AALTO UNIVERSITY
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Analysis of Energy Efficiency in IEEE 802.11ah

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Master's Thesis submitted in partial fulfillment of the degree of Master of Science in Technology

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Abstract

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Recently, machine to machine (M2M) communication has been considerably evolved and occupied a large proportion of the wireless markets. The distinct feature of M2M applications brings new challenges to the design of the wireless systems. In order to increase the competence for M2M markets, several enhancements have been proposed accordingly in different wireless technologies. The thesis introduces these M2M enhancements with a focus on the Wi-Fi solution - 802.11ah technology.

802.11ah is a new amendment of Wi-Fi technology for M2M applications. In 802.11ah, a new mechanism named TIM segmentation has been introduced to provide scalable operation for a large number of devices as well as reduce the energy consumption. The scope of the thesis is to evaluate the energy efficiency of TIM segmentation in uplink traffic assuming Poisson process. To thoughtfully understand the principle of this mechanism, the fundamental MAC layer functions in Wi-Fi technologies have also been introduced. In addition, the thesis also proposed an energy-saving solution called additional sleeping (AS) cycles.

The performance evaluation is based on a Matlab system-level simulator. The simulations are carried out for various TIM segmentation deployments for a selected M2M use case, the agriculture scenario. The results show that the TIM segmentation can deteriorate the performance for uplink transmission. This is because that in sporadic traffic, restricting the uplink access causes the increase in packet buffering and these packets leads to simultaneous transmission. This can be a serious issue especially for the network with a large number of devices. The random backoff procedure in Wi-Fi cannot efficiently solve this collision problem. In addition, results shows that the AS cycles can reduce the energy consumption in busy-channel sensing and also decrease the collision probability by adding extra randomness.

Key words: IEEE 802.11ah, Energy Efficiency, M2M, IoTs

Preface

First and foremost I would like to deeply thank my advisors, Prof. Olav Tirkkonen and M.Sc. Osman N. C. Yilmaz for their excellent guidance and valuable comments on simulations and background studies.

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Finally, I would like to express my deepest gratitude and respect to my family, especially my wife to whom I owe everything I have achieved, for her love and invaluable support.

Espoo, 19 May 2015

Yue Zhao

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List of Abbreviations

ACK	Acknowledgement
AID	Association Identifier
AIFS	Arbitration Interframe Space
AIFSN	Arbitration Interframe Space Number
AP	Access Point
AS	Additional Sleep
BLE	Bluetooth low energy
BSS	Basic Service Set
CCA	Clear Channel Assessment
CDF	Cumulative Distribution Function
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
CTS	Clear to Send
CW	Contention Window
DCF	Distributed Coordination Function
DIFS	Distributed Interframe Space
DRX	Discontinuous Reception
DTIM	Delivery Traffic Indication Map
DSSS	Direct Sequence Spread Spectrum
EDCA	Enhanced DCF Channel Access
ESS	Extended Service Set
FDD	Frequency Division Duplex
FHSS	Frequency Hopping Spread Spectrum
HCCA	Hybrid Controlled Channel Access

HCF	Hybrid Coordination Function
IEEE	Institute of Electrical and Electronics Engineers
ISM	Industrial Scientific and Medical
IoTs	Internet of Things
LTE	Long Term Evolution
M2M	Machine to Machine
MAC	Medium Access Control
MIMO	Multiple Input Multiple Output
MTC	Machine Type Communication
NAV	Network Allocation Vector
NDP	Null Data Packet
Non-TIM	Non Traffic Indication Map
NS-STA	Non-Sensor Station
OFDM	Orthogonal Frequency Division Multiplexing
PCF	Point Coordination Function
PHY	Physical
PS	Power Saving
PSM	Power Saving Mode
PRAW	Periodic Restricted Access Window
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
RA	Random Access
RACH	Random Access Channel
RAR	Random Access Respond
RAW	Restricted Access Window
RRC	Radio Resource Control

RTS	Request to Send
S1G	Sub 1 GHz
SIFS	Short Interframe Space
SIG	Special Interest Group
SRR	Short Range Radio
S-STA	Sensor Station
STA	Station
TIM	Traffic Indication Map
TWT	Target Wakeup Time
TXOP	Transmit Opportunity
VCS	Virtual Carrier Sense
WLAN	Wireless Local Area Network
WNM	Wireless Network Management
WSN	Wireless Sensor Network

1 Introduction

Recently, machine to machine (M2M) communications through wireless technologies has attracted extensive attention in both industry and academia. M2M refers to the automatic communication between devices without human intervention which is also known as machine type communication (MTC). Examples of M2M applications may include intelligent buildings and utilities, industrial automation, emergency services, smart cities and transportation, agriculture and environment monitoring [1]. It has been one of the fastest growing areas of the wireless communication market. The report from Machina Research predicts that by 2020, over three hundred million embedded MTC devices will be connected in the UK [1]. It also anticipates that by that time, more than 80% of new vehicles will be connected. Compared with typical human-centric communications, M2M communications have distinct features, such as short infrequent data transmission and scalability of massive devices. These features create diverse challenges for existing wireless technologies to facilitate M2M solutions.

Currently, M2M communications are generally accomplished by two broad categories of wireless technologies, namely cellular networks and short range radio (SRR). Cellular networks, such as Long Term Evolution (LTE) can provide wide area connectivity and require the use of SIM card which has to be locked to a specific operator. Typical SRR technologies, such as Wi-Fi operate in license-free band which do not require the interaction of operators. However, both of these technologies may have drawbacks for some M2M applications since they have been mainly developed for human-centric communications. For example, both LTE and Wi-Fi drain the device battery very fast which may not be suitable for energy-critical M2M use cases. Also, the lack of ability to cope with a large number of devices may become an issue for massive MTC applications. Recently both LTE and Wi-Fi have been properly enhanced to expand for the wide range of M2M use cases.

In LTE, 3GPP has initialized the M2M enhancements in Release 12 [2]. The enhancements include device cost reduction, energy saving, coverage extension, and scalability improvement. In terms of energy saving, the maximum discontinuous reception (DRX) cycle has been extended from 2.56 second to 2 minutes to support longer sleeping time [3]. Furthermore, a device power saving mode (PSM) has been introduced to extend the device battery lifetime [4] [5]. Release 13 will further improve the device PSM mode to maximum device sleeping time [3]. Also, it will support the coexistence of 1.4MHz narrow-band to simplify the radio implementation [3].

In the area of Wi-Fi technologies, a new amendment named 802.11ah has been proposed for M2M applications. To support large scalability as well as reducing power consumption, 802.11ah introduced an efficient paging and scheduling method called traffic indication map (TIM) segmentation. This mechanism divides the devices into pages (also called groups) and enables each page of devices to follows a periodic time-distributed channel access. Devices can only wake up to access the channel in their own page time and be forced to sleep in others' time. Therefore, for a specific duration of time, the number of devices allowed to access the channel is reduced. These devices are required to wake up periodically to read beacons for downlink access. Furthermore, 802.11ah introduced a Non-TIM mode in which the device does not required to read beacons so longer sleeping time is achieved to further save energy. In addition, in 802.11ah the STAs channel access parameters have been divided into two types, sensor type and non-sensor type to prioritize the sensor service. [6]

The scope of the thesis is to evaluate the energy efficiency of the TIM segmentation mechanism introduced in 802.11ah. For a specific M2M traffic, different settings of TIM segmentation parameters, for instance, number of TIM group and access time duration of each group may significantly affect the system performance. However, 802.11ah standard does not define specific values for these parameters but provide a flexible range to select instead. Therefore, it is important to understand the impact of different parameter settings of TIM segmentations on the energy consumption. The parameter selected to evaluate in the thesis is the number of TIM groups. The impacts of both sensor and non-sensor type STA parameters are also considered.

The thesis selects the simulation method to model the protocol of 802.11ah MAC layer. The simulation is based on the state machine transition from a device perspective. It assumes a M2M use case, agriculture and farming scenario in sporadic uplink traffic based on Poisson arrival. The performance evaluation of TIM segmentation with different number of groups and channel access parameters are carried out. Results show that TIM segmentation mechanism with CSMA/CA channel access method may deteriorate the channel access in uplink. The reason of this has been analyzed in detail and its effect on other wireless system, such as LTE also discussed. In addition, the thesis proposes an energy saving solution called additional sleeping (AS) cycle and evaluates its performance in different traffic conditions.

The thesis consists of six chapters. In Chapter 1, the background, motivation and the structure of the thesis are described in order to give the scope of the thesis.

Chapter 2 describes the recent advancements in M2M communications for different wireless technologies including LTE, Wi-Fi and Bluetooth. These M2M enhancements are discussed mainly in terms of cost reduction, energy saving, coverage extending and scalability improvement.

Chapter 3 presents a technical overview of the Wi-Fi technology. First, the historical development of Wi-Fi technology is described. Then, the detailed physical (PHY) and multiple access control (MAC) layer functions are discussed, especially the channel access procedures. Last, the traffic indication map mechanism is explained.

In Chapter 4, the background and M2M enhancements in 802.11ah are presented. The characteristics of two types of STA deployment proposed in 802.11ah, TIM and Non-TIM, are described in detail. These characteristics are mainly discussed from the perspective of channel access and power saving. In addition, an energy harvesting potentials of various ambient sources is investigated to evaluate the feasibility for 802.11ah network.

In Chapter 5, the simulation method to model 802.11ah MAC layer is introduced. A MATLAB-based simulator is developed for performance evaluation in a selected M2M use case, agriculture and farming scenario. The selected assumptions are explained in detail as well as the parameters settings.

Chapter 6 shows the simulation results of TIM segmentation with various number of groups in distinct settings of STA channel access parameters. Based on the results, the system parameters have been optimized for a sporadic data traffic case. In addition, an energy saving solution is proposed and evaluated under different traffic load assumptions.

Finally, Chapter 7 concludes the thesis work.

2 M2M Enhancement in Wireless Technologies

2.1 LTE Enhancement for M2M

M2M or MTC has been anticipated to be one of the key potential applications for future 5G technologies [7]. 5G MTC can be divided into two categories: massive MTC and mission-critical MTC [8]. Massive MTC requires wide area coverage, low cost and complexity, scalable connectivity and deep penetration [7]; mission-critical MTC requires low end-to-end latency, high reliability and availability which enables real-time control and dynamic industrial automation [8]. Among all the wireless technologies, LTE can be a favorable candidates for 5G MTC due to its mature radio technology. Recently, in the latest LTE release, 3GPP has proposed many enhanced M2M features. The enhancements have been generally performed in terms of device cost reduction and power saving, network coverage extension and scalability improvement.

2.1.1 Enhancement for Low Cost Device

2.1.1.1 Device Category 0 in Release-12

In Release-12, 3GPP has defined a low complexity device category known as Category 0 (Cat-0) [9]. This category enables low cost modem implementation through lower the data rate requirements, operating single reception antenna, and introducing a half duplex mode.

The current LTE system targets high throughput performance with peak data rates of 150 to 300 Mbps [2]. This leads to the high cost of the LTE modem and may be over-qualified for M2M applications requiring lower data rates. To reduce cost, Cat-0 limits the peak data rate to 1Mbps in both uplink and downlink. Also, before Cat-0, two reception antennas operation were mandatory for all LTE device categories. This aims to provide high throughput by advanced antenna techniques, such as multiple input multiple output (MIMO). The drawback of supporting these advanced techniques is increasing the complexity of the modem implementation and raising the cost thereof. Thanks to Cat-0, the proposed single reception antenna operation can simplify the modem implementation and reduce cost considerably. Furthermore, the half-duplex frequency division duplex (FDD) mode proposed in Cat-0 can avoid the implementation of some RF filters since there is no simultaneous transmission and reception. For example, the duplexer and switches can be removed to save cost. [4]

2.1.1.2 Device Category Low Cost in Release 13

To further reduce the device cost, based on the Rel-12 Cat-0, Release 13 will introduce a new low cost device category particularly for M2M operations [9]. One of the features of this new device category is that it only support 1.4 MHz bandwidth. This category will co-exist with other LTE category devices on a single, wider-band carrier [2]. Currently, all LTE device categories including Cat-0 have to support the full carrier bandwidth of up to 20MHz. This allows the devices to exploit the full performance of the bandwidth deployed. However, most M2M applications require low data rates. In this case, a small bandwidth operation, such as 1.4 MHz would be sufficient. The single small bandwidth operation can allow simpler radio implementation and lower device cost thereof.

Another feature of this new device category is that the baseband and radio parts can be integrated on the same chipset [4]. This will further reduce the complexity of modem implementation. Furthermore, the requirement of maximum transmit power will be reduced to 20dBm [9]. Also, some relaxation of signal processing techniques will be also considered. For instance, the highest modulation order will be restricted in downlink and the devices will not be required to report the channel quality. It is expected that these enhancements in Release can bring device cost below 1 US dollars [2].

2.1.2 Energy Saving for Years of Battery Life

Ultra low power consumption can be a critical issue for energy-critical devices. In some cases, the battery should be able to run for years without charging or replacement. To achieve this goal, LTE has enhanced its power mode and proposed some efficient signaling methods. It is expected that 10 year battery life can be achieved with these solutions with two AA batteries [3].

2.1.2.1 Extended Discontinuous Reception

In release 12, the maximum duration of DRX cycle has been extended from 2.56 second to 2 minutes [4]. This enables longer sleeping cycles for some delay-tolerant MTC devices. DRX mechanisms is first introduced in UMTS to conserve the battery power for mobile terminals. It allows devices not to continuously listen to the channel for downlink access so that the devices can turn off its radio sporadically to save power. The DRX mechanisms is briefly described in the next three paragraph.

After a device successfully finishes the data transmission or reception, it first starts a DRX inactivity timer (T_1). This timer indicates the time to wait before entering DRX mode. During this time, if a data arrives, the device can immediately transmit or receive the data while simultaneously resetting the timer to zero. If there is no data coming before the DRX inactivity timer expires the advertised value T_1, the devices can enter the DRX mode. In this phase, the device is still registered with the network and keeps the radio resource control (RRC) connection.

After the devices initials the DRX, it starts the periodical DRX cycles which consists of on and off period. During on period, the device wakes up to monitor physical downlink control channel for downlink traffic indication. After monitoring, if it identifies no downlink indication, it keeps sleeping in the consecutive off period. The duration of each DRX cycle can be flexible. After the device starts DRX mode, it usually sets up several short DRX cycles which followed by long cycles.

After the device remains in DRX mode for some time without any packet arrival, the network may release its RRC connection and devices can move into idle state. In this case, DRX cycle is paging cycle and device wakes up periodically to listen to the paging message for downlink indication or system information updates. The DRX mode can be terminated by the device as soon as it detects a data arrives, either downlink or uplink. More details description of DRX mechanisms can be found in [10] and the effect of DRX parameters on M2M services has been evaluated in [11].

2.1.2.2 Device Power Saving Mode

To extend battery life for MTC devices, Release 12 also introduces a power saving mode (PSM) [5]. It has increased the device sleeping time in idle modes compared to DRX mechanisms. The sleeping time will be further increased in Release 13 [2].

The principle of PSM is similar to DRX mechanism. The device which supports PSM can obtain an active timer from the network. The value of this timer determines the duration for which the device remains reachable for a device-terminated transaction. The device starts the active timer when it initializes the transition from connect to idle mode. When the active timer expires, the device moves to PSM mode. In this mode, the device is not reachable since it remains sleeping and cannot check the paging channel. However, the device is still registered with the network.

