Green Frame Aggregation Scheme for IEEE 802.11n Networks

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ABSTRACT

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Maha Saleh Alaslani

Frame aggregation is one of the major MAC layer enhancements in the IEEE 802.11 family that boosts the network throughput performance. It aims to achieve higher throughput by transmitting huge amount of data in a single transmit opportunity. With the increasing awareness of energy efficiency, it has become vital to rethink about the design of such frame aggregation protocol. Aggregation techniques help to reduce energy consumption over ideal channel conditions. However, in a noisy channel environment, a new energy-aware frame aggregation scheme is required.

In this thesis, a novel Green Frame Aggregation (GFA) scheduling scheme has been proposed and evaluated. GFA optimizes the aggregate size based on channel quality in order to minimize the consumed energy. GFA selects the optimal sub-frame size that satisfies the loss constraint for real-time applications as well as the energy budget of the ideal channel situations.

The design, the implementation, and evaluation of GFA using testbed deployment is done. The experimental analysis shows that GFA outperforms the conventional frame aggregation methodology in terms of energy efficiency by about 6× in the presence of severe interference conditions. Moreover, GFA also outperforms the static frame sizing method in terms of network goodput and maintains almost the same end-to-end latency.
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Chapter 1

Introduction

The last decade has seen a dramatic global growth in wireless communication systems. Statistics show that the number of wireless subscriptions in any given country has exceeded its own population [4]. As the usage of wireless networks increases, energy efficiency of mobile devices has become a real challenge. Recently, the IEEE 802.11 group [2] have introduced several improvements to both physical and MAC layers in IEEE 802.11n/ac in order for it to become the baseline technology in next generation WLANs. In order to achieve high throughput and efficiency, IEEE 802.11n introduces two frame aggregation techniques, namely MAC Service Data Unit Aggregation (A-MSDU) and MAC Protocol Data Unit Aggregation (A-MPDU). These frame aggregation techniques can increase the throughput under ideal channel conditions by reducing both the headers and timing overheads. However, a large aggregated frame causes other stations in the network to wait longer before they get a transmit opportunity. Moreover, under error-prone channels, a single bit error in a large aggregated frame may waste a long period of channel time and lead to lower network performance and energy efficiency. Therefore, this work specifically addresses the energy consumption of the IEEE 802.11n MAC aggregation, and proposes a novel implementation of energy-aware frame aggregation scheme, in order to minimize the total energy consumption.
1.1 Problem Definition and Motivation

Worldwide energy consumption is now one of the main concerns throughout the world, because of the potential economical and expected environmental impact. As a consequence, energy efficiency has become a key factor to evaluate the cost and performance of a communication network, by considering the way in which networks are constructed and operated. However, there is a real demand for in depth evaluation of this consumption, to point out the most relevant targets for potential energy savings and to identify where the largest improvements could take place.

![Power consumption breakdown on a modern laptop under wireless FTP upload](image)

Figure 1.1: Power consumption breakdown on a modern laptop under wireless FTP upload [1].

In 2002, the energy consumption of different parts in the global Internet are analyzed [5]. The study shows that 80% of the total Internet consumption at that time was consumed by the local area networks (LAN), through hubs and switches. Later
on 2005, the researchers of [6] estimated the relative energy contribution of the Network Interface Cards (NICs) and all the other network elements and concluded that the NICs were responsible for almost half of the total power consumption. A number of interesting studies have already been established an in-depth characterization and analysis of the energy consumption of the different components of modern computers [7, 8, 1]. The studies show that the significant consumers of power in a typical laptop are the CPU, optical drive, hard disk, display, graphics card, memory, and wireless card subsystems. Authors in [1] measured the power consumption over a variety of workloads of each component and they found that the total system power consumption varies a lot from 8 Watt to 30 Watt depending on the workload, and moreover that the distribution of power consumption among the components varies even more widely. Fig. 1.1 shows a typical example from an IBM mobile computer during a wireless FTP transfer, it demonstrates that nearly 26% of power consumed is by the display, 16% by the CPU, 3% by the memory, and 18% by the wireless interface.

The power consumption of the wireless LAN card involves usage of the transceiver at the source, intermediate as in the case of ad hoc networks, and receivers. The wireless card has numerous power states when enabled: transmit, receive, and standby modes. Maximum power is consumed in the transmit mode, and the least in the standby mode. As an example, the IEEE802.11a/g compatible Atheros AR5424 card requires 1.97 W in transmit, 1.52 W in receive, and 1.47 W in standby mode [3]. In addition, turnaround between different modes typically takes between 6 and 30 microseconds. Power consumption for IEEE 802.11n/MIMO compatible wireless AR9380 NIC is also measured [3]. AR9380 can be configured in 3 different SS configurations, namely SISO, MIMO2 and MIMO3, where one, two, or three RF-chains are used according. With three RF-chains, AR9380 requires 2.45 W in transmit mode, 1.85 W in receive mode, and 0.69 W in standby mode. Thus, understanding the power
consumption of the mobile radio in wireless NIC is important for the efficient design of communication protocols.

Consequently, energy conservation has been largely considered in the modern devices design and in the different components such as CPU, disks, displays, network interface cards, etc. Energy-efficient protocols and methods may result by incorporating low-energy strategies into the design of data communication networks. This thesis addresses the incorporation of energy conservation at IEEE 802.11n MAC layer of the protocol stack for wireless networks.

IEEE802.11n/ac introduced several energy efficient enhancements such as MAC level frame aggregation; there are two types of frame aggregation in IEEE 802.11n/ac networks, A-MSDU and A-MPDU. A subframe loss in an A-MSDU results in retransmitting the whole A-MSDU again. Clearly, noisy channels may cause many bit errors resulting in a lot of aggregate retransmissions, which contribute negatively to the device power consumption. On the other hand, a lost (or corrupted) sub-frame in any A-MPDU does not disturb the reception of other sub-frames in the same aggregate. This is because each MPDU has its own FCS to allow the re-transmission of only the corrupted MPDU(s). To address this issue, we develop new scheme for estimating the optimal A-MPDU sub-frame size for different channel quality without sacrificing the network performance. The main goal of our proposed scheme is to increase the energy efficiency of frame aggregation protocol that is used by IEEE 802.11n/ac wireless devices.

