# HYBRID CONTENTION-ADDRESSING ALGORITHM FOR ENERGY EFFICIENCY IN IEEE 802.11 WAKE-UP BASED RADIO NETWORK UPLINK

BY

**DARE, Tunde Michael**

**MENG/SEET/2017/7499**

**DEPARTMENT OF TELECOMMUNICATIONS ENGINEERING**

**FEDERAL UNIVERSITY OF TECHNOLOGY**

**MINNA**

**NOVEMBER, 2021**

# HYBRID CONTENTION-ADDRESSING ALGORITHM FOR ENERGY EFFICIENCY IN IEEE 802.11 WAKE-UP BASED RADIO NETWORK UPLINK

BY

**DARE, Tunde Michael**

**MENG/SEET/2017/7499**

**A THESIS SUBMITTED TO THE POSTGRADUATE SCHOOL FEDERAL UNIVERSITY OF TECHNOLOGY, MINNA, NIGERIA IN PARTIAL FULFILMENT OF THE REQUIREMENT FOR THE AWARD OF MASTER OF ENGINEERING IN COMMUNICATION ENGINEERING**

**NOVEMBER, 2021**

# ABSTRACT

Power consumption is a key consideration in every Wireless Local Area Network Medium Access Control (WLAN MAC) algorithm design for wireless devices and extending battery life requires more efficient power management scheme considering that carrier sensing by WLAN modules, false wake-ups, collisions and number of contention rounds are major contributors to energy overhead. Researchers over the years have proposed and implemented various schemes using a low power wakeup radio for carrier sense which has proven to be effective. This thesis analyzes the energy efficiency and latency performance of IEEE 802.11 wake-up based radio network uplink using Hybrid Contention-Addressing Algorithm. In this algorithm, Wake-up radio (WuR) senses the channel and wakes its co-located WLAN module when the channel is available for transmission. The station (STA) that wakes up to transmit packet is decided by distributed contention. But the technique put forward in this thesis differs from previous method because each contention round is used to select and queue a set of STAs as against one. The selected and queued STAs then goes on in the addressing stage to transmit as soon as they receive the wake-up message (WuM) in quick succession. The problem of false wakeup stemming from wakeup latency and delay between sleep and wake up of successive STAs is dealt with by the addressing technique which broadcasts an ACK frame modulated with a WuM bearing the unique address of the STA to transmit next. In this way, two stations cannot wakeup simultaneously nor can one wakeup while the other is still in the process of waking. Extensive analysis confirmed that the HCA-CSAM/CA effectively reduces energy overhead by up to 97%, 60hrs increase in battery lifetime and 68.3% reduction in latency compared with ESOC with a better tradeoff between energy consumption and throughput.

**TABLE OF CONTENT**

CONTENT

PAGE

**CHAPTER TWO**



**CHAPTER THREE**

## LIST OF TABLES

## LIST OF FIGURES

## LIST OF APPENDICES

# GLOSSARY OF ABBREVIATIONS AND ACRONYMS

ACK

AP

BSA

CTS

CW

DCF

DIFS

LAN

MAC

PHY

PS

RA

RTS

SA

SIFS

STA

TA

WuM

WuR

WLAN

Acknowledgment

Access Point

Basic Service Area

Clear To Send

Contention Window

Distributed Coordination Function

Distributed (Doordination Function) Interframe Space

Local Area Network

Medium Access Control

Physical (layer)

Power Save (mode)

Receiver Address

Request To Send

Source Address

Short Interframe Space

STAtion

Transmitter Address

Wake-up Message

Wake-up-Radio

Wireless Local Area Network

# CHAPTER ONE

# 1.0 INTRODUCTION

## 1.1 Background to the Study

The IEEE 802.11 WLAN has developed over the years as a preferred technology for wideband wireless technology, therefore, requiring WLAN modules implant into wireless devices such as tablets and smartphones. However, the power-sapping nature of WLAN radio limits battery life making it necessary to improve energy efficiency of the radio. A WLAN radio is required to receive messages immediately by staying in the continuous wake-up mode (CAM) but idle awaiting period spent in sensing the channel leads to much power consumption.

Using low power Wake-up Radio (WuR) in conjunction with the Wireless Local Area Network (WLAN) module lowered power consumption of the WLAN by assuming the responsibility of sensing the channel giving room for further reduction in power consumption by clever adjustment of the algorithms (*Magno et al.*, 2016; Piyare *et al*., 2017; *Kondo et al*., 2012). The aim of developing the wireless telecommunication technologies was to provide services equivalent to those of wireline networks.

Wireless networks have come to support high-bandwidth data transmission for wireless device users while providing voice communication. Depending on area of coverage, Wireless data networks are classified (*Boukerche*, 2005) into: Wireless Local Area network (WLAN), in which cell radius is approximately 100m, especially in office environments and homes, Wireless Metropolitan Area Network (WMAN) masking areas as giant as whole cities and Wireless Wide Area Network (WWAN) of approximately 50000 m cell radius.

IEEE 802.11 is a component of the Local Area Network (LAN) technical standards IEEE 802 set that stipulates PHYsical layer (PHY) and Medium Access Control (MAC) algorithms in computer communication for realizing wireless local area network (WLAN) first released in 1997 as contained in MAN, Committee and Computer (2009). The IEEE 802.11 and HiperLAN standard are both under the Wireless Fidelity (Wi-Fi) alliance. The standard uses frequency bands of 2.4 GHz, 5 GHz, 6 GHz, and 60 GHz. Wi-Fi initially provided an 11Mbps approximate throughput with recent developments increasing it to 30 Gbps (Fabris Hoefel R. P., 2020; Lopez-Perez *et. al.*, 2019).

A WLAN network is comprised of an Access Point (AP) at the centre with multiple stations (STAs) linked to it (Chen *et al.*, 2016; Tang and Obana, 2018; Kondo *et al.*, 2012). In centralized mode, all STA communication is over the access point (APs) while in the decentralized mode, communication between STAs takes place directly without going through the AP in an ad hoc manner.

Due to its high market acceptability, numerous amendments have been developed for the basic IEEE 802.11-1997, the prominent among them being 802.11a, 802.11b, 802.11g, 802.11n and 802.11p as shown in Figure 1.1. Carrier-Sense Multiple Access with Collision Avoidance (CSMA/CA) technique is adopted for every standard with support for both centralised and ad-hoc networks (Sanabria-Russo and Bellalta, 2018; Oller *et al.*, 2014).

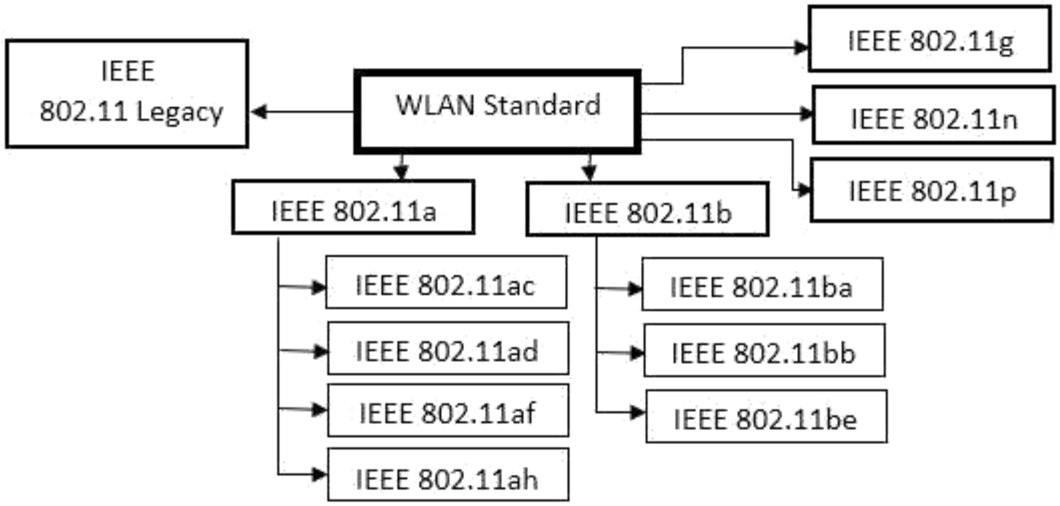


Figure 1.1: WLAN Standards

Carrier-Sense Multiple Access (CSMA) has been developed as a media access control (MAC) protocol that requires that a station (STA) ascertains that the channel is free of other traffic prior to transmission. In a wake-up radio enabled STA, the wake-up radio (WuR) determines if transmission is in progress by another STA on the shared channel before waking its WLAN module using carrier-sense mechanism (Ghose *et al*., 2018; Chen *et al.*, 2013; Spenza *et al.*, 2015). When a channel is detected in use, the STA waits for an in-progress transfer to complete before setting up its transmission. CSMA allows multiple STAs to communicate with the AP over the same channel.

Earlier IEEE 802.11 contention based algorithms allows a single station (STA) to win the contention and then transmit while numerous other STAs wait their turn to contest for the channel (Tang *et al.*, 2018), which translates to prolonged wait for the STA and possible loss of buffered data due to power outage by the devices in large networks. There also exists a latency period between "sleep" of a STA that transmitted and the "wake-up" of the succeeding STA (Tang and Obana, 2018), this could be leveraged to further reduce latency and save energy.

## 1.2 Statement of the Research Problem

The traditional contention based algorithms allows numerous stations (STAs) to contend for access to the channel with a single station winning at the end of the contention period. This means that other stations would have to wait for subsequent contention rounds which they may not also win. There is therefore the need to have a technique that allows a set of multiple stations to win contention and all transmit in a defined order. This would reduce the STA waiting time, save energy as the number of contention rounds reduces and also improve throughput as the ordering reduces collision. The research issues that still has to be addressed include: how to further reduce energy consumption thereby improving battery life using hybrid contention- addressing approach and how to develop techniques of achieving more efficient channel access scheme that limits collision in the system, reduces latency and gives better throughput.

## 1.3 Aim and Objectives of the Study

The Aim of this research work is to design a Hybrid contention-addressing algorithm for energy efficiency and latency reduction in IEEE 802.11 wake-up based radio network uplink.

The Objectives of this work are to:

i. Evaluate the Wake-up Radio Based Early Sleep Optimal Contention Window (WuR-ESOC) algorithm, the backoff algorithm and the Broadcast-based wake-up control framework.

ii. Develop a mathematical model for the Hybrid Contention-Addressing CSMA/CA (HCA CSMA/CA) algorithm and test the model with parameters applied to the evaluated algorithms using MATLAB.

iii. Evaluate the energy efficiency, latency and throughput of the HCA-CSMA/CA and carry out comparative analysis of HCA-CSMA/CA and WuR ESOC (Tang and Obana, 2018.)

## 1.4 Justification for the Study

To improve energy efficiency, there is need to reduce latency in the system. The longer it takes for data to get from source to destination, the longer the transmitting radio will have to stay awake and in the process consuming much energy. The more the number of devices connected to an AP, the more the likelihood of collision. When data collides on a network, data could be lost or become corrupted and need resending which slows down the system and decreases performance.

In addressing latency in the system, collision must be considered and to deal with collision there is the need to design an algorithm that allows multiple stations to access the channel without any two of them transmitting simultaneously and guarantees minimal recovery time from failed transmissions. Though the introduction of wake-up radio (WuR) into the WLAN system worked in reducing power consumption, the collaboration is yet faced with issues such as collision, wake-up latency, throughput maximization, contention window adjustment, spectral efficiency and the need for further reduction in energy consumption.

## 1.5 Scope of the Study

The research focuses on contention based wake-up-radio (WuR) enabled IEEE 802.11 algorithm. This research work looks at energy efficiency in the uplink by developing an algorithm.

## 1.6 Thesis Outline

This thesis is divided into five (5) chapters. The first Chapter is the introduction to the topic. Chapter two includes the review of the literature while Chapter three covers the methodology and design considerations. The results obtained are discussed in Chapter four while Chapter five carries the conclusions with the recommendations.

## CHAPTER TWO

## 2.0 LITERATURE REVIEW

### 2.1 Historical Background of 802.11 Standard

The IEEE 802.11 is a subset of the IEEE 802 LAN technical standards that specifies the set of physical layer (PHY) and MAC algorithms for executing WLAN data communication. The main goal of the standard is to furnish wireless connectivity to computerized machinery, equipment, or stations that require fast deployment, which may be transportable or hand-held, or which may be hooked up on moving vehicles within a local area (MAN, Committee and Computer, 2009). IEEE 802.11-based wireless LAN (WLAN) has grown immensely over the last decade providing its users with access to the Internet.

The IEEE 802 project focused on the Medium Access Control (MAC) and PHYsical layer (PHY) layer. At its inception, the Wireless Local Area Network (WLAN) was reckoned as a PHY for one of the standards with 802.3 as the first candidate considered.

Further findings revealed that a radio medium differ from the conventional wire medium significantly in terms of attenuation, which exist even over short distances and difficulty in detecting collisions creating challenges for the integration of the 802.3 Carrier Sense Multiple Access with Collision Detection (CSMA/CD).

With the coordinated medium access perceived to offer better performance compared to 802.3’s contention-based scheme, 802.4 was considered. Therefore, WLAN started as

802.4L but researchers later realized in 1990 the difficulty of token handling in radio networks and on March 21, 1991 the 802.11 project was approved with the standardization body realizing the need of a wireless communication standard that would possess its own MAC (ref).

The 802.11 standards provided maximum data rate of 2Mbps that latter improved to 11 Mbps with IEEE 802.11b. Data rate of 54Mbps was achieved with IEEE 802.11a and IEEE 802.11g. With different techniques adopted to increase the maximum data rates, a wireless LAN device based on IEEE 802.11g now provides data rate in the range of 100-125Mbps. However, IEEE 802.11n gives a maximum data rate of approximately 540Mbps.