The UE in PSM is required to periodically wake up to perform tracking area update. This enables the network to keep track of the device's location as well as connect with the device for downlink packets delivery. The PSM mode can be terminated immediately once the device originates an uplink transmission. According to the characteristics of PSM, it will be preferred for M2M applications with infrequent mobile-originated traffic, such as remote sensing and smart grid [4].

2.1.3 Enhancement for Deep Coverage

Coverage can be a crucial issue for some M2M use cases with high penetration loss, such as smart metering of utility located in the basement. The loss caused by indoor penetration may create unreliable network connections. Therefore, in Release 13, coverage enhancement will targets to allow over 155 dB path loss [9]. Compared with existing FDD-LTE networks, the link budget will be improved by 15dB.

Release 13 will propose some coverage enhancement solutions which requires to change the standard [9]. These solutions include power boosting of data and reference signals, repetition/retransmission and overhead reduction. The repetition technique refers to redundant transmission which sends the same data in consecutive transmit time intervals. This will change the frame structure of specifications and sacrifice the spectrum efficiency and delay. On the other hand, Release 13 will also propose solutions which require no specification changes [9]. For example, relaxing the performance requirements is a method, such as allowing longer acquisition time and higher error rate.

2.1.4 Scalability Improvement

To control congestion and overload for massive MTC devices, Release-12 has continued to optimize the network control techniques proposed in Release-11 [2]. In Rel-13, M2M device will be able to send assistance information to tell network its traffic type [2]. This can assist the network to accordingly configure radio resource parameters. For instance, network can configure a short inactive timer after it identifies the device transmits data infrequently. This enables the device to release the connection quickly and reduces the traffic congestion thereof.

Another related enhancement is the random access channel (RACH) in LTE [12]. The RACH is formed by a periodic sequence of random access (RA) slots which are reserved for access request of uplink transmission. When the device in idle mode generates a new data, it first need to access the network for scheduling request recourses for data transmission. In this case, a contention-based random access procedure is required.

The random access procedure is a four message handshake procedure between device and eNodeB. When a device requires to access to the network, it first waits for the next available RA slot to send a preamble frame. The preamble is randomly selected among the available orthogonal numbers which are periodically broadcasted in downlink control channel. After this, the eNodeB will broadcast a Random Access Respond (RAR) message for all the devices transmitting the preamble. In the RAR, the eNodeB shows the detected and undetected preambles. Devices with detected preamble will be allocated an uplink resource to send an RRC connection request message to eNodeB. The eNodeB will respond an acknowledgement (ACK) frame for the successful reception of this request message. After this, the channel access is established and devices can start data transmission. If a device identifies the eNodeB has not detected its preamble, it can perform backoff according to the backoff indicator in RAR and then attempt the preamble retry. [12]

A detailed discussion of current improvements of the RACH for M2M applications can be found in [13]. Some solutions, such as dynamic allocation of RACH resources have already been deployed by 3GPP to cope the overloading issues in massive MTC. The basic mechanism of dynamic RACH resource allocation is that the network can allocate additional RA slots to MTC devices when traffic congestion occurs. However, the drawback of this solution is sacrificing resources for data transmission.

2.2 M2M Enhancements in Short Range Radio Technologies

2.2.1 Wi-Fi

Wi-Fi is a wireless broadband data technology based on the 802.11 specifications [14]. In order to strengthen the competence for M2M applications, a new Wi-Fi amendment named 802.11ah has been recently proposed [6]. This amendment has primarily been enhanced in terms of coverage extending, power saving and scalability operation. It will enable Wi-Fi technologies to be more suitable for a large range of M2M use cases.

In order to extend the coverage, this new standard will operate in band below 1GHz. It will support narrow band modes to reduce device cost. For example, in Europe 802.11ah will operate in 863-868 MHz and allows either five 1 MHz channels or two 2 MHz channels [1]. To improve the scalability of Wi-Fi system, an efficient paging method called TIM segmentations has been introduced. The details of these mechanisms will be explained in the later chapter.

2.2.2 Bluetooth

The Bluetooth is a wireless personal area technology which was invented by the famous telecommunication vendor Ericsson in 1994. It was developed to connect mobile phones with its peripheral equipment, such as headsets [15]. The Bluetooth Special Interest Group (SIG) is responsible for the standard development and certificating manufacturers. By 2014, the members of Blue SIG has been increased up to 24,000 companies.

Recently, this technology has been considerably evolved, especially for M2M applications. In order to support energy-critical M2M applications, Bluetooth SIG announces the specification version 4.0 also known as Bluetooth low energy (BLE) in 2010 [16]. In this version, a low power mode is introduced to save the device energy cost.

In the version 4.1 [17] proposed in 2013, the M2M enhancements have been further developed in terms of empowering developer innovation and improving customer usability. To support more flexible applications, the multiple-roles capability has been added. This allows a single device to act as both Bluetooth Smart peripheral and a Bluetooth Smart Ready hub simultaneously. On the other hand, its usability has also been updated mainly in three areas: cellular coexistence, better connections and higher throughput. Firstly, in the version 4.1, Bluetooth modules can coordinate with LTE radios automatically to reduce the near-band interference. Secondly, the reconnection time interval has been modified to be more flexible. This enables recent-connected devices to automatically reconnect once they are in proximity. Last, it supports more efficient block data transfer with minimum overhead between two devices.

The latest version of Bluetooth is version 4.2 [18] proposed in 2014. In this version, the IP connectivity has been enhanced so that Bluetooth devices can directly access the Internet via IPv6. Also, the throughput has been increased up to 2.5 times faster than version 4.1.

3 Fundamentals of Wi-Fi Technology

3.1 Introduction to Wi-Fi

Wi-Fi refers to a family of standards, IEEE 802.11 specification, for wireless local area networks (WLANs). The Institute of Electrical and Electronics Engineering (IEEE) standards association has developed several global standards in the area of wireless communications, such as Wi-Fi, Bluetooth, and Zigbee. In order to provide further interoperability of various types of Wi-Fi products, the Wi-Fi Alliance is organized by well-known companies ranging from the chipset manufacturers, such as Intel and Qualcomm; to terminal manufacturers, which include Apple, TP-link and Huawei; and network manufacturers, such as Nokia and Ericsson.

The Wi-Fi technology is originally designed for human to human communication through wireless connection. Computers, smart phones and tablets are some of the most common devices which can use Wi-Fi technology. These devices can connect to the network, such as Internet via wireless access points (APs). With the development of mobile Internet application and popularity of the smart phone usage, there is a huge demand for high data rate services through Wi-Fi connection. Therefore, the throughput enhancement is one of the most important theme in the Wi-Fi standard development. The IEEE 802.11 specification only regulates the PHY and MAC layer of Wi-Fi technology, and the Wi-Fi network uses the same link layer protocol to connect with other local area networks, for example, Ethernet.

The Wi-Fi technology operates in 2.4GHz and 5GHz industrial, scientific and medical (ISM) bands. These bands are also used by other short range radio technologies, for example, Bluetooth and Zigbee. All of these devices in ISM bands share the same spectrum with each other.

The IEEE standard association updates the Wi-Fi standard through amendments which define new features and concepts. Several representative amendments are listed to show the development of the Wi-Fi technology as follows:

- IEEE 802.11a: The PHY layer technology, orthogonal frequency-division multiplexing (OFDM), is first introduced to enhance the throughput. Also, the 5 GHz ISM band is first used since the 2.4 GHz band has already been crowded. This amendment is incorporated into the published standard IEEE 802.11-1999.

- 802.11e: The concept of Quality of Service (QoS) is primarily defined for delay-sensitive applications, such as voice and video streaming. This amendment is integrated into the standard IEEE 802.11-2007.
- 802.11n: This standard supports the advanced physical layer technology, MIMO for throughput enhancement. Furthermore, frame aggregation in the MAC layer is introduced. It is an amendment to standard version IEEE 802.11-2007.
- 802.11ac: Very high throughput of 1Gbps is accomplished through the use of downlink multi-user MIMO technology and the maximum order of quadrature amplitude modulation (QAM) has been increased to 256. It is approved in 2014.

3.2 Connection Management

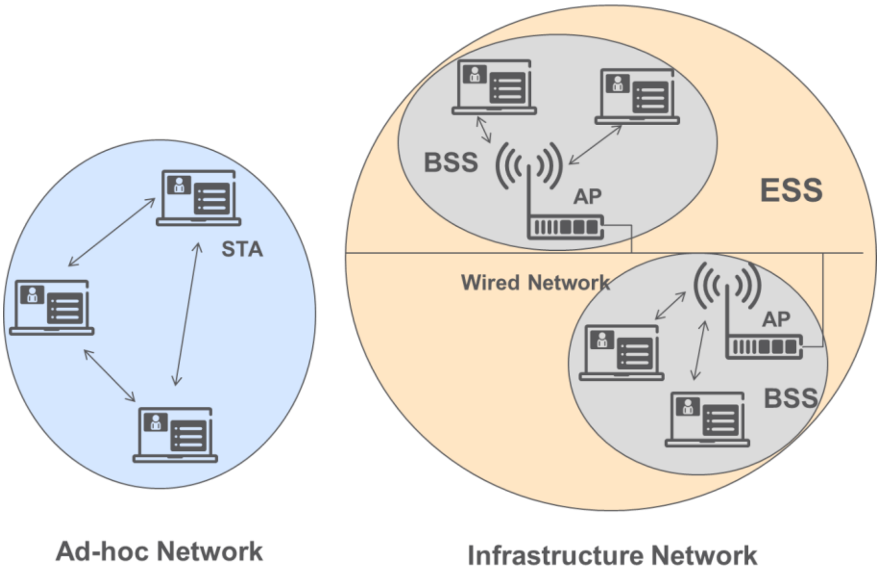

Figure 1. Basic service set and extended service set.

Wi-Fi networks can be configured into three modes: infrastructure, ad-hoc and mesh. The infrastructure mode is the most widely used as in cellular network, such as 3G and 4G. It consists of two types of STA, AP STA and non-AP STA, or simply as AP and STA. The AP is connected to the wired network, usually Ethernet while the STA is associated to the AP as a client. As illustrated by Figure 1, one AP and several STAs together form a basic service set (BSS) and several BSSs constitute an extended service set (ESS). As a comparison, in an ad-hoc network, terminals can communicate directly with each other without the help of AP. A mesh network is a hybrid configuration which combines the infrastructure and ad-hoc modes.

The Wi-Fi networks usually provide secure connectivity which can be tackled locally by the network administrator with suitable encryption and authentication methods. The authentication is a procedure in which a Wi-Fi STA establishes its identity to an AP. Once the authentication is complete, the STA can start the association in which it registers in the AP to acquire the full access to the network.

The association procedure only exists in the Wi-Fi network with infrastructure mode. Every Wi-Fi STA can only associate with one AP. After the mobile device authenticates to an AP, it will sends an association request to the AP. The AP processes this association request and decides whether the request is allowed or not. If the AP grants the association, it will send an association respond frame which contains a status bit shown that the association procedure is successful. Also, the respond frame assign the STA an association identifier (AID) for requesting the buffered downlink data which will be explained in the later Chapter. If the AP refuses the association, it will send an association respond frame, which includes the failed status bit, and ends the procedure.

3.3 PHY layer

The PHY layer is the lowest layer in the protocol architecture which enables the signal waveform to transmit in the wireless medium. It provides several fundamental functions, such as modulation, carrier sensing, and collision detection.

The modulation method in the Wi-Fi technology consists of Frequency Hopping Spread Spectrum (FHSS), Direct Sequence Spread Spectrum (DSSS) and OFDM. The FHSS is a method of transmitting wireless signals by rapidly switching the carrier frequency bands according to a pseudo random sequence. In DSSS, the signal is divided into small piece, each of which combined with a different higher data-rate binary sequence. The OFDM allows multicarrier transmission in which the available spectrum has been divided into a large number of narrowband sub-carriers. It allows efficient implementation in practice by baseband digital signal processing techniques. The OFDM has also the advantage of mitigating frequency selective fading and robust against inter-symbol interference. [14]

The Clear Channel Assessment (CCA) is a logical function in the physical layer for carrier sensing and collision detection. Through this function, the Wi-Fi device can determine the current state of the wireless channel (idle or busy). One way of CCA is that it measures the energy level in the wireless medium and detect whether the level is above the threshold or not. If the measured energy level is above the threshold, the device determines the channel is busy and otherwise it determines it is idle. The energy can be generated by any types of signal operated in the ISM band. These signals can be Wi-Fi signals or others, such as Bluetooth and Zigbee. The CCA function can also determine the wireless channel condition without measuring the energy level of the medium. In this case, the STA determines that the channel is busy if it detects a carrier with the characteristics of the Wi-Fi standard. [14]

3.4 MAC layer

3.4.1 Channel Access

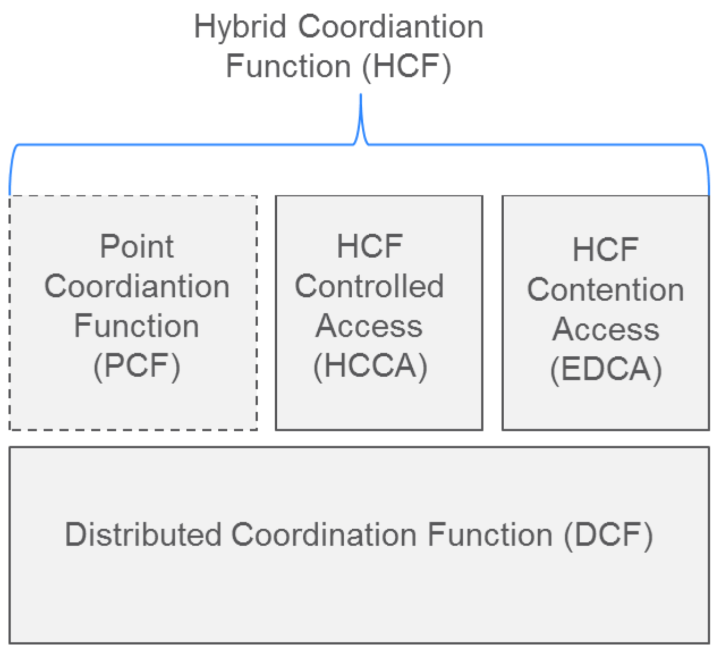

Figure 2. MAC architecture.

A representation of the MAC architecture is shown by Figure 2. The DCF provides the fundamental contention-based channel access method. This function deals with the asynchronous best effort traffic in which all users attain equal chance to access the medium. The Point Coordination Function (PCF) is an optional method which can support contention-free channel access. It is based on polling controlled by the AP and can meet the requirement of real time communications, for instance, voice and video streaming.

The PCF is currently replaced by Hybrid Coordination Function (HCF) which combines the contention-based and contention-free method. The HCF is composed of a contention-based function called Enhanced Distributed Channel Access (EDCA) and a control-based function named Hybrid Controlled Channel Access (HCCA). These functions aims to provide required quality of service (QoS) in which the traffic categories are defined to support prioritized transmission. The HCCA allows contention-free channel access while EDCA does not. Since the thesis scope is the contention-based channel access, only the details of DCF and EDCA are discussed here.

