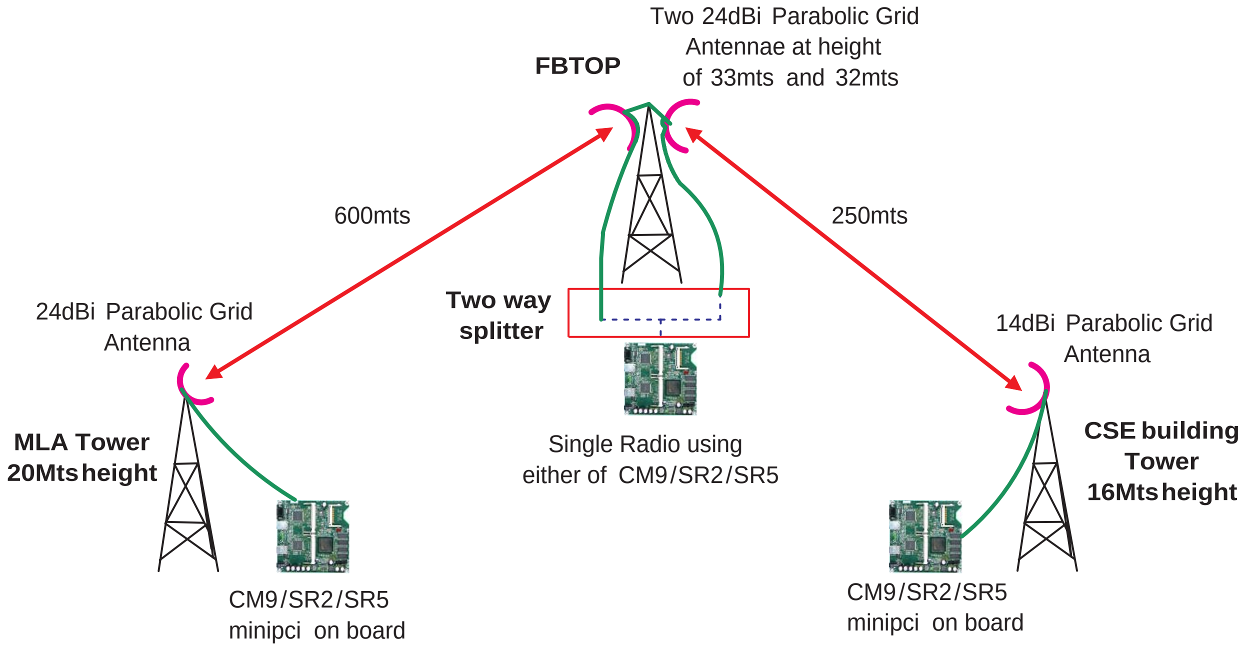


Figure 3.4: A point-to-multipoint outdoor test bed of RR-Scheduled SRAWAN MAC

Point-to-multipoint throughput measurements also has to be taken in many other cases like 11g/11a at different data rates using different minipci cards.

3.3 Performance results of Weighted Fair Queuing scheduled SRAWAN MAC

Weighted Fair Queuing is implemented to provide QoS such that bandwidth/delay performance bounds are guaranteed. Various traffic flows like Voice/Video/FTP are generated

PHY	Effective TCP throughput of SRAWAN MAC	Effectiev TCP Throughput in legacy 802.11 MAC
802.11b	6.33 Mbps	5.6 - 6.0 Mbps