IEEE 802.11e and IEEE 802.11i provided quality of service (QoS) support and management frame security while IEEE 802.11n standard introduced MAC enhancements designed to take-care of MAC layer limitations. IEEE 802.11s standard supported mesh topology while IEEE 802.11u provided better non-802.11 networks with internetworking.

The "fast session transfer" feature was added to IEEE 802.11ad standard, which enables a wireless device to make smooth transition between the 2.4 GHz, 5 GHz bands and 60 GHz frequency bands. IEEE 802.11ac standard provides 1 Gbps throughput for multiple-station WLAN and 500Mbps throughput for single link.

## 2.2 Duty Cycling

A WLAN module power utilization is almost same in transmission mode as in the listening mode resulting in high energy consumption. To get the energy efficiency to improve, Duty-Cycling technique was proposed in Giuseppe (2009); Yang *et al.* (2018) allowing the power-sapping WLAN main radio to wake only when there is a chance for it to transmit data, otherwise it stays in sleep mode and saves energy as Figure 2.1 depicts.

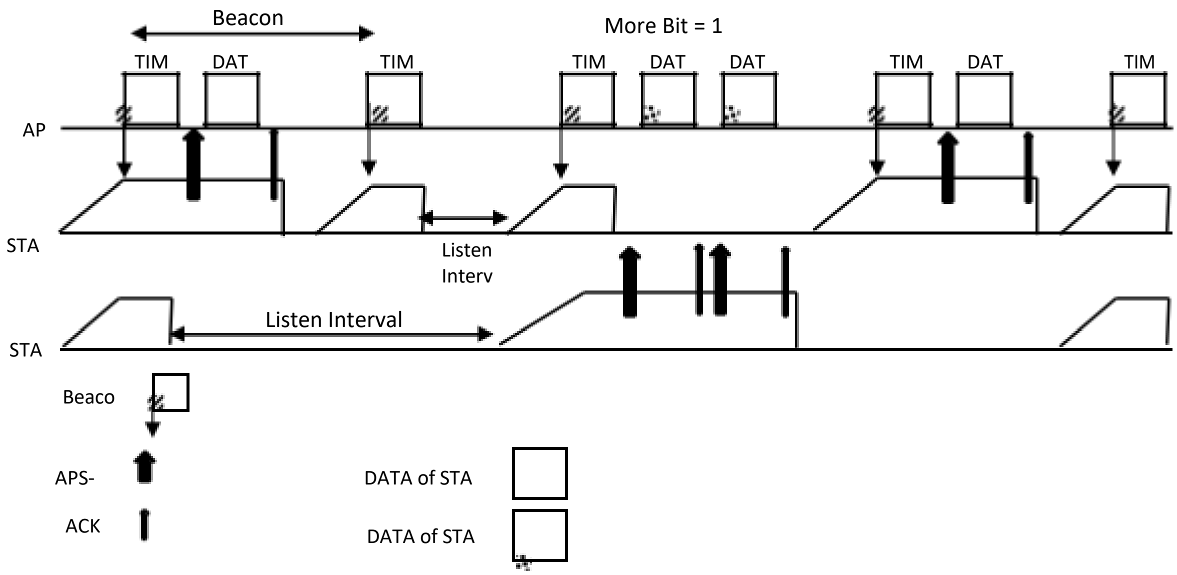


Figure 2.1: Legacy Power-Save Mode (PSM)

(MAN, Committee, and Computer, 2016) specified a power-save techniques in duty cycling which includes the power-save mode (PSM) which enables the Access Point (AP) to wake up a STA that is in sleep-mode only at the time it is required to communicate data. The automatic power save delivery (APSD) is used during “direct link” data transmission of the AP and it can be unscheduled or scheduled (Yang, Deng and Chen, 2018). The power save multi-poll (PSMP) mechanism, transmission opportunity power save mode (TXOP PSM) and Target wake time (TWT) in which both STA and AP coordinate together to wake the STA at a defined time thereby allowing the STA to remain the sleep mode till this time as also specified in MAN, Committee and Computer (2016).

The sleep duration of the WLAN became difficult to extend to any appreciably since the module:

i. Intermittently listen for transmissions in progress on the channel even when there are no data destined for it at the AP that is actually necessary for reducing data latency. However, idle-listening accounts for large part of the power consumption since eighty percent of the battery life-time of WLAN module is spent listening (Yang, Deng, and Chen, 2018).

ii. Receives all the transmitted data even those not destined for it (known as overhearing) that gets discarded after finding out that they are not meant for it. Energy consumed processing this data amounts to wastage.

Besides inefficient power consumption, the Duty-Cycle protocols also cause significant data latency as the module could not communicate in the sleep-mode thereby requiring that that some packets be continuously re-transmitted before they can be correctly received (Spenza *et al.*, 2015). In addition, this technique necessitates a high degree of synchronization between AP and the STA which contributes to the protocol overhead. Several approaches used in the duty-cycle technique as outlined in Yang, Deng and Chen (2018) include:

i. The unicast technique where all STAs associated with the AP is assigned a unique ID (AID) but this requires more protocol overhead for addressing STAs individually.

ii. The Broadcast/Multicast PSM allows the AP to broadcast a beacon to all STA associated with it to receive buffered packets. This approach has helped at refining power management in WLAN over the years.

iii. The introduction of the Automatic Power Save Delivery (APSD) with IEEE 802.11e. With the APSD, a STA does wake up periodically to listen for beacon, rather it transmits a trigger frame whenever it wants to retrieve the pending frames in the AP buffer.

iv. The power save multi-poll mechanism came with IEEE 802.11n and it allows AP to schedule uplink and downlink for STAs by intermittently broadcasting a PSMP frame (Palacios *et al*., 2014).

v. Transmission Opportunity (TXOP) requires that STAs switch between ‘sleep’ and ‘wake-up’ mode, but the STA cannot receive data when in sleep mode.

These techniques among others have helped to save power but these challenges drove researchers to come up with numerous enhanced MAC protocols aimed with the goal of prolonging the battery lifetime in wireless devices.

### 2.3 WLAN Radio with Wake-Up Radio

The wake-up radio is a low-power radio developed by the IEEE 802.11ba standard task group to increase energy efficiency of devices on wireless networks with IoT in focus. It is deployed to sense the channel uninterruptedly and in effect easing the WLAN module of that task resulting in energy saving.

#### 2.3.1 The wake-Up Radio Architecture

The wake-up radio is connected with the WLAN module and shares the same antenna and ISM band (2.4GHz/5GHz) with it which reduces hardware cost in Piyare *et al*. (2017); Chen *et al.* (2016). On-Off-Keying (OOK) is used as the modulation scheme while RF envelope detection is used for reconstructing the signal at the receiving end (Magno *et al.*, 2016; Daly *et al.*, 2007). However, overhearing and high rate of false wake-up are among others, research gaps.

Figure 2.2 shows the architecture of a wake-up radio at both the receiver and the transmitter ends. As affirmed in Yang *et al.* (2018), the WuTx in the AC generates the WID of the targeted STA, modulates it on the empty WLAN frames using the OOK modulation scheme, spreads the signal over the whole of the available spectrum (OFDMA) then sends the WuM as soon as the channel is sensed idle.

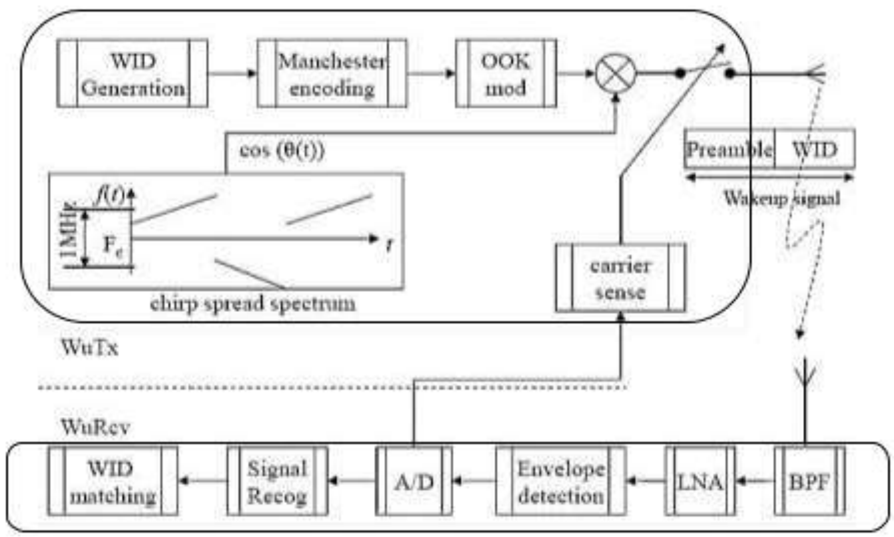


Figure 2.2: Wake-up Radio (WuR) Architecture (Tang *et al.*, 2012)

At the receiver, the WuM is recovered by Radio Frequency (RF) Band Pass Filter (BPF), which amplifies the signal first, then the envelope detector retrieves the WID. On matching the WID, the WLAN module is triggered to wake. But in more recent works, the AP's WLAN module is also configured to serve as the transmitter thereby eliminating the transmission end of this architecture as it appears in Dare *et al.* (2020).

### 2.3.2 The Wake-Up Message (WuM)

Figure 2.3 shows a WuM frame comprise of frame header. The frame header holds the wake-up preamble that synchronizes bit interval between Tx and Rx and a start frame delimiter (SFD) that tells the Rx the beginning of the frame and commencement of decoding of the packet content as proposed in Tang and Obana (2018); Magno and Benini (2014).

The WuM frame also contain a non-compulsory address field (broadcast or unicast based), error detection field required in frame check sequence (FCS) using cyclic redundancy codes (CRC), a payload field for the application data, command and extra instructions given by user as specified in MAN, Committee and Computer (2016).

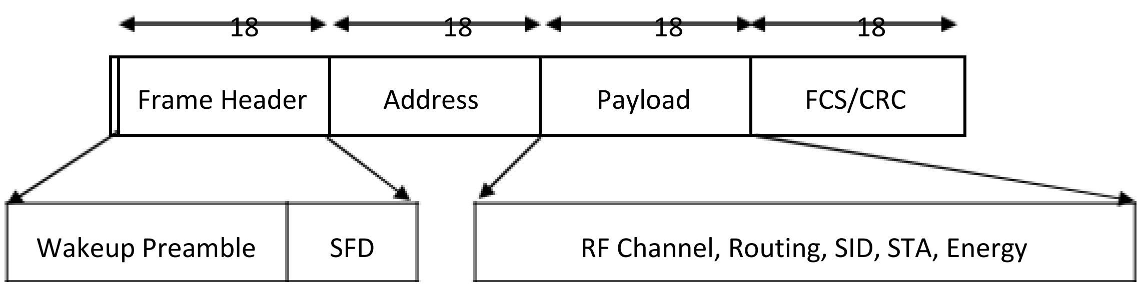


Figure 2.3: Wake-up Message Frame (MAN, Committee and Computer, 2016)

Various communication medium can also be used to transmit WuM, such as RF-based Medium using frequencies from ≈3 KHz to 300 GHz, audio medium where acoustic and ultrasonic signals are used, and Optical medium where lasers are used for sending WuM.

### 2.3.3 Energy Efficiency

Energy consumption refers to energy expended due to communication by the radios (Wake up radio and the main WLAN radio). The energy efficiency of MAC-layer algorithms depends on the effectiveness of various channel access techniques using contention. But contention depends on communication patterns, STA density and RF transmission characteristics among others. The MAC algorithms are classified in Giuseppe (2009) into: TDMA-based, hybrid protocols, and contention-based.

Low duty-cycle is relied upon in contention-based protocols to reduce the STAs energy consumption. To avoid idle listening in this approach, the STA is configured to switch into sleep mode when there is no data to transmit. However, duty-cycling mechanism does not effectively deal with idle listening since STAs still senses the channel even in the process of waking up.

Wake-up radio (WuR) systems was proposed in Tang and Obana (2018); Tang *et al.* (2016[a]); Magno and Benini (2014) to tackle the challenge of idle listening by ensuring that the STA wakes-up on demand by a Wake-up message (WuM). The wake-up radio (WuR) is a low-power second radio integrated with the STA for the wake-up communications while the WLAN radio module does data transmission.

The ESOC algorithm (Tang and Obana, 2018) is wake-up radio based and it uses the backoff freezing (BOF) technique to address Wake-up latency in order to better the energy efficiency of the IEEE 802.11. It recovers the carrier sense mechanism by resetting backoff counters correctly thereby giving the “freezing” impression and ensures timely sleep to reduce false wake-up duration and reduce false wake-up probability by contention window size adjustment.