1.2 Thesis Objectives and Contributions

Due to the growing importance of the energy consumption in Wi-Fi based networks, researchers have been showing increasing interest in designing energy efficient protocols. In this thesis, a novel Green Frame Aggregation (GFA) scheme is proposed.
GFA is considered an energy efficient frame aggregation scheme for IEEE 802.11n/ac wireless devices. GFA estimates the optimal A-MPDU sub-frame size while taking into consideration the energy constraints of error-prone channels. The main objective of GFA is to minimize energy consumption while maintaining network performance. To the best of our knowledge, this is the first work that evaluates a power-aware frame aggregation scheme using real hardware measurements.

Our main contributions are as follows:

1. Design an adaptive A-MPDU frame sizing scheme in the light of Quality of Service (QoS) and energy specifications.

2. Characterize the impact of GFA on our IEEE 802.11n/ac based testbed and show that it achieves high energy efficiency while boosting the network goodput and maintaining almost the same latency.

1.3 Thesis Organization

The thesis is organized as follows. Chapter 2 provides a general background on IEEE 802.11 standard and some of the related works. Chapter 3 describes the methodology used in the study. Following that, Chapter 4 presents the performance evaluation of the new protocol. And Finally, the conclusion remarks are discussed in Chapter 5.
Chapter 2

Background and State of the Art

This chapter provides a general background on IEEE 802.11 wireless LAN standard. It provides an overview of the major IEEE 802.11n enhancements. Also, the chapter covers the state of the art and the related work done on energy efficiency in IEEE 802.11 wireless networks. It briefly shows the design of traditional static frame aggregation technique that this thesis compares with our proposed design.

2.1 IEEE 802.11 standard

At 1990, Institute of Electrical and Electronics Engineers (IEEE) developed IEEE 802.11 wireless local area networks standard for home and office uses over the ISM unlicensed band [9]. IEEE 802.11 is a collection of specification for the local area network technologies which is a member of the IEEE 802 slandered family dealing with Ethernet, Token Ring, Wireless LAN, Bridging and Virtual Bridged LANs. IEEE 802.11 standard describes the MAC layer, while the sub standards (802.11a, 802.11b, 802.11g, 802.11n, and 802.11ac) describe the physical layer also. The IEEE 802.11 standards are summarized in Table 2.1.
### IEEE 802.11 Standards

Table 2.1: IEEE 802.11 Standards.

<table>
<thead>
<tr>
<th>Standard</th>
<th>Band (GHz)</th>
<th>Bandwidth (MHz)</th>
<th>Modulation</th>
<th>Antenna Technologies</th>
<th>Data Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>802.11a</td>
<td>5</td>
<td>20</td>
<td>OFDM</td>
<td>N/A</td>
<td>54 Mbps</td>
</tr>
<tr>
<td>802.11g</td>
<td>2.4</td>
<td>20,40</td>
<td>DSSS, OFDM</td>
<td>MIOM</td>
<td>54 Mbps</td>
</tr>
<tr>
<td>802.11ac</td>
<td>2.4, 5</td>
<td>40, 80, 160</td>
<td>OFDM</td>
<td>MIOM, MU-MIMO</td>
<td>6.93 Gbps</td>
</tr>
</tbody>
</table>

IEEE 802.11b [10] was the first widely wireless networking standard used. This standard has a maximum throughput of 11 Mbps and it uses the carrier sense multiple access with collision avoidance (CSMA/CA) method and operates on the 2.4 GHz band which interfere with many devices operate on the same frequency band such as microwave ovens, Bluetooth devices, baby monitors and cordless telephones. IEEE 802.11a [11] was ratified in 1999 as amendment to the original standard and allows transmission and reception of data rate up to 54 Mbps. It was designed to support unlicensed national information infrastructure bands (5 GHz frequency) in wireless communication as regulated in the United States by the Code of Federal Regulations. The 5 GHz band gives the 802.11a an advantage within crowded environment which will avoid the service degradation caused by interfering with other devices. On the other hand, the overall range of 802.11a is slightly less than that of 802.11b where the signals absorbed more rapidly by any solid object in the path. Later on 2003, IEEE 802.11g [12] was emerged. It also allows throughput rate up to 54 Mbps while using the same 2.4 GHz band as IEEE 802.11b. This standard as known as Wi-Fi, becomes widely implemented over the entire world. High throughput IEEE 802.11n [2] was developed to overcome the limitation of the legacy IEEE 802.11b and IEEE 802.11g by improving the maximum data rate from the 54 Mbps of IEEE 802.11g to more than 400 Mbps. It also introduced multiple input multiple output (MIMO), and spatial streaming communications. In 2013, IEEE 802.11ac [13] has been introduced as an extension of 802.11n, providing a single link minimum of 500 Mbps and 1 Gbps overall in the 5GHz band.
The Standard 802.11 includes the protocols and operations of wireless networks. It only handles the two lowest layers, the physical layer and Media Access Control layer, as shown in Fig. 2.1. All the 802.11 standards need to be backward compatible to the older standards.

### 2.1.1 IEEE 802.11 physical layer

The physical layer shows the electrical and physical characteristics for devices. In particular, it presents the relation between a machine and a transmission medium. The physical layer is responsible for setting up and ending a connection to a communications environment. The three sub layers of the physical layer are as follow:

- The Physical Layer Convergence Procedure (PLCP) as an intermediate layer that is responsible for the Clear Channel Assessment mode and creating different physical layer packets.

- The Physical Medium Dependent (PMD) layer which is responsible for the
modulation and coding techniques.

- The Physical Management layer that takes care of the management issues.

2.1.2 IEEE802.11n physical layer enhancements

For high throughput, range and the reliability, IEEE 802.11n [2] slandered added several enhancements to the physical layer, including multiple input and multiple output (MIMO) setting with advanced signal processing and modulation technique, wider channel, and several modulations and coding schemes. Details description of IEEE802.11n physical layer enhancements are introduced as the following:

Multiple Input Multiple Output (MIMO)

Multiple input and multiple output or MIMO is an antenna technique for wireless communications, which is used to boost the wireless range by using multiple receive and, or transmit antennas. IEEE 802.11n defines several antenna configurations ranging from ”1x1” to ”4x4”. The first number refers to the number of transmit antennas and the second refers to the number of receive antennas. Generally, more antennas lead to higher data rate. In fact, neither the data rate nor the range does not increase by using multiple antennas simultaneously. What matters is how the device uses the antennas. For this, the IEEE 802.11n introduced several signal processing techniques such as Spatial Multiplexing (SM), Transmit Beamforming (TxBF) and Space-Time Block Coding (STBC). Each of these technique is described briefly below:

- Spatial Multiplexing (SM)

SM transmits a signal through various antennas over independent spatial paths to increase the PHY data rate by subdividing the transmitted signal into several pieces. It called spatial streams because each transmission propagates along a
different path and those pieces will have different strengths and delays. The device can double the capacity and increase the data rate when multiplexing two spatial streams into one channel (the radio frequency wave). IEEE 802.11n devices can implement at least two spatial streams and up to maximum of four.