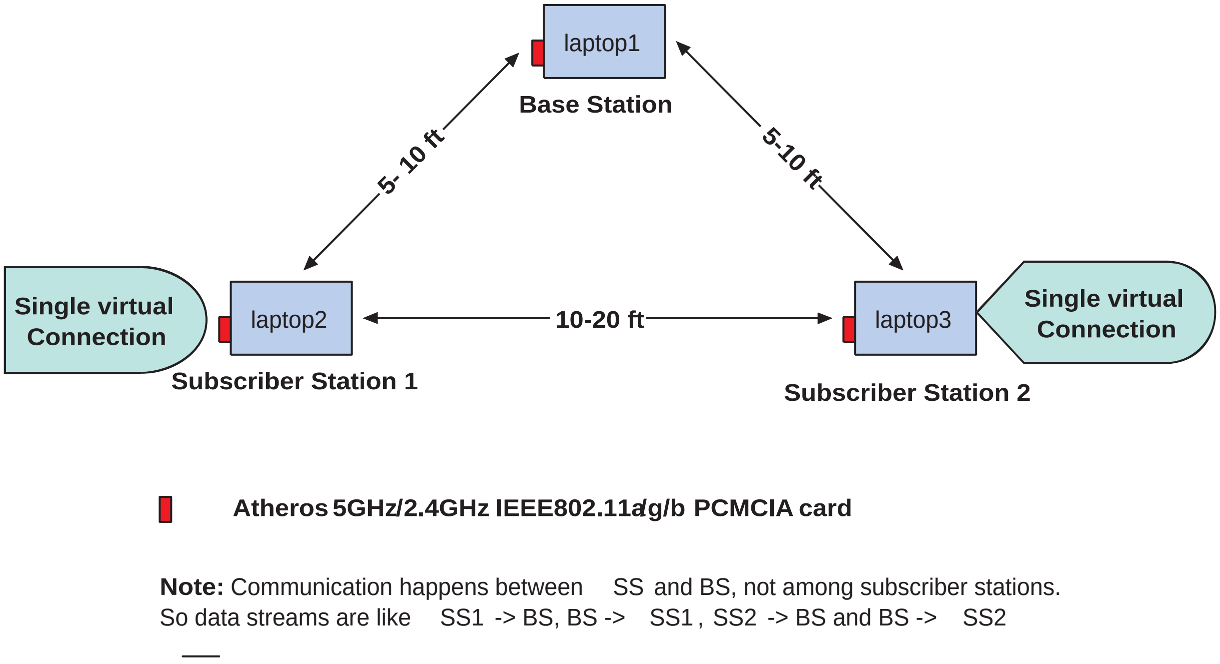
Table 3.4: Point-to-Point network performance of RR scheduled SRAWAN MAC in Outdoor environment

to evaluate the behaviour of WFQ packet scheduling on SRAWAN MAC. WFQ implementation is tested without multiple connection support per SS and with multiple connection support per SS. All the experiment are conducted between laptops with PCMCIA cards.Multiple connections from the same SS are differentiated based on the source and destination ports of the traffic flow. The following two subsections describe the experimental analysis of WFQ on SRAWAN MAC.

3.3.1 Single connection per SS:

In this experiment only one connection can be established between the SS and the BS. So, all the traffic flowing between the SS and the BS is classified as the same kind and given same weight for all the traffic. Because of this, only one kind of traffic flow is assumed between SS and BS. Inorder to evaluate the behaviour of WFQ fair packet scheduling algorithm by transmitting multiple types of traffic flows each from one different SS. In single connection per SS implementation we experimented till two SSs, each transmitting different traffics in all the combinations. The experimental setup is shown in the Figure 3.5. Tests were done in all the combinations of Voice/Video/FTP traffic flows between BS and two SSs and the test results are shown as follows.

1. **Voice-Voice** & **Video-Video:** In this test case, each SS perform either VoIP or Video conversation with BS. Voice traffic is generated by flushing UDP packets of fixed size at periodic intervals. Voice codecs generate packets of fixed size at periodic intervals. Video traffic is generated from video traces with some garbage data in the video packets. We tested all the combinations of voice codecs shown in Table **??** from two SSs. And also few video trace files are tested in all combinations with two SSs. These two voice conversations and video conversations are continued for about



Note: Communication happens between SS and BS, not among subscriber stations.
So data streams are like SS1 -> BS, BS -> SS1 , SS2 -> BS and BS -> SS2

Figure 3.5: Experimental test bed of Single connection per SS in WFQ scheduled SRAWAN MAC

60-300 secs. Both the connections got accurate bandwidth and delay performance bounds in voice or video flows.

2. **Voice-Video:** Here one SS generates voice data and the other carries video traffic. Voice data and video traffics are generated in the same manner described above with some garbage data in the payload. This test also gave accurate bandwidth and delay performance bounds.

3. **Voice-FTP:** Behaviour of voice/video traffic in presence of FTP traffic is the most important test case. Because in normal 802.11, existing VoIP conversations performance might come down in presence of TCP traffic. In this test case both the kinds of traffic voice and FTP are generated one each from an SS. Output performance values have shown that, VoIP application quality has not at all decreased in presence of TCP traffic. This shows that VoIP traffic can co-exist harmoniously in SRAWAN MAC with expected performance bounds.