The total energy consumption of WLAN in ESOC for every contention round was divided into three parts; Energy consumed for successful transmission ($E_S$), energy consumed for transmission with collision ($E_C$) and energy consumed for false wake-up with no early sleep ($E_F$). These energies were expressed as (Tang and Obana, 2018):

$$E_S = ((E_I \times (T_{WU}+T_{SL}) + T_X \times E_T) \times N_S \qquad (2.1)$$

$$E_C = ((E_I \times (T_{WU}+T_{SL}) + T_C \times E_T) \times N_C \qquad (2.2)$$

$$E_F = (E_I \times (T_{WU}+T_{SL}) \times N_F \qquad (2.3)$$

Where, $N_S$ = number of successful transmissions, $N_C$ = number of collisions, $N_F$ = number of false wake-up, $T_{WU}$ = Time taken for a WLAN module to wake up completely, $T_{SL}$ = Time taken for a WLAN module to go to the sleep state, $T_{TX}$ = Time of a DATA transmission, including ACK, DIFS, SIFS, $E_I$ = Power of a WLAN module in the idle period (1 Watt) and $E_T$ = Power of a WLAN module in the transmission (1 Watt)

$$N_S = 1 \times \frac{\quad}{\quad} \qquad (2.4)$$

$$= \sum \frac{( \times ( ))}{\quad} \qquad (2.5)$$

$$= (\sum -1 \times ( \quad \frac{\quad}{\quad} ) + \sum (\sum - \times ( , \quad \frac{\quad}{\quad} )) \times \qquad (2.6)$$

where, = probability that a slot is idle, = the probability that a only one station starts a transmission and it transmitted with success without collision, .= probability that a $\leq 2$ stations transmit and a collision occurred,

$$=(1- \quad )^{-1} \tag{2.7}$$

$$= {}^{1} \quad \times (1 - \quad )^{-1} \tag{2.8}$$

$$= \quad \times (1 - ) - \tag{2.9}$$

$$( \; / \; ) = {}^{1} \quad \times \quad (\Sigma) \times (1 - \Sigma)^{-1-} \tag{2.10}$$

where, BO = transmission probability, $^{1}$ = Number of k-combinations out of N elements, NWU = wake-up period in terms of slots,

Total Energy consumed by the station E is

$$= \; + \; + \tag{2.11}$$

Most energy-efficient algorithms are focused on centralized basic service area (BSA) which rely on an AP to moderate communication among STAs, schedule STAs for accessing the channel to lower contention while also ensuring that STAs spend much of the time in sleep mode thereby consuming less energy for most of the time spent in the network (Magno *et al.*, 2016; Tang *et al.*, 2012; Chen *et al.*, 2016; Santos *et al.*, 2012). Energy consumption analysis have to reflect costs for sending, receiving and discarding traffic. The decentralized mode in Boukerche (2005.) allows STAs to communicate among themselves directly without going through an AP in an ad hoc fashion.

Energy consumption for wireless communication is largely by the WLAN radio and wastage is mainly from idle listening and overhearing (Yang *et al.*, 2018 and Bianchi, 2000). Idle listening entails listening to the channel without wireless transmission in progress while overhearing denotes to a STA listening to wireless communication with another STA.

In Tang and Obana (2018) the authors proposed that if the duty ratio of a STA is symbolized as $O_{STA}$, a duration in which the STA is awake but its WuRx is not, and it consumes $P_{STA}$ power from CPU operation, memory not considering power demand for packet transmission, and assuming that the STA rest period is 1-$O_{STA}$ during which the STA stays in sleep-mode while the WuRx is active consuming $P_{WuRx}$ power, the WuRx Power consumption ratio can

be computed as $r_{WuRx}$

$$\text{Power consumed WuRx} = (\quad) \times (1- \quad) \tag{2.12}$$

Average power (STA system) =

$$(\quad \times \quad)+(\quad \times(1- \quad))+(\quad \times \quad \times(1- \quad) \tag{2.13}$$

Therefore

$$= \frac{(\quad)\times(1- \quad)}{(PSTA\times OSTA)+(PWuRx\times(1-OSTA))+(PSTA\times FPP\times(1-OSTA)} \tag{2.14}$$

η is the ratio of power consumed by a WuRx enabled STA to that of a STA without WuRx. This ratio defines how much reduction in power consumption is obtained with the WuR:

$$\eta = \frac{\cdot}{(PSTA\times FPP\times(1-OSTA)} \tag{2.15}$$

## 2.4 Previous Related Research on Energy Efficiency with Wake-Up Radio

The wake-up radio is a low power radio that is used to achieve energy efficiency by playing the role of the main radio in sensing the channel. Its work ranges from ensuring the availability of the channel to waking the main radio up to transmit or receive data.

### 2.4.1 Channel Sensing

Research into wake-up radio technology was at inception targeted at wireless sensor networks (WSN) (Chen *et al.*, 2013; Spenza *et al.*, 2015) with successes achieved by research in that area (Guntupalli *et al.,* 2018; Basagni *et al.,* 2016; Magno *et al.,* 2016; Pegatoquet *et al.,* 2019; Ghose *et al*., 2018) has cause attention to shift towards deploying them for reducing energy consumption in WLAN modules.

The WuR is saddled with the role of carrier sensing adopting asynchronous wake-up scheme in Magno and Benini (2014); Tang *et al.* (2012) thereby allowing the WLAN STAs to remain in a deep-sleep mode till awoken by its low-power WuR (Oller *et al.*, 2014) for data communication. (Magno, and Benini, 2014) proposed this integration using the collocated WuRx to continuously monitor the channel thereby achieving the design of a wake-up receiver with high sensitivity (at least -35dBm), low power (less than 2μW), fast reactivity (less than 300μs) and with addressing capability. Wake up receiver proposed by Magno *et. al*. (2016) takes less than 200nW and operates with a -55dBm sensitivity in the higher power consumption version. Using the WuR for sensing instead of the WLAN module reduced the energy consumption significantly but not without deficiency in areas such as latency, collision, false wake-up, traffic variation with significantly impacts sleep scheduling, achieving balanced enhanced data rate, algorithm overhead and sensitivity in terms of power consumption.

### 2.4.2 WLAN Wake-Up Message Transmitter

Using the WLAN transceiver as a transmitter for the WuM was proposed in Tang and Obana (2017), Oller *et al.* (2014); Kondo *et al.* (2012) against the traditional method which necessitates that an additional radio known as the wake-up transceiver (WuTx/WuRx) be installed alongside the main radio on individual STA as seen in Tang *et al.* (2012) in the network. This resulted in reduced intricacies and budget and with more modification in Oller *et al.* (2014), energy consumption.

In Oller *et al.* (2014) the authors proposed a novel WuR system that makes it possible for any IEEE 802.11 enabled mobile device to be used as a WuR transmitter by using the subcarrier On-Off-Keying (OOK) Modulation described in Figure 2.4 to achieve a high frequency 2.4GHz WLAN signal to imitate the low frequency 15KHz wake-up message eliminating the need for hardware modification in the module. In Tang *et al.* (2016) the authors proposed the technique of transmitting wake-up ID by changing the frame length of a WLAN message.

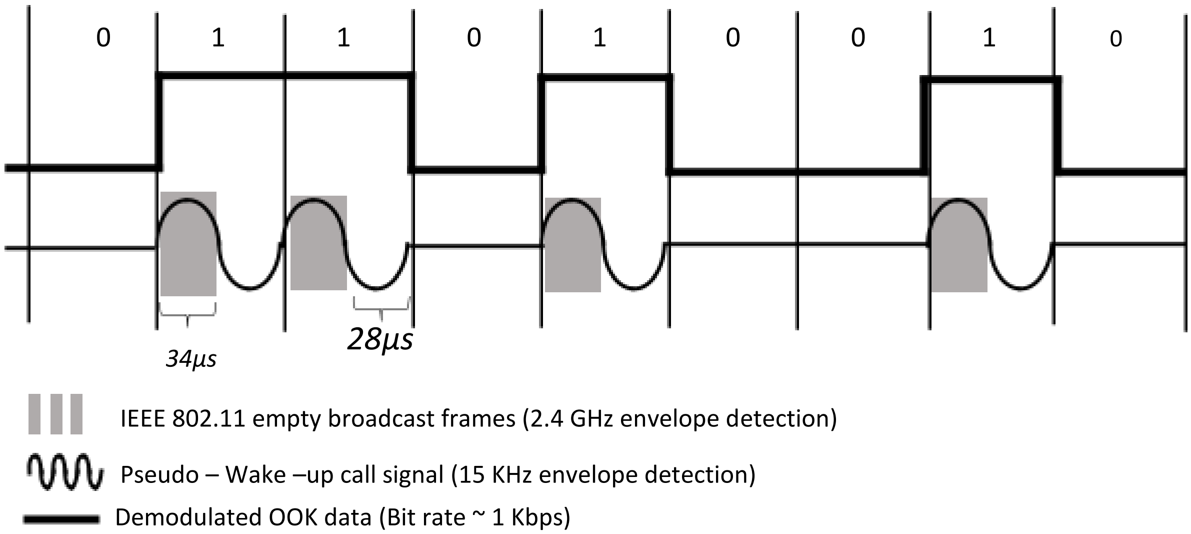


Figure 2.4: On-off-Keying Modulation scheme

### 2.4.3 Contention/Collision

In the contention-based algorithms, the various STAs associated with an AP with buffered data accesses the available channel for transmission of packets by contending for it (Tang and Obana, 2017; Tang *et al.*, 2016[a]; Tang and Obana, 2016[b]; Kondo *et al.*, 2012). One STA out of the lot wins the contention and is granted access to the channel while the others backoff waiting for a repeat of the contention procedure (Tang and Obana, 2018). This is to help avoid collision which degrades the overall throughput (Sanabria-Russo and Bellalta, 2018), produces latency and drops energy efficiency.

The contention Window is a technique that helps in scheduling channel access thereby decreasing collision probability. Improved network throughput is achieved by dynamic adjustment of Contention window (Barcelo *et al.*, 2010). In Tang *et al.* (2016[a]), the authors adjusted the contention window using the WuR which also improved energy efficiency by reducing duty time per packet and contention for the channel is initiated by measuring the inter-frame space.

### 2.4.4 Latency

Collision accounts largely for latency where the MAC algorithm of the network is not properly tuned (Tang and Obana, 2016[b]; Tang and Obana, 2018; Tang *et al.*, 2016[a]; Chen *et al.*, 2016; Hamamoto *et al.* 2016). However, in Tang and Obana (2018); Tang and Obana (2016[b]) the authors investigated wake-up latency in the carrier sense mechanism proposing back-off freezing (BOF) technique capable of helping the carrier sense mechanism recover in the event of a false wake-up as presented in Figure 2.5. The WuR awakens its affiliated WLAN module as soon as it counts to zero. If the WLAN module wake-up falsely to discover the channel occupied, it returns to the sleep state again but freezes its backoff counter. Large contention window (CW) however, produces less spectral efficiency due to more numbers of idle slots.

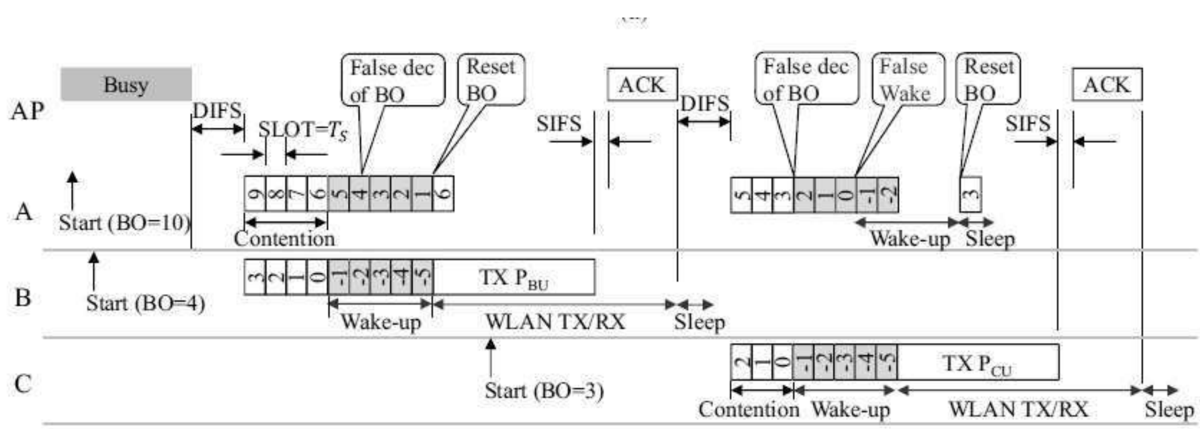


Figure 2.5: Back-Off Freezing (BOF) Technique (Tang and Obana, 2018)

The WuR's back-off counter ( ) is configured to decrement continuously into negatives after counting to 0 if the channel is sensed idle, but freezes when the channel becomes occupied. This technique allows the $C_{BO}$ to count further down while the WLAN module wakes-up. If > − at the time the channel becomes occupied again, it is regarded as

> 0 at the time it enters the wake-up period and also entails that got falsely counted-down by (Time required for WLAN to wake-up completely). The WuR then resets its to + , assigned as the value of at the time wake-up procedure commenced.

A WuR activates its WLAN module when its reaches 0. If a WLAN module gets falsely activated to a busy channel, it returns to the sleep mode and by so doing addresses false wake-up, decreases transmission latency while also improving energy efficiency. This technique produces large number of idle slots as the size of the CW becomes larger. This also translates into less spectral efficiency creating a trade-off between spectral efficiency and energy efficiency.

**2.5 Integrated Wake-Up Radio Energy Efficiency Algorithms**

The broadcast channel is the basis of all WLAN network communication. It is a shared single communication channel that all the STA on the network uses and the broadcast aspect entails that a data sent by a station (STA) is received by all others that is an advantage where the data is destined for all the STAs in the BSA. The medium access control (MAC) algorithms helps to determine which STA transmits next on a channel accessed simultaneously my multiple STAs. It controls resource sharing and utilization.

Simultaneous two-way communication between a pair of STAs (*full duplex*) is achievable in frequency (Frequency division duplexing-FDD) or time (Time division duplexing-FDD) domain. The FDD affords two different frequency bands for each STA, one for transmission and the other for reception. The TDD offers two different time slots instead requiring that the STA in the BSA take turn in time to use the shared channel. But to share bandwidth; frequency, time and spread spectrum multiple access are deployed.

The Frequency Division Multiple Access (FDMA) temporarily assigns a unique channel to a STA that wants to communicate causing other STA in the network to be barred from using that channel. However, this assigned channel can be divided into a pair with one part serving transmission and the other reception. This system of sharing frequency band and bandwidth is known as the FDMA/FDD.

Time Division Multiple Access (TDMA) assigns separate time slots to the STA that wants to access the channel allowing only one STA to transmit in a single time slot. The assignment of time slots is repeated periodically in frame. The periodicity of the time frame means that a station transmission is not continuous, requiring therefore, that digital modulation be used with it. The Spread Spectrum Multiple Access uses a bandwidth much larger than what is required to transmit the data while ensuring that many users are able to share the bandwidth without interfering. This technique is also deployed in two forms; frequency hopped multiple access spreads the signal on time and narrow frequency channels, the code division multiple access (CDMA) spreads the narrowband signal energy over wideband spread signal.