3.4.1.1 Distributed Coordination Function

The DCF is a distributed channel access manner by which the STA itself can determine the time and method to access. It is also known as carrier sense multiple access with collision avoidance (CSMA/CA) [14]. The fundamental mechanism of CSMA/CA is ''Listen before Talk'' in which STAs listen to the channel before transmitting data. Thus, the STA is required to contend with others in order to access the channel. The complete diagram of this procedure is illustrated by Figure 3.

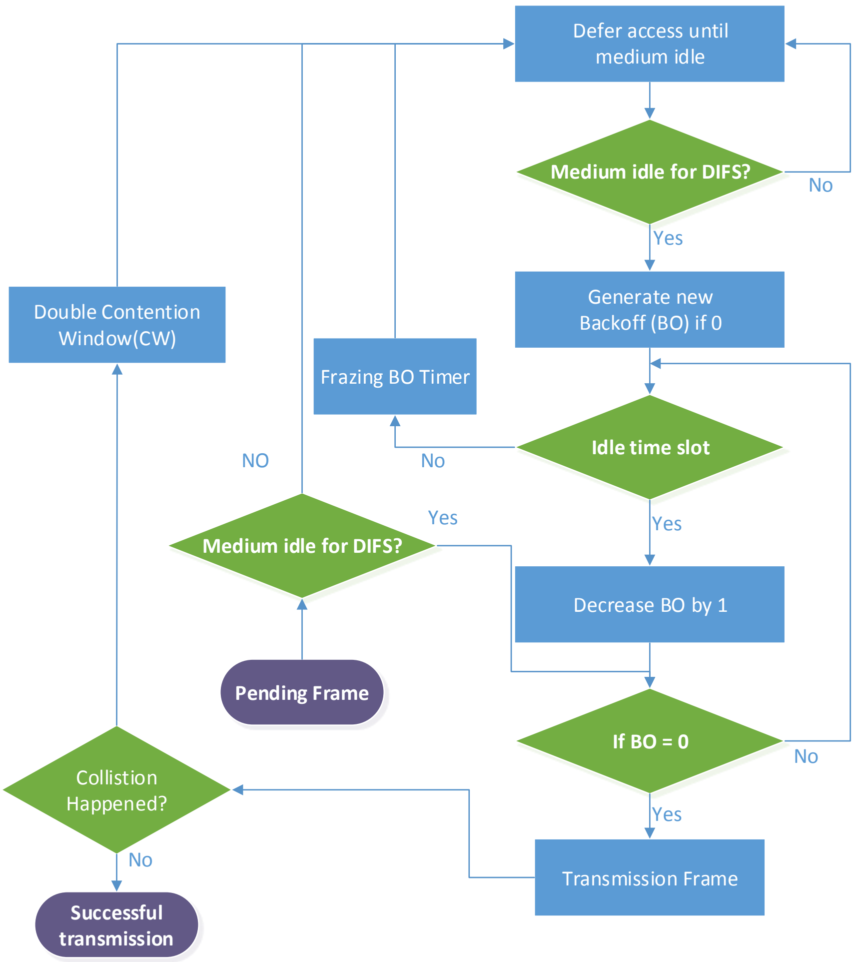

Figure 3. DCF channel access diagram.

When an STA generates a packet which is required to deliver, it first senses if the medium is idle for a period of time of DCF interframe space (DIFS). If the channel becomes busy during DIFS, STA keeps sensing the channel until it becomes idle again. After the channel is sensed idle for DIFS, the STA generates a random backoff counter which is uniformly distributed between 0 and contention window (CW), and initializes the backoff procedure. The backoff time is slotted and the STA senses the channel condition slot by slot. Every time the STA determines that the channel is idle for one backoff slot, it decreases the backoff counter by one. When the backoff counter decreases to zero, the STA starts transmitting data. The channel sensing time in backoff is equal to the product of the backoff counter and backoff slot. The backoff counter is frozen if the channel becomes busy; and continues decreasing after channel is sensed idle for DIFS. The size of the CW is initialized to be the minimum value and one backoff slot duration is fixed based on the PHY layer characteristic.

The backoff procedure provides a random channel access method which can avoid collision relatively but cannot ensure a reliable transmission. Therefore, STAs need to receive an acknowledgement (ACK) frame to confirm that the transmission is successful. A time interval called short interframe space (SIFS) is used to separate two consecutive frames in the same dialogue, for example, data and ACK. This amount of time enables the receiver to have adequate time to process the data.

A collision occurs when two or more STAs transmit data simultaneously. The STA is not able to detect a collision while transmitting since the duplex radio does not exist. Therefore, once an STA starts a transmission, it will continue until the transmission finishes whether a collision occurs or not. After the transmission, if the STA cannot receive the ACK, it can identify that a collision may have occurred and double the size of its CW in the next transmission attempt. Therefore, the STA retransmits the packets with a doubled CW than its previous transmission and discards the packet after maximum number of retransmission attempts (seven times).

DIFS is the minimal channel sensing time before transmission since the STA may generate the backoff counter with the value of zero. The relationship between SIFS and DIFS is illustrated by Formula (3.1), where aSlotTime represents the duration of one backoff slot.

$$DIFS = SIFS + aSlotTime \times 2 \qquad (3.1)$$

The reason why SIFS is shorter than DIFS is to prioritize the ACK frame transmission and enable the current dialogue to continue. If other STA initializes the channel access inside SIFS period, the ACK frame will be transmitted before other STA finishes DIFS sensing.

After the STA finishes transmitting the data, it waits for a time interval called ACKTimeout to receive the ACK frame. After the period of ACKTimeout, if the STA does not receive the ACK, it determines that a collision may have occurred. The value of ACKTimeout is illustrated by Formula (3.2), where aPHYRxStartDelay indicates the delay caused by the PHY layer.

$$ACKTimeout = SIFS + aSlotTime + aPHYRxStartDelay \quad (3.2)$$

3.4.1.2 Enhanced Distributed Channel Access

In the earliest Wi-Fi amendments such as 802.11a/b/g, DCF is the only contention-based channel access method. The drawback of this method is that all types of data traffic follow the same parameters and procedure to access the channel, thus cannot provide QoS for voice and video streaming. Therefore, in the later amendment 802.11e, a new contention-based channel access method called EDCA is introduced to provide QoS.

The data traffic in EDCA has been divided into four types: background, best effort, video and voice. The traffic type is also called access category since each of them follows different parameters and procedure to access the channel. The EDCA provides traffic prioritization by applying distinct parameters for each access category. Therefore, the idle channel sensing time that comes before backoff procedure has changed into a flexible duration called arbitration interframe space (AIFS) instead of a fixed duration DIFS in DCF. The value of AIFS is illustrated by Formula (3.3) where AIFS number (AIFSN) is depend on the access category.

$$AIFS\,[AC] = AIFSN\,[AC] \times aSlotTime + SIFS \quad (3.3)$$

As illustrate by Table 1, various traffic type follows different AIFSN parameters and can be prioritized by providing distinct AFIS durations. For video and voice traffic, the value of AIFSN equals to two and the AIFS can attain the minimum value which equals to DIFS. Also, the EDCA function assigns different CW parameters to various traffic type. Therefore, smaller CW can achieve higher priority since it has a higher probability to generate a smaller backoff counter. However, the lower priority traffic can still win the competition to access the channel due to the random backoff procedure. The details of AIFSN and CW for different access categories are illustrated in Table 1.

Table 1. EDCA parameters.

Access category	**AIFSN**	**CWmin**	**CWmax**
Background	7	15	1023
Best effort	3	15	1023
Video	2	7	15
Voice	2	3	7

In EDCA, the STA attains a transmission opportunity (TXOP) after accessing to the channel. The TXOP is a time interval during which the STA can exchange several frames instead of competing each time to transmit the new frame. The information of TXOP can include the starting time and maximum duration. Both the video and voice have TXOP length limit in order to meet the latency requirement.

3.4.2 Request to Send/Clear to Send Mechanism

Request to Send (RTS) / Clear to Send (CTS) is a four way handshake protocol to send and receive frames. It is not a compulsory channel access method. The complete procedure of channel access with RTS/CTS is illustrated by Figure 4. If the STA needs to send the data, it first competes to access the channel and send an RTS frame. After that, it waits for an SIFS time to receive a CTS frame. If the STA can successfully receive the CTS frame, it then starts the frame exchange. If the STA cannot not receive the CTS, it identifies that a collision may have occurred and competes to access the channel again to retransmit the RTS frame.

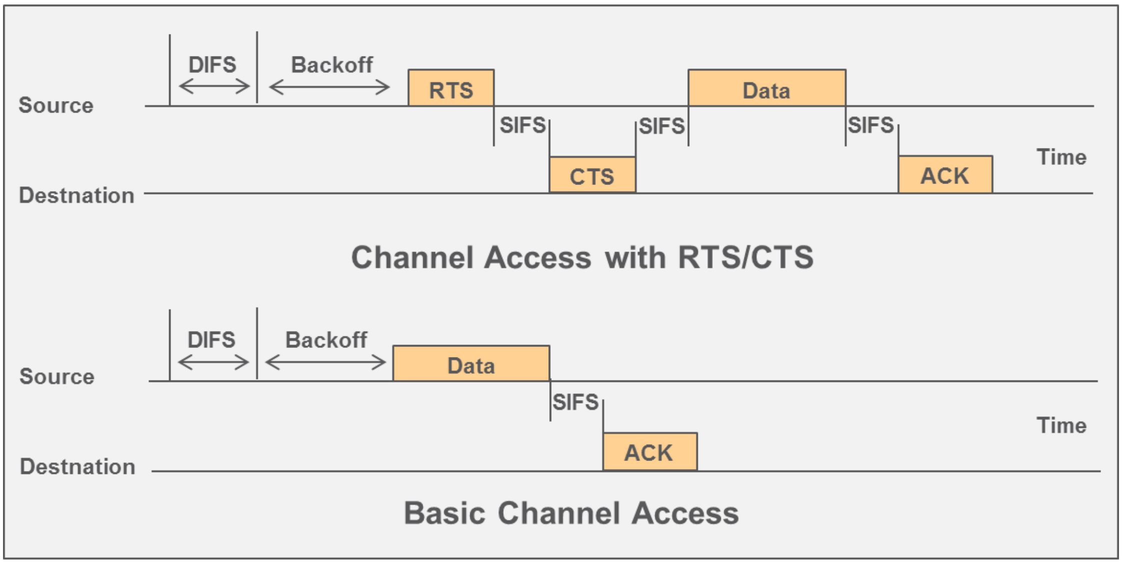

Figure 4. Comparison between basic access and RTS/CTS.

One beneficial of RTS/CTS mechanism is reducing the time wasted on collided transmission since the collision only occurs between RTS frames. This time is considerably short compared with that in the case of normal data frame. Furthermore, RTS/CTS mechanism can partly solve the hidden node problem in infrastructure mode. This is because all the STAs can hear the CTS frame from the AP and therefore can identify the transmission of a hidden node.

The drawback of the RTS/CTS mechanism is that the transmission overhead has been increased by transmitting additional frames. Therefore, it is not recommended to use RTS/CTS signaling for small data transmission.

3.4.3 Virtual Carrier Sense

An STA senses the channel busy once other seizes the channel and starts the transmission. In this case, the STA can receive the full PHY header of the packet transmitting in the medium and acquire the transmission ending time by decoding the duration field of the PHY header. After this, the STA can set up its network allocation vector (NAV), go to sleep and wake up when the current transmission is completed. This is the virtual carrier sense (VCS) mechanism utilized to reduce the energy consumption during carrier sensing. The STA can be configured to perform VCS or not after successfully decoding the PHY header.

Both data and control frames contain the duration information in their PHY header. As illustrated by Figure 5, STA can perform VCS if it receives the data packet or ACK frame. Furthermore, the RTS/CTS mechanism can also be combined with VCS since both RTS and CTS frame contain transmission duration information.

However, the STA cannot perform VCS if it cannot receive the full PHY header correctly. This may occur if the STA wakes up in the middle of one data transmission. In this case, the STA misses the full PHY header of the data since PHY header is transmitted in the beginning of the data. Furthermore, STA cannot perform VCS if a collision or error occurs for the data transmission.

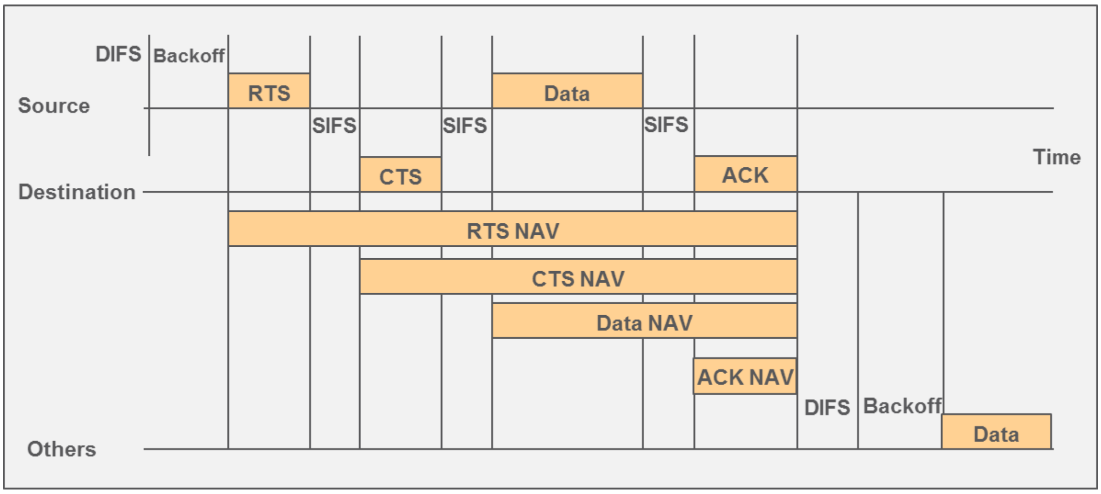

Figure 5. Illustration of virtual carrier sense mechanism.

3.5 Traffic Indication Map

Original Wi-Fi technologies does not support sleeping mode. In this case, the Wi-Fi device has to keep sensing the channel even when it has no packet to send. This causes huge energy cost since devices always turn the radio on. In order to save energy, power saving (PS) mode or sleeping mode is introduced accordingly [14]. With this method, devices can go to sleep when it has no packet to deliver. Once an STA generates an uplink data, it wakes up from PS mode to access the channel; and turns off its radio after finishing uplink transmission.

The STA in PS mode cannot receive downlink data. Therefore, the AP needs to buffer downlink packets for all the STAs in PS mode. All the buffering downlink information is stored in a Traffic Indication Map (TIM) element which is contained in every beacon frame. In TIM element, there is a virtual bitmap between each TIM bit and each user as illustrated by Figure 6. Each user can identify its bitmap location by calculating its AID which is assigned during association process. Each bit in the TIM virtual bitmap represents an AID of an STA. In existing Wi-Fi standards, STA have 12 AID bits which can support maximum 2007 users.