4. **FTP-Video:** Similarly to above test case, traffic co-existence behaviour is verified between video traffic and FTP traffic. Video traffic quality is upto expected bandwidth values.

5. **FTP-FTP:** This test scenario shown that WFQ gives fair share of bandwidth for all FTP traffic flows in SRAWAN MAC. Here two SSs are connected to the BS. Each SS generate FTP flow between the BS. Each of these two FTP traffic are given fair amount of bandwidth resoure in uplink direction.

3.3.2 Multiple connection per SS:

Here, each SS establishes 20 virtual connections to BS, so that each connection can carry different kind of traffic with its own traffic flow parameters. This 20 is not a fixed number, but for experimental purpose we have choosen that many connections. QoS is concerned about the performance bounds of real-time multimedia applications and at the same time provides fair share of bandwidth among other traffic flows. So, we have tested this WFQ scheduled SRAWAN MAC with all combinations of Voice/Video/FTP traffic in total of 20 connections. The experimental setup is shown in Figure 3.6. Performance results are gathered in few combinations of traffic flows described in detail in following subsections.

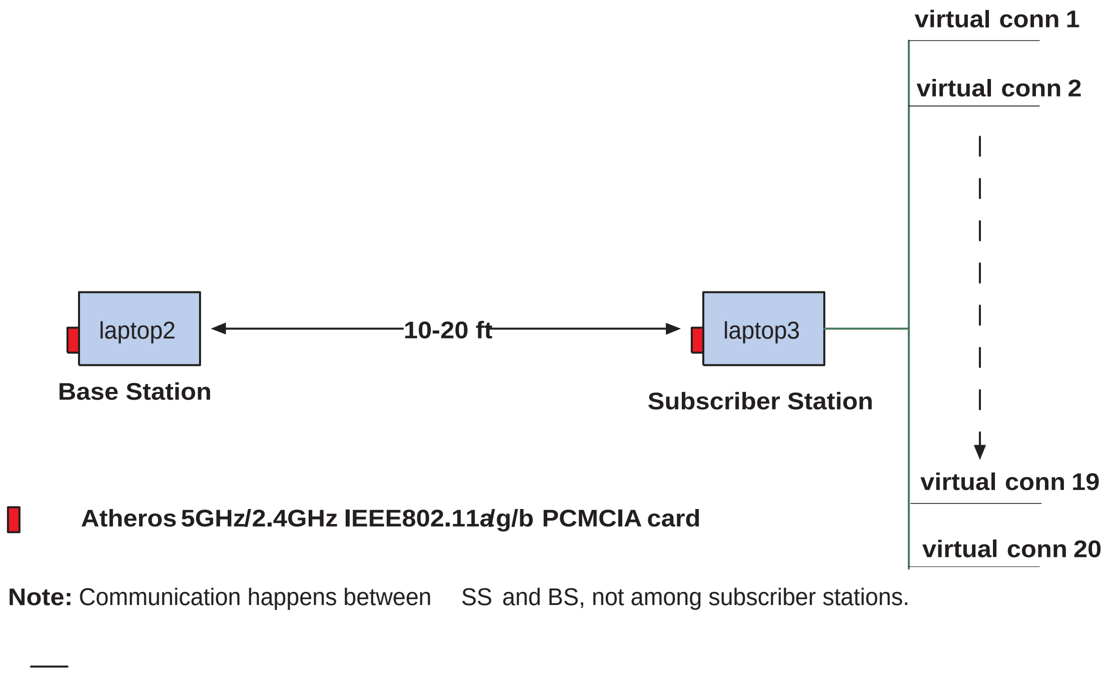


Figure 3.6: Experimental test bed of Single connection per SS in WFQ scheduled SRAWAN MAC

Voice traffic performance analysis:

In this test, all the virtual connections are carrying voice traffic generated by standard voice codecs like G.711, G.729 and so on. One test case is all the traffic flows going in uplink direction i.e., from SS to BS direction. And second test is all the traffic flows of same type are going in downlink direction (BS to SS direction). These two tests are done for all the well known standard voice codecs with voice codec attributes shown in Table 2.2. The Table 3.5 shows the bandwidth performance of all these 20 traffic flows run for 60secs.

