Design of Energy Efficient Protocols-Based Optimisation Algorithms for IoT Networks

By

Thair Al-Janabi

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Supervised By: Professor Hamed Al-Raweshidy

Department of Electronic and Computer Engineering

College of Engineering, Design and Physical Sciences

Brunel University London

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To my beloved family and friends.

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Abstract

The increased globalisation of information and communication technologies has transformed the world into the internet of things (IoT), which is accomplished within the resources of wireless sensor networks (WSNs). Therefore, the future IoT networks will consist of high density of connected nodes that suffer from resource limitation, especially the energy one, and distribute randomly in a harsh and large-scale areas. Accordingly, the contributions in this thesis are focused on the development of energy efficient design protocols based on optimisation algorithms, with consideration of the resource limitations, adaptability, scalability, node density and random distribution of node density in the geographical area. One MAC protocol and two routing protocols, with both a static and mobile sink, are proposed.

The first proposed protocol is an energy efficient hybrid MAC protocol with dynamic sleep/wake-up extension to the IEEE 802.15.4 MAC, namely, HSW-802.15.4. The model automates the network by enabling it to work flexibly in low and high-density networks with a lower number of collisions. A frame structure that offers an enhanced exploitation for the TDMA time slots ($\text{TDMA}_{\text{slots}}$) is provided. To implement these enhanced slots exploitation, this hybrid protocol first schedules the $\text{TDMAs}_{\text{slots}}$, and then allocates each slot to a group of devices. A three-dimensional Markov chain is developed to display the proposed model in a theoretical manner. Simulation results show an enhancement in the energy conservation by 40% - 60% in comparison to the IEEE 802.15.4 MAC protocol.

Secondly, an efficient centralised clustering-based whale optimisation algorithm (CC-WOA) is suggested, which employs the concept of software defined network (SDN) in its mechanism. The cluster formulation process in this algorithm considers the random diversification of node density in the geographical area and involves both sensor resource restrictions and the node density in the fitness function. The results offer an efficient conservation of energy in comparison to other protocols. Another clustering algorithm, called centralised load balancing clustering algorithm (C-LBCA), is also developed that uses particle swarm optimisation (PSO) and presents robust load-balancing for data gathering in IoT.

However, in large scale networks, the nodes, especially the cluster heads (CHs), suffer from a higher energy exhaustion. Hence, in this thesis, a centralised load balanced and scheduling protocol is proposed utilising optimisation algorithms for large scale IoT networks, named, optimised mobile sink based load balancing (OMS-LB). This model connects the impact of the Optimal Path for the MS ($\mathrm{MS}_{\mathrm{Opath}}$) determination and the adjustable set of data aggregation points (S_{DG}) with the cluster formulation process to define an optimised routing protocol suitable for large scale networks. Simulation results display an improvement in the network lifespan of up to 54% over the other approaches.

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SYMBOLS

α	Energy parameter
β	Distance parameter
γ	$\mathrm{MS}_{\mathrm{Opath}}$ weight parameter
δ	Load balancing constant
ε_{FS}	Amplifier energy for free space
ε_{TR}	Amplifier energy for transmitter
Θ	Stationary probability
ϱ	Spiral constant
μ	Route length parameter
ξ	Probability of finding the channel busy during the second CCA
ρ	Channel utilisation
τ	Load balancing parameter
Φ	Number of CHs covered parameter
ψ	Distance parameters
ω	Probability of finding the channel busy during the first CCA
$b_{i,j,r}$	steady state probability
BO	macBeaconOrder
$\mathrm{C}_{\mathrm{MAX}}$	Maximum number of CCAs
CW	Contention Window
d_0	Transmission distance threshold
DG	Percentage of SDG

$D_{i;i+1}$	Delay by the MS in moving from S_{DGi} to S_{DGi+1}
E_{DA}	Energy for data aggregation
E_{elec}	Energy dissipated per bit
E_{Tot}	Mean energy
$G_b(t)$	Backoff stage
$G_c(t)$	State of the backoff counter
G_i	Time spent by the MS at S_{DGi}
$G_r(t)$	State of the retransmission
K_{CH}	Number of CHs
K_i	Number of sleep stages
$K_i\mathrm{TDMA}_{\mathrm{slots}}$	maximum number of $\mathrm{TDMA}_{\mathrm{slots}}$ for each device
LB_{avg}	Mean number of CMs belonging to each cluster
L_c	Durations of packet collision
L_s	Durations of successful packet transmission
LS_i	Number of $\mathrm{TDMA}_{\mathrm{slots}}$ sleep for SG_{i}
N	Number of IoT devices in the network
NA_r	Percent of all the live nodes
NBF	Number of Backoff stages
N_{BP}	Number of BPs in each $\mathrm{TDMA}_{\mathrm{slot}}$
NG	Number of SG_{i}
P_C	Probability of collision
P_{CAF}	Probability of the packet getting discarded due to CAF
P_{CCA}	Probability of channel sensing
PCKL	Total packet size
P_f	probability of failure
P_{idle}	Probability of the device being idle
P_{RL}	Probability of the packet getting discarded due to RL
P_{Rx}	Probability of successfully receiving
P_{SL}	Probability of the device being Sleep

$\mathrm{P_{SW}}$	Probability of sleep/wake-up
$\mathrm{P_{Tx}}$	Transmission probability
PW	Power consumption
$\mathrm{PW_{CCA}}$	Channel sensing power
$\mathrm{PW_{idle}}$	Idle power
$\mathrm{PW_{Rx}}$	Receiving power
$\mathrm{PW_{SL}}$	Sleep power
$\mathrm{PW_{tx}}$	Transmission power
R	Maximum frame retransmission
S	Network Throughput
$\mathrm{Slot_{seq}}$	Sequence of the current $\mathrm{TDMA_{slot}}$
SO	macSuperframeOrder
SYNC	Synchronisation message
T_{BN}	beacon notification interval
T_h	Threshold
$\mathrm{V_{MS}}$	Velocity of the MS
W	population size

ABBREVIATIONS

ACK	Acknowledgement
ACO	Ant Colony Optimisation
AP	Announcement Period
BE	Backoff Exponent
BEB	Binary Exponential Backoff
BI	Beacon Interval
BP	Backoff slots period
BS	Base Station
CCA	Clear Channel Assessment
CC-WOA	Centralised Clustering based Whale Optimisation Algorithm
CDMA	Code Division Multiple Access
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
CFP	Contention Free Period
CH	Cluster Head
C-LBCA	Centralised Load Balancing Clustering Algorithm
CM	Cluster Member
CP	Contention Period
CTS	Clear To Send
CW	Contention window
DEEC	Distributed Energy Efficient Clustering
DR	Data Rate

FDMA	Frequency Division Multiple Access
GA	Genetic Algorithms
GPS	Global Positioning System
GTS	Guaranteed Time Slot
HSW	Hybrid Sleep/Wake-up
HyMAC	Hybrid MAC
IoT	Internet of Things
ID	Identification Address
LEACH	Low-Energy Adaptive Clustering Hierarchy
LIB	Linear Increase Backoff
LRWPAN	Low-Power Low-Rate Wireless Personal Area Networks
MAC	Medium Access Control
macMaxBE	MAC Maximum Exponential Backoff
macMinBE	MAC Minimum Exponential Backoff
MIEEPB	MS Improved Energy Efficient PEGASIS-Based Routing Protocol
MS	Mobile Sink
$\mathrm{MS}_{\mathrm{Opath}}$	Mobile Sink Optimal Path
NP	Notification period
NSM	Network Scheduling Message
NWPSO	Non-linear Weight PSO
OMS-LB	Optimised Mobile Sink Based Load Balancing
PAN	Personal Area Network
PEGASIS	Power Efficient Gathering in Sensor Information Systems
PHY	Physical
PSO	Particle Swarm Optimisation
PSO-C	Particle Swarm Optimisation based Clustering
QoS	Quality of Service
RFID	Radio Frequency Identification
R-MAC	Reservation MAC

RM-LB	Random Move Load Balancing
RTS	Request to Send
SD	Superframe Duration
S_{DG}	Data Gathering Points
SDN	Software Defined Networks
SEP	Stable Election Protocol
SG	Subgroups
SI	Swarm Intelligent
SMAC	Sensor MAC
SMO	Spider Monkey Optimisation
SMO-C	Spider Monkey Optimisation based Clustering
ST	Scheduling Table
TDMA	Time Division Multiple Access
$\mathrm{TDMA}_{\mathrm{slots}}$	Time Division Multiple Access time slots
TEEN	Threshold sensitive Energy Efficient sensor Network
TL-LEACH	Two Level LEACH
TOP	Transmission Only Period
TSEP	Threshold Stable Election Protocol
VGDRA	Virtual Grid-Based Dynamic Routes Adjustment
VZ_s	Virtual Zones
WOA	Whale Optimisation Algorithm
WSN	Wireless Sensor Network
ZMAC	Zebra MAC

Chapter 1: Introduction

1.1 Overview

Recently, WSNs have received considerable research attention due to its indispensable role in numerous applications, such as embedded systems, environmental monitoring and biodiversity mapping [1]. WSNs generally include numerous heterogeneous nodes that are deployed in unattainable and harsh environments [2], which makes the maintenance and the development of such networks as difficult. The nodes in WSNs not only sense and detect the environment, but also transfer the collected data to the base station (sink) by using particular routing and medium access control (MAC) techniques. The sink node in WSNs can be either static or mobile (MS), or it can be both in some sensor networks [3]. Furthermore, the movement path of a MS can be controllable, random or pre-identified [3, 4].

There is a need to involve intelligence into IoT operations by analysing the data and predicting the optimal routing control, rather than employing the traditional inactive techniques. Furthermore, an intelligent IoT network should be able to compensate for failure in any part in the network and to control it with a minimum amount of degradation in its performance. The involvement of artificial intelligence (AI) in IoT is essential because it allows the controller, based on the collected information, to automate the network and make smart decisions without human interference. However, one major issue for IoT is the lack of a controller and software platform that can support numerous types of AI techniques and integrate them into the network management operation according to requirements. Hence, implementation of intelligent IoT requires a collaboration procedure across many technologies, such as cloud and SDN, with AI techniques as smart software.

IoT control operation techniques should not only perform data collection and analysis of the current situation of the IoT network. For, they should also be getting smarter so as to make life easier by integrating more than one AI methodology. This will lead to improved operation effectiveness, automated risk management and maintenance as well as the facilitation of new production and respond to avoid any potential unplanned network downtime in the future. AI is playing a successful role in improving IoT due to its remarkable intuition capability and capacity for inspecting data, thus allowing for smarter decisions. For example, AI techniques can deliver network automation as well as, earlier patterns prediction and identification with much greater accuracy than the traditional methodologies. Thus, AI is considered as a step toward smart life by providing an intelligent platform to the things to automate them by making smart decisions for day life applications such as air conditions, vehicles, coffee machine, TV, light, etc.

Moreover, the WSN is considered as a basic communication model in the development of the IoT [2]. The IoT is a fast developing technology in wireless communications and includes a wide range of applications, such as smart home, healthcare, agriculture, military, smart transport system, smart postal, smart city, smart environment monitoring, smart water, security, industries, military services and most WSN applications [5]. A general concept of the IoT is that it “enables physical objects to see, hear, think, and perform jobs by having them talk together to share information and coordinate decisions” [5]. The crucial challenge of WSNs relates to sensor resource restrictions, such as the processing unit, storage memory, energy supplier, and radio communication abilities [2]. The current routing algorithms (will be presented Section 2.4) utilise the resources of WSN nodes to accomplish their calculations or to store network information. Furthermore, the associated MAC protocol does not efficiently consider the collisions and channel failure in such high-density networks.