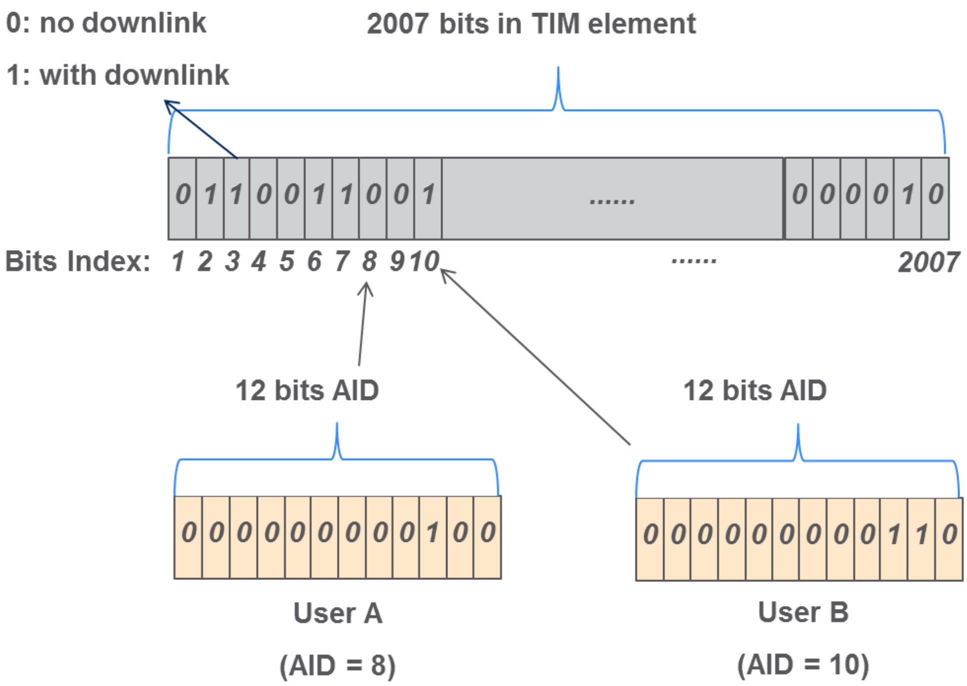

Figure 6. One example of TIM bitmapping and AID.

Figure 6 indicates the relationship between TIM and AID. User A and User B are assigned different AIDs which are 8 and 10 bits, respectively. During decoding the TIM element, they can locate their bit corresponding to their AID and determine the presence of buffered downlink data.

The beacon which contains TIM element is called TIM beacon and it is periodically broadcasted by the AP (every TIM interval). There is also a special TIM element called delivery TIM (DTIM) element which also informs the presence of the buffered data for a specific group. The beacon which carries DTIM element is called DTIM beacon. The AP broadcasts the DTIM beacon every DTIM interval and every STA in PS mode needs to wake up to receive this beacon. A DTIM interval can be set up into several TIM intervals based on system configuration. After broadcasting the DTIM beacon, the AP will transmit the pending frame for a specific group.

Every STA has set up its listen interval and wake up periodically from PS mode to listen to beacon frames. After the STA receives the beacon, it decodes the corresponding bit in the TIM element to determine whether the AP has buffered downlink packet or not. If the STA finds that there is no downlink data, it continues to sleep. If the STA finds that there is pending downlink packet, it sends a PS-Poll frame to the AP to inform that it has been already active for downlink packet reception. After the AP receives the PS-Poll, it sends an ACK to the STA and then starts downlink data transmission. The AP can only send downlink data to the STA which has already sent the PS-Poll frame since without PS-Poll, the AP cannot identify whether an STA is awake or not.

To further save energy, the Wi-Fi technology also introduces a wireless network management sleep (WNM-sleep) mode. The STA in WNM-sleep mode need not wake up every DTIM interval to read the beacon. Instead, it can set up its listen interval to be several DTIM intervals and sleep for longer time by skipping several DTIM cycles.

4 IEEE 802.11ah

4.1 Introduction

The IEEE 802.11ah is a standard developed for M2M communication in order to compete with the existing short range radio technologies, such as Bluetooth and Zigbee. This new technology will be deployed in sub 1 GHz (S1G) ISM bands which describes in details as follows: 863 - 868.6 MHz (Europe), 950.8 MHz - 957.6 MHz (Japan), 314 - 316 MHz, 430 - 432 MHz, 433 - 434.79 MHz (China), 917 - 923.5 MHz (Korea) and 902 - 928MHz (USA). The S1G band can extend the transmission range up to kilometer level with its better propagation characteristics.

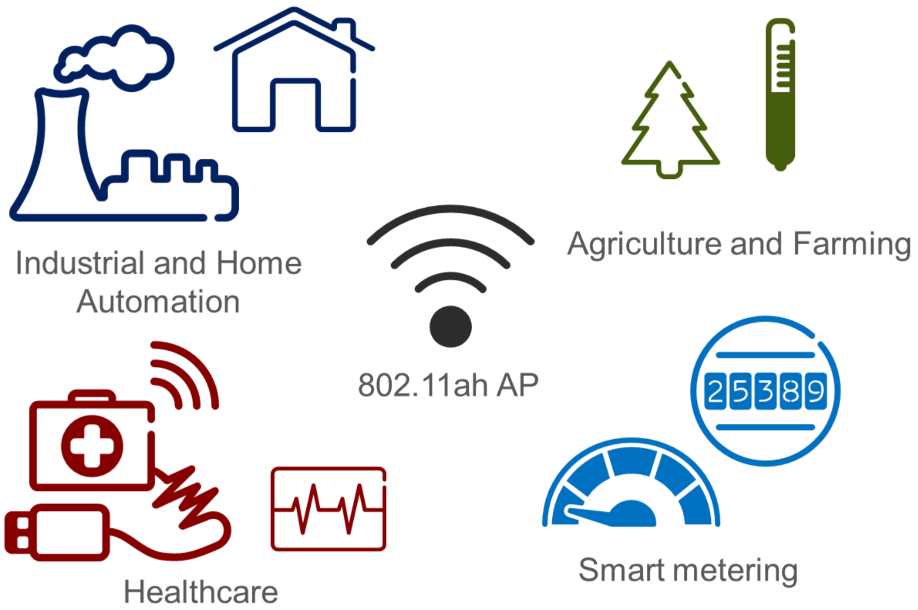

Figure 7. The use cases that are envisioned to be operated via IEEE 802.11ah.

The major use cases of 802.11ah may involve industrial and home automation, smart metering, agriculture and farming, and healthcare as illustrated in figure 7. These applications are mostly accomplished by wireless sensors by monitoring the physical surroundings and cooperatively passing the collected data to the network. The 802.11ah introduces an efficient paging and scheduling method to provide scalability for thousands of STAs and it only supports infrastructure mode. Meanwhile, advanced power saving mechanism is proposed to solve the high energy consumption issue existing in the conventional Wi-Fi technologies.

In the literature, the new MAC features enhanced in 802.11ah have been explored as well as performance assessment presented in four selected M2M scenarios [19]. The technical overview of 802.11ah has also been discussed in [20] with a theoretical analysis provided of the performance evaluation of transmission range and MAC layer throughput. However, these performance evaluations are mostly based on the assumption of distributed coordination function (DCF). In addition, [21] analyzes the grouping strategy in order to reduce the channel congestion in 802.11ah by using the restricted access window (RAW). The impact of RAW has been evaluated under a saturated channel with an analytical modelling [21].

In 802.11ah, STAs are divided into two types: sensor type to support sensor service and non-sensor type for offload service. The sensor STA is expected to have limited available power, low traffic volume; and use the data frame with a small payload size. By contract, for non-sensor STA, power consumption is not critical and maximizing their achievable throughput is more important [6]. Sensor and non-sensor STAs access the channel with different EDCA parameters as illustrated by Table 2 and 3. For sensor STA, the access category is best effort by default setting. As a comparison, non-sensor STA chooses voice as the default access category. By accessing the channel with EDCA method, the 802.11ah technology can support required QoS.

In 802.11ah system, an AP can indicate the type of STAs that it supports. It can select to support sensor type STA, non-sensor type STA, or both. The terminal indicates its STA type during its association with the AP.

Table 2. EDCA parameter values for sensor STA.

Access category	**AIFSN**	**CWmin**	**CWmax**
Background	7	15	1023
Best effort	2	3	15
Video	5	7	15
Voice	4	7	15

Table 3. EDCA parameter values for non-Sensor STA.

Access category	**AIFSN**	**CWmin**	**CWmax**
Background	7	15	1023
Best effort	3	15	1023
Video	2	7	15
Voice	2	3	7

4.2 Traffic Indication Map Station

4.2.1 Traffic Indication Map Configuration

To efficiently indicate buffered downlink data for a large number of devices through TIM, a hierarchical addressing of AID for STAs is defined in 802.11ah. As illustrated in Figure 8, the TIM is divided into four pages, where each page consists of 32 blocks and each block consists of eight sub-blocks. Each sub-block contains eight bits and each bit corresponds to an AID of an STA. With this hierarchical addressing scheme, a maximum of 2048 AIDs of STAs can be addressed within one page and an overall of 8129 STAs in four pages. Through the AID, the STA can identify the position that it is located inside page, block, and sub-block.

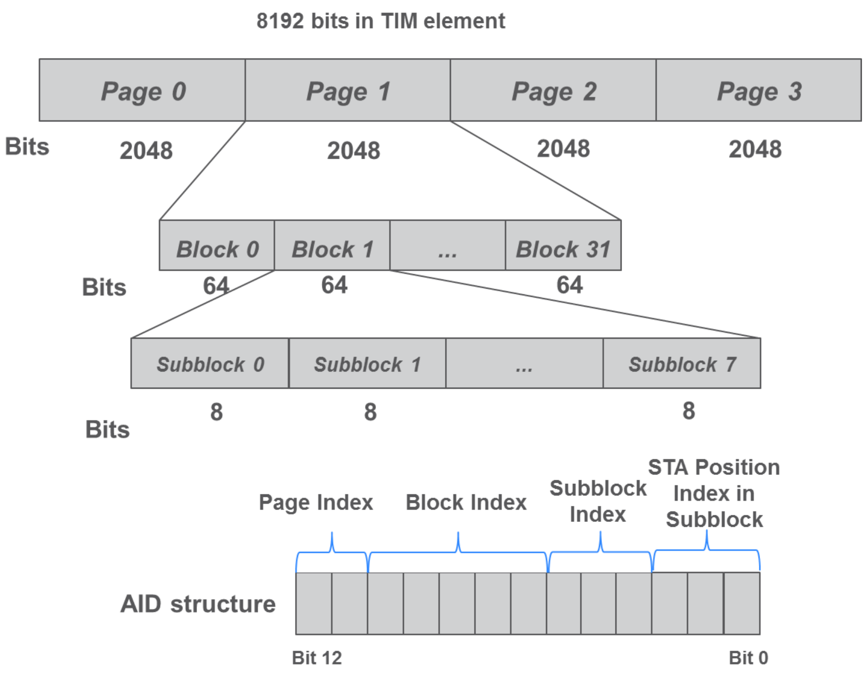

Figure 8. TIM and AID in 802.11ah.

In 802.11ah network, the beacon can be very large if it contains the TIM element for a large number of users. Thanks to the hierarchical addressing method, the beacon can just carry the TIM element for one page or one block. The page and block indication information is contained in the DTIM beacon. Therefore, the STA can first check the presence of downlink buffered data for its page or block by reading the DTIM beacon and then decide to read the beacon that carries its TIM element. Since hierarchical addressing method distributes the TIM element into several beacons and spreads downlink request into various time intervals, it is very beneficial for the networks with large number of STAs.

4.2.2 Periodic Time-distributed Channel Access Configuration

In 802.11ah, all the TIM STAs are divided into TIM groups, each given a periodic data transmission and reception segment, for example, TIM intervals, varying from 1 ms to 67 s as shown in Figure 9. In each TIM interval, only a group of STAs, such as TIM STAs are allowed to access the channel.

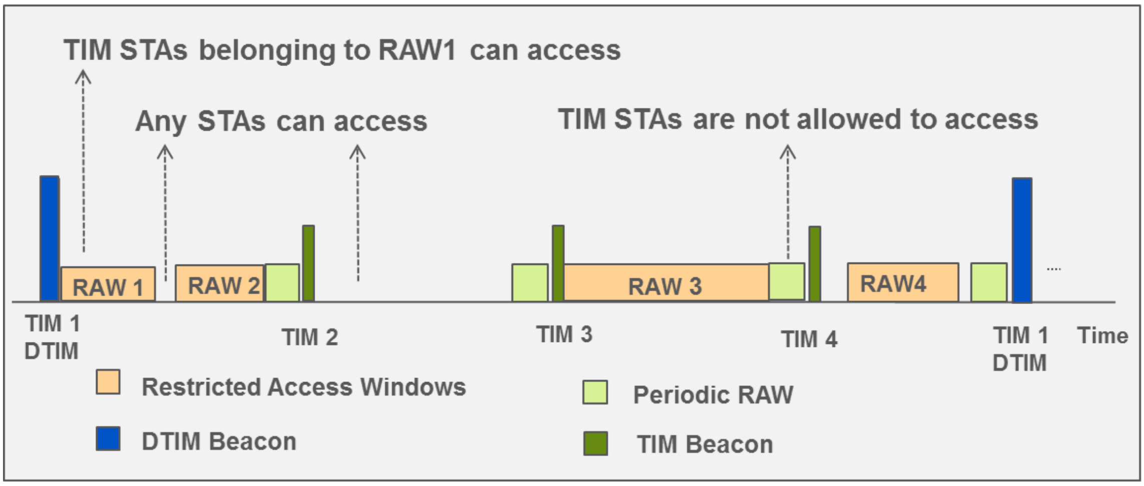

Figure 9. DTIM and TIM intervals.

Between two consecutive delivery TIM (DTIM) beacons, TIM beacons are broadcasted by the AP for each TIM interval and TIM group thereof. TIM STAs need to listen to both beacons, for instance, in order to receive downlink data. However, TIM beacon elements for the first TIM group can also be included in the DTIM beacon so that the AP does not need to broadcast TIM beacon for the first group. In this case, TIM STAs of the first group can attain group information by only receiving the DTIM beacon.

As illustrated by Figure 10, all TIM STAs wake up to listen to the DTIM beacon which contains all the TIM group information including buffered downlink information for each group, TIM beacon arrival time and TIM interval duration, etc. After receiving the DTIM beacon, all TIM STAs can determine the presence of downlink information for its group. If there is no buffered downlink data for a group, then STAs in the group do not need to read the TIM beacon and can go to sleep until the next DTIM beacon. If there is downlink data pending for the group, then all the STAs of the same group have to also listen to their TIM beacon which contains the buffer information for all the STAs in the group. After receiving the TIM beacon, if the STA determines there is downlink packet pending, it will send a PS-Poll frame to the AP for delivery. If there is no buffered downlink data for the STA, then it can go to sleep until the next DTIM beacon.

It should be noted that in the DTIM beacon there is also paging information by which all TIM STAs are also divided into different pages. Usually, DTIM beacon allocates 13 bits for paging and grouping information. Therefore, STA only needs wake up to receive the TIM beacons if it detects that downlink data exists both in its page and group. To some extent, paging mechanism is a sub-grouping idea which can save energy through reducing the number of STAs waking up to receive TIM beacon.