Codec	**Expected Bit rate**	**Achieved Bit rate for each of 20 connections in Downlink direction (BS -> SS)**	**Achieved Bit rate for all 20 connections in Downlink direction (SS -> BS)**
GSM 6.10	13.2	13.18	13.165
G. 711	64	64.095	63.793
G. 723.1	6.3	6.402	6.378
G. 726 - 32	32	31.914	31.948
G. 729	8	7.976	7.98

Table 3.5: Voice codec bandwidth performance results in WFQ-SRAWAN MAC with multiple-connection support per SS

Video traffic performance results:

Video traces are used to emulate video traffic flows. Here in this test three different video traces each of 256Kbps bit rate are carried over three different virtual connections between the SS and the BS. As the traffic flows are differentiated based on the source port and destination port numbers. So, TCP header is decoded in MAC header to map into some traffic flow type. When UDP datagrams of size more than IP maximum data transfer unit are passed to IP layer it does fragmentation of UDP datagram such that only first packet of this fragmented datagram will have source and destination ports. So, even though video traces contain datagrams of size more than MTU size, it is fragmented at transport layer so that all the datagrams are of size less than MTU. Because of this all the IP packets contain source and destination ports. The test is done as follows. Three of virtual connections carry three different video traffics from SS to BS direction. The performance values of these three virtual connections (or traffic flows) are given below:

- **SS-V1** —> **BS** - 0.254060Mbps
- **SS-V2** —> **BS** - 0.252953Mbps
- **SS-V3** —> **BS** - 0.253119Mbps

Voice-Video traffic co-existence behavioural results:

In this experiment out of 20 virtual connections, 3 are three different video traffics and other 17 virtual connections carry the voice traffic generated by the same voice codec. All the traffic is carried from SS to BS direction. The performance values of all three video connections are almost same as the results shown above even in existence of 17other VoIP conversations. And all the 17 VoIP conversations got the most accurate bandwidth values as that of values shown in Voice traffic performance results.

TCP traffic analysis

The main experiment of our interest is to find out how does multimedia applications behave with some FTP traffic co-existing with them. Voice/Video/TCP traffic behaviour in WFQ Scheduled SRAWAN MAC with multiple virtual onnections per SS is described with the following test results.

- **TEST 1: Voice/TCP traffic co-existing behaviour:** In this experiment, voice and TCP traffic are carried to know whether voice traffic can co-exist harmoniously with TCP traffic. Here 19 voice flows are generated from the SS to the BS, and one TCP flow is carried from the BS to the SS direction. Here the voice data is generated with the standard voice codec parameters for all codecs. Table 3.6 shows the voice flows results obtained while carrying 19 voice flows from the SS to the BS and one TCP flow is carried from the BS to the SS.

  In Table 3.6 *Expected Bandwidth* column says the expected bandwidth for each voice flow. Similarly *Avg bandwidth for each voice flow recvd at BS* column says the average of all the bandwidths obtained for 19 voice traffic flows at BS. We can make a statement from the above results that WFQ scheduled SRAWAN MAC provides guaranteed performance bounds to VoIP traffic with any kind of traffic flow.

Voice Codec	**No. of Voice flows**	**No. of TCP flows**	**Expected Bandwidth**	**Avg bandwidth for each voice flow recvd at BS**	**TCP flow throughput received at SS**
GSM 6.10	19	1	13.2Kbps	13.86	0.652Mbps
G.723.1	19	1	6.3 Kbps	6.369	1.919Mbps
G.726-32	19	1	32 Kbps	31.867	0.319Mbps
G.729	19	1	8 Kbps	7.987	1.078Mbps

Table 3.6: Voice codec bandwidth performance results in WFQ-SRAWAN MAC with TCP traffic flow

- **TEST 2: Video/TCP traffic co-existing behaviour:** Here video traffic quality is evaluated while one tcp traffic flow is existing. 3/4 video flows each of 256 Kbps is carried from the SS to the BS. And 1 TCP flow is run from the SS to the BS. Results are taken when these two traffic flows are run from the SS to the BS for around 100 secs. Each of the video traffic is of 256Kbps data rate codec flow. The results of the video quality and TCP connection are given as follows.
    - **3 video - 1 TCP flow:** Bandwidth values of three Video flows at BS side is:
      Expected bandwidth for each flow is 256 Kbps
      Video stream 1 -> 253.343 Kbps
      Video stream 2 -> 252.129 Kbps
      Video stream 3 -> 228.326 Kbps