In order to ensure fair allocation of the time-slot to STA in TDD, the contention techniques is adopted. Contention based MAC protocols can be classified into: (i) No-coordination where STA transmit as soon as they have data to send as in ALOHA (ii) Carrier sensing where STA listens to the channel before transmitting as in CSMA (iii) Carrier sensing with collision detection in which STA listen before and during transmission, and halts if a collision occurs as with CSMA/CD (iv) Carrier sensing with Collision avoidance uses handshake to determine the STA that can send a data as with IEEE 802.11 CSMA/CA.

To further reduce the energy consumption of the STA, besides time slot allocation that keeps the WLAN module in the sleep mode most of the time, the use of a low-power wake-up radio was proposed in Tang and Obana (2017); Tang and Obana (2016[b]). The radio senses the station for ongoing transmission before waking its WLAN module. A synthesis of the issues and the proposed solutions to Wake-up based WLAN protocol presented in Table 2.1 highlight the progress made in improving power consumption in WLAN networks.

Research have integrated the WuR in addressing numerous issues with the IEEE 802.11 algorithms ranging from power consumption, collision, protocol overhead to latency among others. The WuR based algorithm reduces the STA energy consumption significantly compared to IEEE traditional CSMA. The semi-passive Wake-up Radio architecture provides enormous energy efficiency relative to the duty-cycle technique. The major setback of WuR based systems is overhearing which also leads to additional energy consumption by traditional WuR algorithm.

**Table 2.1 Issues and Proposed Solutions to WuR Based WLAN Protocols Summary**

| References | Problem addressed | Proposed Techniques |
|---|---|---|
| Tang and Obana, 2017; Tang and Obana, 2018; Barcelo *et al.*, 2010; Oller *et al.*, 2014; Tang *et al.*, 2015. | Power consumption from channel sensing | WuR-ESOC, WuR-CSMA, Broadcast-based wake-up control framework, (DirCorr(OCS), BOF, IEEE 802.11-based WuR system, CSMA/ECA, ECMA |
| Tang *et al.*, 2016[a]; Barcelo *et al.*, 2010. | CW adjustment | CSMA/ECA, WuR-CSMA |
| Tang and Obana, 2017; Tang *et al.*, 2016[a]; Tuysuz, 2018. | Collision | ECMA, Broadcast-based wake-up control framework, WuR-CSMA |
| Tang and Obana, 2017; | Protocol overhead | Broadcast-based wake-up control |
| Tang and Obana, 2018; | False wake-up | CW Adjustment |
| Tang and Obana, 2018. | Time | Early Sleep, negative CBO |
| Tang and Obana, 2018; Tang and Obana, 2016b. | Wake-up latency | BOF, WuR-ESOC |
| Tang and Obana, 2018. | Throughput | WuR-ESOC |
| Tang *et al*., 2015. | LPF distortion and frame length detection | Threshold-Selection |
| Tang *et al*., 2015. | Wake-up control reliability | DirCorr (OCS) |
| Tang and Obana, 2017. | Contention Initiation | SNR/RSSI estimation |

## 2.6 Wake-Up Radio Based Carrier Sense Multiple Access (WuR-CSMA)

The WuR-CSMA requires that WLAN radio be equipped with a low-power WuR operating on the same channel with it. Figure 2.6 shows the system model of the WuR-WLAN STA

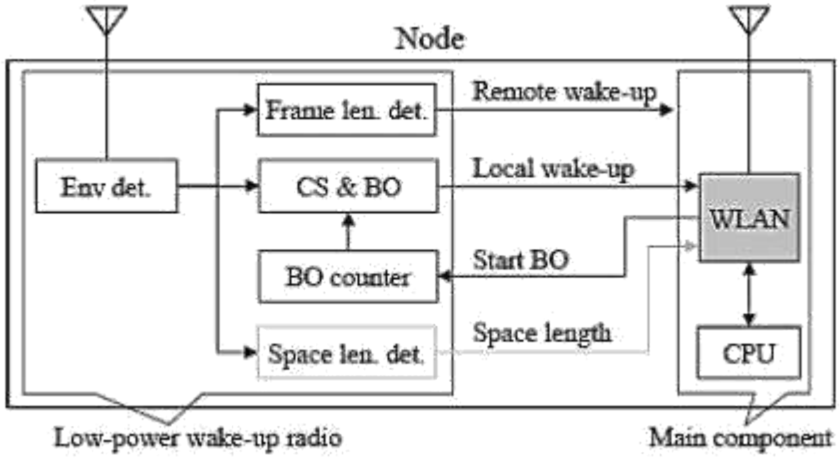


Figure 2.6: System model of the WuR-WLAN STA (Tang *et al.,* 2016[a])

Different wake-up-based techniques have been proposed over the years (Tang and Obana, 2016[b],; Chen *et al.*, 2013; Kondo *et al.*, 2012). These techniques leverage the use of narrowband wake-up signaling (WuS) and the wake-up receiver (WRx), receiving and decoding the WuS. The wake-up receiver (WRx) is designed either as a separate receiver or as a sub-radio in the WLAN receiver. The RF integrated circuit (RFIC)-based WRx allows the WLAN module to remain in sleep mode for as long and as often as possible, thereby maximizing the energy-efficiency of WuS detection.

When the WLAN module has buffers data for uplink but the channel is busy, the module will set a back-off value and also sets the back-off counter of the WuR to that value and then returns to sleep. The WuR senses the channel, decreases its back-off counter until it gets to a zero but freezes its current value if channel is sensed busy before it counts to zero. The WuR activates the WLAN module soon as the back-off counter reads zero. If a WLAN module with buffered data for uplink senses the channel to be busy, the module is required to sets a back-off value for itself and the WuR back-off counter within the contention window

(CW) established by the AP and then returns to sleep again. While the WuR senses the channel, it also decreases its back-off counter per idle slot but freezes it if channel is busy.

### 2.7 Broadcast-Based Wake-Up

(Tang *et al.*, 2016[a]) focused on uplink while broadcast-based wake-up control technique focuses on data downlink. The AP (also a WuR transmitter) broadcasts a wake-up message (WuM), OOK modulated on TIM and indicating the availability of packets.

The WuR determines the availability of inbound packets by measuring RSSI/SNR of the WuM on sensing the channel, demodulates the TIM, gets the number of contending STAs then calculates SNR threshold. If normalized SNR surpasses threshold SNR, the WuR initiates back-off counter and decrements its counter per idle slot. The WuR activates WLAN module the instant its back-off counter decrements to zero. On full wake up, the WLAN module senses the channel to ensure that it is free then it transmits a clear-to send (CTS) frame to the AP granting clearance for the buffered data to be sent. If it discovers the channel busy, the WLAN goes back to sleep. This kind of module activation is known as False wake-up.

As soon as the AP receives the CTS message, it transmits the buffered data to the STA in bursts and also sends SIFS between frames then signals the end of the transmission by clearing the "more-data" flag. DIFS signals recommencement of contention between remaining STAs vying for a chance to use the channel. DIFS Interval or longer decrements the number of contending STAs by 1 while the SNR threshold gets updated. The AP broadcasts a WuM as shown in Figure 2.7, prompting STA B and STA C with buffered data to contend for the channel. The normalized SNR of B and C is above threshold in the first instance so they compete for the channel. STA B sets a back-off value of 3 on its counter and wins the contention as it decrements to zero ahead of C, activates it WLAN module which afterwards sends a CTS to the AP initiating receipt of PB1 and PB2.

However, in period between receiving wake-up signal and full wake-up (wake-up period TWU), the channel is perceived as idle by contending nodes causing C to decrement its counter and activate its WLAN within this duration. Within the wake-up duration of C, B comes to full activation causing C to meet the channel busy on full wake up and thereby return to sleep (False Wake-up).

To improve power efficiency, the falsely awoken STA is immediately returned to sleep-mode (early-sleep). Transmission of DIFS by AP indicates the end of data-sent to the previous station initiating another round of contention. The limitation of this approach include false wake-up warranted by the idle WLAN module duration of wake-up (Wake-up latency).

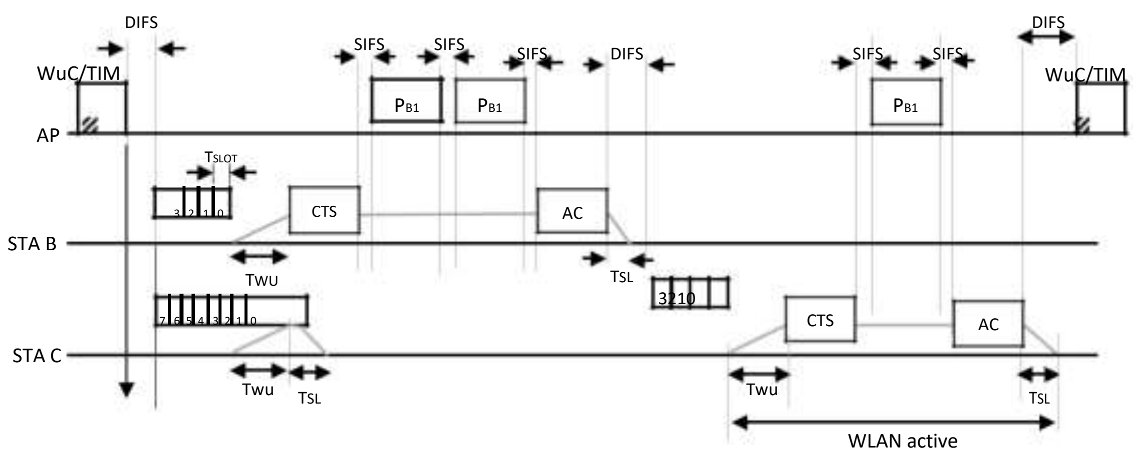


Figure 2.7: Downlink transmission scheduling in a WLAN with an AP and two stations (STA)

## 2.8 Back-Off Freezing (BOF)

This approach utilizes the WuR as though its backoff counter freezes within the duration of the WLAN module Wake-up process and in this way helps to restore the carrier sense mechanism to the count it was before the false wake-up thereby bringing false wake up to a minimum.

Considering an AP associated with 2 STAs B and C as presented in Figure 2.8, in order to deal with wake-up latency, the backoff counter $C_{BO}$ of WuR C is decreased to 3 at the time the $C_{BO}$ of B reads zero. The innovation here is, when the $C_{BO}$ of B counts to zero then wakes up its associated WLAN module, within the duration of wake-up of the module, the $C_{BO}$ of the WuR B continues to decrement its counter into negatives. At this point the $C_{BO}$ of C resets to **$1+ N_{WU}$** (where $N_{WU}$ = Wake-up period in slots).

Considering this scenario, $C_{BO}$ of C was at 3 when that of B reached Zero and at -1 when the channel became busy again, therefore it is reset to -1 + 4 = 3 when the channel gets busy corresponding to where it was when B activated its module and making it seem like the CBO of C froze. A process referred to as Back-off Freezing (BOF).

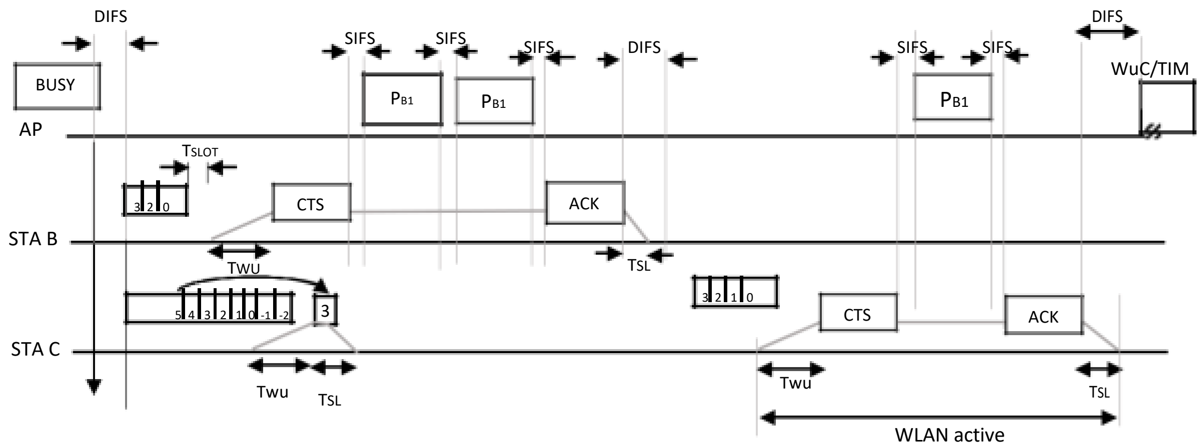


Figure 2.8: Back-Off Freezing Scenario

## 2.9 WuR-ESOC

The technique was developed primarily to find a way of reducing false wake-up duration resulting from the perceived idleness as the WLAN module wake-up (Tang and Obana, 2017; Tang and Obana, 2018; Tang and Obana, 2016[b]).

The scenario description in Figure 2.9 and the method is similar to what obtains in Tang and Obana (2016[b]) except for the fact that a falsely activated STA is immediately returned to sleep **before** becoming fully active and in this way reducing false wake-up duration. The limitation is that to completely get rid of false wake-up between any two STAs, say STA A and STA B, $C_{BO}(A) + C_{BO}(B) > N_{WU}$. This is only achievable with large CW that by implication lowers the spectral efficiency.