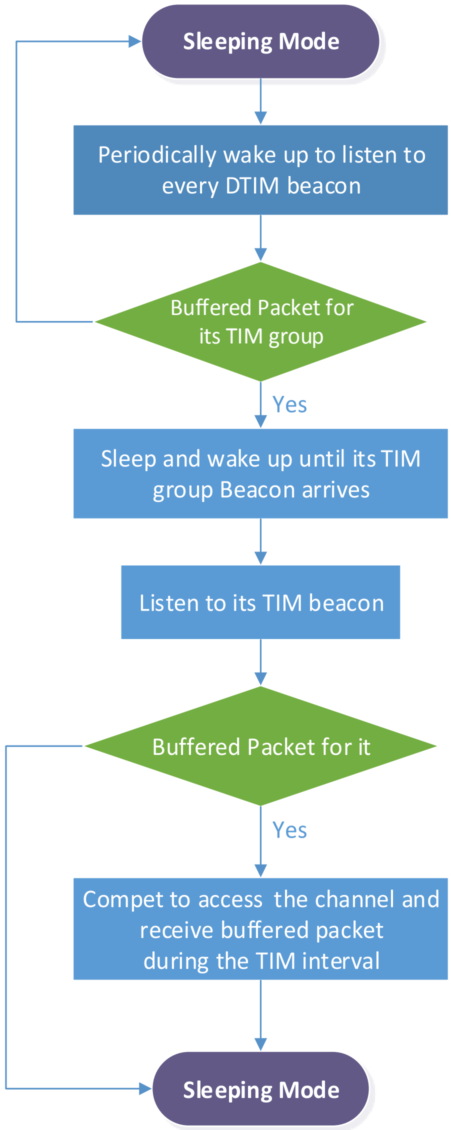

Figure 10. Diagram of downlink channel access for TIM-STA

Due to the TIM segmentation for a massive number of STAs, the TIM element length contained in the TIM beacon has been shortened. Therefore, TIM STAs can save energy by reading a short beacon instead of a long beacon in the existing Wi-Fi. Furthermore, STAs are only required to read corresponding beacons for downlink access instead of reading all beacons. TIM segmentation can also reduce the collision rate since it reduces the number of STAs which compete simultaneously for downlink delivery. Even though TIM deployment is mainly considered for downlink, uplink data transmissions can benefit from the time-distributed channel access e.g., in case of simultaneously triggered transmissions by a massive number of STAs.

4.3.3 Restricted Access Window Configuration

The RAW can further restrict the data transmission and reception segment by assigning a certain portion of TIM interval to a subgroup STAs in a TIM group. As illustrated in Figure 9, the AP can allocate one RAW or multiple RAWs in each TIM interval with a flexible length. All the RAW information including starting time, duration and member identity is contained in the DTIM beacon so that every TIM STA can identify it. The time which is restricted by RAW is only available for its members to access while others, which are not members of the RAW, are not allowed to access. The time which is not restricted by RAW is available for all TIM STAs in the respective group.

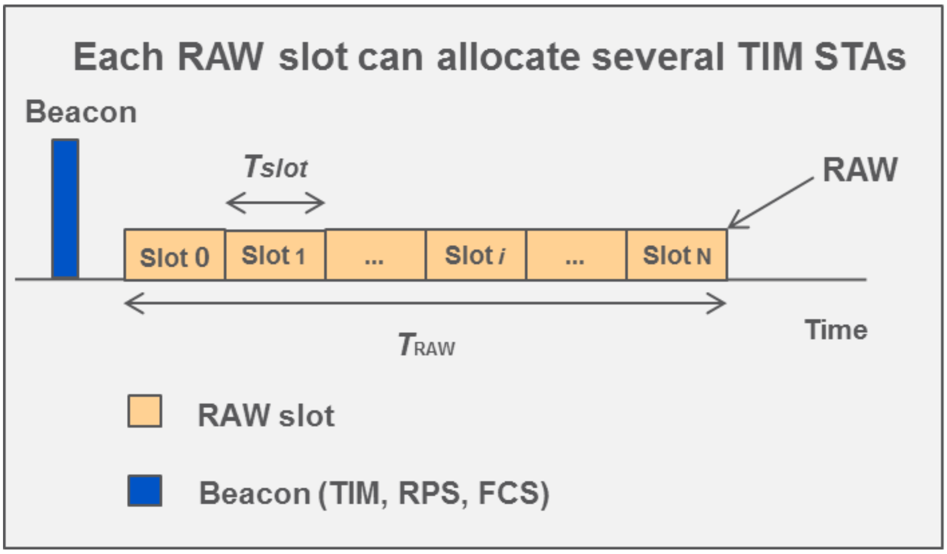

Figure 11. RAW slot for TIM-STA

As illustrated by Figure 11, the RAW time is divided into several slots and each slot can be allocated to one or multiple users. The AP can allocate the number and time duration of RAW slots in each RAW in a flexible way. The AP broadcasts a resource allocation frame in the beginning of the RAW which indicates the distribution of RAW slots. All the STAs belonging to the RAW wake up to receive the resource allocation frame to locate their access slot. The STA can only initialize channel access in its own slot and sleep in the slots allocated to other STAs. Once an STA accesses the channel and starts its transmission, it can select to finish its transmission by crossing to others' slot or not.

4.3 Non-Traffic Indication Map Station

In order to further save energy, 802.11ah introduces non-TIM mode which does not oblige STA to read beacons for downlink data delivery, thereby longer sleep times become possible. In this case, non-TIM STA may send a PS-Poll frame to the AP regardless of whether the AP has indicated there is buffered data for it.

A non-TIM STA can set up a target wakeup time (TWT) to wake up and communicate directly with the AP. As illustrated in Figure 9, TWT is protected by a special time called periodic restricted access window (PRAW) which is periodically allocated in each TIM interval. The PRAW information, such as starting time and duration, is contained in all beacons so that all TIM STAs can be aware of it and do not access the channel in this restricted time. At TWT, the AP will transmit a Null Data Packet (NDP) paging frame if it has buffered data for the non-TIM STA. If the AP has no buffered data, it will not transmit the NDP paging frame.

If a non-TIM STA does not set up a TWT, it can be allowed to access the channel anytime even inside RAWs or PRAWs. Therefore, the PRAW cannot protect a non-TIM STA from other non-TIM STAs. And the RAW cannot protect a TIM STA from non-TIM STAs.

4.4 Investigation of Energy Harvesting Potentials

Recently, energy harvesting technology has emerged as an attractive alternative to supply power for the sensor device due to its low cost and simple implementation. It is suitable for sensors deployed in atrocious condition which makes it inconvenient to replace the battery. Wireless sensors with energy harvesting can extract the energy from the surrounding environment and fulfill the availability of self-power to extend its lifespan. It is a proven technology and applicable for M2M communications. Companies such as EnOcean have already developed series of products for home and office automation. However, the current harvesting technologies mainly support the device which requires low energy consumption due to the low energy efficiency of the existing harvesting materials and lack of availability of energy in some cases. Therefore, it is reasonable to investigate the harvesting potentials for variant ambient energy sources in order to evaluate its feasibility of power supply for 802.11ah communications.

Based on the survey carried out for the thesis, solar energy is the most available harvesting source outdoors. The power density of direct solar radiation on the Earth's surface is roughly 100 mW/cm^2 while this value drops down to 1mW/cm^2 in cloudy weather. Current solar panel acquires the energy efficiency from 12% to 25% and literature generally selects 15% as an example [22]. For indoors case, a 6 cm^2 solar cell can harvest 42 µW power from the office light while this value can be increased to 650 µW by adding a common 60 W lamp bulb which is 18 inches away from the measurement point [22].

Table 4. Energy harvesting potentials for ambient sources.

Energy source	Harvesting device	Measurement condition	Measured value
Solar outdoors sunny [22]	Single crystal silicon solar cell (6 cm^2 size, 15% efficiency)		15 mW/cm^2
Solar outdoors cloudy [22]			150 µW/cm^2
light indoors [22]		8 inches from 60W lamp	2.9 mW
		18 inches from 60W lamp	0.65 mW
		Normal office light	0.042 mW
Vibration indoors [22]	Piezoelectric	1cm^3 prototype at 120 Hz	20 to 350 µW
Push button [23]		Button (35mm long,7mm diameter)	2mJ per push
Heel strike [24]		1 cm^2 measure on a person weight 70 kg	10 to 800 mW
Temperature variations [25]	Thermoelectric generator	ΔT= 5°C	60 µW/cm^2
		ΔT= 10°C	135 µW/cm^2
ISM band (902–928 MHz)[26]	RF-DC conversion circuit	15m away	5.5 µW
TV broadcasts [27]		6.6km away	20 µW
AM radio [28]		5km away	0.02µW
Cellular network [29]			109 µW

Vibration or motion can harvest the energy varying from 20 to 350 µW/cm^3 [22]. The MIT media lab measured that piezoelectric button can deliver 2 mJ of energy per push [23]. Piezoelectric material can also harvest 800mW power from the heal strike of a people weighting 70 kg [24].

Thermal energy is harvested through thermoelectric materials which create electric voltage when there is a temperature variance on each side. On average, the thermoelectric generator can harvest around 60 µW/cm^2 power when the temperature variation is around 5 °C. Its harvesting power can be increased to 135 μW/cm^2 if the temperature variation expands to 10 °C [25]. The drawback of this technology is that if the surrounding temperature keeps constant, the thermoelectric device cannot harvest energy at all.

RF signal is also a highly available energy source which can be used for harvesting [26] [27] [28] [29]. For instance, measurements from the TV broadcast signal in UHF band show that 20 μW power can be supplied [27]. Furthermore, in the 800 MHz band of cellular networks, the RF signal can harvest power around 0.1 mW [29].

The Table 4 summarizes the energy harvesting potentials from ambient energy sources. In the later section, the solar harvesting energy is selected to support the 802.11ah network since solar energy is one of the most available sources and its mature harvesting technology can provide considerable energy harvesting potential.

5 Modeling of the IEEE 802.11ah MAC layer

In the literature, the performance evaluation of 802.11 MAC layer has been presented by either analytical modelling [30] or simulations. The analytical models built are mostly suitable for saturated data traffic in which devices always have packets to send [30] [31] [32]. This may not be suitable for some M2M applications since the characteristic of M2M traffic is short and infrequent. For example, sensors may just send several bits to report the monitored data every minute. Furthermore, analytical methods may not accurately model some of the complex behavior of MAC layer, such as virtual carrier sense and power saving mechanisms. Compared with analytic method, simulation modeling can provide more flexible traffic scenario selection for each device as well as accurately simulate various MAC layer functions. Therefore, the simulation method has been selected in the thesis for performance evaluation.

5.1 Simulation Modeling Method

The simulation modeling of the IEEE802.11ah MAC layer is based on a state machine transition. The channel access procedure of each STA is divided into eight states which consist of sleeping, idle-channel sensing, busy-channel sensing, virtual carrier sensing (VCS), backoff, transmission, ACK-waiting and ACK-reception, respectively. Each STA can automatically perform state transition according to the channel condition and its data traffic.

The complete state machine transition diagram is illustrated in Figure 12. The beacon reception procedure is not illustrated for the simplicity of the diagram. The STA is assumed to sleep when it has no data. It wakes up to perform channel sensing once a packet is generated in the buffer. Idle-channel sensing denotes that the STA senses the channel idle while busy-channel sensing refers to that the STA senses the channel busy. Therefore, the STA may change its state from sleeping to busy-channel sensing since it may wake up in the middle of the transmission of other STAs. The STA shifts its state from sleeping to idle-channel sensing if it wakes up and senses the channel idle. The STA can count the time duration of each state. If it identifies that a constant state of idle-channel sensing over a setting value, such as DIFS, it will automatically shift into backoff state. The STA moves to transmission state after backoff and then enters into the state of ACK-waiting after transmission. From ACK-waiting state, it shifts into ACK-reception if the transmission is successful, otherwise it moves into idle-channel sensing state to access to the channel again. After ACK-reception, the STA can enter into sleeping if its buffer is empty; otherwise it shifts to idle-channel sensing to attempt to transmit the next packet. During the state of idle-channel sensing or backoff, STA can also shift into VCS if other STA successfully access to the channel. In addition, the STA can shift state from busy-channel sensing or VCS to idle-channel sensing once it identifies the channel becomes idle again.

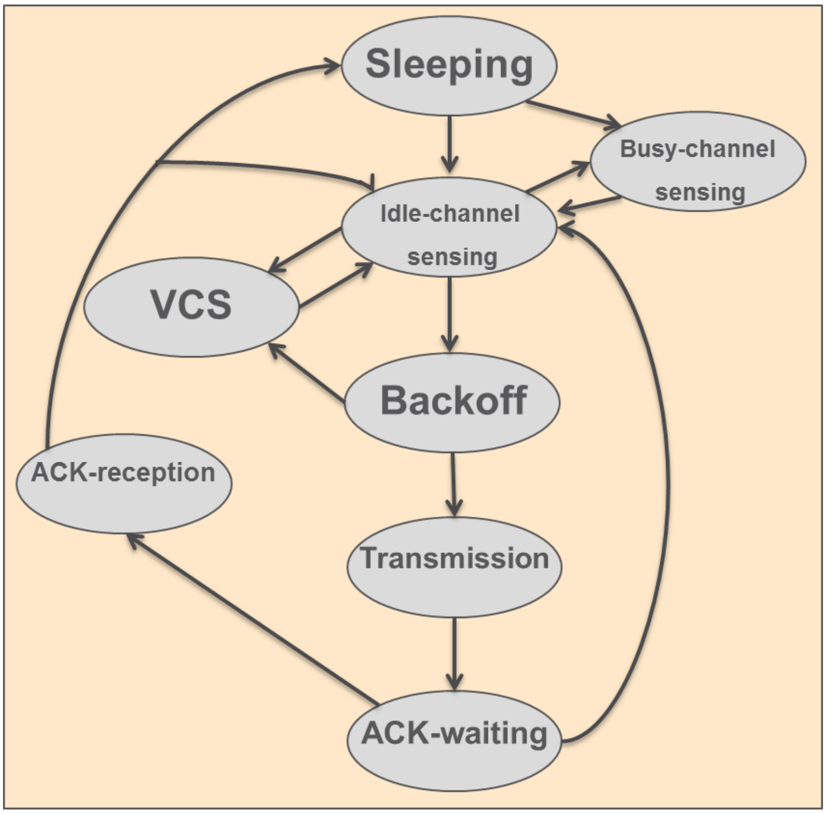

Figure 12. State machine transition diagram

It is also assumed that all the STAs wake up to receive their TIM beacons even though downlink traffic does not exist in our simulation. All the TIM STAs know the beacon broadcast time and are forced to sleep once the time before bacon broadcasting is not adequate to transmit a packet. The ACK-waiting state is assumed to have the duration of SIFS even though the collision occurs. The duration of transmission and ACK/beacon-reception state can be calculated by the quotient of the corresponding packet length and PHY layer data rate. The virtual carrier sense procedure is assumed that each device automatically go to sleep after it receives the PHY header of one packet correctly.

Figure 13 indicates an example of the slotted modelling of the channel access procedures. The y axis denotes the user index while the x axis refers to the simulation slot. One simulation slot has the time duration of 50 µs and all of the STAs can detect the channel condition (idle or busy) of each slot. To simplify the model, the simulation slot is approximated to represent the backoff slot and three slots represent the SIFS duration. Therefore, the Wi-Fi system is modeled as a synchronized slotted system in which each STA performs state transition slot by slot. The state transition information is kept inside a defined matrix and the time value of each state for every user can be obtained by processing the matrix. One drawback of this slotted method is that it increases the collision probability since all the STAs can only start channel sensing in a specific time, yet the slot duration is selected to reflect a realistic performance evaluation.