Hence, the growth and updating of WSNs is often limited, because of node resource restrictions and inappropriate design protocols.

The aforementioned problems can be tackled through an efficient MAC protocol and a smart network administration, such as a SDN [1, 6], cloud computing [7] and intelligent algorithms [8, 9]. A dynamic MAC protocol that effectively adapts the device radio, according to the network load, between the sleep/wake-up modes, is crucial for battery-powered networks to conserve energy. SDN technology facilitates easier programming and centralised network architecture by separating the control plane from the data plane [10, 11]. The implementation of SDN technology provides additional dynamic and flexible network control, reduces network complexity and effectively balances the load and traffic among the entire network [1, 6]. Intelligent algorithms, such as the swarm and genetic algorithm (GA), are utilised as optimisation software that forms an overall view of the whole network. Moreover, the SDN controller can utilise these intelligent algorithms to develop optimised decisions, for instance, by the developing of an optimised routing technique for data gathering and the new applications.

The next sections of this chapter are organised as follows. Firstly, in the first and second sections, the challenges and the motivation are discussed, thereby uncovering the rationale for the work in this thesis. The other section describes the aim and objectives of this work. Then, the following section provides the contributions of this thesis that pertain to performance enhancement of IoT networks. The outline of the thesis is presented in the last section.

1.2 Technical Challenges

The technical challenges that are associated with IoT networks can be categorised into three groups: network specification challenges, node resource challenges and protocol design challenges. Each of these groups of challenges is described in the following subsections.

1.2.1 Network Specification Challenges

Nowadays, IoT networks are involved in many life applications, becoming increasingly popular, more complex and deployed on a large-scale. Sensors, which are considered as the basic main units of these networks, are randomly and densely deployed over vast, often harsh, geographical area [2, 12] and must therefore be frequently replaced, as they are not rechargeable. Moreover, in the architecture of WSN, many problems are chronic, such as decentralised and independent network control, which prevents global network administration and optimisation [13, 14]. Extensive efforts have been undertaken to enhance the centralised monitoring of the large-scale IoT. However, the number of IoT devices in vast environments is increasing and a scalable routing protocol has, therefore, become essential [2, 15, 16].

Generally in clustering, two different types of sink node, mobile and static, are considered [3]. Where in the networks with a static sink, devices positioned in the communication vicinity of the sink exhaust, because of the higher data-relaying load, much higher energy than the devices positioned farther away from the sink. In order to tackle this problem, sink node mobilisation has been presented, in which the mobile sink transfers along a specific path throughout the network to collect the data from the CHs with lower energy exhausting. Therefore, WSN clustering algorithms with a static sink suffer from energy hot-spot problems, especially with large scale networks, because the sensor nodes closer to the sink node dissipate more energy than the others [14, 17]. This is because the use of the static sink only covers a small-scale network region. Hence, in a large-scale network, it is practically impossible to cover the entire region using a static sink. Additionally, the use of a static sink in large-scale networks leads to high-energy exhaustion among the CHs and increases the hot spot problem due to the connection to the sink. As a result, the use of a mobile sink is essential in large-scale networks [17]. In sum, determining the optimal path, reducing network complexity, synchronising overall network with the mobile sink and prolonging the life of the network present huge challenges, particularly in large-scale networks.

1.2.2 Node Resources Challenges

WSNs have inherent issues that limit their performance, such as sensor resource restrictions that affect power supply, memory units, computational capabilities and short-range communications capabilities [2]. Moreover, due to the associated resource restrictions, only very small functions can be configured using the IoT nodes, principally those related to the power supply. On the other hand, the sensors in WSNs have the responsibilities of sensing the environmental phenomena and the sensed data are then gathered, being then sent to the sink node across the CHs. For example, the sensor has the functionality of detecting environmental conditions, such as temperature, fire and humidity. Furthermore, the sensor nodes are associated with other applications, such as tracking, surveillance, among many others. Therefore, it can be concluded from the varied range of applications and functionality that IoT devices are deployed in a wide and an unattended geographical area that make their maintenance, such as replacing their batteries, arduous.

1.2.3 Protocol Design Challenges

IoT networks suffer from many challenges that are caused because of the insufficiency of the protocols designed for such networks, whether they are MAC or routing protocols. For instance, cluster-based hierarchical routing protocols with a static sink are broadly accepted as highly energy efficient and can prolong the lifetime of the network [13, 18]. Each cluster comprises a set cluster members (CMs) and a CH; the CHs collect packets from the CMs and send them to the sink. However, the number of CHs, the number of CMs, load balancing, residual energy and communication cost are all crucial metrics in the formulation of clusters. These are considered so, because they can limit the appropriateness of clusters for an efficient network, for unbalanced cluster construction and unbalanced energy dissipation can enormously reduce network lifespan.

Moreover, the performance of such routing designs can significantly decline in large-scale or in high-density networks [19] and consequently, mobile sink designs have been suggested for such networks. However, the technique used by the mobile sink to roam across the network to gather data has suffered from delay issues. Consequently, the scheduling of mobile sinks and efficient path determination are perceived as key research challenges, particularly in large-scale networks. Furthermore, current routing protocols use the sensor's resource to conduct their computations or to memorise network information. The development and growth of the IoT, however, is often restricted due to sensor resource constraints.

On the other hand, several factors need to be considered during MAC protocol design to satisfy the application requirements and to mitigate the energy depletions [20], including collision, idle-listening, sleep-wake up synchronisation and overhearing. Collision occurs when two devices start their transmission at the same time, which causes energy waste. Idle-listening, which is generally higher with unscheduled or contention-based networks, happens when a device continuously senses the channel situation which obviously depletes power. Overhearing is considered as the main issue in IoT networks, where the density of the devices and the traffic is high. It occurs when a device receives a packet that does not belong to it, which correspondingly wastes a lot of energy [21, 22].

1.3 Motivations

WSNs comprise a huge number of low-cost low-power sensor nodes [12], which have several resource restrictions in terms of energy (battery powered), memory, processing units and radio for communications capability [2]. However, the main concern with WSNs is the energy limitation problem of the sensor node, because the lifespan of the whole network depends on the energy that has been initially supplied to these nodes.

Furthermore, the structure of IoT networks, which is currently entering into many real life applications, relies on WSN communication, such as monitoring the physical and environmental conditions [5]. Furthermore, the IoT devices increase, deploy in a random manner and usually install in harsh and large-scale geographical area [15,16].

Most of IoT applications need to have a long lifespan and the network needs to be scalable. Hence, they require energy efficient and well-structured design protocols to be able to achieve these outcomes. The advances in the development of low powered sensors means they can now provide solutions to problems in many fields, including healthcare and national defence. However, these sensors suffer from a restricted power supply and a lack of certain resource facilities that make such networks still need more enhancement and new capable techniques.

The above mentioned issues and the challenges mentioned in Section 1.2, provide the motivation to design energy efficient routing protocols based on optimisation algorithms and SDN technology. Furthermore, cloud computing is also taken into account in the routing design in order to utilise its resources to save and implement protocol calculations. Moreover, regarding high density and low-powered IoT networks, there is the motivation also to design an analytical hybrid MAC model that works efficiently with such networks.

1.4 Aim and Objectives

The main aim of this thesis is to develop energy efficient protocol designs for battery-powered environments, such as WSNs and IoT networks. Accordingly, the focus is on factors such as node density, random distribution of node density, communication cost, load balancing, collision probability and network complexity. The consideration of these factors is useful in the development of efficient protocols suitable for various sensing applications with more energy conservation. The essential objectives of this thesis are itemised as follows.

- Provide an energy efficient hybrid MAC protocol, which is suitable for high-density IoT networks. In addition, develop an analytical model that has the ability of predicting the performance of the provided hybrid protocol.
- Minimise the energy consumed by the clustering algorithms-based static sink.
- Develop an energy efficient routing protocol for large-scale IoT networks.
- Reduce network complexity, processing, data saving and other functionalities that are implemented by the IoT nodes, and involve new technologies, such as SDN and cloud, to perform network functionalities.
- In general, develop protocols for IoT networks that consume minimum energy at both the node and network levels.

1.5 Thesis Contributions

This thesis presents four main contributions that are summarised as follows.

- An on-demand sleep/wakeup extension to the IEEE 802.15.4 standard is proposed using a hybrid protocol for high density IoT networks, called the HSW-802.15.4 MAC protocol. This protocol integrates scheduled sleeping periods into the standard in order to utilise the energy of the nodes efficiently by adapting dynamically the sleep/wake-up periods, according to the variance in the network load, collision status and channel failure. Furthermore, an efficient frame structure is proposed based on a hybrid time division multiple access-carrier sense multiple access with collision avoidance (TDMA-CSMA/CA) MAC protocol with a beacon-enabled mechanism. The BS, firstly, arranges and schedules the $\mathrm{TDMA}_{\mathrm{slots}}$ and the ST message, subsequently allocating each $\mathrm{TDMA}_{\mathrm{slot}}$ to a group of devices, which compete for the medium using the CSMA/CA. It is worth indicating here that the proposed hybrid protocol is different from the traditional CSMA/CA-TDMA hybrid protocol in the literature, in which all the devices compete to access the channel, following which each successful device is allocated an individual $\text{TDMA}_{\text{slots}}$. A Markov model is also proposed in order to analyse a per user stochastic behaviour for the suggested HSW-802.15.4 protocol with a dynamic sleep mode.

- An optimised set of clusters is developed by proposing two efficient fitness functions. The first fitness function is offered to consider the node density in the geographical area, whereas the second, is established to deliver a load balancing clustering algorithm for IoT networks. Furthermore, both of the proposed clustering algorithms are also designed to address the residual energy and the communication cost factors when constructing an optimal set of clusters.

- A new routing algorithm with a static sink is put forward. This is implemented using an efficient WOA based on the concept of SDN. The proposed protocol considers both sensor resource restrictions and the random diversification of node density in the geographical area. The fitness function that considers the node density is used to identify the optimal set of the cluster heads. It is suggested that the cluster formulation process begins by dividing the sensing area by the SDN controller into virtual zones (VZs) to balance the number of CHs according to the node density in each VZ. Then, the WOA for each VZ is used in order to identify the optimal set of the cluster heads.

- An optimised routing protocol is proposed with a scheduled MS based on SDN and cloud technologies for large scale IoT networks, called the OMS-LB routing protocol. It is designed to be energy efficient and based on optimisation algorithms, i.e. PSO and GA. It is implemented by the SDN controller and it is suggested to be positioned over the cloud. The fitness function that considers the load balancing is used to identify the optimal set of the CHs. Furthermore, an efficient fitness function is employed with the OMS-LB protocol to identify the optimal set of S_{DG}, which is used by the MS as a data collection point, by using the PSO. The optimal path for the MS (MSO_{path}) is determined by merging all the fitness functions and choosing the optimal path using both a GA and the PSO. Moreover, the proposed routing technique will prevent significant energy dissipation by the CHs and by all nodes, in general, by scheduling the whole network.