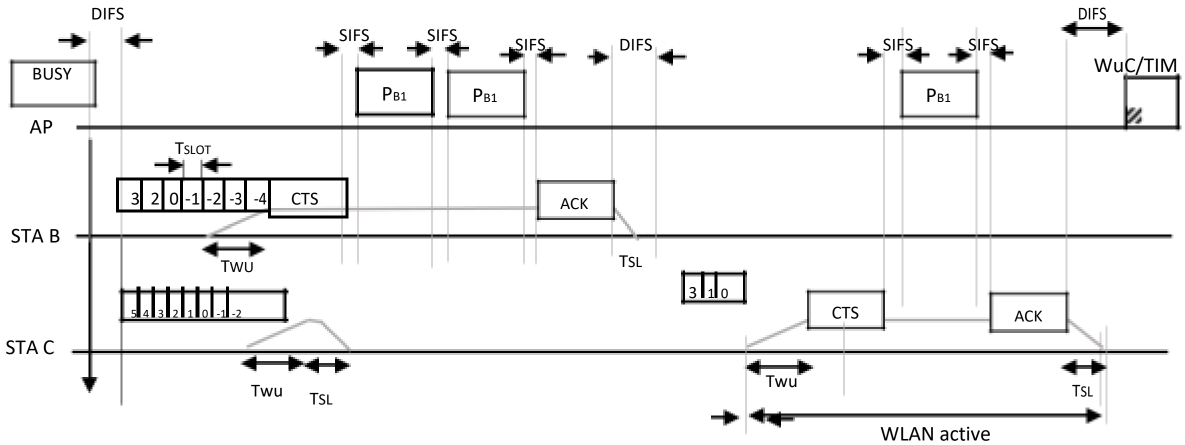


Figure 2.9: Backoff counters reset for falsely activated STA

# CHAPTER THREE

## 3.0 MATERIALS AND METHODS

### 3.1 The Main Procedure of the HCA-CSMA/CA Algorithm

1. The AP sets the contention window size to CW=w, meaning that the number of stations (STA) that can transmit in a session is w. In this projects, 5, 10, 20, 50, 100, 200, 500, 370, 800 and 1000 STA's were considered.
2. The Stations' (STAs) WLAN modules randomly selects a backoff value (BO) and sets their WuR counters to one of those on the contention window BO=*i* (where *i* is between 0 and w) thereby allowing the AP to fetch w number of stations for uplink per session out of the whole cluster N as shown in Figure 3.1. The WuR only wakes its WLAN module up for transmission when the WuR counts from *i* to zero.

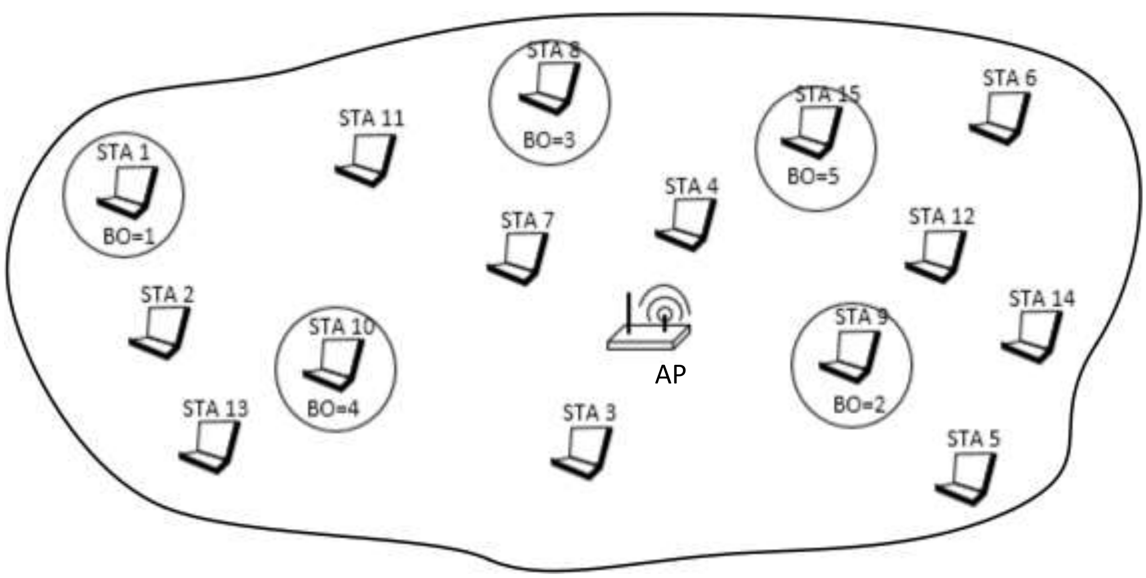


Figure 3.1: Basic Service Area (BSA)

3. The AP can only accommodate w STAs per session, thereby allowing w STA out of N to set their BO value between 1 and w while the backoff counter of other STAs not successful in this contention remains idle.
4. The WuR of each contending STAs listens to the channel. If the channel is sensed to be idle for a duration of Distributed Inter-Frame Spacing (DIFS), ($T_{DIFS}$ = 34$\mu s$ or 4$T_{SLOT}$. Where $T_{SLOT} = 9\mu s$), the STAs starts decrementing their counter from BO=$i$ to zero.
5. The algorithm allows all w STAs fetched to both decrement their counter and wake up simultaneously resulting to the transmission of their RTS packets in quick succession as depicted in Figure 3.2. The AP listens to the STA for a duration of SIFS before taking further action.

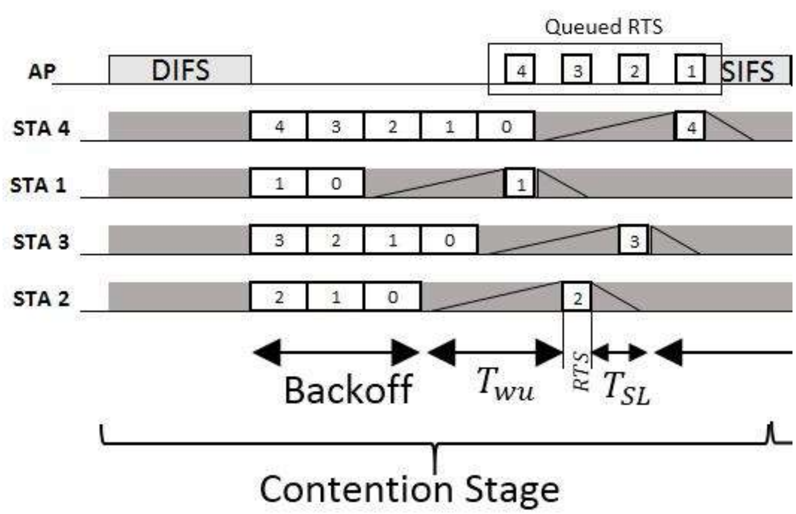


Figure 3.2: Example of RTS uplink transmissions in a WLAN with an AP and four nodes 1, 2, 3 and 4 at the contention stage

6. If a STA experiences collision and is therefore not able to transmit a RTS in the contention stage, it loses the opportunity to transmit in that session and can only attempt again after a fresh contention.
7. The contention window is adjustable before the commencement of a fetch session in accordance with the prevailing network traffic. This is because excessive contention window where the network is idle degrades the network throughput as (Bianchi, 2000; Li *et al.,* 2021).
8. The AP receives the RTS from all w STAs and queues them. It shall afterwards use the transmitting-STA address (SA) in the RTSs frame to address a CTS packet to the requesting STAs in the order in which their RTS were queued up.
9. After listening to the channel for a duration of SIFS without activity, the AP commences the addressing stage as depicted in Figure 3.4 by addressing a wake-up message (WuM) to the first STA on the queue using the SA address on the RTS it sent in the contention stage. It then pauses for a wake-up period of before sending the CTS.

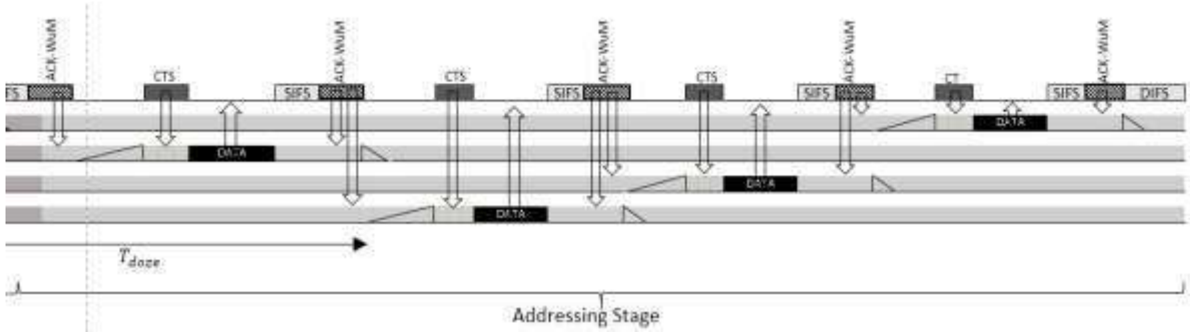


Figure 3.3: Example of uplink transmissions in a WLAN with an AP and four nodes 1, 2, 3 and 4 at the addressing stage

10. The first station STA1 on the queue receives the WuM, wakes its WLAN module up over a duration of , receives the CTS then transmit the packet.
11. If the AP senses the channel idle for a duration of SIFS after receiving packet from the STA1, it broadcasts an ACK-WuM frame (acknowledgement-wakeup message) bearing the address of the station it sent a CTS message to last, signifying successful transmission of the packet. The ACK-WuM frame is also OOK modulated with the WuM addressed to the next station STA2 on the queue, thereby waking STA2 up while STA1 sleeps. The ACK-WuM packet therefore serves two functions, it serves as ACK for STA1 and as a WuM for STA2 and it performs both functions simultaneously.
12. The ACK-WuM OOK modulated technique creates a sleep/wake-up overlap between STA1 and the succeeding STA2 which further helps to reduce the wake-up latency contribution to overall latency.
13. When a STA is done transmitting its packets, the next STA's transmission is initiated using the ACK-WuM frame. This process continues till all the fetched STAs are done transmitting after which contention is re-initiated for another w set of STAs to be fetched for transmission. This procedure is further explained in flowchart shown in Figure 3.4.

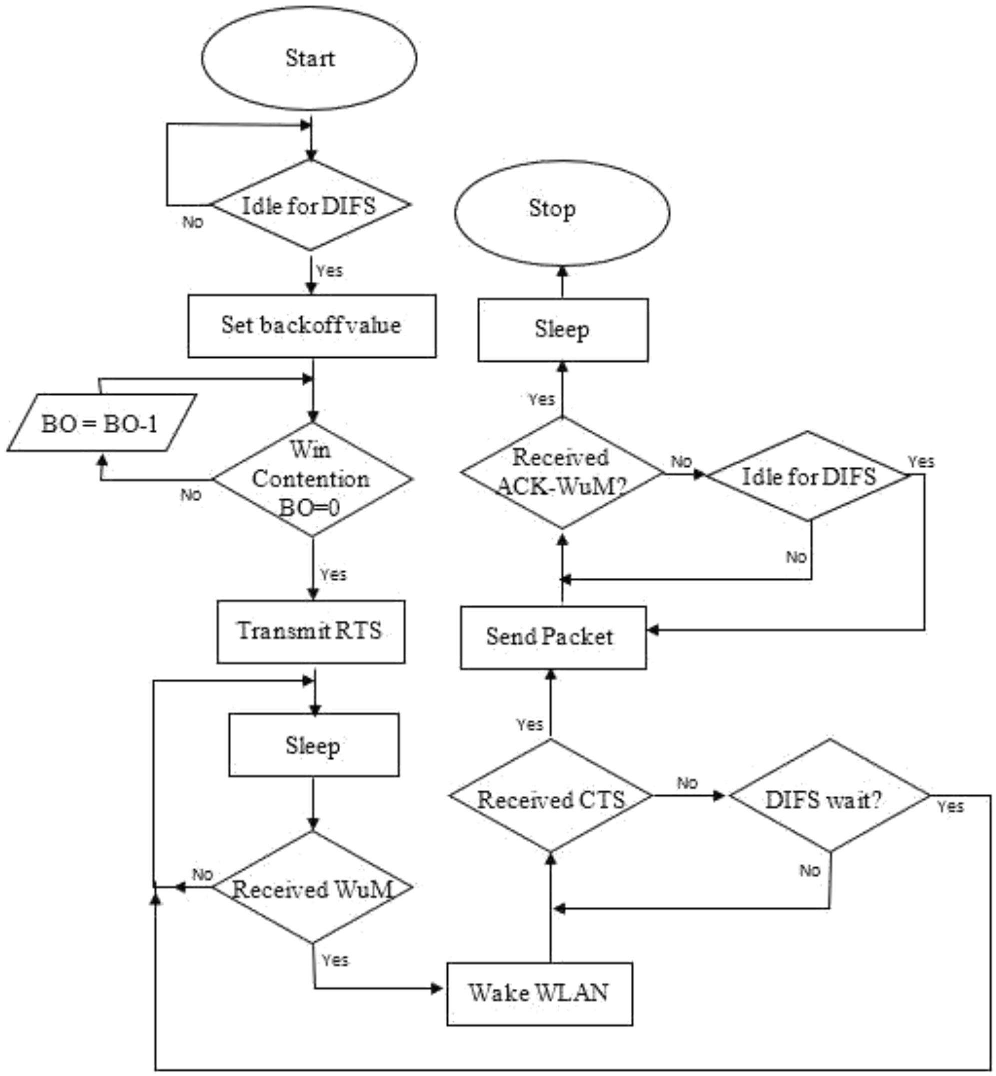


Figure 3.4: The HCA Algorithm Flowchart

## 3.2 The Wake-Up Model

Wake-up message (WuM) is conveyed from a WLAN module (AP) to non-WLAN WuR by emulating an OOK modulation to send a WuM by modulating the envelope of a WLAN signal.

This approach performs better with low-power consumption, and OOK modulation surpasses frame length modulation in efficiency. WuM borne in the envelope of a WLAN message is decoded by a WuR using envelope detection. Emulating the OOK modulation creates large overhead for wake-up per STA and to reduce algorithm overhead and wake-up latency, a broadcast wake-up policy is employed in this work. Instead of allowing an AP independently acknowledge receipt of data packet from STA1 then send a WuM to activate STA2, each ACK frame carries a WuM, which simultaneously acknowledges receipt of data packet from STA1 and also activates STA2 for for uplink.