- **Space Time Block Coding (STBC)**

  STBC sends multiple copies of the data stream over various antennas to boost the reliability of data transfer. The receiver has a better chance to identify the original signal stream in the presence of radio frequency interference and noise by comparing different copies of arrived signal. In this way, STBC will reduce the errors experienced at a given signal-to-noise ratio (SNR). However, this feature is only used when the number of transmitting antennas exceeds the number of receiving antennas and can be combined with SM for the best performance results.

- **Transmit Beamforming (TxBF)**

  TxBF is used to concentrate RF energy in a particular direction to guide the transmitted signal towards the intended recipient. This will improve the received signal strength and ensure high data rates by taking the advantages of environmental phenomena like signal reflection and multipath. Through the consideration of this technology, the transmitter needs to know how that signal will likely to be received either implicitly on the assumption that propagation is identical in both directions or through feedback from the receiver.

**40 MHz Channel Bandwidth**
40 MHz channels use twice as much bandwidth as the 20 MHz channels in the legacy IEEE 802.11b/g/a. The new IEEE 802.11n products can use both 20 and 40 MHz wide channels in either the 2.4 GHz ISM or 5 GHz UNII. IEEE 802.11n transmitter can provide up to 150 Mbps when using a 40 MHz channel as comparing with a 20 MHz channel which can establish a connection up to 72.2 Mbps.

Modulation and Coding Schemes

Modulation of RF, coding rate and guard interval set the actual PHY data rate that ranges from 6.5 Mbps to a maximum of 600 Mbps which could be achieved through the use of all the possible options of the IEEE802.11n. The guard intervals are used to ensure a distinct transfer that does not interfere each other. This guard interval is vital to avoid Inter-Symbol Interference (ISI) caused when using several paths. Long and short guard interval of 800 ns and 400 ns are supported compared to the legacy IEEE802.11a/b/g that supports only 800 ns interval. Short Guard time interval (SGI) can enhance the data transfer rate by 11% and keeps sufficient symbol separation for most environments. The RF modulation is the way by which data is communicated through the air. On the other hand, how much of the data stream is already in use for the transfer of usable data is known by Coding Rates. In this context, Modulation and Coding Scheme (MCS) can be defined as an integer assigned to each permutation configuration of modulation, coding rate, guard interval, channel width, and number of spatial streams.

2.1.3 IEEE 802.11 Media Access Control (MAC) layer

MAC layer presents the functional and procedural means of data transfer between network entities and provides a way to detect and correct the errors that may occur in the physical layer. The responsibilities in the MAC layer are divided into the
MAC sub-layer and MAC management sub-layer. The MAC sub-layer defines access mechanisms and packet formats. The MAC management sub-layer defines power management, security and roaming services.

2.1.4 MAC frame formats

![MAC frame format](image)

Figure 2.2: MAC frame format [2].

The MAC frame includes a set of fields which appear in the same order in all frames. Fig. 2.2 shows the MAC frame format. The first three fields (frame control, Duration/ID, and Address 1) and the last field (FCS) constitute the minimum frame format and are present in all frames, including the reserved types and subtypes. The fields Address 2, Address 3, Sequence Control, address 4, the quality of service control, HT control, and frame body are found only in certain kinds of frames. The frame body field has a variable sizes which is determined by the MSDU maximum size (2304 bytes) or the maximum A-MSDU (3839 or 7935 octets, depending upon the station capability), as well as any overhead of the security encapsulation.

**Frame Control Field**

The Frame Control field, contains control information used to determine the type of 802.11 MAC frame and provide the necessary information for the following fields to understand how to process the MAC frame.

**Duration/ID Field**

All control frames used this field, except with the subtype of Power Save (PS)
Poll, refer to the remaining time necessary to receive the following frame transmission. When the sub-type is PS poll, the field involves the association identity (AID) of the transmitting station.

**Address Fields**

Depending upon the type of the frame, the four address field shall contain a mix of the following address types:

- **BSS Identifier (BSSID)**: BSSID uniquely identifies each Basic Service Set (BSS). When the frame is from station in the BSS infrastructure, the BSSID is the MAC address of the Access Point. When the frame is from a station in the Independent Basic Service Set (IBSS), the BSSID is generated randomly, locally administered MAC address of the station, which initiated that IBSS.

- **Destination address (DA)**: DA refers to the MAC address of the final frame destination.

- **Source Address (SA)**: SA indicates MAC address of the source.

- **Receiver Address (RA)**: RA indicates the MAC address of the next immediate station.

- **Transmitter Address (TA)**: TA refers to MAC address of the station that sent the frame over the wireless medium.

**Sequence control**

This field contains two subfields, the Sequence Number field that indicates the sequence number of each frame and the Fragment Number field which indicates the sequence number of each fragment sent of a fragmented frame.

**Frame Body**
The frame body consists of the data in either management type or data frames.

**Frame Check Sequence**

The transmitting station uses a cyclic redundancy check (CRC) for all the fields of the MAC header and the frame body to produce the Frame Check Sequence (FCS) value. The receiving station then applies the same CRC to decide its own value of the FCS to check whether or not any errors happened in the frame.

### 2.1.5 IEEE 802.11n MAC layer enhancements

In this subsection, we briefly mention the most important IEEE 802.11n MAC layer enhancements [2] with an emphasis on frame aggregation, which maximizes throughput and efficiency.

**Frame Aggregation**

There are two techniques that implements the frame aggregation: aggregate MAC protocol service unit (A-MSDU) and aggregate MAC protocol data unit (A-MPDU).
A-MSDU: The basic idea of A-MSDU is to allow multiple MSDUs to be sent to the same receiver aggregated in a single MPDU, as shown in Fig. 2.3. This schema can improve the efficiency of the MAC layer especially when there are many small MSDUs. The receiver must support the reception function for A-MSDU. For an A-MSDU to be created, a layer above the MAC receives and buffers multiple packets (MSDUs). The A-MSDU is completed either when the size of the frames reaches the maximum A-MSDU size or the maximum delay reaches. Its maximum length can be either 3839 or 7935 bytes. The size can be found in the High Throughput (HT) capabilities element that is advertised by a HT station in order to declare its HT status. There are also certain constraints when constructing an A-MSDU:

- All MSDUs must have the same traffic identifier (TID) value.
- Lifetime of the A-MSDU should match the maximum lifetime of its constituent elements.
- The destination address (DA) and sender address (SA) parameters in the sub-frame header must match to the same receiver address (RA) and trans-
mitter address (TA) in the MAC header.