1.6 Thesis Outline

This section discusses the outline and the work of this thesis in more detail, which is structured into six chapters and presented as follows.

Chapter Two:

This chapter reviews the previous studies, which have been categorised into two main subjects, according to the energy waste by the IoT networks, namely, MAC protocol and routing protocol studies. The first part of the chapter starts with a discussion of the existing MAC protocols that have been classified into three groups: contention-based protocols, contention-free protocols and hybrid protocols. The contention based protocols are classified into two subcategories known as simulation-based and analytical-based protocols. The other section of this chapter describes the existing related research for the routing protocols of both static and mobile sinks. Additionally, this section considers the improved routing protocols based on SDN technology and an overview of the IEEE 802.15.4 standard is also presented in this chapter.

Chapter Three:

This chapter presents modelling and analysis of the proposed dynamic HSW-802.15.4 protocol that supports energy efficiency by tuning the parameters of the MAC and enhancing the protocol performance in terms of the channel collisions and utilisation. The proposed protocol is built according to the hybrid protocols by joining the benefits of a contention-free, i.e. TDMA, with contention-access, i.e. CSMA/CA, protocols. Additionally, this chapter describes the formulation of the problem, the frame structure and the methodology of the proposed HSW-802.15.4 protocol. For calculation of the network metrics, an analytical model for a three-dimensional Markov chain compatible with the proposed model-based dynamic sleep mode is presented in this chapter. The thesis includes addressing the energy depletion of the IEEE 802.15.4 standard, due to its suitability for low-power, low-data rate networks, such as IoT and WSN applications, but this standard suffers many issues that cause more energy waste. Finally, validation and discussion of the proposed protocol are presented, with the results being compared with those from the existing IEEE 802.15.4 standard.

Chapter Four:

This chapter discusses the suggested centralised clustering algorithm using an efficient WOA based on the SDN concept, which is called CC-WOA. The exploration of WOA is presented in this chapter also. The CC-WOA is developed to be used with heterogeneous, randomly distributed and dense IoT networks. It defines a fitness function that considers the sensor resource restrictions, in terms of the remaining energy and the communication cost. It also considers random diversification of node density in the geographical area during the selection of the optimal set of CHs for cluster formulation. Furthermore, in this chapter, it is suggested that the SDN controller considers the random distribution of node density in two positions, before the selection of CHs by dividing the sensing area into VZs and then, during the selection of the CHs by the WOA fitness function. Finally, this chapter provides the effectiveness of the proposed protocol in terms of network lifetime, throughput and the effect of the node density and the VZs on network performance by comparing its results with other protocols.

Chapter Five:

This chapter demonstrates an efficient routing protocol based on load adjustment for large-scale IoT networks under the control of a centralised architecture. The architecture of the proposed protocol, using a mobile sink and based on optimisation algorithms, i.e. PSO and GA, is discussed. The devices with this protocol are divided into a well-balanced set of clusters. The CHs, in turn, will be separated into groups of clusters, called the optimal set of S_{DG}. The $\mathrm{MSO}_{\mathrm{path}}$ algorithm that identifies the optimal path for the mobile sink in some way to visit each data gathering point is discussed. The scheduling method that synchronises the entire network with the mobile sink having been implemented effectively. The SDN controller is presented in this contribution to be responsible for protocol calculations and make the decision with the utilisation of the cloud resources.

Chapter Six:

This chapter concludes the thesis, with the contributions being restated. There is also a brief discussion about possible future solutions and the impact of this thesis.

Chapter 2: Literature Review

2.1 Introduction

This chapter presents a series of energy efficient design protocols for low powered networks that are related to the work in this thesis. Considerable research can be found in the literature aimed at offering efficient design protocols for a variety of IoT and WSNs applications, such as environmental control and monitoring [23, 24]. Furthermore, the findings from many surveys about low powered devices and their associated protocols have been presented in the literature. Examples of such studies are: those relating to the routing protocol surveys in [25, 26], MAC protocol surveys in [20–22, 27–30] and other emerging technologies surveys in [31–33].

This thesis, in general, is focused on the development of energy efficient design protocols, with consideration of resource restrictions, scalability, adaptability, number of devices, and random distribution of device density in the geographical area. Accordingly, in this literature review, the energy efficient techniques for both MAC and routing protocols are discussed. On the one hand, MAC protocols are categorised according to their method of accessing the channel, regarding which there are three categories, namely, contention-based access protocols, contention-free protocols and hybrid protocols. In respect of the latter-most, these protocols aim to include the benefits of both the contention-free and contention-based protocols, while trying at the same time to relieve their weaknesses. On the other hand, the routing protocols are classified into two main groups: routing protocols based on static sinks and routing protocols-based on mobile sink. This literature review also covers some other energy efficient related protocols based on emerging technologies and methods, which are SDN-based routing protocols, cloud computing and optimisation algorithms.

This chapter is organised as follows. The first section, the existing MAC protocols and their categories are discussed, with the contention-based category being divided into two subcategories: simulation-based and analytical-based protocols. The second section presents an overview of the IEEE 802.15.4 standard, while in the third section, the existing related research for the routing protocols is reviewed. In addition, the improved routing protocols based on SDN technology are discussed.

2.2 Medium Access Control Protocols

In this literature, the MAC protocols have been divided according to their channel access techniques, into three main categories, which are: Contention-based MAC Protocols, Contention-Free MAC Protocols and Hybrid MAC protocols.

2.2.1 Contention-Based MAC Protocol

Regarding the contention-based protocols, the devices compete for the channel using different techniques in order to secure it and transfer their data. The main drawback of these protocols is the insufficiency of scalability, principally due to the rise in the number of collisions between simultaneous transmission from various devices, especially when their number increases [20]. This literature divides the contention-based MAC studies into two categories: the analytical-based studies and the simulation-based ones. Furthermore, it splits the former based on a Markov mode into two classes: those that mimic and evaluate the performances and properties of the IEEE 802.15.4 standard, and those that attempt to improve the performance of this standard.

2.2.1.1 Analytical-Based MAC Protocols

Many studies have been aimed at assessing and understanding the analytical MAC model of the IEEE 802.15.4 standard. These studies have attempted to mimic aspects and mechanisms widely used by the IoT and WSN devices to investigate and identify the properties and performances of those networks. Most of the analytical models for the IEEE 802.15.4 standard are built according to the Markov model, presented by Bianchi [34] for the IEEE 802.11 standard. That is, Bianchi designed a Markov chain model that mimics the functionalities of the IEEE 802.11 standard for ideal channel conditions and saturated networks. In this subsection the analytical model of the MAC protocol is split into two classes: the performance evaluation studies and the performances improvement studies.

i. Performance Evaluation Studies

From a performance evaluation perspective, a comprehensive Markov chain model and analysis of the IEEE 802.15.4 [35] MAC and PHY layers have been conducted by many authors [36–44]. For example, Pollin et al. [37] proposed a two-dimensional Markov model, with an extension of saturated and unsaturated mechanisms for the slotted CSMA/CA mechanism. The proposed model mimics the MAC behaviour of the IEEE 802.15.4 in the presence of both acknowledged and unacknowledged uplink data communications. The performance of the IEEE 802.15.4 standard in terms of power depletion and throughput was also analysed. The procedures to adjust the MAC parameters, such as NB and the back-off exponent, have been described too.

In contrast, Sahoo et al. [38] proposed a modified model including retransmission with determinate retry limits for IEEE 802.15.4. However, there was an inexact match between the analytical and the standard results for both energy depletion and throughput. Park et al. [39] proposed a generalised analytical model of IEEE 802.15.4 with retry limits and acknowledgements under unsaturated star networks. This model was developed with the aim of reducing power depletion, while accomplishing reliability and packet transmission delay. The vital MAC variables used were named as macMaxCSMABACKoffs, macMinBE and macMaxFrameRetries. The authors presented numerical results for an accurate Markov model in order to evaluate the performance metrics in terms of delay, reliability and energy depletion.

Zayani et al. [40] developed an IEEE 802.15.4 model that takes into consideration the functionalities of this standard on both the PHY and MAC layers. At the PHY layer, the model is similar to the mathematical framework used by Zuniga and Krishnamachari [41] for calculating link unreliability. Moreover, the MAC layer is inspired from an improved Markov model proposed by Park et al. [39]. This model considers the effect of underlying packet discards at either ther PHY or MAC layers [40].

Anastasi et al., in [45], claimed that the IEEE 802.15.4 MAC protocol suffers from an unreliability issue, whereby the network performs poorly in terms of the percent of data that can be successfully delivered to the specified receiver. Consequently, the authors provided an expanded description of IEEE 802.15.4 MAC performance in terms of reliability. That is, the authors provided extra simulation results to explain the influence of the IEEE 802.15.4 MAC default parameters (namely, macMaxBE, macMinBE, macMaxFrameRetries and macMaxCSMABACKoffs) on the observed MAC performance degradation. The core outcome of this study is that the performance of IEEE 802.15.4 MAC can be enhanced by achieving an appropriate adjusting of its parameters, which requires replacement of the current standard parameters.

Performance estimation in all the above studies has involved trying to provide optimal Markov models for the CSMA/CA mechanism that mimics the behaviour of IEEE 802.15.4; however, they did not take the sleep/ wakeup mode into consideration.

ii. Performance Improvement Studies

To improve energy preservation and the performance of the IEEE 802.15.4 standard, several researchers [46–51] have proposed models with periodic sleep or idle periods, and device contention, as perfect solutions.

The CSMA/CA-based design protocols, such as IEEE 802.11 and IEEE 802.15.4, are among the most popular and broadly deployed MAC protocols. However, huge amount of energy depleted by the CSMA/CA-based MAC protocols due to the higher number of collisions to access the channel and idle listening. Therefore, the methodology for implementing such protocols does not fully meet the requirements of IoT networks and leaves much to be considered. Also, the overhead is caused by the large number of control packets, which may be a matter of higher energy depletion than the data packets. Another concern regarding the CSMA/CA is basically their incompatibility to work efficiently in a large scale network [52].

For instance, Minooei and Nojumi [53] studied the improvement of the BEB in the structure of IEEE 802.11. After that, Lee et al. [54] examined the performance of the back-off algorithm, which they named the Non-Overlapping BEB (NO-BEB), in the construction of IEEE 802.15.4 networks. The NO-BEB involves adapting the BEB method by choosing the value of the contention window (CW) after a failure to access the channel. In general, in order to decrease the number of collisions during the CW to access the medium, the CW is elected in a random manner from the interval [CWi1, CWi] instead of [0, CWi], where CWi is the CW of the i^{th} backoff stage [53]. This modification ensures that no overlapping can occur with the preceding interval (that is, [0,CWi]). Consequently, the devices experience a diverse number of channel access failures, which results in better chances of obtaining diverse CWs from the non-overlapped states. Furthermore, the NO-BEB is modelled using the Markov chain in [54] and outperforms the BEB in terms of throughput and channel access delay.

Zhu et al., in [55], presented Linear Increase Backoff (LIB). This protocol is adapted over the traditional CSMA-CA mechanism to provide enhanced services for time crucial applications. The main aim of the LIB protocol is to improve the performance in terms of transmission delay, with the same level of energy consumption and throughput. With this protocol, when either of the CCAs identify that the channel is occupied by other devices, then the back-off counter will be linearly increased, instead of ordinarily exponentially increased. This is as a result of the fact that the exponential increase in the ordinary back-off counter may force some devices to wait for a prolonged interval prior to being capable of inspecting the channel using its CCAs. This permits other devices, with somewhat smaller back-off intervals, to commence and capture the channel firstly and more frequently.