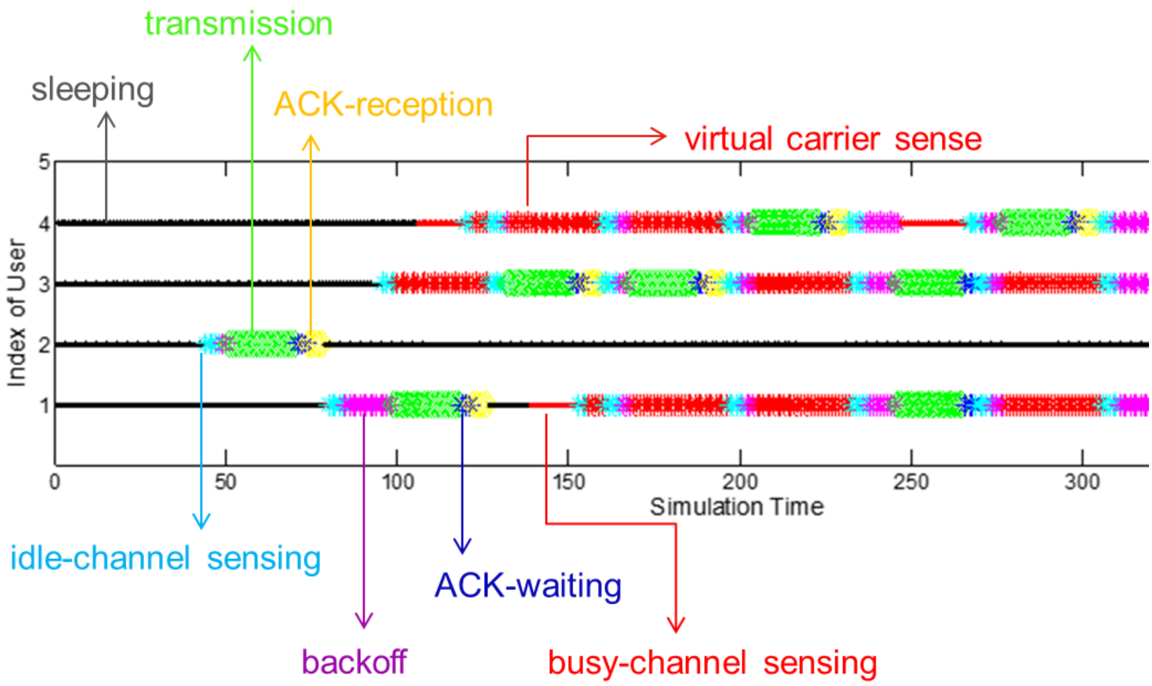

Figure 13. An example for the states in the simulation model

5.2 Simulation Assumptions and Parameters

The energy consumption is the product of the time values attained from the system-level simulations and the power parameters from the chipset datasheet. In the thesis the power parameter is discussed from the perspective of radio interface. It is assumed that the STA consumes the same amount of power between channel sensing and receiving since the radio interface performs the same operations. Furthermore, the power consumption of channel sensing is assumed to be the same no matter the channel condition is idle or busy.

As shown in Table 5, chipset power consumption values in different modes, such as transmission, reception, channel sensing are taken from 802.11n [33], whereas the values for the sleeping mode are taken from 802.15.4 chipset [34]. It is assumed that the sleeping power consumption in 802.11ah could go down to the level of 802.15.4 with the introduced enhancements and anticipated chipset optimizations.

Table 5. STA Power consumption values in different modes.

Mode	Power (mW)
Data transmission	255
Data reception	135
Channel sensing	135
Sleeping	0.036

Table 6. Main simulation assumptions (default).

Simulation time	600 s
PHY layer data rate	150 kbps
Number of STAs	288
Average inter-arrival time	Poisson, 10 s
SIFS	160 μs
AIFS	Sensor STA: 264 μs Non-Sensor STA: 316 μs
CWmin	Sensor STA: 4 Non-Sensor STA: 16
CWmax	Sensor STA: 16 Non-Sensor STA: 1024
Backoff slot	52 μs
DTIM interval	60 s
DTIM beacon length	102 bytes
Data length	134 bytes
ACK length	14 bytes
Maximum number of retransmissions	7

To figure out the fundamental reason of the energy consumption, the event is analyzed in data transmission and reception, and channel sensing based on Wi-Fi standards [6]. For the data transmission mode, successful transmission and retransmission (due to packet collision) are taken into account. In the data reception mode, the ACK-waiting and ACK/beacon-reception are included since it is assumed that downlink traffic is not used in the simulation modelling. Finally, the channel sensing is assumed to include idle-channel listening, busy-channel listening, backoff, physical (PHY) header decoding failure and virtual carrier sensing (VCS).

To evaluate the performance, 802.11ah MAC layer is modeled with 802.11ah parameters illustrated in Table 6. The physical layer is assumed ideal as the impact of MAC parameters on the system performance is particularly analyzed. It is also assumed that the physical layer data rate is set up to be 150kbps which is the lowest rate supported by the 802.11ah physical layer. The hidden node problem is not considered and CTS/RTS is not deployed since the identical small data size is utilized for each STA.

In the simulator, a test scenario is modeled which is based on an agriculture and farming use case. The scenario parameters, for example, the number of STAs and inter-arrival time, are selected to reflect a similar channel occupancy ratio as in [19], yet with a less number of STAs and a shorter inter-arrival time comparatively. Thus, more number of data packet transmissions per STA can be observed in the given simulation time, 600 s. The scenario is modeled with sporadic data traffic based on Poisson arrival.

6 Simulation Results

6.1 Impact of TIM Segmentations

To analyze the system performance against different TIM segmentations, the system-level evaluations are carried out for different number of TIM groups, which are 1, 2, 4, 6 and 8, keeping the DTIM interval fixed (60 s). Therefore, in the evaluations, TIM beacon interval is inversely proportional to the number of TIM groups. For the selected use case, the total number of users is assumed to be 288. Each user generates uplink data packets following Poisson process, which is widely used for modeling wireless data traffic [35], with an average inter-arrival time of 10 s. It is assumed there is a single traffic type in the simulation which is best effort mapping to EDCA access category [6]. Following the impact of the TIM segmentation is evaluated for S-STA and NS-STA parameters respectively.

6.1.1 Sensor Type EDCA Parameters

In this part, the EDCA parameter type is assumed to be the S-STA. In this case, the minimum and maximum values of the contention window are 4 and 16 respectively while the AIFS has the same duration as DIFS [6].

As shown in Figure 14, where the red and blue curves refer to the channel occupancy and collision probability respectively, both collision probability and channel occupancy broadly vary with the number of TIM groups. The collision probability is considerably small for TIM deployment with one group. This is because TIM segmentations cause the STA having buffered packets which are sent simultaneously in the beginning of each TIM interval. Furthermore, when the number of TIM groups grows, the collision probability increases since the packets are more likely to buffered and transmitted simultaneously in the beginning of the TIM interval. However, the collision probability then slightly decreases since with the increase in the TIM segmentation, the number of STAs in each group decreases and the number of simultaneous competing STAs reduces thereof.

For single TIM group setting, through the considerably small collision probability, it can be inferred that roughly all the generated packets can individually occupy the channel. When the number of TIM groups is more than one, channel occupancy first drops, then increases. This is because that competition among STAs are restricted into the certain segments; however when the segmentation increases, the number of queued packets that are to be sent simultaneously increases as well. Thus, these packets experiences higher channel congestion and larger number of retransmissions.

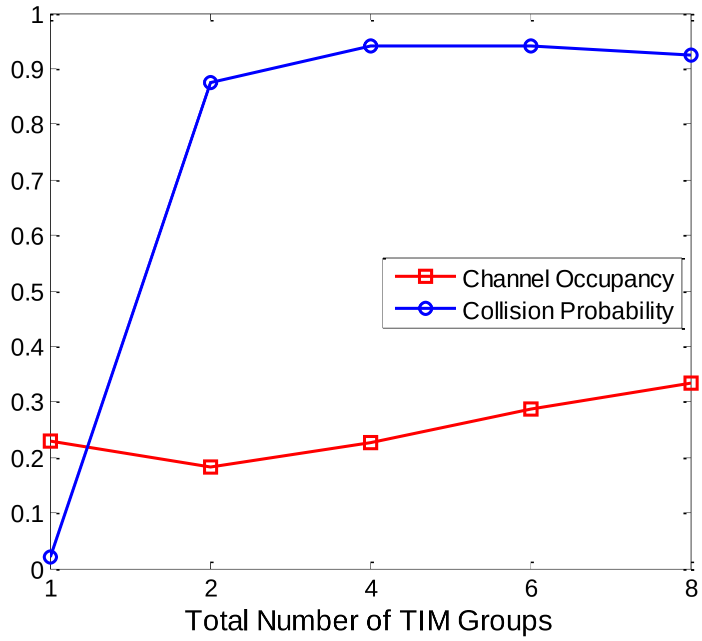

Figure 14. Collision probability and channel occupancy vs. TIM segmentation (no RAW implementation). Sensor-type EDCA parameters are assumed.

In order to evaluate the packet delivery condition, the packet delivery ratio is defined to be the percentage of the packets successfully transmitted. Accordingly, the packet discard and buffer ratios are defined as the percentage of the packets discarded and remained in the buffer.

Figure 15 shows the packet delivery conditions. For TIM deployment with one group, all the packets can successfully be transmitted while more than half of the generated packets cannot be delivered when the number of TIM groups increases. Also, it can be observed that the variation of packet delivery ratio is largely correlated with the packet discard ratio. Furthermore, the impact of TIM segmentation on discard ratio is the same as that on collision probability because discard ratio is proportional to the collision probability. In addition, the packet buffer ratio slightly increases when the number of TIM segmentation grows since the packets are more likely to arrive after the last access to the TIM interval in case of sporadic data traffic.

In order to understand the energy cost behavior of an STA during the channel access, the energy consumption is decomposed according to status of the STA. Successful transmission indicates the energy spent in data transmission without any collision while retransmission refers to the energy spent due to collisions. ACK/beacon-reception denotes the energy spent on receiving ACK and beacon frame while ACK-waiting indicates the energy consumption of carrier sensing while waiting for ACK. Idle-channel sensing and backoff refer to the energy consumed on DIFS sensing and backoff procedure respectively in an idle channel. Channel sensing under a busy channel is decomposed into three parts including PHY header decoding failure, busy-channel sensing and VCS. If an STA wakes up and senses the channel busy, it has to sense the channel until it becomes idle again. Busy-channel sensing denotes the energy spent in this period of busy time. During carrier sensing, an STA can perform virtual carrier sensing once it successfully decodes the PHY header of the packet transmitting in the channel. Therefore, virtual carrier sense is used to represent the energy of decoding the PHY header during this procedure. However, an STA cannot perform virtual carrier sensing if it cannot decode the PHY header because of collision. In this case, the STA has to listen to this collided channel until it is idle. PHY header decoding failure shows the energy cost in this period.

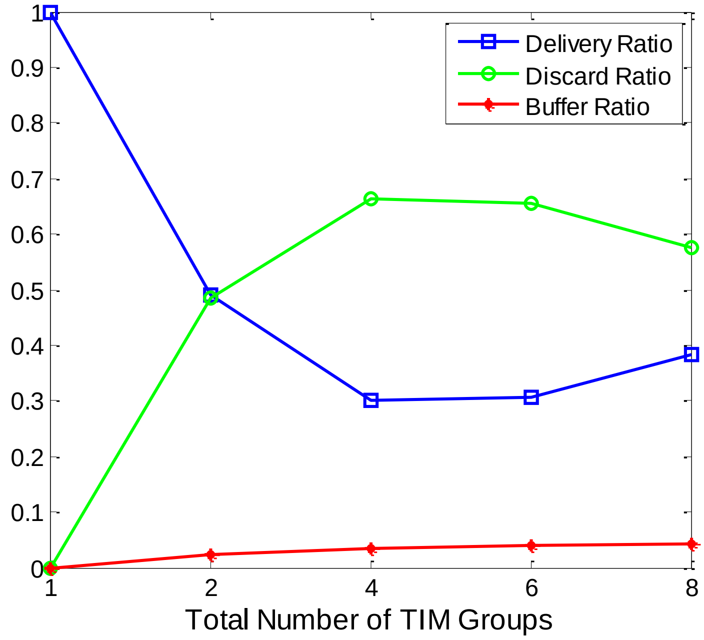

Figure 15. Packet delivery condition vs. TIM segmentation (no RAW implementation). Sensor-type EDCA parameters are assumed.

Figure 16 shows the average energy consumption per STA in each status. For TIM deployment with one group, the energy consumption is significantly small. As a comparison, STAs consumes larger amount of energy for TIM deployment with more than one group. This is because that TIM restriction for uplink channel access leads to simultaneous channel access attempts among TIM STAs. Therefore, they waste large amount of energy, especially due to retransmissions and PHY header decoding failures.

All in all, it is straightforward to make a statement that for sporadic traffic, STAs cannot benefit from the TIM segmentation using sensor parameters if the traffic is uplink dominated.

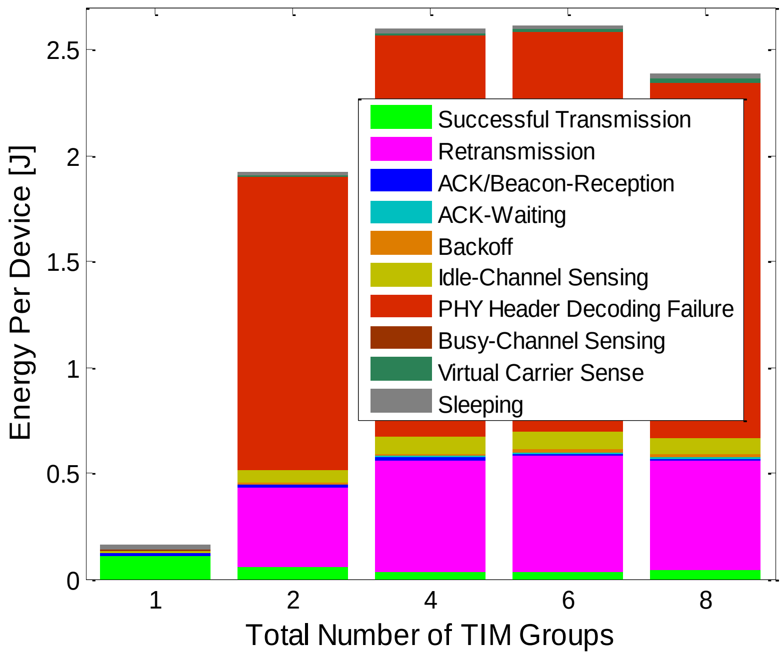

Figure 16. Average energy consumption per device vs. TIM segmentation (no RAW implementation). Sensor-type EDCA parameters are assumed.