Thus, broadcasting or multicasting is not permitted. The main drawback of using the A-MSDU is under error-prone channels. By packaging all MSDUs into one MPDU with a single sequence number, for any MSDU that is damaged, the entire A-MSDU must be retransmitted.

![A-MPDU Frame aggregation](image)

**Figure 2.4: A-MPDU Frame aggregation [2].**

- **A-MPDU:** A-MPDU aggregation joins several MPDU with common PHY header. Fig. 2.4 illustrates A-MPDU in details. The major difference compared to the A-MSDU is that the functions of A-MPDU are performed after the MAC header encapsulation process. Thus, all MPDUs within the A-MPDU must be addressed to the same destination address. Also, there is no waiting / hold time to construct an A-MPDU so the number of MPDUs that will be assembled completely depends on the number of packets already in the transmission queue. The maximum obtained A-MPDU length is 65,535 bytes, and the utmost number of subframes is 64 because a block ACK bitmap field maps each frame by two bytes to a total of 128 bytes in length. An A-MPDU inserts a set of fields known as delimiters before each MPDU and it adds padding bits varied from 0-3 bytes at the tail. The basic purpose of the delimiter header is to
define the MPDU position and length inside the aggregated frame. It is worth mentioning that the cyclic redundancy checking (CRC) field in the delimiter verifies the authenticity of the 16 preceding bits. After receiving the A-MPDU, a de-aggregation process initiates. First of all, it verifies the A-MPDU for any errors based on the value of CRC. If it is correct, A-MPDU is extracted, it continues with the next subframe till it reaches the end of the PSDU and it checks every four bytes until it locates a valid delimiter or the end of the PSDU. The delimiter signature has a unique pattern to assist the de-aggregation process while scanning for delimiters.

**block ACK**

The block ACK is introduced in the MAC 802.11e design. It is further enhanced in 802.11n to be comply with the frame aggregation. Although part of a large aggregate frame can dramatically reduce the overhead in transmission, frames with high bit error rate (BER) have a higher error probability and may need further retransmission and the network performance will be degraded. The block ACK mechanism overcomes this problem by simply acknowledging the correct MPDUs in the aggregate frame. The sender just needs to resend those recognized MPDUs. Block ACK mechanism eliminates the problem of a large frame in error prone channel and further enhances the performance of 802.11n MAC. The block ACK mechanism applies only to A-MPDU, but not A-MSDU. That is, when the MSDU is found to be incorrect, the whole A-MSDU must be transmitted again. The maximum number of MPDUs in any A-MPDU restricted to 64 as one block ACK bitmap can only acknowledge at most 64 sub-frames.

**Reverse direction**

Reverse direction mechanism is a novel technique to improve the efficiency of the Transmit Opportunity (TXOP). TXOP provides contention-free access to the channel
for a specific period. The TXOP process only helps forward transmission, but not in the opposite direction of the transmission. For application with traffic in both directions, the performance will be degraded through random back off and contention of the TXOP transmission opportunities. Reverse direction mechanism allows the TXOP holder to allocate the remaining TXOP time to its receivers to enhance the channel utilization and performance of reverse direction traffic flows.

In the reverse direction process, two stations types are defined: RD initiator and RD responder. The station that has the TXOP and can send the Reverse Direction Grant (RDG) is RD initiator. The RDG acknowledgement is sent by the RD responder when it receives a frame with RDG frame, if it has data to be sent or without RDG if there is no data to be sent to the RD initiator.

The main enhancement in reverse direction mechanism is the delay time reduction in reverse link traffic. Data packets in the reverse direction can be transmitted immediately when the RD responder is allocated for the remaining TXOP and do not need to wait until the station holds TXOP. A delay-sensitive applications, like VoIP, can benefit from this mechanism.

### 2.2 State of the Art

In the last few years, many researchers were focusing on energy consumption of the wireless devices across various layers of the communication system. For the physical layer, several transmission techniques, power control algorithms, and adaptive modulation and coding mechanisms have been studied from the energy efficiency point of view.

Moreover, many papers have been proposed to address the issue of energy efficiency in the Medium Access Control (MAC) layer and several recent research studies have focused on IEEE 802.11 n/ac MAC frame aggregation. This section highlights
the work related to this thesis with a brief summary of some of the alternative methods.

2.2.1 Static Frame Aggregation Schemes

MAC frame aggregation scheduler was not specified by the IEEE 802.11n standard, and each driver vendor implemented its own version. A naive frame scheduler is determined by three constraints, the maximum A-MPDU length, the frame air duration which specified by the regulatory requirements and the block ACK windows where the losses can play a role. The naive scheme does not take into consideration different channel situations that can potentially further deteriorates the network performance. Ath9k [14] aggregation scheduler which is used in our testbed deployment as shown later, prefers timeliness over capacity; instead of waiting to assemble the maximum allowable A-MPDU size which can boosts the network throughput, it always assembles a fix size MPDU frames as many as available at that time in the buffer subject to the regulatory and receiver constraints. This A-MPDU aggregation algorithm is illustrated in details in Algorithm 1. Thus, while it may not use optimal A-MPDU sub frame sizes, the main goal is to improve the end-to-end delays while increasing the throughput without worrying about the energy consumption.
**Input:** Number of frames in buffer \((Q)\), Regulatory A-MPDU size limit \((\delta_1)\), Receiver A-MPDU limit advertised in its HT Capabilities element \((\delta_2)\), Number of frames in this A-MPDU \((n)\)

**Output:** A-MPDU aggregate frame

\[ n = 0, \text{A-MPDU} = 0; \]

\[ \text{while } Q \neq 0 \text{do} \]

\[ \quad \text{// Check for regulatory or receiver limits;} \]

\[ \quad \text{if } n \geq \delta_1 \text{ or } n \geq \delta_2 \text{then} \]

\[ \quad \quad \text{break;} \]

\[ \quad \text{end} \]

\[ \quad \text{Add padding (if necessary) to align A-MPDU frame boundary;} \]

\[ \quad \text{Link this frame to the aggregate A-MPDU;} \]

\[ \quad Q--; \text{// Decrement buffer count by 1;} \]

\[ \quad n++; \text{// Increment frame count by 1;} \]

\[ \text{end} \]

\[ \text{Deliver assembled A-MPDU to driver transmit function;} \]

**Algorithm 1:** A-MPDU aggregation as implemented in ath9k [14] driver

The effect of IEEE 802.11n A-MPDU and A-MSDU frame aggregation mechanisms is analyzed by Kim et al. [15]. They mainly focused on the throughput of the network. A model based on an enhanced discrete time markov chain is proposed to study frame aggregation post-backoff behavior. As expected, A-MSDU outperforms A-MPDU under an error-free environment due to its smaller overheads and the larger aggregated frame size. Lee et al. [16] proposed a multiple receiver frame aggregation scheme to boost the capacity of the video traffic in any IEEE 802.11n based WLAN. They found that the number of video streams that can be supported on these kind of networks depends heavily on how frame aggregation is implemented. Their multiple-receiver scheme increases the number of supported video streams by a factor of 2.