      Throughput achieved by the single TCP flow is: 0.245Mbps
    - **4 Video traffics - 1 TCP flow run for 100 secs:** Expected bandwidth for first three Video traffics is 256Kbps and for 4th video flow is 64Kbps. Below are bandwidth values obtained at BS while transferring above 4 video flows and 1 TCP traffic from SS.
        1. In test Run 1:
           Video stream 1 -> 253.041 Kbps
           Video stream 2 -> 252.077 Kbps

Video stream 3 -> 222.733 Kbps
Video stream 4 -> 60.329 Kbps

Throughput achieved by the single TCP flow for traffic in SS -> BS direction: 0.219Kbps

2. In test Run 2:
   Video stream 1 -> 253.344 Kbps
   Video stream 2 -> 252.670 Kbps
   Video stream 3 -> 226.346 Kbps
   Video stream 4 -> 59.544 Kbps
   Throughput achieved by the single TCP flow for traffic in SS -> BS direction: 0.228 Kbps

From these test results we can assume that video traffic flows are also getting good performance bounds while co-existing with TCP traffic. Because of some approximate weight factor for video and TCP streams some of the video streams got less bandwidth. So, we can say that with perfect weight factors for traffic flows, WFQ scheduled SRAWAN MAC provides expected performance bounds for all real-time multimedia applications even when co-existing with TCP traffic flows. Unlike normal 802.11, voice/video traffic performance does not degrade while TCP flows are carried simultaneously in WFQ scheduled SRAWAN MAC. Hence, in WFQ scheduled SRAWAN MAC, all the scheduling services can co-exist harmoniously without any deviations from expected performance bounds.

Chapter 4

Conclusions and Future work

4.1 Conclusions

In this thesis work we came up with a TDMA based MAC protocol for a point-to-multipoint network setup called as SRAWAN (Sectorized Rural Area Wireless Access Network) MAC. This protocol is implemented on off-the-shelf 802.11 hardware so that 802.11 PHY used as it is. Implementation is named as *Bharani*. Entities in this network are base station and subscriber station. For a subscriber station to enter into BS network, initially it goes through few management phases where it gets tightly time synchronized with BS. Once the registration phase is completed, from then onwards SS can request for a new connection for every new service flow. This protocol is developed in colloboration with Arada Systems, Bangalore. Myself, Pavan Kumar Surishetty and Dr.Bhaskaran Raman are part of the protocol design team in IIT Kanpur. The motivation behind developing this work is to improve the throughput efficiency and provide guaranteed performance bounds for real-time multimedia applications in long distance 802.11 networks. Below are some of the conclusions made on this SRAWAN MAC in comparison with legacy 802.11 MAC.

- Efficient throughput performance in comparison to normal legacy CSMA/CA MAC which are clearly described in performance results chapter.
- Provides guaranteed bandwidth/delay bounds so that all kinds of traffic flows are given expected performance.
- Protocol is working fine between laptops and also between laptop and WRAP board

- Giving expected throughput performance of upto 42Mbps at 54Mbps in 11a/g and 7.92Mbps at 11Mbps in 11b.
- Provides QoS to real-time multimedia applications like voice/video and so on.
- All the traffic flows like Voice/Video/FTP can co-exist harmoniously without any performance degradation.

4.2 Future Work

- Bharani characterization in outdoor in all the different experimental setup by varying rate/mode(11a/b/g)/minipci card(CM9/SR2/SR5)/distance and in many other dimensions.
- SRAWAN MAC is also giving expected throughput values between WRAP boards, but is not reliable all the times.
- Most of the problems are coming in 11a when distances are increased between nodes.
- Outdoor experiments are conducted only in 11b, need to be tested rigorously in outdoor in 11g/11a
- Rate control algorithm has to be implemented so that even when nodes change their positions, they will not get disconnected because of range variation with transmit rates.
- Periodic ranging should be embedded so that even though entities in the network disconnect, they comeback in sync by periodically being in sync with each other.
- Multi-connection implementation has to be tested on single board computers like Soekris/WRAP boards etc.
- WFQ-SRAWAN MAC and RR-SRAWAN MAC have to be rigorously tested in indoor/outdoor at large scale in number of nodes.

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