Yet, it is essential to analyze the impact of sensor parameters before making a final conclusion. When sensor-type EDCA parameters are used, the initial CW size is four, thus around one quarter of STAs will generate backoff counter 0 and attempt to transmit data simultaneously. Therefore, these transmissions from one quarter of STAs will collide with each other resulting in PHY header decoding failures for the rest of TIM STAs. Based on the observations from the simulations, this will repetitively continue and cause additional energy consumption. Therefore, it is important to analyze the TIM segmentation behavior with different EDCA parameters e.g., non-sensor type EDCA parameters as will be discussed in the following section.

6.1.2 Non-Sensor Type EDCA Parameters

In this part, the traffic type is assumed to be the NS-STA best effort mapping to the EDCA access category. In this setting, the minimum and maximum of the contention window is 16 and 1024 respectively while the AIFS has a slightly longer duration than DIFS [6].

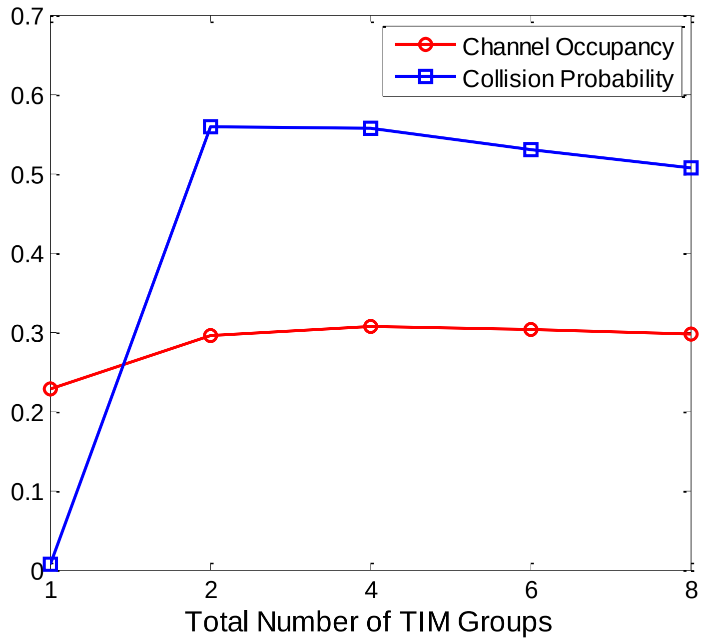

Figure 17. Collision probability and channel occupancy vs. TIM segmentation (no RAW implementation). Non-sensor-type EDCA parameters are assumed.

In Figure 17, the red and blue curves refer to the channel occupancy and collision probability respectively. The collision probability is expectedly small for TIM deployment with one group as in Figure 14 since simultaneous transmission probability is lower. Compared with Figure 14, NS-STA EDCA parameter configuration results in a lower collision probability than that in S-STA EDCA parameters. This is because STA with NS-STA parameter configuration utilizes larger CW to access the channel which has better ability of collision avoidance.

As illustrated by red curve in Figure 17, with the increase of the number of the TIM groups, the channel occupancy increases, similarly to Figure 14, since the simultaneous transmissions caused by TIM segmentation cause high collision and increase the retransmission time. Furthermore, the trend of collision probability then keeps constant since the collision probability does not change much as the number of TIM segmentation grows.

Figure 18 shows the packet delivery status in case of NS-STA EDCA parameter configuration. Same as the S-STA case, all the packets are successfully transmitted for TIM deployment with one group without any restriction of the channel access. By means of the large CWs utilized in NS-STA EDCA parameter, the discard ratio is considerably small even though the number of the TIM segmentation is increased. In addition, the packet buffered ratio slightly increases since the packets are more likely to arrive after the final access TIM interval. The buffered packets which are pending to be transmitted are the reason of delivery level below 1.

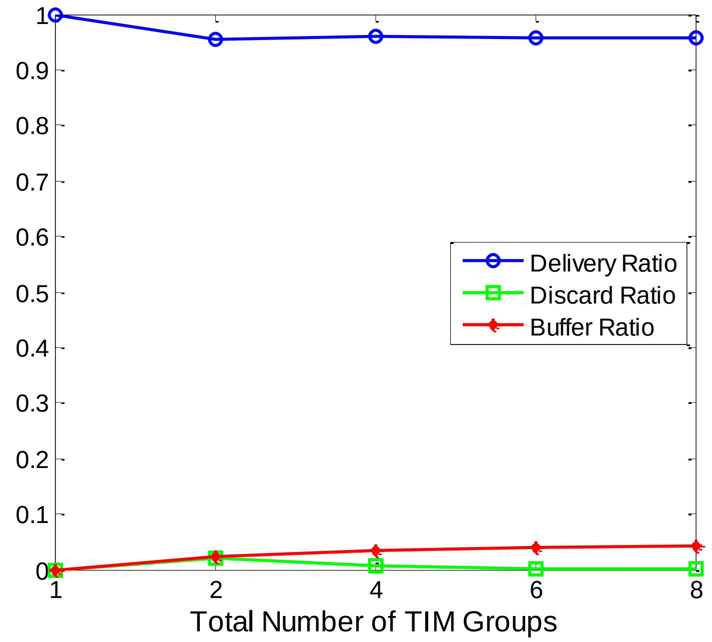

Figure 18. Packet delivery condition vs. TIM segmentation (no RAW implementation). Non-sensor-type EDCA parameters are assumed.

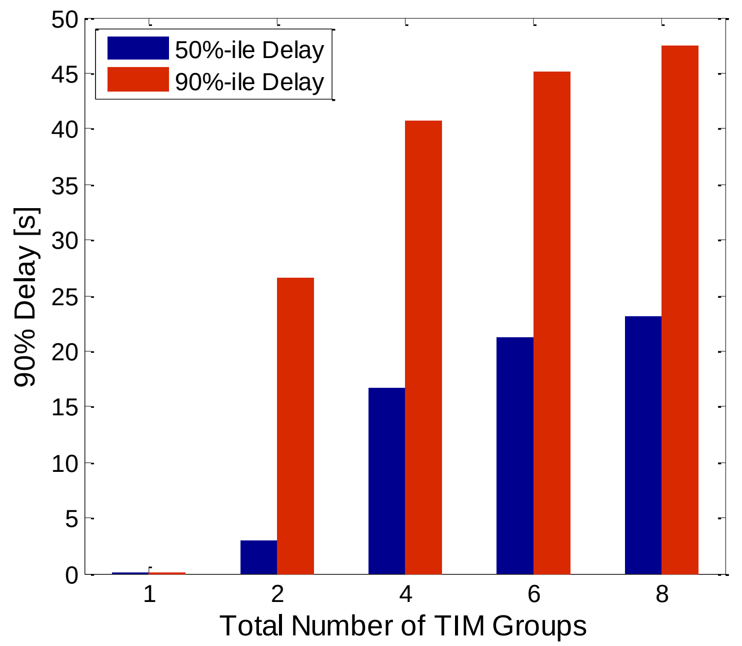

Figure 19. 50%-ile and 90%-ile delay vs. TIM segmentation (no RAW implementation). Non-sensor-type EDCA parameters are assumed.

Figure 19 shows both the 50 and 90 percentiles of the cumulative distribution function (CDF) of the delay for non-sensor parameter deployment. The delay is only considered for the packets which are successfully transmitted and it is calculated from the time of generating a packet to the time of successfully delivering the packet. The delay can result from the packet buffering or the time needed for the channel access, transmission and retransmission.

As illustrated in Figure 19, both the 50 and 90 percentile delays are considerable small for TIM deployment with one group since the packets can almost be immediately transmitted with a very small collision probability. However, when there is a segmentation, especially the 90 percentile delay is getting significantly longer despite the larger CW configured via NS-STA EDCA parameter selection.

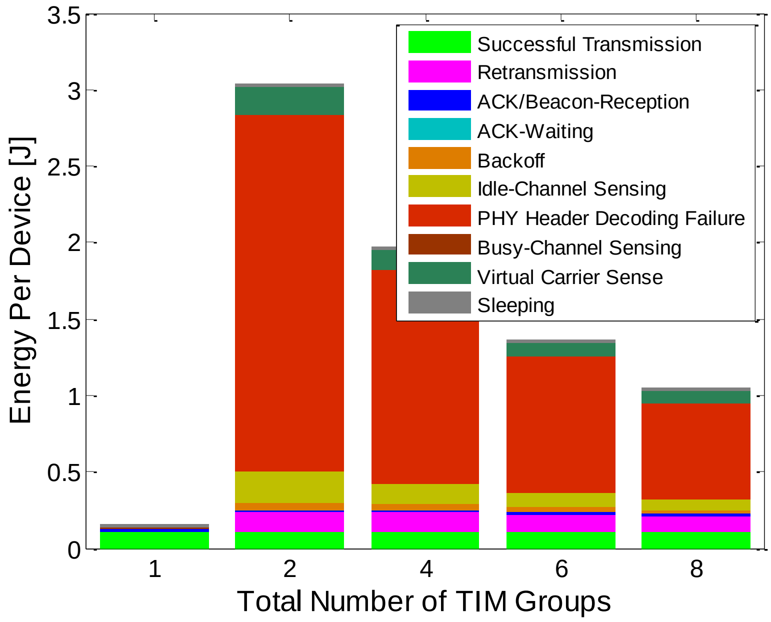

Figure 20. Average energy consumption per device vs. TIM segmentation (no RAW implementation). Non-sensor-type EDCA parameters are assumed.

Figure 20 shows the average energy consumption per device for NS-STA EDCA parameter configuration. For TIM deployment with one group, the energy consumption is considerably small and STA does not waste much energy in channel sensing. As a comparison, in case of TIM segmentation with more than one group, STA consumes larger amount of energy due to channel sensing as well as PHY header decoding failure. This is because that transmissions from a large number of STAs are simultaneously initiated at the beginning of each TIM interval when there are multiple TIM groups. Yet, the energy consumption decreases as the TIM segmentation grows further e.g., with respect to TIM deployment with two groups since the number of the simultaneously-competing STAs is reduced.

The STAs that are configured with the CW parameter from the NS-STA EDCA parameter set still consumes large amount of energy due to PHY header decoding failure. This is because when a large number of STAs compete to access the channel at the same time, 1/16 of the STAs wound generate backoff counter zero and transmit simultaneously. These STAs collide with each other while the remaining STAs fail to decode the PHY header as a result of the collisions. This problem can be solved after the CW size is enlarged sufficiently proportional to the total number of competing STAs.

6.2 Parameter Optimization

6.2.1 Additional Sleeping Cycles

In this part, a solution called additional sleeping (AS) cycles is proposed to minimize the energy consumption in 802.11ah, especially the energy spent in channel sensing. The fundamental mechanism of AS is that the STA intelligently moves to the sleeping state instead of sensing the channel once it senses the channel busy. This additional sleeping time is based on the sleeping window of each STA. Every time an STA goes into additional sleeping cycle, it generates a random sleeping value which is uniformly distributed in [SWmin, SWmax] where SWmin and SWmax represents the minimum and maximum values of sleeping window respectively. AS cycles can be adjusted based on the channel occupancy condition. Thus, the STA can generate larger sleeping windows if the data traffic is high while this window size can be reduced once the traffic alters to lower state.

The channel occupancy or load is represented by L which indicates the percentage of busy channel. T{busy} is defined to represent the mean value of channel busy time and it equals to T{data packet} + T{SIFS} + T{ACK}, where T{data packet} is the average packet length. Each STA can set up its sleeping window according to L and T{busy} and one example can be SWmin = T{busy}*(1-L) and SWmax = T{busy}*(1+L). It is assumed that the traffic occupancy information, L and average packet length T{data packet} are contained in each of beacon frame so that TIM STAs can adjust their sleeping window according to the channel condition. It should be note that for especially the delay-sensitive service, the system ought to limit the maximum number of attempts of additional sleeping.

The AS mechanism can work with VCS or without VCS. Once the STA identify the channel moves from idle state to busy state, it can first try to decode the PHY header to perform virtual carrier sensing. If it fails to decode the header, it can move to the AS mode to save energy. The STA can also ignore the VCS mechanism by directly shifting into the AS mode once it detects that the channel is busy. It is noteworthy that STA cannot perform VCS if it wakes up during the transmission of another STA and in this case it can move to the AS mode immediately. In the thesis, the AS mechanism is assumed to be activated only when the STA wakes up in the middle of another transmission.

The number of TIM groups is selected to be one as it performs sufficiently well in terms of energy-consumption in uplink as discussed in the earlier section. The EDCA parameters are selected based on the best effort access category for both S-STA and NS-STA. Their impact on the energy consumption is compared in addition to the AS solution. In the parameter setting of AS solution, the sleeping window of each STA is fixed where SWmin and SWmax equal to 6 and 12 ms respectively.

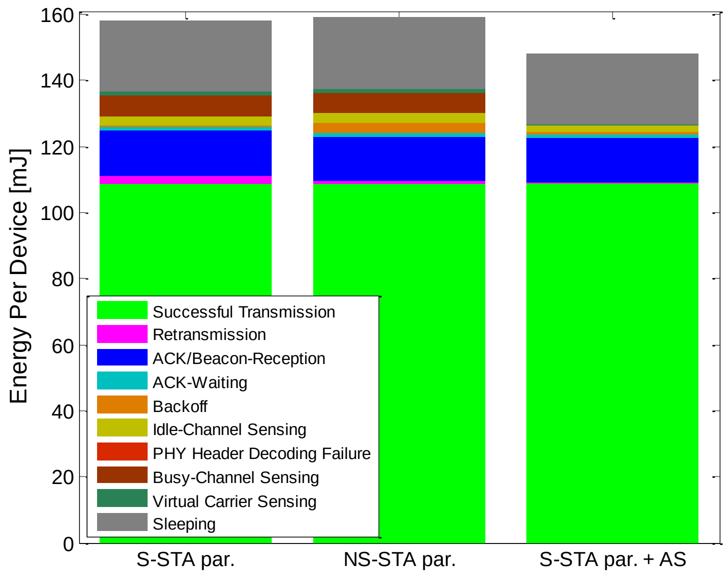

Figure 21. Energy consumption in case of sporadic uplink traffic in 10 minutes

Figure 21 shows that NS-STA parameters results in slightly more energy consumption with respect to S-STA parameters. This is because NS-STA parameters dictate larger CW when competing for the channel, thereby extends the channel sensing time (due to larger backoff period). Even though larger CW reduces the energy consumption by minimizing retransmissions, thanks to reduced collision probability, the gain is still negligible for the modeled traffic scenario. As observed from Figure 21, the proposed AS mechanism can save almost all the energy spent during the busy-channel sensing as the STA can sleep during the most of this period. Moreover, the AS mechanism can reduce the collision probability by means of added randomness to the sleeping time and minimizes the energy spent for retransmissions.