### 2.2.2 Adaptive Frame Size Aggregation Schemes

Several recent research studies in the field of wireless networking have studied IEEE 802.11 MAC frame aggregation. Most of the existing work focused on increasing throughput and minimizing delay. Simple frame aggregation scheduler is presented by Selvam et al.in [17]. It selects the frame size and aggregation type based on
the duration of frame transmit opportunity. The scheduler estimates the optimal
time for transmission based on expiry time of a waiting frame in the queue and
it selects the optimum A-MSDU frame size using a lookup table that consists of
various bit error rates and the corresponding frame size. Either A-MSDU or two
level aggregation scheme is used based on the total size of frames that are waiting
in the buffer. Their proposed method outperformed the state of the art fixed size
frame size adaptation algorithm under error-prone channels for both uni-directional
and bi-directional transfers. Their analytical model is built based on Bianchis model.
In a similar work, Teymoori et al. [19] proposed a method to obtain the optimal
frame size based on a constrained convex optimization problem. The main goal is to
maximize the overall network throughput with regard to node delay constraints. On
the other hand, Error-Sensitive Adaptive Frame Aggregation algorithm (ESAFA),
proposed by Moh et al. [20], adjusted the aggregate size dynamically according to
the application acceptable frame error rate. This methods improved both the delay
and the network throughput compared to state of the art, static frame aggregation
methods.

2.2.3 Energy Efficient Frame Aggregation Schemes

There is very limited work on energy efficiency for frame aggregation in WLANs.
Keranidis et al. [21] investigated the IEEE 802.11 MAC-layer enhancements and its
impact on energy consumption in wireless devices. They showed that frame aggre-
gation mechanisms can reduce the energy consumption by 75%. In a similar effort,
Seungwoo et al. [22] introduced a frame aggregation scheme that enhances energy ef-
ficiency by adjusting the number of sub-frames per aggregate according to the current
battery capacity. However, this scheme may not be useful in the case of the A-MPDU
frame aggregation where only corrupted sub-frames are being retransmitted. More-
over, this scheme transmits a single frame only \textit{i.e.}, disabling frame aggregation, when the channel quality exceeds a specific threshold which may result in severe drop in the throughput. Finally, Zhihui \textit{et al.} [23] proposed Energy Efficiency Frame Aggregation scheduling algorithm (EEFA). EEFA varies the frame size based on bit error rate. It reduces the energy consumption by ensuring the data transmission and retransmission are completed at the channel access time. It divides the transmission time into two phases, one for the aggregated frame and the other is dedicated only for retransmissions. Clearly, this is going to impose a huge overhead when the channel quality is high. Furthermore, EEFA estimates the appropriate frame size using a predefined model. In fact, this scheme lacks the online component that GFA scheme is providing.
Chapter 3

Green Frame Aggregation Design and Implementation

3.1 Motivation

As mentioned earlier, there are two types of frame aggregation in IEEE 802.11n/ac networks, namely A-MSDU and A-MPDU. The former creates the larger frame by aggregating multiple MSDUs that are going to the same destination using only a single MAC header and a single Frame Check sequence (FCS) trailer. The maximum A-MSDU length can be either 3839 or 7935 bytes based on the advertised High Throughput (HT) capabilities information field. A-MSDU can improve the efficiency especially when there are many small MSDUs. On the other hand, A-MPDU creates much larger data frame up to 65535 bytes by combining multiple MPDUs into a single frame. The actual A-MPDU size may vary according to vendor implementation. In fact, the maximum A-MPDU length may be further limited by the HT receiver capabilities.

In fact, a subframe loss in an A-MSDU results in retransmitting the whole A-MSDU again. Clearly, the aggregation performance is affected by the channel interference level. Noisy channels may cause many bit errors resulting in a lot of aggregate retransmissions, which contribute negatively to the device power consumption. On
the other hand, packing frames as aggregates in an error free channel may result in huge power saving since the frame transmission time is going to be shorter and hence the radio active time will also be shorter. Alternatively, it is worth noting that an A-MPDU is able to aggregate several MPDUs. A lost (or corrupted) sub-frame in any A-MPDU does not disturb the reception of other sub-frames in the same aggregate. This is because each MPDU has its own FCS to allow the re-transmission of only the corrupted MPDU(s).

![Figure 3.1: The effect of varying the A-MPDU sub-frame size on the energy consumption over various channel conditions.](image-url)

To motivate the problem even further, an experiment is performed to investigate the relationship between the MPDU frame size and the energy consumption under error-prone channels. In this experiment, the channel Frame Error Rate (FER) is varied between 0-99% and the size of the MPDUs i.e., sub-frames, in the aggregated...
frame is varied within the allowed range which is limited by Linux configuration. The energy consumption is calculated using the equations in the following subsection. The implementation setup is described in details in Sec. 4.1. Fig. 3.1 illustrates the possibility of huge reduction in energy consumption by simply varying the A-MPDU sub-frame size based on the channel interference level. To address this issue, we develop new scheme for estimating the optimal A-MPDU sub-frame size for different channel quality without sacrificing the network performance. The main goal of our proposed scheme is to increase the energy efficiency of frame aggregation protocol that is used by IEEE 802.11n/ac wireless devices. In the next section, we are going to illustrate how GFA selects the optimal A-MPDU sub-frame size based on the channel quality and the energy budget.

3.2 Green Frame Aggregation Design

Wireless transmissions are generally more prone to error than the wired network and several protocols and applications in wireless networks highly depends on predicting the quality of the wireless channel for good performance, reliability and coverage. In realistic wireless networks, the link quality can be estimated by measuring the signal strength and error rates. Moreover, choosing the appropriate quality estimation techniques is vital to optimize the protocol under study.

SNR (signal to noise ratio), RSSI (received signal strength), BER (bit error rate) and FER (frame error rate) are the most popular estimation techniques. Each one of these techniques used in a different situation.