The displayed linear increment of the back-off counter can ensure it preserves the back-off intervals to a reasonable extent, which permits the devices to achieve an adjustable access to the channel. Furthermore, LIB involves other amendments of the ordinary CSMA-CA mechanism by dropping a packet that cannot be transmitted within the current superframe and not postponing and then, retransmitting it within the following one. Also, the devices have to be in the sleep mode, instead of receiving an idle status, throughout the back-off stages, at the end of a successfully data transmission, and when exceeding the higher number of back-off states. Furthermore, a complete Markov-based model has been established for the LIB protocol to analyse its specification and simulation results demonstrate that LIB can effectively accomplish a significant decline in the transmission delay.

Chiasserini et al. [46], for example, considered the performance of sleeping devices in WSNs; however, they did not focus on the performance evaluation of the IEEE 802.15.4 MAC layer. Alternatively, Misic et al. [47] suggested a model of a beacon enabled IEEE 802.15.4 with a sleep mechanism. With the proposed mechanism, it is assumed that a device turns to sleep for a specific amount of time when there are no packets in its buffer [ibid]. Xiao et al. [48] proposed a Markov model that took into consideration the sleep-based mode of the IEEE 802.15.4 standard. Jurdak et al. [49], on the other hand, implemented non-beacon IEEE 802.15.4-based RFID devices. To conserve energy, a device remains in sleep mode, if it has no packet to send or the RFID tag has not received any data. Ghazvini et al. [50] suggested an energy efficient MAC protocol, based on IEEE 802.15.4, for WSNs that reduces energy depletion and network collisions by permitting devices to move between sleep and listening modes during the active period, when they have no packets to transmit. However, all these studies focused only on contention-based channel access, and have not taken into consideration network density, the numbers of collisions or even channel failure.

The performance of the hybrid IEEE 802.15.4 MAC protocol was also studied by [57,58]. The research conducted in [57] offered a general Markov model that takes into consideration both the slotted CSMA/CA and GTS in a heterogeneous network set-up and non-saturated conditions. The authors in [58] focused on reducing the collisions caused by the hidden node problem in IEEE 802.15.4 networks using the GTS slots.

2.2.1.2 Simulation-Based MAC Protocols

It is generally agreed that MAC protocols are the simplest techniques in terms of system set-up and implementation, some of which are described below.

Amongst the most basic MAC protocols are the random access protocols, such as ALOHA and slotted-ALOHA, stated by [59,60], respectively. In these protocols, the devices either send the packet as soon as it is generated or start the transmission at the commencement of the following slot. The key downside of these random-based protocols is the high rate of collisions, which restricts the value of the throughput and eliminates the utilisation of the channel bandwidth [60]. CSMA protocols are considered an advancement toward decreasing the collisions suffered by ALOHA methods [61]. However, these protocols do not significantly diminish the collisions and there can be degradation in the throughput caused by the hidden and collided node problems. The hidden node issue may be solved by the implementation of busy tones, where transmitters and/or receivers are forced to send a persistent busy tone, while a packet is being transferred or received [62]. Furthermore, one of the most commonly deployed random channel access methods is the IEEE 802.11 MAC protocol, which was built according to the CSMA with a collision avoidance (CSMA/CA) technique.

Another MAC protocol is the Sensor MAC (SMAC) protocol, described and developed in [22,63,64]. It is one of the basic MAC layer protocols for WSNs that deal with matters that cause energy depletion, such as idle collisions, overhearing and listening. This protocol covers three main times: SYNC, DATA and SLEEP periods. All the nodes with the same cluster wake-up for a pre-calculated schedule time and synchronise their clocks at the beginning of the SYNC period. As shown in Figure 2.1, the RTS and CTS method based on the CSMA/CA protocol is implemented to access the medium by the devices that have data to transmit. Those that do not have any packets to transmit go to sleep mode by turning their radio off and set a timer to wake-up later after the duration of the SLEEP period. The sleep/wake-up periods are different and decided according to the device application and scenario. Every device sleeps for a specific period of time and, then, wakes up and listens to the medium in order to verify whether other devices are transmitting with the medium or not.

The main objective of the SMAC design protocol is energy saving and self configuration, while fairness per device can be non-compulsory. The S-MAC protocol attempts to mitigate unnecessary energy consumption by alternating and tuning the situation of each device's radio between the sleep and wake-up states, according to a pre-defined duty cycle [21]. Whilst the scheme of this protocol can be regarded as easy and uncomplicated, it is really only suitable for networks with low communication traffic and where latency aspect is not a vital concern. Forthermore, in applications like alarm structures, latency is a significant issue and the construction of the S-MAC protocol causes a transmission delay and suffers from an extended sleep period [63].

Another important issue with S-MAC is that the packets can be transmitted using one hop transmission only, and thus, an enhancement with adaptive listening has been implemented, as seen in Figure 2.1. With this enhancement, the protocol becomes able to send the data through two hops; however, this adaptive enhanced design also has the challenge of overhearing. Figure 2.1 shows that device C can hear CTS broadcasted by device B, so it can turn its radio off at the beginning of the SLEEP period but has to be active again at the end of next transmission [22]. It is worth to mentioning that in the S-MAC protocol, the possibility of data transmission is not

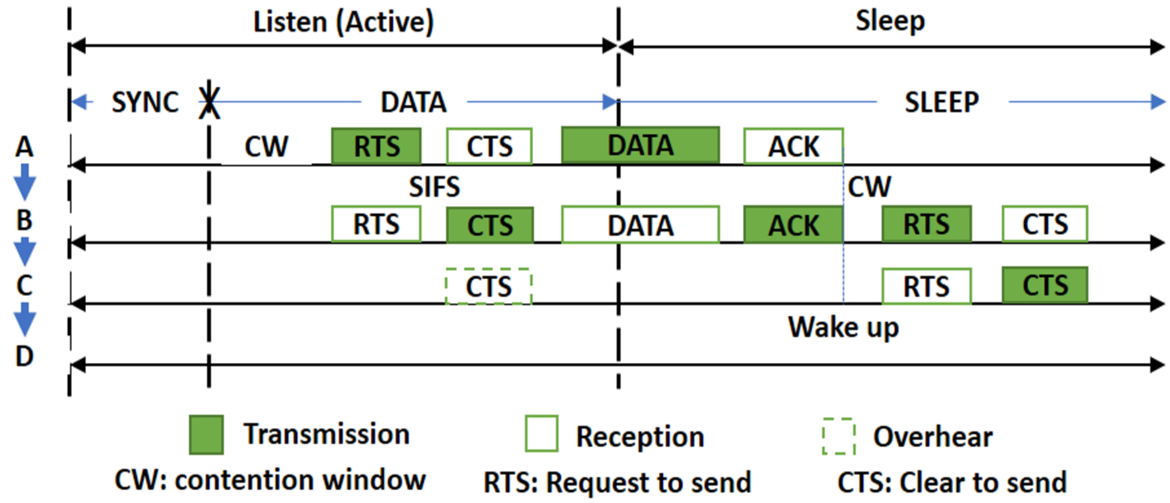


Fig. 2.1. Adaptive listening in S-MAC [22]

considered; therefore, each device is needed to be in an active mode throughout the entire listening interval.

2.2.2 Contention-Free MAC Protocol

Contention-free protocols have the advantage of avoiding collision concerns by pre-assigning transmission time slots to the devices in the network. However, such protocols have the drawback of inefficient network performance in terms of power saving and volume of data sent within the low network loads. Furthermore, contention-free protocols suffer from an inadequate number of resources for high network load [65]. In general, contention-free protocols are categorised into three main types: TDMA, frequency division multiple access (FDMA), and code division multiple access (CDMA). In TDMA, the complete available bandwidth is assigned to a single user for a portion of time [66], whereas the FDMA protocol works by continuously assigning a portion of the available frequency bandwidth to each user in the network [67]. In CDMA, each user is assigned a particular code, which is then utilised in the bit patterns modulation [66, 68]. Henceforth, some of the other related studies on contention free based-TDMA MAC protocols are discussed.

Heinzelman [13] proposed a TDMA-based MAC protocol in which the available bandwidth is scheduled into time slots and each device is allocated one or more slot. In order to conserve energy, the devices send or receive during the allocated time only and turn their radio off throughout all other time slots. The TDMA protocol is mostly appropriate for fully traffic network loads. However, throughout the low traffic networks, the CH nodes need to keep their radio on continuously during all the allocated time slots to collect the data from the network devices, which leads to a rapid wasting of their residual energy. Figure 2.2 demonstrates the frame structure of the TDMA protocol [28].

Then, an improved Low-Energy Adaptive Clustering Hierarchy (LEACH) was proposed by [18] and it is equipped with an energy efficient TDMA MAC technique to collect the data in each cluster. In LEACH, the CHs are responsible for data collection and are elected randomly with a probability based on the residual energy of the cluster members. Then, the CH builds the TDMA schedule by dividing the channel into time slots that are allocated evenly among the cluster members. The selected CH then broadcasts the scheduling information to the cluster members and each sends its data to the CH to be routed to the base station. However, the MAC protocol used in the LEACH protocol is not adjustable to the inconstancy in the network traffic, which is because it distributes the time slots evenly among the devices in the cluster.

The core drawback of contention-free design protocols is that the channel utilisation is dropped at low network loads [36]. This is because these protocols have the difficulty of having to be adjusted when the number of the devices in the entire network are changed. Another weakness is that these devices require efficient utilisation of their hardware resources. Furthermore, the flexibility and the scalability perspectives within a low energy consumption are considered as the main desired characteristics, which need to be considered during the protocol design process for

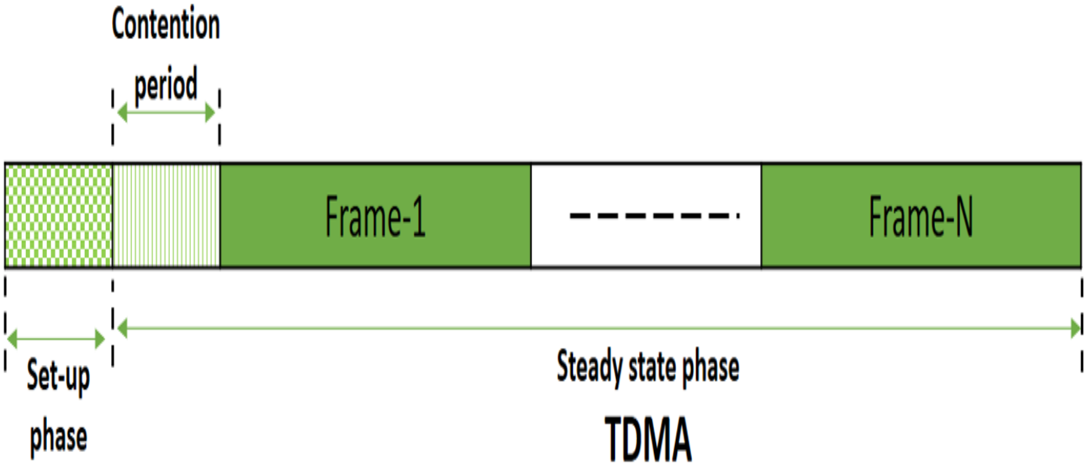


Fig. 2.2. Operation diagram of TDMA protocol [28]

IoT networks. However, the drawbacks of the contention free MAC protocols are considered as challenges to be provided as MAC protocols for these networks. In comparison with TDMA, CDMA and FDMA are less appropriate for deploying in IoT networks. Moreover, the CDMA protocols are inappropriate for low-cost and low power devices due to their complexity and high computation requirements during the encoding and decoding calculations. With the FDMA protocols, the devices need more circuitry abilities to switch and join among various radio channels [20].