The STA notifies the AP whether data remains to be transmitted by setting the more data flag in the frame control field in each data frame, and to maintain fair scheduling, the AP clears the 'More Data' flag of STA when the allocated time for that STA is exhausted. A STA with no data left to transmit goes to sleep, after notifying the AP. The WuM has the same preamble as a WLAN signal, therefore, the WuR can estimate SNR/RSSI of a WuM and on this basis activate its collocated main radio.

### 3.3 Sleep/Wake-Up Overlap

With the ACK-WuM frame, it is therefore possible at the addressing stage to have STA4 power up while STA3 shuts down its main radio, both action taking place simultaneously as shown in Figure 3.6 which is an extract of Figure 3.4. This helps to reduce the effect of wake-up latency since it does not have to wait for one STA to fully shut down before the other wakes up its WLAN radio. The effect of the overlap may not be significant considering individual stations but where large number of STAs are involved, time saved becomes substantial.

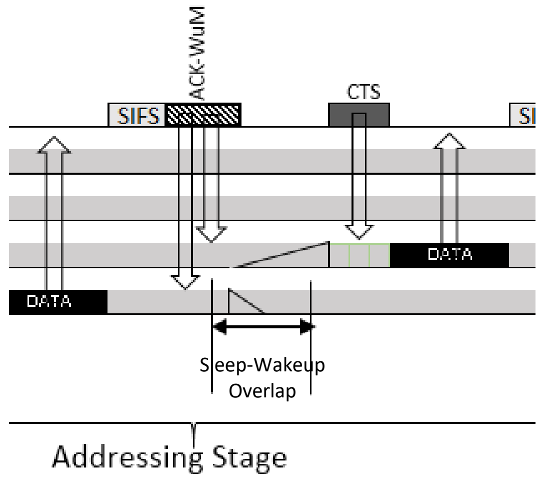


Figure 3.5: Sleep/Wake-up overlap

### 3.4 The RTS Packet

The RTS packet also includes a duration frame as shown in Figure 3.7 which is used to inform the other stations in the cluster of the estimated time needed to transmit the data frame in the transmit operation which includes the time for CTS, ACK and SIFS. Within this period, all other stations backs-off. For this project, the RTS duration frame value is calculated on the basis of Figure 3.5 and Figure 3.6:

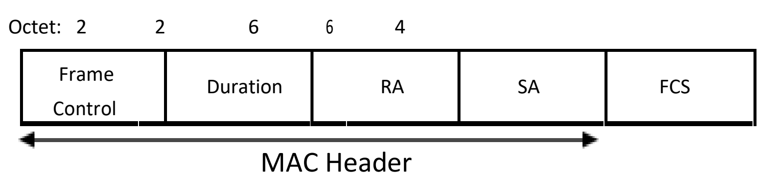


Figure 3.6: RTS Frame (MAN, Committee and Computer, 2016)

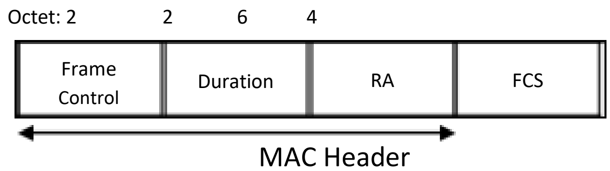

Figure 3.7: CTS Frame (MAN, Committee and Computer, 2016)

### 3.5 The Wake-Up Message (WUM) Packet

The WuM is made up basically of the preamble and the destination MAC address fields as seen in Figure 3.7. The AP broadcasts a wake-up call modulated unto an ACK frame periodically to all STA with the inclusion of a destination MAC address in the wake-up message derived from the queued RTSs. When a STA approves a wake-up procedure, it is activated and responds by transmitting the data message directly to the AP.

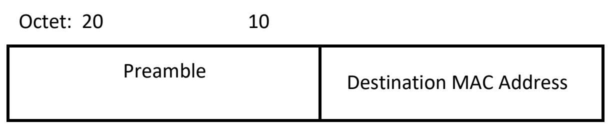

Figure 3.8: WuM Frame (MAN, Committee and Computer, 2016)

### 3.6 Theoretical Analysis

Here the energy overhead of the algorithm is analyzed both at the contention and the addressing stages. A WLAN with an AP and N nodes was considered assuming constant contention window CW=w. WLAN modules have wake-up latency ( ), which is the delay experienced in data communication due to time taken to have the radio wake-up fully, during this period the WLAN radio cannot transceiver but it consumes power. Switching from $1/4^{th}$ clock rate to full clock rate takes about 139μs and 200μs to generate stable carrier frequency. In this work therefore, taking the number of slots required for a full WLAN module wake-up to be = 22 and the duration of a slot to be = 9μs, the wake-up latency is computed as = . which gives 200μs.

Power consumption in the contention stage is largely due to wake-up latency while both wake-up latency and data transmission account for major part of energy consumed in the addressing stage. The WuR (wake-up radio) latency is neglected and idle listening by the WLAN is eliminated. Appendix B gives the main notations used in the performance analysis.

### 3.6.1 Basic Analysis

By applying the classical Bianchi's Markov model for constant backoff window problem (Bianchi, 2000), the probability that a STA transmits in a randomly chosen slot time is expressed as

$$= \frac{2}{(\ +1)} \tag{3.1}$$

$$=1-(1- \ ) \tag{3.2}$$

where, w= Contention window size and = The probability of at least one transmission in the slot time of interest.

Therefore, the probability that a successful transmission occur on the channel given that only one station transmits on the channel and assuming that at least one station transmits can be expressed as:

$$= (\ .(1- \ )^{-1}).(1-(1- \ )^{-}\ ) \tag{3.3}$$

The probability $h$ transmit and a collision occurs is expressed as

$$= 1-(1- \ )- \quad (1- \ )^{-1} \tag{3.4}$$

The probability that a slot is idle is expressed as:

$$=(1-\ ) \tag{3.5}$$

### 3.6.2 Transmission Latency

The time necessary for a bit to propagate over the channel from a STA to another is the propagation delay. At the addressing stage, the delay experienced for a bit of data to be transmitted over the channel is computed as :

The period of a successful transmission

$$=+++2\times+ \tag{3.6}$$

Period of transmission with collision is equal to

$$=++ \tag{3.7}$$

Therefore the time taken by the data-link layer to successfully deliver the packet over the channel with latency is expressed as

$$=+\cdot \tag{3.8}$$

The packet also needs to wait in the queue to be transmitted onto the channel, this is known as queuing delay.

$$= \quad + \quad + \quad +2\times \quad + \quad + \quad \times( \quad + \quad + \quad )$$
$$= \quad + \quad +( \quad + \quad )(\ +1)+ \quad (\ +2) \tag{3.9}$$

### 3.6.3 Power Consumption by WLAN Module

The overall energy required for a STA to transmit a packet with success E can be broken down into (i) Energy required for successful transmission of packet in the addressing stage and (ii) Energy spent in backoff at the contention stage. E is computed using Equation 3.10.

$$= +\qquad (3.10)$$

The time spent in doze by the WLAN module at the contention stage as shown in Figure 3.10 is depicted as

$$. \quad + \quad +$$

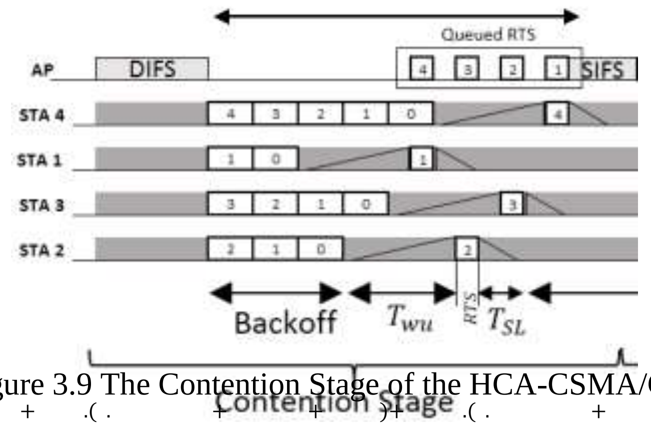


Figure 3.9 The Contention Stage of the HCA-CSMA/CA

$$=( \quad + \quad .( . \quad + \quad + \quad )+ \quad .( . \quad + \quad + \quad ))-$$

$$( .( + )+ .( ++ )) \qquad (3.11)$$

Therefore, the power consumed by the main Radio for doze at the contention stage is calculated as

$$= \quad \times \qquad (3.12)$$

$$= \quad .(( \quad + .( .++ \ )+ .( .++ \ ))-$$

$$( .( + )+ .( ++ ))) \tag{3.13}$$

The duration of doze at the Addressing stage for the WLAN module is calculated as

$$= ( + 1)( + + ) + ( ) + ( ) - -$$

$$= . + . + . + + + + . + . - -$$

$$= .+ . + .++ .+ .$$

$$=( +1) + .( +++ ) \tag{3.14}$$

The power consumed in doze at the addressing stage by the WLAN module can be expressed as

$$= .(( +1)+ .( +++ ) \tag{3.15}$$

Considering the power consumed by the WLAN module in doze state at the contention and addressing stages, the total power consumed in doze state by the main Radio alone is therefore be expressed as

$$=+ \tag{3.16}$$

Adding equations (3.10) and (3.12)

$$= ( + 2) ) + ( - 1) . + ( + 1). ( + + ( ) . - ) + . ( + + \tag{3.17}$$

Looking at the WLAN module transmission of RTS and data packet, the module transmits RTS at the contention stage and data at the addressing stage. To determine power consumed in transmitting the packets, the time spent to transmit this packets will be required. Time taken for successful transmission of RTS at the contention stage is determined as

$$=( +)+( ++) \quad (3.18)$$

Power consumed for the successful transmission of RTS is

$$=( + ).( . + . )+ . \quad (3.19)$$

Now, looking at the power consumed by the WLAN module at the addressing stage for transmission of data, the time spent to transmit is found as

$$=++++ \quad (3.20)$$

The power consumed in the process is therefore expressed as

$$=++++ \quad (3.21)$$

Total Power consumed to transmit data by the Main Radio (to transmit RTS and Data) is

$$= + \quad (3.22)$$

By combining equations (3.17) and (3.19) can be further expressed as

$$=( + +1)( + )+ . + + + \quad (3.23)$$

Therefore, the total power consumed by a STA's WLAN module both for transmission and doze is gotten by combining equations (3.15) and (3.21) to obtain:

$$=+ \quad (3.24)$$

$$=( +2) . - . +( +1)( + + ) +( + + . - +( ) + + . +( + + . ) + ( + . + ) \quad (3.25)$$

### 3.6.4 Power Consumption by WuR Radio

In the contention stage, the WuR is used mainly for backoff. Time in which the WuR is in use in the contention stage is

$$= ( \; + 1) \qquad (3.26)$$

Taking the power consumed by the WuR for backoff as

$$=. \qquad (3.27)$$

The power consumed by the WuR at the contention stage is therefore

$$= \; . ( \; + 1) \qquad (3.28)$$

However, in the Address Stage, the WuR serves to sense the channel and process the WuM. This is expressed as

$$= \qquad (3.29)$$

Total Power consumed by the WuR in transmitting a packet at the contention and Addressing Stage is therefore expressed as a combination of equations (3.28) and (3.29)

$$= + \qquad (3.30)$$

This is elaborately written as

$$= \; .( \; + 1) \; + \qquad (3.31)$$

The total power consumed by a STA by the WuR and WLAN module for doze and transmission is :

$$= + \qquad (3.32)$$

= .( +1) + +( +2) . +( +1).( + ) . +

( +++−+ )+( ++

− )+.+( + ) +( + )( + ) (3.33)

Time in which the channel was sensed busy in the event of successfully sending the RTS packet is expressed as

= .( + )++ .( +++ + )+ (3.34)

Time in which the channel was sensed busy in the event that there was collision in sending the RTS packet.

= .++ (3.35)

The average time taken to transmit the data is therefore obtained as .

=.+.( +)+.( +) (3.36)

### 3.6.5 Throughput

Average throughput is determined using equation (3.38) as a ratio of number of transmitted bits to the average transmission time ( ), considering a full fetch of the contention window w

Γ =

$$\Gamma = \frac{\cdot\ \cdot}{\quad} \tag{3.38}$$

### 3.6.6 Spectral Energy Efficiency

Spectral energy efficiency , is determined as the ratio of the number of transmitted bits to the time and the energy consumed in the transmission.

$$\xi = \frac{\Gamma}{\ } \qquad (3.39)$$

### 3.6.7 Channel Efficiency

The percentage of time that a channel is occupied is the the Channel efficiency which is expressed as

$$\eta = \frac{(\ +\ )}{\ } \qquad (3.40)$$

# CHAPTER FOUR

## 4.0 RESULTS AND DISCUSSION

This section presents results with the Uplink-Hybrid Contention-Addressing CSMA (HCA-CSMA/CA) compared with the CSMA/ESOC. The former means that the AC fetches a given number of stations to access the channel in a predetermined order through the process of contention, the station (STA) uplinks to the AP when it receives a broadcasted CTS bearing its address.

The WLAN module is considered to be activated only when there is buffered data. It remains in sleep mode otherwise. A WLAN comprised of an access point (AP) and numerous stations (STA) contending for the uplink transmission was evaluated. The energy consumption under different contention window sizes was analysed, using scenario where there are numerous stations (N) ready with buffered data number but only a certain number (i) out of N wins the contention for a slot on the contention window. All the i stations that win a slot on the contention window gets to transmit their data in quick succession at the addressing stage.

The results were generated by inputting the standard simulation parameters from IEEE 802.11 specifications shown in Table 4.1 into the developed mathematical equations and computed using MATLAB. The performance of HCA-CSMA/CA was evaluated with interest in the energy consumption, lifetime, latency, throughput, and channel efficiency. The CSMA/ESOC was evaluated and compare with the results of HCA-CSMA/CA.