Signal to noise ratio [24] is a measure of desired signal level relative to background noise. SNR Measurement depends on the definition of the background noise that is the level of environment noise being measured. Although, most of the IEEE 802.11 cards do not typically report SNR, it reports the receive sensitivity to indicate the
minimum power level to receive a signal reliably. For example, a network card may indicate that the card has a receive sensitivity of 96 dBm at 1 Mbps. The card would no longer be able to differentiate between signal and noise if the value is less than 96 dBm. The NIC would not detect the received packet at all, and the packet could be lost. Of course, different data rates, will result in different receive sensitivities. As data rate increases, receive sensitivity decreases and the card will be less resistant to corruption.

The power level of the signal being received can be measured using the RSSI (received signal strength) [24]. The higher the RSSI value, the stronger the signal is. RSSI can be used to indicate when a packet of information can be sent by determining the amount of energy in the communication channel at which the network card is clear to send. IEEE 802.11 defines RSSI as an arbitrary integer value, used internally by the physical and data link layers.

The channel noise, interference, attenuation and signal transmission power are important factors that affect the data transmission performance. We need an ideal way to assess the full end to end performance of the system including the transmitter, receiver and the medium in-between such as bit error rate (BER) and the frame error rate (FER). Bit error rate (BER) is defined as the name implies by the number of bit errors of the received bits per specific time window [25]. Similar measurements can be carried out for the transmission of the data packets or frames that is known as frame error rate (FER).

Most of previous efforts in this direction rely on estimating the channel Bit Error Rate (BER) which may not reflect the acceptable frame error rate of most real-time applications. Most loss tolerant traffic requires the FER to be within 5% [26]. Alternatively, GFA takes into consideration the frame error rate requirements of real-time applications and adjusts the sub-frame size accordingly. The error rate threshold, which is 5% in our scheme, prevents degrading network performance when trying
to maximize energy efficiency. Moreover, this threshold minimizes the overhead of varying the sub-frame size when the FER is within the acceptable limits. It is well known that high throughput can be obtained by transmitting aggregates with the maximum sub-frame size under the best channel condition. Hence, GFA tries to utilize the energy budget associated with the maximum sub-frame size. In this case, our objective function is as follows:

$$E_{\text{min}} = P \times \frac{L}{R}$$  \hspace{1cm} (3.1)$$

where $E_{\text{min}}$ is the minimum energy consumption, $P$ is the power needed to transmit one bit at time, $L$ is the maximum MPDU sub-frame size and $R$ is the transmission rate.

In A-MPDU frame aggregation, only corrupted MPDUs need to be re-transmitted again. Since the original transmission and the following re-transmission are unrelated events, we estimate the expected number of transmissions needed to successfully deliver one frame as

$$N = \frac{1}{1 - FER}$$  \hspace{1cm} (3.2)$$

where $FER$ is the current frame error rate. So, the energy consumption for reliable transmission is

$$E_{\text{min}} = P \times \frac{L}{R} \times N$$  \hspace{1cm} (3.3)$$

Using (3.3), we can get the optimal sub-frame size that satisfies our conditions from the following relationship

$$L = \frac{E_{\text{min}} \times R}{P \times N}$$  \hspace{1cm} (3.4)$$
According to (3.4), GFA updates the A-MPDU sub-frame size whenever the frame error rate changes taking into account the FER threshold.

### 3.3 Green Frame Aggregation Operation

Green frame aggregation aims to reduce the consumed amount of energy that needed for a reliable data transmission. As mentioned in Sec. 2.2.1, the default implementation of the A-MPDU aggregation provides fixed MPDUs size all the time. In GFA, we remove the constraint that maintains the same size across different channel conditions. In order to do that, the minimum energy budget to transmit the maximum allowed MPDU size is calculated which will help in balancing the transmit power per bit with the channel error rate, giving more freedom towards having the most suitable sub-frame size for the next session.

**input**: Frame error rate \((FER)\), frame retransmission count \((N)\), MPDU size limit \((L)\), Tx-power \((P)\) and Current Tx rate \((R)\)

**output**: Optimum MPDU size \((S)\) and Energy consumption \((E)\)

Set FER maximum acceptable limit \(FER_{\text{max}}\);

Calculate Energy budget \(E_{\text{min}}\) for a reliable transmission based on \(E_{\text{min}} = P \times \frac{L}{R} \times N\);

for every time interval \(\tau\) do

if \(FER \geq FER_{\text{max}}\) then

Calculate the MPDU size \(S\) as follow: \(S = \frac{E_{\text{min}} \times R}{P \times N}\)

Adjust MPDU size to \(S\);

end

Preserve the maximum MPDU size \(L\);

end

Recalculate the total energy consumption as \(E = P \times \frac{S}{R} \times N\)

**Algorithm 2**: Green frame aggregation Pseudo Code

The decision of frame sizing as described is mainly based on the channel condition. If the channel quality is less than a predefined frame error rate \((FER)\), then GFA calculates a new MPDU size to satisfy the requirements; otherwise the maximum MPDU size is used. For each specific time window, GFA senses the channel and estimates the channel FER to determine the suitable MPDU size for the next session.
The most interesting challenge is that the expected overhead of implementing such mechanism must be less than the observed energy efficiency gain. The predefined FER threshold is determined in order to maintain the overall network performance. Other than that, GFA cannot be considered effective and useful. The operation of GFA is illustrated in Algorithm 2.
Chapter 4

Green Frame Aggregation

Experimental Results and Analysis

In this section, the performance of GFA is evaluated experimentally using a testbed deployment. In order to evaluate the performance of GFA in terms of energy efficiency, several experiments are conducted over various network scenarios. In all the experiments, GFA performance is compared to the Static Frame-size Aggregation (SFA) scheme that is enabled by default in Linux. By default, the A-MPDU sub-frame size is fixed to 1500 bytes which is the maximum supported frame size in our system. To test the other corner case, the same experiments are repeated while fixing the frame size to the minimum supported MPDU size which is 256 bytes. It is important to note that the duration of each run is 100 seconds and all our results are then averaged over five runs.

4.1 Experimental Setup

GFA is implemented in Linux and evaluated under error-prone channels using a wireless testbed in our campus. In this section, we give a detailed description of the used testbed both from the hardware and software sides. The testbed components are summarized in Table 4.1.
4.1.1 Hardware Setup

Our testbed is composed of several nodes that are basically Shuttle PCs [27]. Each of these boxes is equipped with an Intel E7500 core 2 Duo processor, 1 GB of RAM and AR9380 wireless card which is IEEE 802.11n compatible Atheros chipset. This wireless interface provides three RF chains and supports up to three transmit and receive spatial streams with a maximum link rate of 450 Mbps.