2.2.3 Hybrid MAC Protocol

The hybrid MAC protocol combines the strengths of both contention-free and contention-based protocols. This protocol can be easily adapted to the network changing and is more appropriate for those networks with various loads. Also, it reduces the number of collisions between the devices and offers a better utilisation of the channel. The following paragraphs describe some of the hybrid MAC protocols.

Hybrid MAC protocols that associate elements of the CSMA-based contention mechanism with the TDMA, FDMA or CDMA-based scheduling mechanisms, are described in the following studies. For instance, protocols that associate CSMA with TDMA, which are described by Rhee et al. in [69] and Zhang et al. in [70], act as a CSMA with a light contention state and change to the TDMA MAC time sort procedure at a higher contention state. On the other hand, Salajegheh et al. in [71] proposed a hybrid MAC (HyMAC) that combines CSMA with both TDMA and FDMA. In this type of the hybrid MAC, the devices are allocated a frequency band using FDMA as well as a time slot technique using TDMA. Then, the devices send their packets once they successfully transmit a request for a bandwidth message using the CSMA MAC mechanism. In a comparable manner, other hybrid MAC protocols have been proposed in [72, 73]. In those protocols, the devices combine CDMA with TDMA and utilise CSMA to send their request for a bandwidth message to reserve time slots and codes for their transmission successfully.

Yessad et al. in [74] proposed the Reservation MAC (R-MAC) protocol, which is constructed mainly to consider the WSNs issues with heavy traffic in which there are a higher number of devices. The core focus of the R-MAC design protocol is to reduce overhearing, so that instant swapping among both the sleep and wake-up states of the devices is decreased, which is considered a key source of energy depletion in such low-powered networks. This protocol reduces the number of collisions between the devices by adjusting sleep/wake-up periods according to the traffic load in the network. Each device in this protocol reserves the channel previously for its upcoming transmission, which supports the other neighbouring devices to identify the anticipated transmitter/receiver for each transmission time slot, then they can tune their sleep/wake-up periods to conserve energy.

This reservation assists in reducing the overheard caused by several transmissions and also, mitigates repeated switching between the sleep/wake-up modes. In this protocol, the device employs the RTS/CTS technique throughout the reservation interval. Besides this, it splits the listen interval into various phases: the reservation phase of interval R, transmission phase with N time slots, sleep phase and finally the synchronisation phase. When a device attempts to send data, it inspects the channel to see whether it is idle, then the device decreases its delay back-off counter and transmits the RTS packet when this counter is equal to zero and the medium is still idle. The RTS packet includes information for reserving the time slot and scheduling of the phases. Once the device has collected the CTS control packet from the receiver it waits for the initiation of the reservation phase and then, sends its data in the previously reserved time slot.

In the transmission phase, the previously reserved time slots of the devices are utilised for the transmission and the others can move to sleep mode. A procedure of inconstant listen and sleep intervals, according to the network traffic load, is also suggested in this protocol. This procedure is implemented by investigating and recording the number of transmissions in the preceding listen phase and imposing an assumption that an equivalent network load will arise in the next listen period, so the sleep phase is monitored accordingly. Furthermore, the devices that are around to move to sleep mode notify their neighbour devices by broadcasting a GTS "Going to Sleep" control packet in the synchronisation phase, so that these devices can monitor their schedule properly. However, the problem of idle listening, which is a major issue for energy consumption in low data rate networks, has not been considered by the R-MAC protocol.

A scalable Hybrid CSMAMAC protocol is suggested in [15], which works by splitting each frame period into four portions: notification period (NP); contention only period (COP); announcement period (AP); and transmission only period (TOP). Each frame is commenced by the broadcasting of a control message at the NP, in which the base station (BS) declares the beginning of the COP to each device in the network. Throughout the COP, the devices with data to send employ the p-persistent CSMA mechanism to transmit the request to send (RTS) packet to the BS and those that succeed in doing so, are allocated time slots in the TOP to transmit their data. Moreover, the BS informs the devices about the schedule and their transmission slots during the AP. Furthermore, both the length of the COP and the number of devices that are permitted to be sent in the TOP is varied from frame to frame, which is determined by the BS.

This hybrid MAC protocol is improved by Liu et al. in [16] by the implementation of the fairness and quality of service (QoS) concepts. The improved protocol categorises the devices into different classes and permits the devices to pick up the contention probability rendering to their observed throughput and urgency. However, both the above protocols suffer from supplementary delays and energy depletion caused by the time needed for the COP and the requirement for the contention between devices. Also, this protocol still seems to suffer in a saturated network and with a high number of devices.

An improved hybrid protocol for the WSNs is proposed by Gilani et al. [75]. This protocol, in comparison to the IEEE 802.15.4 MAC, presents an adaptive CSMA/TDMA MAC protocol that enhances the power conservation and improves the volume of packets successfully sent. The aim of this protocol is to improve the performance of the CSMA-CA MAC protocol by incorporating it with the TDMA MAC protocol. Depending on the situation regarding the device queue, the coordinator device adaptively distributes the network tasks between the CAP in the CSMA-CA and TDMA slots. Furthermore, the situation of the device queue can be identified using reserved bits in the communicated frames. The beacon frames that are broadcast in a periodic manner have the advantage of identifying the queue state of the devices. In addition, the greedy algorithm that has been used in the allocation process of the TDMA time slots can help in improving network utilisation and enhance its throughput.

Another hybrid MAC protocol, called zebra MAC (ZMAC), is proposed by Rhee in [69]. The hybrid technique of this protocol works as CSMA in a low network traffic and switches to TDMA when it is high. The objectives of this protocol is to improve the network throughput with this type of the variable traffic and to escape the hidden node issue using the scheduling TDMA mechanism. Usually, each device sends its data packets using its allocated time slot, which is sufficiently large for the communication of several packets. However, if the devices require more than one time slot, they can try to exploit other neighbours' unutilised time slots. To exploit other time slots, the device initiates a long enough random backoff period and starts its transmission at the end of this period, but the device is not able to start its transmission if the primary user needs its own time slot. Moreover, ZMAC is required to implement TDMA scheduling in a periodic manner to recover the deviation in the time clock among the devices.

Generally, the key issue with hybrid protocols is the scalability and consideration of energy depletion for IoT networks. Furthermore, most IoT applications have high device density and those devices are distributed in vast and harsh environments. Despite the above hybrid protocol being more scalable than other protocols, it is still not adequate for the deployment in most IoT applications. Moreover, the hybrid protocols-based on FDMA and CDMA have the issues of high hardware expenses and high complexity, respectively. Hence, the hybrid MAC protocols based on both TDMA and CSMA are the most encouraging from the perspective of IoT applications.

2.3 IEEE 802.15.4 MAC Protocol Overview

The IEEE 802.15.4 standard was designed to meet the requirements of both the MAC sub-layer and the PHY layer in WSNs and IoT networks. The network construction, in these low-power low-rate wireless personal area networks (LRWPAN), is accomplished by the personal area network (PAN) coordinator, which in turn works as a central controller to build and control the overall network. In general, these types of networks support three types of network communications: device-to-device communication (i.e. ad hoc networks), device to PAN coordinator (i.e. uplink transmission) and PAN coordinator to device (i.e. downlink transmission) [44]. Furthermore, the IEEE 802.15.4 standard employs either the slotted CSMA/CA or un-slotted CSMA/CA mechanism to operate and establish the transmission. In the former, the standard uses the beacon-mode to operate the transmission. In contrast, in the latter, the standard uses the non-beacon-mode in order to accomplish the transmission [27]. However, regarding to the work in this thesis, the focus is just on the slotted CSMA/CA mechanism literature.

The beacon-enabled IEEE 802.15.4 standard adopts the slotted CSMA/CA model, which is unlike the CSMA/CA model used in the IEEE 802.11 standard. Many changes and enhancements have been implemented for the formal model over the latter in terms of: clear channel assessment (CCA), backoff delay and the behaviour of the time slots. These enhancements make the channel sensing and accessing procedures using the IEEE 802.15.4 standard more efficient and suitable for LRWPAN networks. The main differences between the two standards are [44]:

- A device in IEEE 802.11 spends more energy due to the continuous checking of the channel situations throughout the whole period of the backoff counter. This case is different in the IEEE 802.15.4 standard, in which the device moves to the idle stage throughout the backoff counter in order to conserve more energy and checks the channel situation only after the end of that counter delay.
- The backoff counter in IEEE 802.11 is suspended and passed whenever the channel is busy, which is different from the IEEE 802.14.5 standard, which keeps the decreasing of the backoff counter irrespective of the channel situation.
- The size of the contention window (W) for IEEE 802.14.5 is reset to the minimum value after each retransmission attempt, which not the case for IEEE 802.11.

The superframe structure of the IEEE 802.15.4-based slotted CSMA/CA is shown in Figure 2.3, which is generated and sent periodically to the devices by the PAN coordinator in order to synchronise and establish the transmission using the beacons. These beacons identify the beacon interval (BI) between two consecutive beacons and the superframe duration (SD). In general, the superframe is divided into an active period and an elective inactive period. Throughout the latter, the devices can move

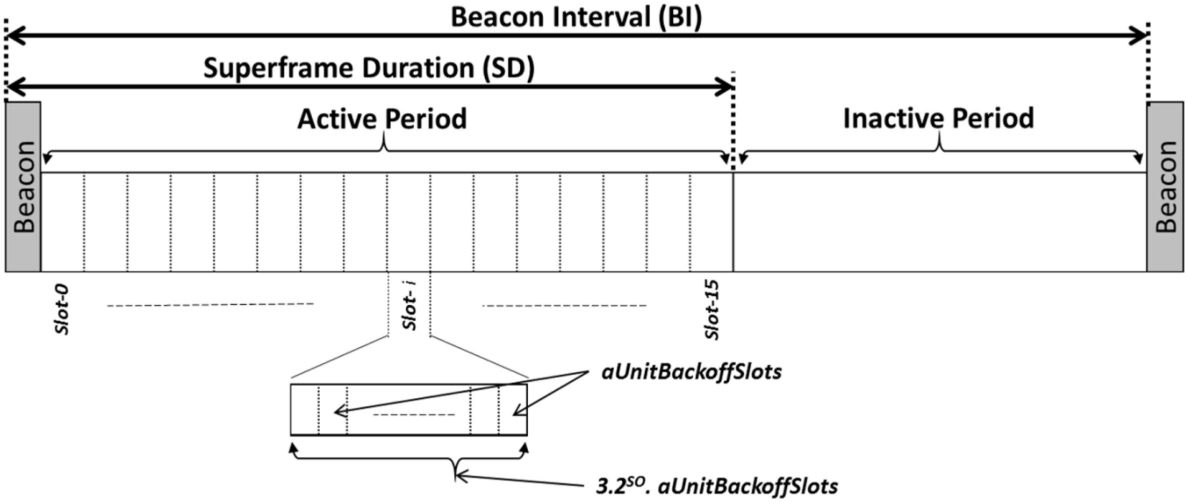


Fig. 2.3. IEEE 802.15.4 frame structure [35]

to a low-power sleep mode in order to save their energy. The active period, on the other hand, is divided into two portions known as a contention free period (CFP), which is optional and a contention access period (CAP).