**Table 4.1 Parameters for Testing the HCA Model**

| S/N | Parameters | Value |
|---|---|---|
| 1 | | 0.000034sec |
| 2 | | 0.000009sec |
| 3 | | 0.000189sec |
| 4 | | 0.000018sec |
| 5 | | 0.0000014sec |
| 6 | | 0.000016sec |
| 7 | | 0.0000014sec |
| 8 | | 0.000141sec |
| 9 | | 0.000002sec |
| 10 | | 0.000002sec |
| 11 | | 2×Tslot |
| 12 | $_{wu}$ | 0.0000015 W |
| 13 | $_{SL}$ | 0.000001 W |
| 14 | A | 1 W |
| 15 | β | 1 W |
| 16 | $_{wur}$ | 0.01 W |
| 17 | $_{wum}$ | 0.024 W |
| 18 | N | 1000 |
| 19 | L | 1600 bits |

## 4.1 Energy Consumption

The total energy consumption of the STA's main radio and WuR is plotted against the contention window for the HCA and ESOC in Figure 4.1. For the HCA, the total energy consumption of the WLAN STA increased rapidly between CW= 0 and CW= 200 then rate of increase slowed afterwards. The HCA offers a 97% reduction in maximum energy consumption compared to the ESOC as graphed in Figure 4.1. The energy consumption increases as the contention window also increase as larger contention window result in larger fetch, which also leads to increased energy for processing the fetched batch. But more significantly, the rise in energy consumption is due to the fact that STAs will have to wait for longer period of time before sending packets and in the process, listen to the channel (WuR). The energy consumed for doze and transmission of the RTS packet at the contention stage is about 30% of the overall energy consumed by the main radio and 23% of the total energy consumed by the STA for transmission of data packet, a STA expends about 77% of the total energy consumed on transmission of packets and this means that energy is prudently utilized since very little of it is wasted outside transmission.

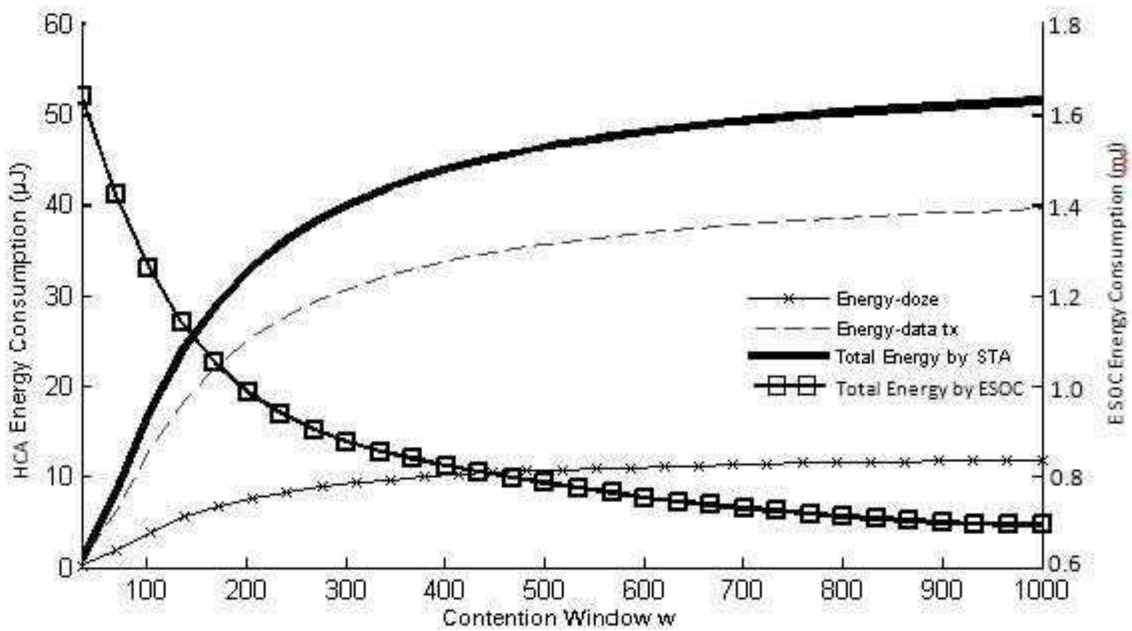


Figure 4.1: Total Energy Consumption by STA

The improvement in energy consumption of the hybrid-HCA over traditional techniques is attributed to reduced probability of false wakeups. The addressing technique ensures that stations only wake up when they receive a wake-up message (WuM) thereby preventing the possibility of waking up under false presumption that the channel is free as false wake up is responsible for major part of a WLAN energy consumption. STAs spend larger period of time in sleep awaiting the address bearing wake up message (WuM), this contributes to the increase in energy saving.

## 4.2 Latency

Figure 4.2 shows the latency curve obtained with packets of constant length. The figure shows decrease in the latency as the contention window size increases. This is due to less probability of having STAs choosing the same time slot to send packets. Therefore, smaller probability of data collision. Though larger contention window size means that STAs will have to wait longer before receiving CTS frame that permits them to use the channel but this waiting period is still small relative to the increased delay that data collision yields, therefore, transmission latency is reduced.

The greatest power consumption is attained at contention window of 1000 thereby producing the least latency at that value. On the overall latency is minimal, ranging between 9.396ms and 9.404ms for contention window of 1 and 1000 respectively. The difference in latency between w=1 and w=1000 is 8ms which is significant in an urban environment with large number of STAs. The latency of the hybrid HCA improved over the traditional techniques due to the sleep/wakeup overlap and reduced reoccurrence of contention.

The latency gotten from the HCA-CSMA/CA compares with that obtained in ESOC and maxEF as shown in the Table 4.2

**Table 4.2 Latency Comparism**

| CW | Latency | | |
|---|---|---|---|
| | **HCA** | **ESOC** | **maxEF** |
| 956 | 9.396 | 29.6 | 53.18 |
| 310 | 9.398 | 9.398 | 17 |
| 172 | 9.4 | 5.5 | 9.4 |

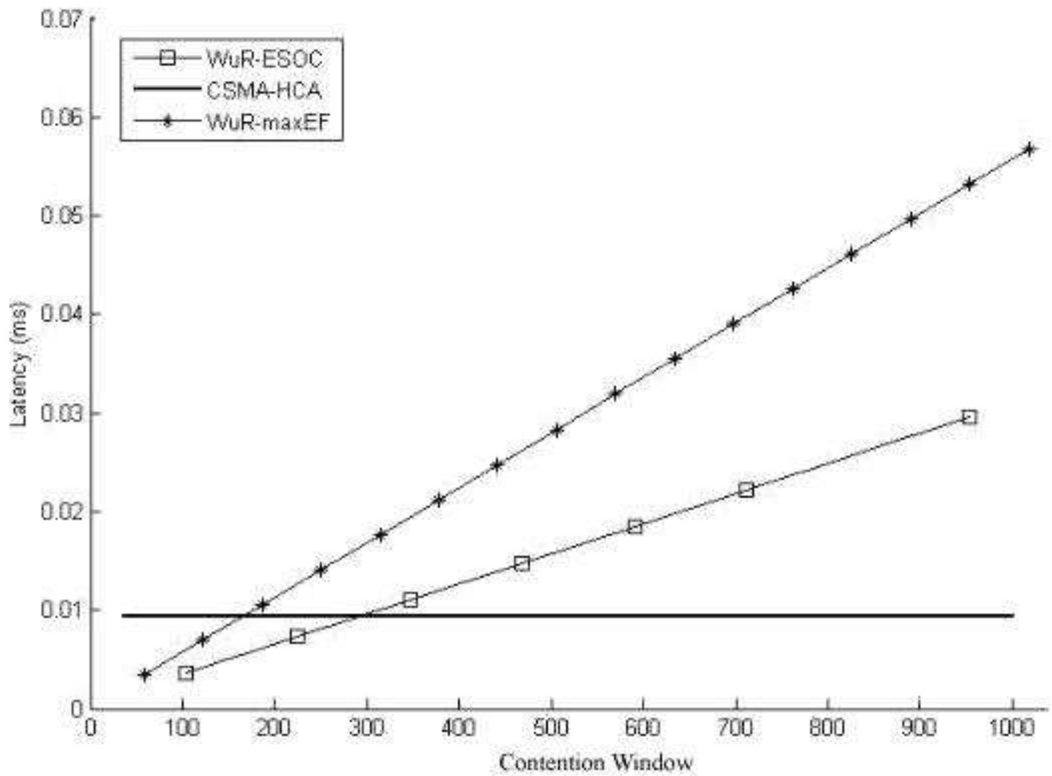


Figure 4.2: Latency compared with ESOC and MaxEF

At contention window of 956, the latency gotten from HCA is lower than that of ESOC by 68.3% and lower than that of maxEF by 82.3%. At CW of 310, the latency of ESOC and HCA are the same but lower than maxEF while at CW of 172 the latency of HCA equals that of maxEF but higher than ESOC. The HCA presents better latency performance than ESOC and maxEF at CW higher than 310.

### 4.3 Throughput

The curve comparing the throughput with the size of the contention window is shown in Figure 4.3. This shows increase in the throughput as the size of contention window gets larger due to decreasing probability of collision. The ratio of the number of bits transmitted to average slot time ($T_{avr}$) is computed as the average throughput.

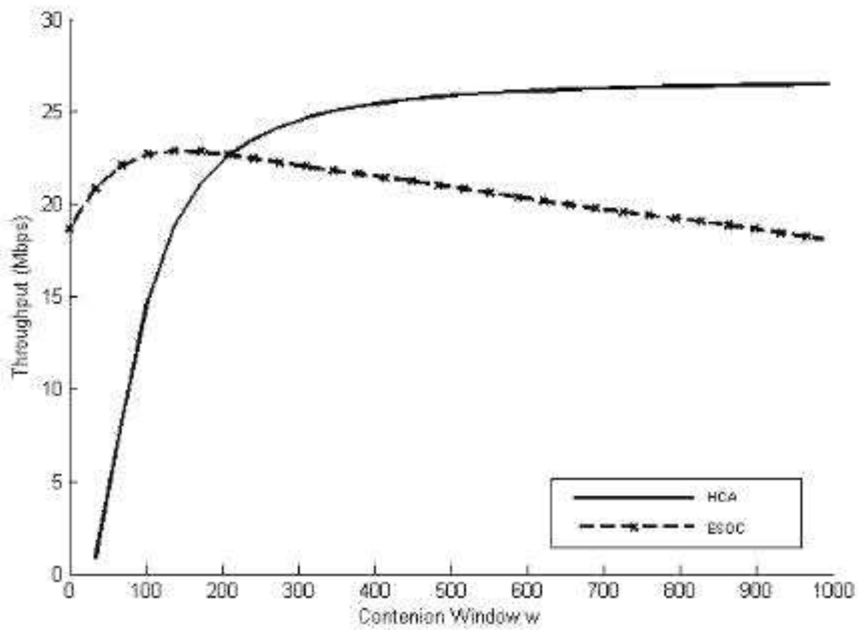


Figure 4.3: Throughput/w for HCA and ESOC

The throughput performance of ESOC is better with CW below 207 while above this value HCA shows higher values than ESOC which is due to higher collision probability for the HCA at lower values of CW as a result of incessant repetition of contention procedure handling larger number of STA than the ESOC.

But as the CW increases, the repetition of contention procedure decreases and though the number of station handled is much higher, the ordering procedure in the addressing stage greatly reduced the collision probability compared to that of ESOC at higher CW resulting in better throughput.

The maximum throughput for the HCA exceeds ESOC by 16%. The HCA offers the highest throughput and lowest latency at w=1000 where the least probability of collision is expected as shown in Figure 4.3.

### 4.4 Channel Efficiency

Channel efficiency is the percentage of time that a channel is actually used. It is computed as ratio of the time spent in transmission to the average slot time.

Figure 4.4 a shows an increase in channel efficiency as contention window increases implying that the percentage of time in which the STA uses the channel with respect to average time for data transmission ( ) increases as the size of the contention window increases. A maximum channel efficiency of 83.86% is achieved at the 1000 contention window. The 6.14% reduction in the channel efficiency with respect to ESOC is due to the time spent in queuing the RTS and addressing the CTS which is not sensed on the channel.

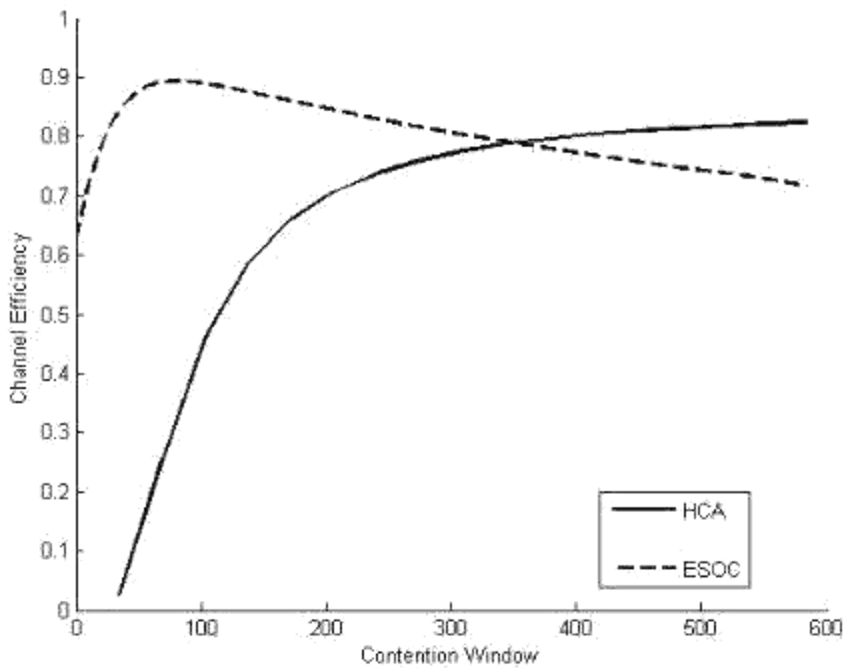


Figure 4.4: Channel efficiency of HCA-CSMA/CA and ESOC compared

The aim of optimizing energy consumption and reducing the latency of WLAN uplink without compromising throughput was achieved. The HCA-CSMA/CA offers a 97% maximum energy consumption over the ESOC and the peak theoretical battery lifetime exceeds that of ESOC by approximately 60hrs. Throughput increased by about 16% while the latency is kept approximately constant across the contention windows (CW) at 9ms. From this analysis, increased contention window resulted in reduced latency, but it requires more energy consumption which in effect reduces battery lifetime.