4.1.2 Software Setup

The testbed nodes run Fedora 20 with Linux kernel 3.14.8 and Linux Ath9k wireless driver [14], which is a Free and Open Source Software (FOSS) developed by Atheros. This driver implements A-MPDU frame aggregation but not A-MSDU. Hence, we will limit our discussion to A-MPDU frame aggregation. For fair comparison, we disable the rate control algorithm and fix the link rate to 405 Mbps in all the experiments. Moreover, this high rate allows us to test GFA over high interference levels. To generate traffic in the network we use netperf [28] which is a benchmarking utility that provides performance measurement for various types of flows. We manage to introduce interference in our network by using the crowded 2.4 GHz band which interfere with the production WLAN on our campus.

The maximum and minimum allowed MPDU frame size in our testbed, limited by Linux configuration, are 1500 bytes and 256 byte respectively. Furthermore, the wireless driver limits the A-MPDU aggregated frame length to 32 MPDUs only. It is worth noting that the actual aggregate size is limited to frame air duration of 4
ms to comply with the operation regulatory requirements. Moreover, the A-MPDU density, \textit{i.e.}, number of of MPDUs in A-MPDU, is partly dependent on the wireless link rate [29].

<table>
<thead>
<tr>
<th>Chipset</th>
<th>AR9380</th>
</tr>
</thead>
<tbody>
<tr>
<td>Antennas</td>
<td>1x1</td>
</tr>
<tr>
<td>Mode</td>
<td>Sleep</td>
</tr>
<tr>
<td></td>
<td>0.12</td>
</tr>
<tr>
<td></td>
<td></td>
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</tbody>
</table>

Table 4.2: AR9380 power consumption across various operation modes [3].

The power consumption of the wireless interface cards in our testbed, Atheros AR9380, was measured in [3] using their innovative online Energy consumption Monitoring Framework (NITOS). They specified PHY-layer configurations at the transmitter node, and repeatedly monitor the energy consumption of each wireless NICs at both the transmitter and the receiver side. After that, they isolated specific events, such as frame transmission/reception and average multiple events in order to determine the NIC card power consumption under each specific PHY-layer configuration. The power consumption results using various operation modes are summarized in Table 4.2. AR9380 consumes around 2.45 W when the link rate is 195 Mbps. As we describe in the next section, we are going to use this piece of information to estimate the power needed to send one bit at time.

### 4.2 Single-hop topologies

The performance analysis of a single hop topologies is analyzed. The path distance between the network nodes is varied from two, five to ten meters and the interference
Figure 4.1: A-MPDU sub-frame size versus the channel frame error rate for GFA and SFA with two meters path long.

Figure 4.2: A-MPDU sub-frame size versus the channel frame error rate for GFA and SFA with five meters path long.
Figure 4.3: A-MPDU sub-frame size versus the channel frame error rate for GFA and SFA with ten meters path long.

Figure 4.4: Energy consumption of both GFA and SFA versus the channel frame error rate with two meters path long.
Figure 4.5: Energy consumption of both GFA and SFA versus the channel frame error rate with five meters path long.

Figure 4.6: Energy consumption of both GFA and SFA versus the channel frame error rate with ten meters path long.
level between the source and destination is increased from 9%, 38% to 95% for the two, five and ten meters respectively.

First of all, we compare all the schemes in terms of A-MPDU sub-frame size while varying the distance between the nodes. The results for MPDU size are shown in Fig. 4.1, Fig. 4.2 and Fig. 4.3 for the two, five and ten meters respectively. Obviously, Static Frame-size Aggregation (SFA) scheme fixes the A-MPDU sub-frame size regardless of the channel condition. In fact, this comes at the cost of high energy consumption especially when the channel quality is low. On the other hand, GFA adaptively varies the A-MPDU size according to the channel quality.

![Graph](image)

Figure 4.7: The dynamic behaviour of GFA over time. The A-MPDU sub-frame size is selected based on the channel quality.

As well as the energy consumption results are illustrated in Fig. 4.4, Fig. 4.5 and Fig. 4.6 again for the two, five and ten meters respectively. It is clear from these
figures that as the channel quality gets lower, GFA starts outperforming SFA with large sub-frames. In extreme interference conditions, GFA uses the minimum allowed MPDU size which helps saving $6 \times$ more energy. Although SFA with small sub-frame size always maintains low energy consumption, this comes at the cost of low utilization as we are going to show later. The dynamic nature of GFA is illustrated in Fig. 4.7. This figure shows that GFA smartly selects the appropriate MPDU size according to channel FER.

As described earlier, GFA dynamically selects the MPDU size that suits the channel condition observed in a specific time interval. Hence, when the MPDU size gets smaller in response to high interference, the aggregated frame (A-MPDU) gets longer as more sub-frames can fit in the allowed frame air time. This is considered a plus in low quality channels as only corrupted frames in an A-MPDU gets retransmitted, resulting in increased network goodput. Fig. 4.8 shows the average A-MPDU length while increasing the distance between the network nodes. As shown, GFA has an av-
average A-MPDU length of 13, 15 and 16 for the two, five and ten meters long. Where, the SFA with big A-MPDU sub-frame size keeps almost the same A-MPDU length with an average of 12 sub-frames. It is worth noting that using static small A-MPDU sub-frame size will increase the total A-MPDU length up to 31 MPDUs. However, the overhead associated with these sub-frames will affect the throughput especially when the channel quality is good.

![Figure 4.9: Average goodput in one-hop networks.](image)

The performance of GFA in terms of network goodput and end-to-end delay is also analysed. As shown earlier, GFA increases the overall A-MPDU length which boosts the overall goodput. The average goodput is plotted in Fig. 4.9. The error bars in this figure represent the 95% confidence intervals. GFA goodput is increased by 5%, 15% and 40% compared to the SFA with big A-MPDU sub-frame size. On the other hand, GFA increases the total goodput by more than 60% compared to static small sub-frames.
Figure 4.10: RTT CDF for both GFA and SFA in two meters path long.

Figure 4.11: RTT CDF for both GFA and SFA in five meters path long.
In addition to the increase in goodput, GFA starts to dominate the other scheme in terms of latency as the interference level increased. The Cumulative Distribution Function (CDF) of the performance metrics for various protocols are shown in Fig. 4.10, Fig. 4.11 and Fig. 4.12 across two, five and ten meters. GFA achieves slightly lower end-to-end delay compared to the static schemes in the extreme noise level. The reason for this is the fact that transmitting A-MPDUs with smaller sub-frames leads to improved data transmission reliability.