As shown in Figure 2.3, the duration of the CFP and CAP can be specified by identifying two important parameters, namely, the macSuperframeOrder (SO) and the macBeaconOrder (BO). The BO value depends on the BI and it is specified as follows:

$$\mathrm{BI} = \mathrm{aBaseSuperframeDuration} \times 2^{\mathrm{BO}} \qquad \text{for} \;\; 0 \leq \mathrm{BO} \leq 14 \quad (2.1)$$

where, the aBaseSuperframe Duration is equal to the number of symbols that establish the superframe when the value of the SO is initialised to zero or when the BO is set to 15. The value of the SO identifies the period of the beacon interval plus the active portion and it is given by:

$$\text{SD} = \text{aBaseSuperframeDuration} \times 2^{\text{SO}} \qquad \text{for} \;\; 0 \leq \text{SO} \leq \text{BO} \leq 14 \quad (2.2)$$

The CFP, which is employed for QoS purposes, is constituted from up to seven Guaranteed Time Slots (GTSs) that directly follow the CAP. The PAN coordinator allocates these GTSs to particular devices upon their request. A device with an allocated GTS has complete access to the channel throughout its allocated time. On the other hand, the devices implement the slotted CSMA/CA technique (shown in Figure 2.4) during the CAP to access the medium. Furthermore, this technique implements the Binary Exponential Backoff (BEB) procedure in order to minimise the collision probability that is caused due to the attempt to access the medium. The BEB procedure is operated by initially setting three main parameters, namely: the Contention Window (CW), Number of Backoff stages (NBF) and the Backoff Exponent (BE), with the values of two, zero and macMinBE = 2, respectively. Then, each devices selects a random backoff duration from the interval $[0; 2^{BE}-1]$. Whenever the backoff counter reaches zero, the device uses two Clear Channel Assessments (CCA1 and CCA2) to detect whether the channel is idle or busy.

Moreover, the transmission is commenced only if the channel is detected to be idle for two consecutive CCAs, with the condition that the residual time slots in the present CAP are adequate for transferring both the packet and the ACK. Otherwise, if the condition is not satisfied, then the devices have to delay the transmission to the following superframe. However, if any of the CCAs discover that the channel is busy, then the following steps are implemented:

- The CW value is reset to two.
- The BE value is increased by one, up to a macMaxBE value. However, if the BE value reaches the macMaxBE, then it cannot be altered unless there is the occurrence of either failed or successful transmission, in such a case, the BE value needs to be reset to macMinBE.

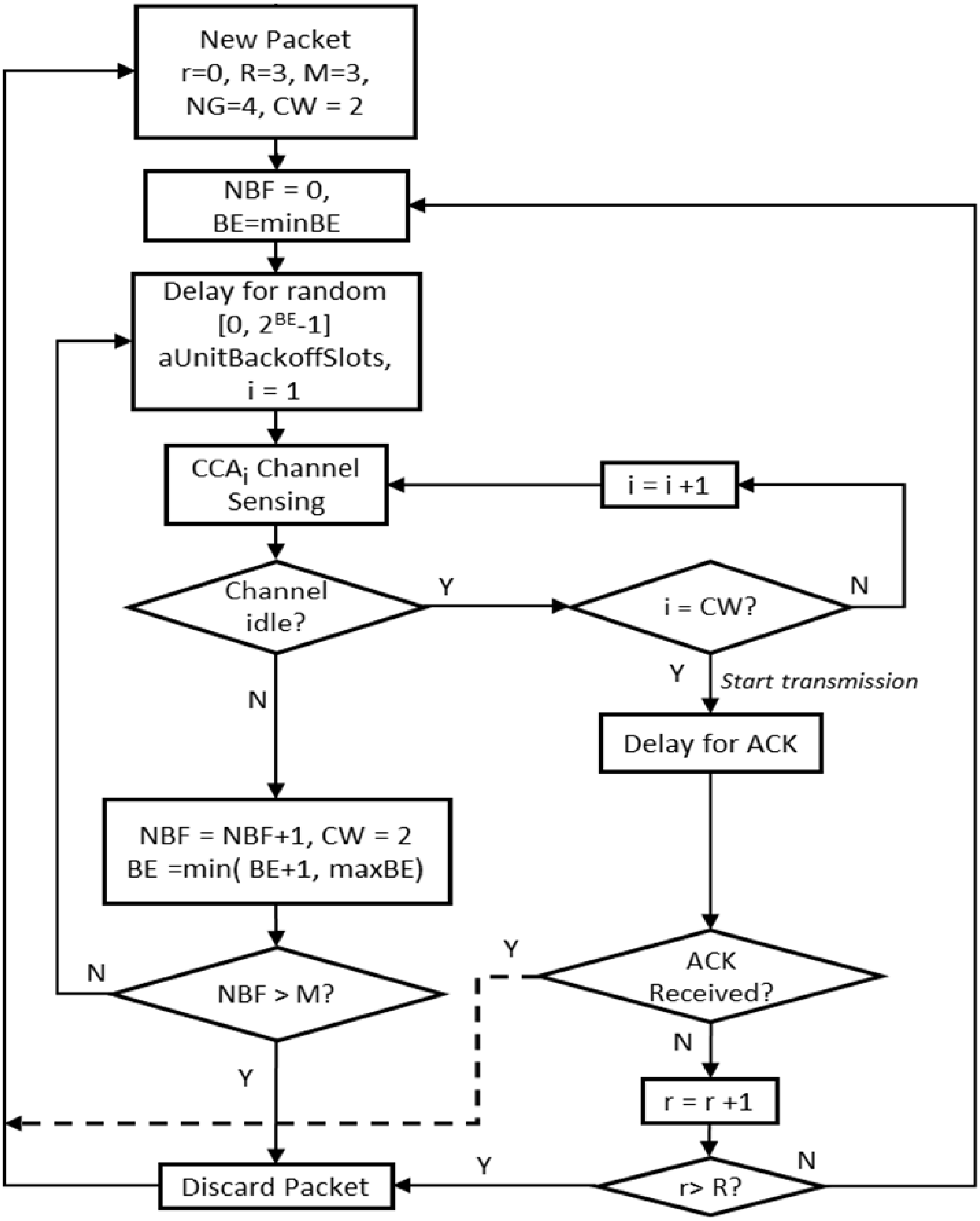


Fig. 2.4. Flowchart of the channel access mechanism [35]

- The backoff of the device is increased by one, up to a maximum value of macMaxCSMABackoffs and the packet will be discarded if the backoff value crosses it.

After any successful transmission, the device waits for an ACK packet from the receiver. If the ACK packet is not received, that mean a collision has occurred and the device needs to implement the retransmission process, up to macMaxFrameRetries tries. However, if the number of tries crosses this, then the packet will be discarded.

The IEEE 802.15.4 MAC mechanism is distinguished by numerous robust features, which are useful for WSNs. However, many deficiencies can be identified in the mechanism of the IEEE 802.15.4 standard that can lead to a deterioration in network performance. For example, the determination of the BE value is random and during the BE determination process, the network does not consider network intensity, the communication level in the medium, and the probability of channel failure and packet collisions. Additionally, IEEE 802.15.4 MAC lacks the essential dynamic and adaptive mechanisms that would enable it to perform more efficiently: in various network loads (low or high loads), under saturation networks (when devices always have packets to transmit) and with minimal power depletion of IoT devices. The IEEE 802.15.4 standard is commonly installed in the WSNs and IoT networks, which are, in general, high-density networks; however, this standard seems unable to perform efficiently in a high-density network. For, packet collisions and channel failures occur and retransmission actions are commenced, which leads to higher power depletion. As a result of these problems, the IEEE 802.15.4 standard is less suitable for IoT and WSN communications. Consequently, improved mechanisms and algorithms for this standard are required to mitigate its issues and to make it perform more efficiently in such networks.

2.4 Routing Protocols

According the work presented in this thesis, this section has been divided into three subsections. Each subsection briefly reviews several energy-efficient algorithms that have been anticipated either for mobile-sink nodes path determination or for clustering-based routing algorithms.

2.4.1 Static Sink-Based Routing Protocols

Clustering techniques in the WSN environment can be defined as the grouping of sensor nodes into clusters to achieve a high level of energy efficiency, improve network lifespan, and to enhance network scalability. There are many clustering algorithms available in the WSN literature, such as LEACH [13, 18], stable election protocol (SEP) [76, 77], and other clustering-based optimisation algorithms [14, 78–82]. This subsection reviews the current literature on traditional and optimised cluster based routing protocols.

2.4.1.1 Traditional Clustering Protocol

Several energy-aware traditional-based clustering protocols [13, 18, 76, 77, 83–85] have been proposed to improve the performance of WSN and IoT networks, some of which are summarised below.

The LEACH [13] is a hierarchical distributed and probabilistic protocol in which the cluster heads collect the data from the nodes, then aggregate and transmit them to the sink node. The main purposes of LEACH are: firstly, to expand a WSN's lifetime by regularly attempting to disperse the energy consumption between all the network nodes; and secondly, to decrease the energy consumption in the network nodes by accomplishing data aggregation [86]. Moreover, simulation rounds are essential units of the LEACH protocol, with each consisting of two stages: cluster set-up stage and steady state storage. At the first stage, each node is selected to be a CH with a probability (“ρ”) and that chosen broadcasts the decision. After its election, all the CHs broadcast a cluster head advertisement message to the other nodes using the CSMA of the MAC protocol through the same level of energy. After that, non-CH nodes choose their cluster for this round, by selecting the CH based on the received signal strength of the advertisement message and return this information back to the CH once more using the CSMA in MAC protocol. The cluster head then constructs a TDMA schedule for each node in its cluster to collect the data in a specific time slot and broadcasts this schedule back to all the nodes. Nodes that have been CHs have a $(1/\rho)$ probability of becoming CHs in the coming rounds.

The scenario is achieved by getting each node to pick out a random number T between 0 and 1. A node becomes a CH for the present round if the random number is lesser than the following threshold:

$$\mathrm{T_i} = \begin{cases} \frac{\rho}{1-\rho(\mathrm{r} \bmod \frac{1}{\rho})} & \text{if i} \in \mathrm{G} \\ 0 & \text{if otherwise} \end{cases} \tag{2.3}$$

where, r is the present round sequence and G is the set of nodes that have not been CHs in the previous $1/\rho$ rounds.

Moreover, some valuable extensions to LEACH have been suggested in the literature. For example, a centralised-based LEACH (LEACH-C) protocol was developed later by Heinzelman et al. [18], wherein the cluster construction process is performed by the sink using information about the residual energy of the devices and their current position, so that devices with a greater amount of remaining energy are more suited to becoming a CH. In addition, Two Level LEACH (TL-LEACH) has been developed in [83] to consider two hops of CHs.