# CHAPTER FIVE

## 5.0 CONCLUSION AND RECOMMENDATIONS

### 5.1 Conclusion

In this research work, an analytical model that reduces the energy consumption of IEEE 802.11 WLAN is presented. This model assumes a finite number of contention window and ideal channel conditions. The model is suited for RTS/CTS Access mechanisms in the uplink. Comparison with simulation results of ESOC algorithm shows that the model is effective in conserving energy while ensuring high throughput. At the end of this project work, the aim of optimizing energy consumption and reducing the latency of WLAN uplink without compromising throughput was achieved. The HCA-CSMA/CA offers a 97% maximum energy consumption over the ESOC and the peak theoretical battery lifetime exceeds that of ESOC by approximately 60hrs. Throughput increased by about 16% while the latency is kept approximately constant across the contention windows (CW) at 9ms. From this analysis, increased contention window produces improved latency, but it requires more energy consumption.

### 5.2 Recommendation

The simulation of this mathematical model can be adopted in further project work in this research area. Considerations for real-time packets will be required in further research on this work while also exploring means of improving the throughput to meet the current growing demands on a WLAN network.

### 5.3 Contribution to Knowledge

1. A Hybrid contention-addressing algorithm technique for channel access that helps to reduce energy consumption in IEEE 802.11 network

# REFERENCE


Erkan Alpman, Ahmad Khairi, Minyoung Park, V. Srinivasa, Jeffrey R. Foerster, Ashoke Ravi, Stafano Pellrano (2017). 95 µW 802.11 g/n compliant fully-integrated wakeup receiver with -72 dBm sensitivity in 14 nm FinFET CMOS. IEEE Radio Freq. Integr. Circuits Symp. (RFIC), pp. 172–175.

Barcelo, J., Bellalta, B., Cano, C., Sfairopoulou, A. and Oliver, M. (2010). Dynamic parameter adjustment in CSMA/ECA. Lect. Notes Comput. Sci. (including Subser. Lect. Notes Artif. Intell. Lect. Notes Bioinformatics), vol. 6235 LNCS, pp. 13–24.

Basagni, S., Petrioli, C. and Spenza, D. (2016). CTP-WUR: The collection tree algorithm in wake-up radio WSNs for critical applications. 2016 Int. Conf. Comput. Netw. Commun. ICNC 2016, pp. 1–5.

Bianchi, G. (2000). Performance analysis of the IEEE 802.11 distributed coordination function. IEEE Journal on Selected Areas in Communications, 18(3), 535–547.

Boukerche, A., (2005). Handbook of Algorithms for Wireless Networking and Mobile Computing (Chapman and Hall/CRC Computer and Information Science Series) (1st ed.). Chapman and Hall/CRC.

Li Chen, Stephen Cool, He Ba, Wendi Heinzelman, Ilker Demirkol, Ufuk Muncuk, Kaushik Choedhury, Stafano Basagni (2013). Range extension of passive wake-up radio systems through energy harvesting. IEEE Int. Conf. Commun., pp. 1549–1554.

Chen, S., Ma, R., Chen, H. H. and Meng, W. (2016). A segmented packet collision model for smart utility networks under WLAN interferences. IEEE Trans. Wirel. Commun., vol. 15, no. 5, pp. 3506–3517.

Daly, D. C., Member, S., Chandrakasan, A. P. and Abstract, A. (2007). An Energy-Efficient OOK Transceiver for Wireless Sensor Networks. vol. 42, no. 5, pp. 1003–1011.

Dare, M. T., Zubair, S., Salihu, B. A., David, M. and Abazeed, M. (2020). Literature Review of Energy Efficient Transmission in Wireless LANs by Using Low-Power Wake-Up Radio. 2019 15th International Conference on Electronics, Computer and Computation (ICECCO), (Icecco), 1–6.

Deng, Der-Jiunn, Ke, Chih-Heng, Chen, Hsiao-Hwa and Huang, Yueh-Min. (2008). Contention window optimization for IEEE 802.11 DCF access control. IEEE Transactions on Wireless Communications. 7. 5129-5135. 10.1109/T-WC.2008.071259.

Fabris Hoefel R. P. (2020). “IEEE 802.11be: Throughput and reliability enhancements for next generation WI-FI networks,” *IEEE Int. Symp. Pers. Indoor Mob. Radio Commun. PIMRC*, vol. 2020-August, pp. 1–6.

Ghose, D., Pla, V. and Li, F. Y. (2018). MAC Algorithms for Wake-Up Radio: Principles, Modeling and Performance Analysis. IEEE Trans. Ind. Informatics, vol. 14, no. 5, pp. 2294–2306.

Giuseppe, A. (2009). Energy conservation in wireless sensor networks: A survey. Ad Hoc Networks 7 (2009) 537–568.

Guntupalli, L., Ghose, D., Li, F. Y. and Gidlund, M. (2018). Energy Efficient Consecutive Packet Transmissions in Receiver-Initiated Wake-Up Radio Enabled WSNs. IEEE Sens. J., vol. 18, no. 11, pp. 4733–4745.

Hamamoto, R., Takano, C., Obata, H., and Ishida, K. (2016). Improvement of throughput prediction scheme considering terminal distribution in multi-rate WLAN considering both CSMA/CA and frame collision. IEICE Trans. Inf. Syst., vol. E99D, no. 12, pp. 2923– 2933.

Kondo, Y., Hiroyuki, Y., Suhua, T., Masahito, I., Toshiyasu, T., Hideo, T., and Sadao, O. (2012).
Energy-efficient WLAN with on-demand AP wake-up using IEEE 802.11 frame length modulation. Comput. Commun., vol. 35, no. 14, pp. 1725–1735.

Li, F., Guosheng, H., Quan, Y. and Mande, X. (2021). Adaptive Contention Window MAC Algorithm in a Global View for Emerging Trends Networks." IEEE Access 9: 18402-18423.

L´opez-P´erez, D., Garcia-Rodriguez, A., Galati-Giordano, L., Kasslin, M., and Doppler K. (2019).
“IEEE 802.11be Extremely High Throughput: The next generation of Wi-Fi technology beyond 802.11ax,” in IEEE Communications Magazine, v. 5, n. 9, Sept. 2019

Magno, M., and Benini, L. (2014). An ultra-low power high sensitivity wake-up radio receiver with addressing capability. 2014 IEEE 10th International Conference on Wireless and Mobile Computing, Networking and Communications (WiMob), pp. 92-99.

Magno, M., Jelicic, V., Srbinovski, B., Bilas, V., Popovici, E. and Benini, L. (2016). Design, Implementation and Performance Evaluation of a Flexible Low-Latency Nanowatt Wake-Up Radio Receiver. IEEE Trans. Ind. Informatics, vol. 12, no. 2, pp. 633–644.

MAN, L. A. N., Committee and I. Computer (2016). Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications," in IEEE Std 802.11-2016 (Revision of IEEE Std 802.11-2012), pp.1-3534.

Oller, J., Garcia, E., Lopez, E., Demirkol, I., Casademont, J., Paradells, J., Gamm, U., and Reindl L. (2014). IEEE 802.11-enabled wake-up radio system: Design and performance evaluation. Electron. Lett., vol. 50, no. 20, pp. 1484–1486.

Palacios, R., Mengistie, G., Alonso-zarate, J., Kliazovich, D. and Granelli, F. (2014). "Analysis of an energy-efficient MAC protocol based on polling for IEEE 802.11 WLANs," IEEE Int. Conf. Commun., vol. 2015, pp. 5941–5947.

Pegatoquet, A., Le, T. N. and Magno, M. (2019). A Wake-Up Radio-Based MAC Algorithm for Autonomous Wireless Sensor Networks. IEEE/ACM Trans. Netw., vol. 27, no. 1, pp. 56–70.

Petrioli, C., Spenza, D., Tommasino, P. and Trifiletti, A. (2014). A novel wake-up receiver with addressing capability for wireless sensor nodes. IEEE Int. Conf. Distrib. Comput. Sens. Syst. DCOSS 2014, pp. 18–25.

Piyare, R., Murphy, A. L., Kiraly, C., Tosato, P. and Brunelli, D. (2017). Ultra Low Power Wake-Up Radios: A Hardware and Networking Survey. IEEE Commun. Surv. Tutorials, vol. 19, no. 4, pp. 2117–2157.

Sanabria-Russo, L. and Bellalta B. (2018). Traffic differentiation in dense collision-free WLANs using CSMA/ECA. Ad Hoc Networks, vol. 75–76, pp. 33–51.

Santos, M. A., Villalón, J. and Orozco-Barbosa, L. (2012). A novel QoE-aware multicast mechanism for video communications over IEEE 802.11 WLANs. IEEE J. Sel. Areas Commun., vol. 30, no. 7, pp. 1205–1214.

Spenza, D., Magno, M., Basagni, S., Benini, L., Paoli M. and Petrioli, C. (2015). Beyond duty cycling: Wake-up radio with selective awakenings for long-lived wireless sensing systems. IEEE INFOCOM, vol. 26, pp. 522–530.

Sunghyun Choi, Prado, J.D., Sai Shankar N. and Mangold S. (2004). IEEE 802.11e contention-based channel access (EDCF) performance evaluation. pp. 1151–1156.

Tang, S., Yomo, H., Kondo, Y. and *Obana*, S. (2012). Wake-up receiver for radio-on-demand wireless LANs. EURASIP J. Wireless Commun. and Netw., vol. 2012, pp. 1-13..

Tang, S., Yomo, H. and Takeuchi, Y. (2015[a]). Optimization of frame length modulation-based wake-up control for green WLANs. IEEE Trans. Veh. Technol., vol. 64, no. 2, pp. 768–780.

Tang, S., Yomo, H. and *Obana*, S. 2015[b]). Dynamic threshold selection for frame Length-Based Wake-Up control. IEEE Wirel. Commun. Lett., vol. 4, no. 6, pp. 609–612.

Suhua, T., Chao, Z., Hiroyuki, Y., Sadao, O. (2016[a]). “Energy and spectrum efficient wireless LAN by tightly integrating low-power wake-up radio,” *IEEE Int. Symp. Pers. Indoor Mob. Radio Commun. PIMRC*, no. i, pp. 1–6, 2016.

Tang, S. and *Obana*, S., (2016[b]). "Tight Integration of Wake-Up Radio in Wireless LANs and the Impact of Wake-Up Latency, 2016 IEEE Global Communications Conference (*GLOBECOM)*, pp.1-6.

Tang, S. and Obana, S., (2017). Energy Efficient Downlink Transmission in Wireless LANs by Using Low-Power Wake-Up Radio. Wireless Communications and Mobile Computing, vol. 2017, no. ii, pp. 1–12.

Tang, S. and Obana, S. (2018). Reducing false wake-up in contention-based wake-up control of wireless LANs. Wireless Networks, vol. 0123456789, pp. 1–17.

Tang, S. and Liu Z. (2019). Radio-on-Demand Wireless LAN. Encycl. Wirel. Netw., pp. 1–4.

Tuysuz M. F., (2018). Towards providing optimal energy-efficiency and throughput for IEEE 802.11 WLANs. Int. J. Commun. Syst., vol. 31, no. 13, pp. 3597–3621.

Yang, H., Deng, D. J. and Chen, K. C. (2018). On energy saving in IEEE 802.11ax. IEEE Access, vol. 6, pp. 47546–47556.

Zhang, X. and Shin, K. G. (2012). E-MiLi: Energy-Minimizing Idle Listening in Wireless Networks. IEEE Trans. Mob. Comput. Trans. Mob. Comput. 2012, 11, 1441–1454.

## Appendix A (NOTATIONS)

| S/N | Notation | Meaning |
|---|---|---|
| 1 | L | Packet Length of Data (16 000 bits) |
| 2 | | Power required to transmit (w) |
| 3 | $T_{SLOT}$ | Duration of a single slot on the contention window |
| 4 | $T_{SIFS}$ | Duration of an SIFS |
| 5 | $T_{DIFS}$ | Duration of a DIFS |
| 6 | $T_{WU}$ | Time required for the WLAN module to fully wake up. |
| 7 | $T_{CTS}$ | Time taken to receive a CTS frame |
| 8 | $T_{ACK}$ | Time taken to receive an ACK frame |
| 9 | $T_D$ | Time taken to receive a Data frame |
| 10 | $T_{WuM}$ | Time taken to receive a Wake-up message (WuM) |
| 11 | $\gamma_{WuM}$ | Power required to process a received WuM |
| 12 | $T_{SL}$ | Time taken for a WLAN module to go from fully awake to doze state |
| 13 | $T_{RTS}$ | Time taken to transmit a RTS frame |
| 14 | $\beta_R$ | Power spent to decode an incoming signal |
| 15 | $\gamma_{wu}$ | power consumed for wake up by the WLAN module |
| 16 | $\beta_{doze}$ | Power consumed by the WLAN module in the doze state |
| 17 | $\gamma_{SL}$ | Power consumed by the WLAN module to go from fully awake to doze |
| 18 | $\beta_{WuR}$ | power required to sense the channel by the WuR |
| 19 | | Power consumes by the WuR to sense the channel |

Appendix B (The HCA-CSMA/CA algorithm)