### 4.3 Multi-hop topologies

The energy efficiency of the schemes using a multi-hop wireless topology is also analyzed; one to three nodes are added along the path from the sender to the receiver. GFA is implemented in the source as well as all subsequent relay nodes. Energy efficiency can be quantified by the amount of energy drained from the nodes. In fact, it can be calculated by comparing the amount of energy input (the budget) to the amount of energy output (consumption).
Figure 4.13: The energy efficiency under normal channel conditions while varying the hop count. The y-axis shows a logarithmic scale.

Figure 4.14: The energy efficiency under severe interference while varying the hop count. The y-axis shows a logarithmic scale.
In this set of experiments, the performance of GFA is also evaluated under a severe interference caused by downloading a very large file between two nodes in the network. The aggregated energy efficiency results over normal channel conditions and over the channel with high interference are shown in Fig. 4.13 and Fig. 4.14. These figures show that GFA is able to boost the energy efficiency across various channel conditions. In the case where the channel quality is high, where FER is about 7%, the efficiency is increased up by 8%, 10%, and 22% in the 1-hop, 2-hops, and 3-hops scenarios respectively when compared to the SFA with large A-MPDU sub-frames. Although using SFA with small sub-frames increases the energy saving tremendously, this comes at the cost of lowering the throughput by an order of magnitude as shown later. Over noisy channels, GFA improves the energy consumption significantly as well. At extremely low quality channels (FER is between 80-95%), GFA has increased the efficiency by $6\times$ over the single hop scenario compared to the default static frame size. As the number of hops increases, GFA increases the energy efficiency by $9\times$ and $13\times$ for the 2 and 3-hop scenarios respectively where the channel FER is between 60-80%.
Figure 4.15: The energy efficiency under normal channel conditions in the parking lot topology. The y-axis shows a logarithmic scale.

Figure 4.16: The energy efficiency under severe interference in the parking lot topology. The y-axis shows a logarithmic scale.
In the next set of experiments, we analyze the performance of GFA over both multi-hop and multi-flow scenarios. We vary the number of concurrent flows from one to three and measure the overall performance. The three flows start simultaneously. The nodes are organized in a parking lot topology \textit{i.e.}, the first flow traverses only a single hop, the second flow stops at the second hop and the third flow is the only flow that reaches the third hop. Fig. 4.15 and Fig. 4.16 show the per flow energy efficiency for various number of flows over high and low channel qualities. In the former case, GFA increases the efficiency by about 30\% for all the scenario when compared to static frame sizing with big sub-frames and again SFA with small sub-frames increases the energy saving tremendously. Once more, GFA dramatically boosts energy savings in the extreme interference case by $6 \times$, $12 \times$ and $18 \times$ for the first flow, the second flow and the third flow respectively, same as small sub-frames SFA compared to the SFA with large MPDU case.

![Figure 4.17: Average A-MPDU length in the multi-hop network.](image-url)
The average number of aggregated MPDU per hop is also measured. Again, as the
MPDU size gets smaller, the A-MPDU length gets longer as illustrated in Fig. 4.17.
Over a single hop, the average A-MPDU length for GFA is about 16 MPDUs compared
to 25 MPDUs for SFA with small sub-frames and only 12 MPDUs in the case of static
large sub-frames. As expected, the aggregate length per station is going to decrease
as the number of hops increases due to more collisions and imperfect spatial reuse.
Exactly the same thing happens in the multiple flow case with the average A-MPDU
length for GFA is about 14 MPDUs, and 12, 20 MPDUs for small sub-frames and
large sub-frames SFA respectively as shown in Fig. 4.18. However, it is clear in this
case that there is a fairness issue between the flows. Nevertheless, this issue does not
affect GFA performance.
Figure 4.19: Average goodput in multi-hop networks.

Figure 4.20: Average goodput in parking lot topology.

In response to large A-MPDU frame with smaller sub-frame size, GFA increases the goodput by up to 40% compared to the SFA with big A-MPDU sub-frame size.
On the other hand, GFA increases the total goodput by more than 80% compared to static small sub-frames as shown in Fig. 4.19. As expected, the overall goodput drops by 1/2 and 1/3 for the 2-hops and 3-hops respectively. Fig. 4.20 shows the per flow goodput for all the flows in the parking lot topology. The error bars, which also represents the 95% confidence intervals, show severe unfairness between the flows. As shown, GFA outperforms the default case in terms of network goodput.

![Figure 4.21: RTT CDF for both GFA and SFA in two-hops network.](image)
Figure 4.22: RTT CDF for both GFA and SFA in three-hops network.

Figure 4.23: RTT CDF for both GFA and SFA in parking lot topology.
Moreover, the RTT CDF results over multi-hop networks topology are shown in Fig. 4.21 and Fig. 4.22. As mentioned earlier, one hop latency is slightly lower than the other schemes. As the number of hops increased, near equal performance are obtained with respect to SFA due to the imperfect channel conditions and the existing background interference. Also, the aggregated CDF RTTs of the multi-flow case is shown in Fig. 4.23. Notice that the GFA net-flows RTT is almost similar to the other SFA protocols.
Chapter 5

Concluding Remarks

In this thesis, the importance of frame aggregation techniques and designing new energy efficient protocols were discussed. The main contribution of the thesis is in proposing green frame aggregation protocol (GFA) which is a novel, power-aware frame aggregation scheme for IEEE 802.11n/ac based wireless networks. GFA is based on the A-MPDU frame aggregation technique and benefit from the idea of retransmitting the corrupted sub-frames only. It aims to achieve high level of energy efficiency in all environment situations especially in high interference environments. GFA dynamically chooses the appropriate A-MPDU sub-frame size based on channel quality. GFA efficiently utilizes the energy budget that is associated with the maximum A-MPDU sub-frame size.

GFA is implemented and evaluated on a Linux based IEEE 802.11n wireless cards. The experimental evaluation over various channel conditions shows that GFA can significantly reduce the energy consumption by up to 6× compared to default Linux configuration in extreme noisy environment. Moreover, the results show that GFA outperforms the static frame sizing method in terms of network goodput and maintains the latency performance.

As a future work, we would like to analyse the performance of GFA over bidirectional data transmission link. This is interesting as this link can be used in reporting the channel state during the actual data transmission by sending some frames in the
reverse direction.
REFERENCES


6 Publications

• M. Alaslani, A. Showail, and B. Shihada, "Green Frame Aggregation Scheme for Wi-Fi Networks", Submitted to IEEE International Conference on High Performance Switching and Routing, 2015.