The SEP [76] is a two-level heterogeneity routing protocol;, which represents an enhancement over the LEACH protocol in WSNs. In SEP, sensor nodes are categorised according to their initial energy into two types: normal nodes and advanced nodes. The latter type of nodes have higher energy than the former. Moreover, as in LEACH, the CHs election is accomplished randomly depending on the probability of each node. However, the advanced nodes have higher probability than the normal nodes, because they have higher initial energy. Simulation results showed an increment in network lifetime and throughput compared to LEACH due to the two levels of heterogeneity and they also displayed an improvement in the stability period. An extension of SEP, presented in [77], is called Threshold SEP (TSEP). TSEP is considered as three levels of heterogeneity according to node types. Furthermore, it categorises the nodes depending on their initial energy into three categories: super nodes, advanced nodes and normal nodes. The simulation results presented an improvement in terms of stability, throughput and network lifetime in comparison to other protocols.

Distributed energy efficient clustering (DEEC) was proposed in [84] for heterogeneous networks. In DEEC, the cluster heads are elected between the devices by a probability depending on the level of the residual energy of the device and the whole network energy. In addition, the number of rounds of each device is defined according to the residual and initial energy. The devices with higher residual and initial energy have a higher probability of being cluster heads than other devices. The simulation results showed that DEEC prolongs the network lifetime and the stability period more than other algorithms, such as SEP.

A threshold sensitive energy efficient sensor network protocol (TEEN), developed by Manjeshwar et al. [85], is based on the concept of LEACH in order to enhance the performance of WSNs in the data transmission process. To avoid the repetition of the transmitted data, the TEEN protocol develops two threshold metrics, namely, the soft and hard thresholds. The threshold metrics method can conserve energy by mitigating the amount of data sent, but it is not appropriate for applications demanding periodical data traffic, since the threshold metrics may not be satisfied.

The cluster formulation in the aforementioned clustering protocols is built in a random manner [86]. Hence, the clusters exhibit many weaknesses, such as their limited applicability to a large area network and failure to assure a good selection and dissemination of CHs [87]. In order to provide more efficient clusters, a centralised architecture-based cluster formulation is required, which in turn selects the devices that are more appropriate to be CHs than others.

2.4.1.2 Optimisation-Based Clustering Protocol

An example of optimisation-based protocols is clustering protocols-based PSO, such as those presented by [14, 78–80]. PSO, initially developed by Kennedy et al. [8], is an optimised scheme based on a preliminary set of random populations. It imitates bird flocking or fish schooling behaviour and customises a number of candidate solutions, called particles, that fly around in a search space to find the optimal solution [8]. A PSO based clustering (PSO-C) has been investigated by Latiff et al. [14], which is an energy-aware routing algorithm that employs the PSO algorithm at the base station for cluster construction. It considers both Euclidean distances between the CMs and their CHs, as well as the remaining energy of the devices during the CH selection process.

The authors in [14] considered the cluster formation to be based on a trade-off between the residual energy and the cluster communication costs that define CHs. However, they did not considered the distance between the CHs and the sink nor the node density and random distribution in the CH selection process. Alternatively, Wang et al. [78] proposed using a non-linear weight PSO (NWPSO). This selects the CHs depending on the initial energy and the communication cost, where the latter is the distance from the nodes to the sink, and then, the average distance between the CHs to the sink. However, NWPSO does not consider the distance between the CMs and the CHs nor does it consider the node density and the random distribution of this density [ibid].

Elhabyan et al. [79] suggested a different clustering algorithm using PSO, which presented the fitness function to find the optimum number of CHs based on residual energy and link quality between the CMs and the CHs; the protocol also attempts to maximise network coverage. However, it ignores the distances between the CHs and the sink, and the load balancing in the clusters formation phase, which can significantly influence the energy exhaustion of the CHs among the network and reduce overall network lifetime. Rao et al. [80] proposed an energy-efficient clustering algorithm based on PSO. The author used an adaptive fitness function comprising several parameters such as sink distance, intra-cluster distance and nodes residual energy. However, it does pay any attention to the load-balancing of nodes among the CHs.

Other energy efficient routing protocols in the literature, which employ different swarm optimisation algorithms, such as ant colony optimisation (ACO) [88] and Spider Monkey Optimisation (SMO) [89], have proved beneficial. For instance, ACO, suggested by Dorigo et al. [88], is another routing algorithm that simulates the social intelligence of ants when determining the shortest path from the source food to the nest. ACO based clustering has been further developed by Boucetta et al. [81] for CH selection, with the energy produced having prolonged network lifetime and improved connectivity. Another type of intelligent swarm is clustering based spider monkey optimisation (SMO-C) [82]. To adapt the WSNs clustering, this uses a mathematical model of the social searching behaviour of spider monkeys. The results show an improvement in terms of system quality and low energy consumption [82].

The WOA, developed by Mirjalili et al. [9], pertains to an efficient position updating technique of the search agents, which results in optimal WOA exploration compared to other meta-heuristic algorithms. This feature allows the search agents to reposition around each other in a random manner during the early stages. However, in the rest of the iterations, the search agents keep moving around themselves in a spiral path, with a high level of exploitation and convergence towards the best solution (best search agent) achieved so far. These two phases, namely exploitation and convergence, render the WOA more likely to avoid the local optima throughout the progress of iterations.

On the other hand, the PSO and other meta-heuristic algorithms use only one formula or phase in order to modify the value of the search agents, which increases the possibility of the optimal solution being trapped in the local optima. For this current thesis, the intelligent bubble-net foraging behaviour of humpback whales is utilised in order to develop a new centralised clustering protocol based SDN concept referred to as the CC-WOA. Moreover, both the scarcity of sensor resources and the high and random node density are considered when selecting the optimal set of CHs [90].

However, such routing algorithms do not acknowledge network synchronisation or balancing the load of the devices among the CHs. Furthermore, they assume that the sink is static, which results in more energy being consumed by the CHs as it sends its data to the sink.

2.4.2 Mobile Sink-Based Routing Protocols

2.4.2.1 Sink Mobility

This subsection presents sink node mobility techniques for a large scale WSN sensing field. The prevalence of sink nodes in the WSN monitoring area can be classified into four different categories [3]: static sink, MS, multiple mobile sinks and dual sink, where both static and mobile sinks are used.

With a static sink, the CHs usually use single or multi hop transmission to forward the data to the sink node. However, there is a load balancing problem in this technique, whereby in multi-hops transmission, the CHs closer to the sink node drain more energy as compared to others. This problem leaves many parts of the network disconnected and produces network energy holes, called the hot spot problem [3].

On the other hand, a sink node with mobility features travels across the sensing field to collect the data from the CHs. The sink mobility can be classified into three categories: predictable mobility, random mobility and controllable mobility [3,4]. The controlled mobile sink is presented by Sugihara et al. in [91]. The authors suggested a greedy maximal residual energy heuristic approach in which the sink node transfers to the new location, according to the maximum residual energy in the nodes. The results showed that the controlled mobile sink is more energy efficient as compared to uncontrolled sink mobility in a sensor network. More models for mobile sink improvements are available in [92–94].

In [95], the authors addressed the issue of a number of multiple mobile sink nodes for monitoring the WSN home environment and the mobile sink movement, velocity and starting position. The results showed that the network lifetime was improved once the number of sink nodes had been increased up to a definite point. However, once the number of mobile sink nodes crossed that certain point, then the performance of network lifetime stopped increasing.

The last category is the dual sink network, where both static and mobile sinks are used [4]. The author proposed a static sink located at the middle of the sensing field. At the beginning of the transmission, this sink broadcasts a “hello” message to all sensor nodes in the network. Thereafter, a mobile sink broadcasts a “hello” message, but only to a subgroup of nodes in the network. A comparison of simulation results between a static sink, single mobile sink and dual sink network, showed that the performance of the network using the latter most was much better than for the other sink mobility approaches.

2.4.2.2 Mobile Sink-Based Routing Algorithms

Generally, in WSNs the CHs deplete their energy more quickly than the cluster members deplete theirs, because they send the data to longer distances and perform data aggregation [14, 18]. In order to balance the energy consumption, CH selection and rotation with sink mobility is used to balance the energy dissipation among all sensor nodes in the sensing field without any degradation in network performance. A lot of researchers [19, 96–98] have attempted to develop energy efficient routing algorithms based on MS and the following paragraphs describe some of the related research.

Mobile sink improved energy-efficient PEGASIS-based routing protocol (MIEEPB) was presented by [99]. This protocol enhances the lifetime of a WSN by presenting a multi-chain with multi-head concept based on the MS. However, the trajectory, sojourn and sojourn number of the MS are fixed, which means that this protocol suffers from a higher energy dissipation by the CHs when transferring their data to the MS or the sojourn points. Moreover, the impact of this issue increases the larger the scale of the area network.

Virtual Grid-Based Dynamic Routes Adjustment (VGDRA) was proposed in [97] to reduce the cost of route reconstruction of the sensor nodes by maintaining the best route to the latest location of the mobile sink. Moreover, VGDRA contains a set of communication instructions that manage the process of route rebuilding, such that only a restricted number of nodes are required to re-adapt their data routes toward the mobile sink.

On the other hand, Tian in [98] proposed the TRAIL protocol. In this protocol, the sink node produces a trail path for its movement throughout the entire network. Furthermore, if the device has a trail path, then it uses the recent one to forward its messages to the sink; otherwise, the device uses a random walk technique to forward its messages to a sensor device that has an updated trail path of the sink node or sends it to the sink node directly.

Tunca in [19] suggested a protocol that employs three kinds of nodes: ring, anchor, and regular nodes. Initially, the speed of the MS was defined as being between 0 and 5 m/s. The ring nodes memorise information regarding the location of the anchor node and they are generally positioned at a defined distance from the centre of the network. The anchor node, on the other hand, is positioned as the closest node to the sink. It needs to be changed when the link quality between it and the sink degrades below some threshold. Furthermore, when a regular node has data to be transferred to a sink node, then it first has to inquire of the ring node the anchor node's location. The regular node can start the transmission of data to the anchor node using geographical routing, once it receives this location.

2.4.3 SDN-Based Routing Architecture

SDN technology, firstly, was suggested and dicussed in [10, 11]. This technology, due to its vital and indispensable attributes, has received much consideration for improving the performance of the various types of traditional networks, such as campus networks [10], data centre based cloud [7], etc. Recently, substantial efforts [6, 100–102] in research have been made aimed at improving the performance of the IoT and WSNs by using SDN technology. This subsection discusses some of the research relating to this.

SDN based on the open-flow protocol for WSN nodes has been proposed by Luo et al. [6]. Following this suggestion, Gante et al. [100] discussed taking a broader approach to the administration of SDN in WSNs and discussed its advantages also. The authors proposed that the SDN controller be positioned at the base station and having the responsibility of routing control between the sensor nodes. However, the communication details, such as data and control messages communication, between the sensor nodes have not been presented in their research. Olivier et al. [101] proposed a clustering technique for WSNs to be accomplished by the SDN controller. The sensor nodes are organised into multiple groups of sensor nodes in a hierarchical manner. Furthermore, the SDN controller is positioned at the CH nodes to manage the cluster.