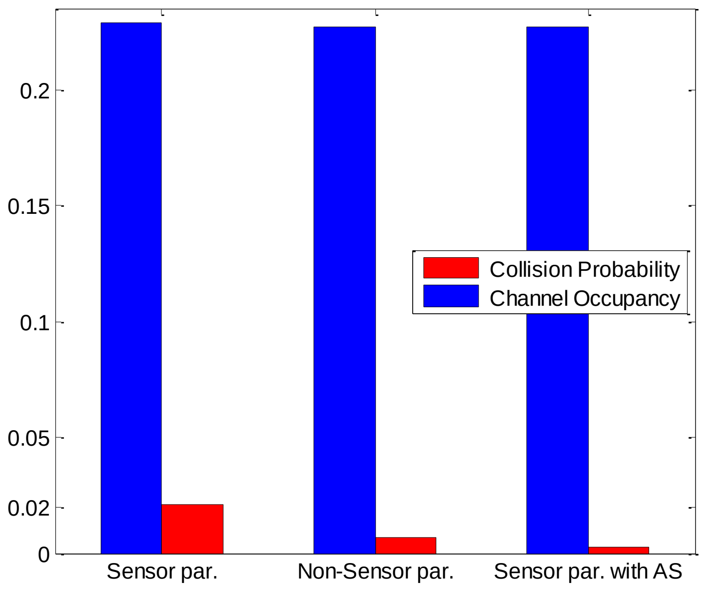

Figure 22. Collision probability and channel occupancy in case of sporadic uplink traffic

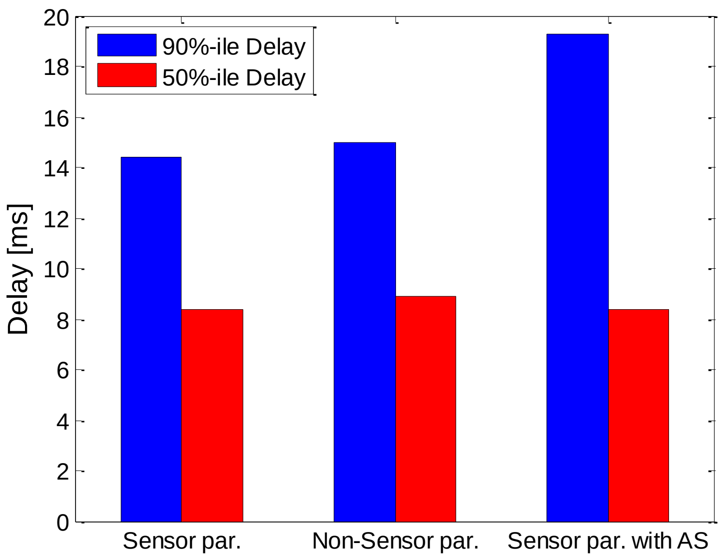

Figure 23. Delay in the case of sporadic uplink traffic

Figure 22 shows that the EDCA parameters do not affect much on the channel occupancy for the modeled traffic scenario. This is because the collision probability in case of S-STA parameter setting is already considerably small and larger CW dictated by NS-STA parameter set cannot save much time wasted on retransmissions. It is noteworthy that the small CW with AS solution can reduce more collisions than large CW.

Figure 23 shows that NS-STA parameters causes STA to generate slightly longer delay respect to S-STA parameters since NS-STA parameters utilize larger CW during backoff procedure and larger AIFS parameter. Thus, the channel sensing time before transmitting has been extended. Even though larger CW can save the time wasted due to retransmissions and decrease the delay, the gain is negligible in the assumed traffic condition. On the other hand, Figure 23 shows that AS method may result in increased 90 percentile delay but it is acceptable for the given scenario. The cost of additional delay is tolerable as long as the energy-efficiency can be noticeably improved, especially when it comes to some M2M use cases which are not sensitive to the delay.

6.2.2 Energy Harvesting Feasibility Analysis

The energy harvesting feasibility of various outdoor energy sources is analyzed in this section. The time required to harvest sufficient energy is calculated for ten minutes of STA energy consumption in our default scenario. It is assumed that the sensor type EDCA parameters are used.

Table 7. Required energy harvesting time for 10 minutes default traffic scenario (1 cm^2 sensor).

Energy Harvesting Method	Without AS mechanism	With AS mechanism
Solar outdoor sunny	10.55 s	9.88 s
Solar outdoor cloudy	17.6 min	16.5 min
Temperature variation (ΔT= 5 °C)	43.9 min	41.2 min
Temperature variation (ΔT= 10 °C)	19.5 min	18.3 min
RF signal in cellular network	26.4 min	24.7 min

Table 7 shows the required energy harvesting time with 1 cm^2 sensor. It can be observed that the solar energy outdoors in sunny weather conditions can harvest significant energy for sensor power supply. As a comparison, other sorts of energy sources require extra time to harvest sufficient power for the sensor. Yet, as shown in Table 8 if a larger harvesting area, e.g., 2 cm^2, is used, other energy sources such as temperature variation could be sufficient as well.

Table 8. Required energy harvesting time for 10 minutes default traffic scenario (2 cm^2 sensor).

Energy Harvesting Method	Without AS mechanism	With AS mechanism
Solar outdoor sunny	5.275 s	4.94 s
Solar outdoor cloudy	8.8 min	8.25 min
Temperature variation ($\triangle$T= 5 ℃)	21.95 min	20.6 min
Temperature variation ($\triangle$T= 10 ℃)	9.75 min	9.15 min
RF signal in cellular network	13.2 min	12.35 min

6.2.3 Impact of Traffic Load and Sleeping Window Size

In order to deeply evaluate the performance of the AS mechanism in different traffic conditions, three traffic load states are selected. The traffic load states are represented by the average packet inter-arrival rate of 10, 5 and 4 seconds, respectively. For each traffic load state, small and large window sizes are simulated. The minimum and maximum values of small SW are selected as 6 ms and 8 ms respectively, while these values are extended to 6 ms and 12 ms for large SW. The EDCA parameters are selected based on the sensor STA with best effort traffic type assumption in all the following simulated cases.

The grayscale colormap is used for the illustration of results in this section. In each figure, x axis shows the sleeping window size where VCS represents the case without additional sleeping mechanism. Small SW and large SW indicate the cases with the AS mechanism with small and large windows respectively. Y axis shows the traffic load which is represented by packet inter-arrival time of 10 s, to 5 s and 4 s.

Figure 24 compares the collision probability in different traffic load conditions and for a set of sleeping window sizes. The AS mechanism decreases the collision probability since STAs are less likely to access the channel simultaneously by sleeping a random time. Furthermore, the large sleeping window reduces collision probability more than small window size since it contributes to more randomness. In a traffic scenario with the inter-arrival time of 4 s (high traffic load), the collision probability is considerably large (over 80%) while the gain of collision avoidance by the AS mechanism is significantly high. As a comparison, the improvement on the collision avoidance in lower traffic load is not obvious.

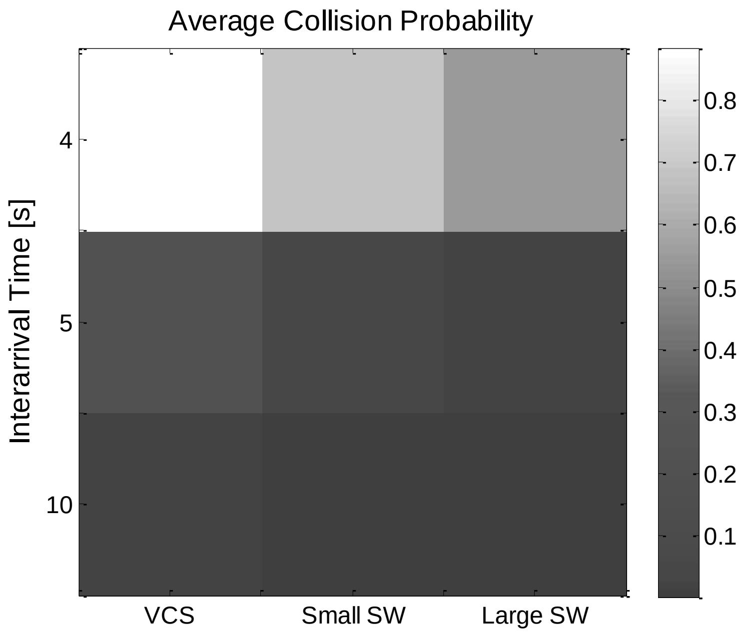

Figure 24. Collision probability vs. traffic load and additional sleeping parameters

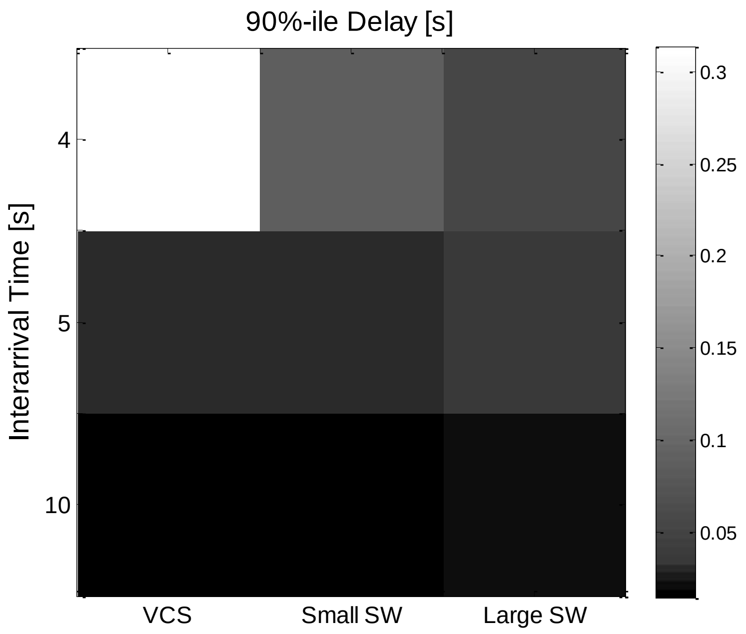

Figure 25. 90 percentile delay vs. traffic load and additional sleeping parameters

Figure 25 shows the 90 percentile delay. In the lower traffic load, for instance, 10 s and 5 s inter-arrival rate, the AS mechanism increases the delay since in this case the delay caused by retransmission is negligible compared with the delay added by additional sleeping cycles. Furthermore, large sleeping window results in a larger delay due to the longer sleeping time.

However, in case of higher traffic load with the inter-arrival time of 4 s, the AS mechanism can decrease the 90 percentile delay since in this case the 90 percentile delay mostly results from retransmissions. The delay cost in additional sleeping is negligible compared with the delay saved by retransmission reduction. In this case, large sleeping window can decrease the delay more than the small one through reducing more collisions.

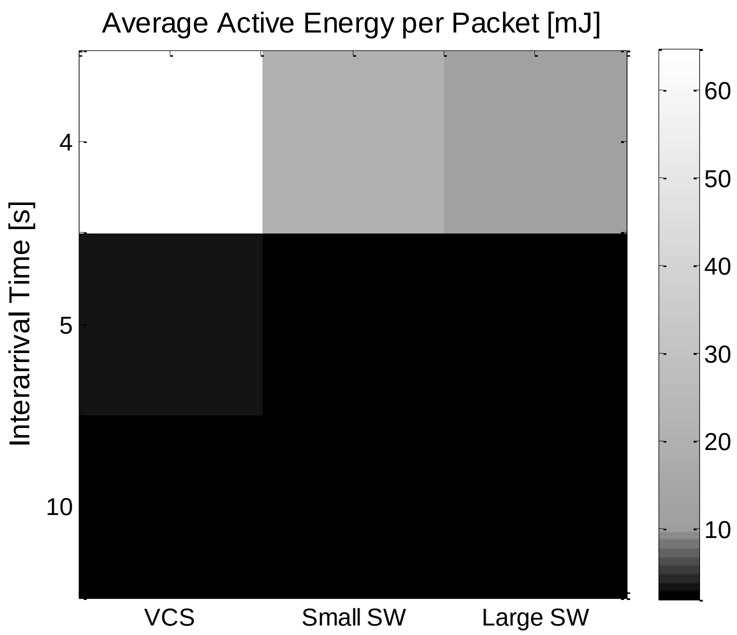

Figure 26. Average active energy consumption per packet vs. traffic load and additional sleeping parameters

Figure 26 illustrates how much energy is spent in active mode in order to transmit one packet successfully. It is assumed that the energy in sleeping mode is negligible compared with that in active mode. In the higher traffic load which has the inter-arrival rate of 4 s, the AS mechanism can save energy considerably since in this case STAs spend much larger amount of energy in retransmissions. The benefit of AS mechanism is not significant for lower traffic load conditions.

7 Conclusions

M2M communications have been anticipated to be the one of the driven force for the future development of wireless technologies. The distinct features of M2M brings new challenges for the design of wireless systems. Recently, in order to increase the competence in future M2M market, several enhancements have been proposed in different wireless technologies. For example, 3GPP has proposed several enhancements for M2M applications in the latest releases, such as Release 12 and 13. In the area of Wi-Fi, a new amendment named 802.11ah has been proposed accordingly.

The thesis briefly introduces the M2M enhancements in different wireless technologies with a focus on 802.11ah technology. The scope is to evaluate the energy efficiency of a new M2M enhancement proposed in 802.11ah known as TIM segmentations. The TIM segmentation is a periodical channel access mechanism to efficiently group devices and save energy. In order to thoughtfully understand the principle of this enhancement, some fundamental MAC layer functions in Wi-Fi have been discussed. The methodology utilized for performance evaluation is system-level Matlab simulation. The simulator is based on state machine transition which models the behavior of 802.11ah MAC layer. It focuses on uplink traffic following Poisson process assuming an agricultural scenario. In addition, the thesis proposed an energy saving solution based on additional sleeping (AS) cycles. In this method, the STA can smartly move to the sleep state instead of wasting energy on channel sensing as soon as it identifies that the channel is likely to be busy.

According to the simulation results, the TIM segmentation of channel access among devices can deteriorate uplink transmission performance in case of sporadic data traffic. This is because that TIM restriction in uplink increases the probability of simultaneous transmissions among a large number of devices and this increases the collision probability. Results shows that energy consumption is optimal when there is only one TIM group (no access restriction). Adding more TIM group segmentations (2 to 8) can increase the energy cost more than ten times. The observation is valid for both sensor and non-sensor type EDCA parameter settings. The performance of AS mechanism has also been evaluated for various traffic load conditions. The results show that AS mechanism can save around 7% energy in low traffic load condition by introducing a tolerable delay in channel access. The gain is even larger for higher traffic load conditions.

The reason why TIM grouping in uplink deteriorates the performance is the CSMA/CA mechanism. The random access procedure in CSMA/CA may not efficiently cope with simultaneous access of a large number of devices. This may be solved by setting a suitable initial size of contention window if the total number of access devices is known in advance. However, in most cases, this number cannot be known so devices have to initialize the channel access with the minimum contention window and gradually increases the size after obtaining the collision feedback by the AP.

On the other hand, the grouping mechanism for uplink access may work in LTE systems. In LTE, when a large number of devices access the channel in the same RA slot, they are required to first send a preamble to eNodeB. The preamble is selected randomly from an orthogonal sets, typically 54 numbers. The orthogonality enables eNodeB to detect different preambles. If multiple devices select the same preamble simultaneously, a collision will occur. The eNodeB may detect the collision based on the different arrival time of the same preambles and broadcast a backoff indicator for the collided devices. The advantages of LTE over Wi-Fi is that these collided devices can perform backoff based on this indicator so they can identify the exact suitable time for the next access retry. However, the drawback is that eNodeB may not able to detect the collision since it may receive the same preambles constructively from the devices at the same place. In this case, these devices will continue to collide with each other in the next transmission.

The related research results, where the focus is on the RAW configuration, have also been submitted as a conference paper [36]. Future work may consider downlink data traffic along with uplink traffic, as well as the physical layer implementation in details. Other MAC features such as Non-TIM operation and hidden node problem solutions can also be considered.

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