Another improvement of the WSNs based-SDN technology is the TinySDN that was proposed by Oliveira et al. [102], which allows multiple controllers for WSNs. The proposed model comprises two main nodes: the SDN assisted sensor node (switch) and the SDN controller node, with its simulation results being concentrated on the delay and memory footprint. The authors in the above studies examined the construction and framework of SDN-based WSNs; however, they did not use the optimisation technique to discover the optimal clustering method, nor did they use cloud resources in their construction, because the SDN controller is executed at the sink.

In WSN routing algorithms, the energy is generally consumed due to the complexity of the network and data transmission. The control functions are placed within the duties of the node, which exploit node resources and increase network complexity [1]. Additionally, unbalanced cluster formulation is an inherent concern in WSNs, for this causes uneven energy exhaustion amongst CHs in the network, which can significantly reduce network lifespan [1]. Furthermore, nodes in networks with the MS consume most of their resources when they identify the time scheduling and path of the MS. These protocols are thus not suitable for large-scale networks, because of their high use of energy, due to either the unbalanced formulation of the clusters or insufficient synchronisation between the CMs, CHs, and the sink(s).

In chapter five of this thesis, an efficient load-balancing routing protocol is proposed, which defines the concept of SDN in a way that reduces the functionality implemented by the nodes and provides an efficient scheduling technique for the MS across the entire network. The SDN controller uses an efficient optimisation technique, which schedules the CMs, CHs, and the MS. This scheduling technique allows the nodes to sleep/wake-up, according to the arrival time of the MS, and thus, enhances the lifespan of the entire network.

2.5 Summary

The chapter has presented the available energy-efficient related protocols for IoT communication. The previous sections discussed several current routing and MAC protocols. According to the energy conserving techniques, the existing protocols have been categorised into multiple subcategories. On the one hand, the MAC protocols have been categorised into three main categories, namely, contention-based protocols, contention access protocols and hybrid protocol. Whilst the contention-based protocols have been divided into two classes: the analytical-based and the simulation based studies. On the other hand, the routing protocols have been classified into three categories: routing protocols based-mobile sink, routing protocols-based static sink and routing protocols based on SDN technology. Finally, the chapter has also provided an overview of the IEEE 802.15.4 standard and its advantages and challenges that need to be considered when associated with IoT devices.

Chapter 3: Hybrid MAC Protocol for High Density IoT Networks

3.1 Introduction

The increased globalisation of information and communication technologies has transformed the world into the IoT. In general, the MAC protocol associated with the IoT is divided into three main categories: contention free protocol, contention-based protocol and hybrid protocol [20]. The contention free protocols have some drawbacks, for example, it is difficult to adapt to variant network loads, i.e. low or high, leading to either inefficient channel utilisation or limited network scalability. Another drawback is that the transmission is delayed when the beacon interval is increased due to the fixed size of the beacon intervals [36]. The contention-based mechanisms suffer from high congestion associated with either a high density of IoT devices or a hidden node problem [36]. Whilst, the performance of the hybrid protocol still seems to suffer from enormous energy depletion in high-density networks. Thus, adaptable scheduling, involving dynamic switching between sleep and wake-up periods, is required to accomplish superior channel access in such networks.

Accordingly, in this chapter, an on-demand extension to the IEEE 802.15.4 standard is proposed to deal with the above mentioned IoT issues. This extension integrates scheduled sleeping periods into the standard. These sleeping periods are dynamically adapted according to the network size, collision status and channel failure, thus leading to efficient throughput and power savings as well as high channel utilisation. Furthermore, an efficient frame structure is proposed based on a hybrid TDMA-CSMA/CA MAC protocol with a beacon-enabled mechanism. The BS arranges and schedules the $\text{TDMA}_{\text{slots}}$ and the scheduling table (ST) message. The channel access patterns are designed to conserve energy, whereby sleep/wake-up mechanisms are aligned to the standard, which enables some groups of devices to switch to a low power sleep model. However, when the network load is low or there is no collision, the devices can continue accessing the channel at any $\text{TDMA}_{\text{slot}}$ after a competition to access the channel using CSMA/CA. Moreover, the devices move into sleep mode only when the medium experiences a high collision rate or channel failure.

The remainder of this chapter is structured as follows: Section 3.2 describes the formulation of the problem behind the development of the proposed HSW-802.15.4. The frame structure and the methodology for the proposed protocol are provided in Section 3.3. Section 3.4 briefly discusses the proposed HSW-802.15.4 based dynamic sleep mode and presents an analytical model for a three-dimensional Markov chain compatible with the proposed model for calculation of the network metrics. Section 3.5 validates the proposed protocol. The numerical results are presented and discussed in Section 3.6. Section 3.7 briefly discusses the contributions added by this chapter, whilst final conclusions are presented in Section 3.8.

3.2 Problem Formulation

On the one hand, the performance of all the analytical models (described in Chapter two) for the legacy IEEE 802.15.4-based slotted CSMA/CA still suffers from high-energy depletion due to a high collision rate or channel failure. Furthermore, the IoT devices compete to access the channel, and consequently, congestion increases as the network density rises. This dramatically worsens network performance in terms of energy consumption, throughput, channel utilisation and delay. In such a scenario, the devices may either have to go through several backoff stages before attempting transmission or possibly experience a transmission failure. Another common dilemma in IEEE 802.15.4 networks concerns the hidden node issue. This increases the number of collisions, which leads to greater energy depletion as a result of a higher number of retransmissions. Moreover, the IoT devices generally suffer from two types of problems, namely: device resource restriction and protocol design.

Regarding device resource restriction, IoT devices are all severely constrained in terms of power supply, communication capability and memory units. In fact, power consumption is the primary restriction placed upon them. Moreover, the vast majority are not rechargeable, because they are usually designed in a small-sized system that constrains the capacity of the battery and memory. Additionally, the periodic battery replacement for those devices is unfeasible due to the device deployment in vital environments and the large number of IoT devices. Furthermore, the complex computations that necessitate unique processing capabilities and extended memory units require massive power resources and thus, dramatically reduce the overall lifespan of the IoT network. The strict resource-constrained situations in which IoT devices operate make energy conservation a primary factor to be considered when undertaking protocol design in such networks.

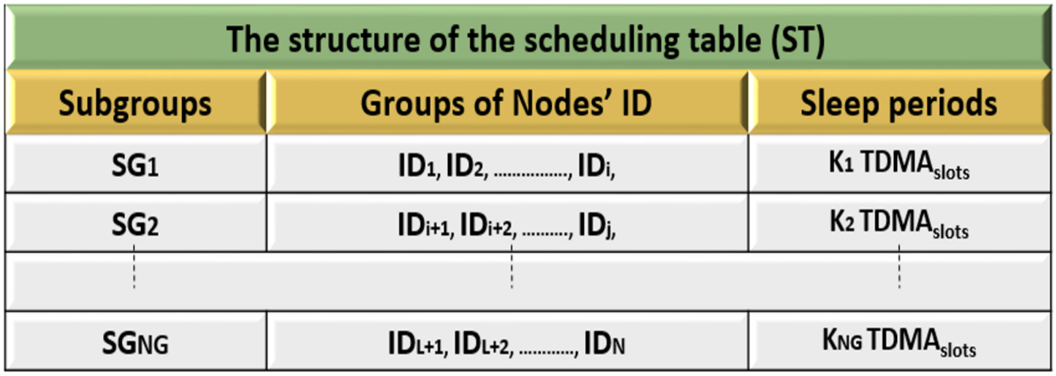
Regarding the protocol design problem, the MAC protocol responsibility should be in handling the channel access mechanisms, failure control, and validation of the superframes. However, MAC protocols such as CSMA/CA and TDMA usually focus on some network parameters and ignore others. For example, TDMA takes into consideration energy saving and neglects throughput, delay and channel utilisation. Furthermore, with TDMA, it is difficult to adapt the channel to the variations in the network density, whether this is low or high load, thus leading to either inefficient channel utilisation or limited network scalability. On the other hand, the hybrid MAC protocol is useful for addressing the weaknesses of the above protocols and also combines their strengths. However, it cannot ensure efficient energy saving in a high-density network. Hence, a dynamic MAC protocol that minimises the energy consumed by IoT devices during their connection process to the Telecom is essential and needs to be designed. Furthermore, extended periods of sleeping devices and the use of energy efficient techniques can all help to extend the battery life of these devices.

Accordingly, in this chapter, an effective power saving structure using a dynamic scheduling MAC technique is proposed. This technique dictates the task to be achieved at a particular time and obliges groups of devices to sleep. Furthermore, the scheduling sleeping technique is adapted according to conditions, such as high collision or channel failure, to determine which group of devices will be active in a certain $\text{TDMA}_{\text{slot}}$. The proposed protocol will accomplish superior channel access enhancement in a high-density network and extend the lifespan of IoT devices.

3.3 Proposed Scheduler HSW-802.15.4 MAC Protocol

The novelty of this chapter is represented by suggesting a new sleep/wake-up extension to the mechanism of the IEEE 802.15.4 standard that forces groups of devices, when the network experience high collisions or channel failure, to sleep mode with different sleep periods. Therefore, this extension makes the proposed HSW-802.15.4 MAC works efficiently with both high and small density IoT networks.

Power dissipation is a vital issue for battery power supported devices in IoT and WSNs. To address this problem, an effective scheduling message, known as the ST (see Figure 3.1), has been proposed to force groups of them into sleep mode. The proposed scheduling method is extremely efficient in terms of energy conservation, especially for battery-powered devices. It selects the mission to be performed at a given moment by determining which group of devices will be active in each $\text{TDMA}_{\text{slot}}$, and by allocating physical layer resources. In this section, the structure of the proposed protocol in terms of network architecture, frame structure and methodology is discussed.



The structure of the scheduling table (ST)		
Subgroups	**Groups of Nodes' ID**	**Sleep periods**
SG_1	$ID_1, ID_2, \ldots\ldots, ID_i,$	K_1 $TDMA_{slots}$
SG_2	$ID_{i+1}, ID_{i+2}, \ldots\ldots, ID_j,$	K_2 $TDMA_{slots}$
⋮	⋮	⋮
SG_{NG}	$ID_{L+1}, ID_{L+2}, \ldots\ldots, ID_N$	K_{NG} $TDMA_{slots}$

Fig. 3.1. The structure of the proposed scheduling table ST

3.3.1 Network Architecture

In this chapter, the use of a star wireless personal area network with a single-hop is assumed. It is composed of a fixed number (N) of devices and a PAN coordinator. Furthermore, it is assumed that, as a high-density network, each device always has a packet available for sending, which means it works in a saturated area. The devices also exhibit locational awareness using the geographical position system (GPS), and can send their location along with their identification address (ID) to the PAN coordinator.

In the proposed protocol, the PAN coordinator divides the network devices into multiple subgroups (SG_i), according to the ID and location of the device. At the commencement of each superframe, the coordinator sends the ST message as a notification during the beacon period. As Figure 3.1 shows, the ST message provides information about the number of subgroups (NG) and the IDs of the devices belonging to each SG_i. Additionally, it contains information about the sleep/wake-up times for each SG, which is used to conserve energy by specifying the maximum number of $TDMA_{slots}$ each device should have. These are known as $KiTDMA_{slots}$.

The $KiTDMA_{slots}$ for each SG_i are chosen by the coordinator according to device priority, so that devices at a SG_i with higher priority are allocated fewer $KiTDMA_{slots}$

than other subgroups. The ST message is thus used to schedule devices to enter a longer sleep mode, rather than a longer contention period (CP). During the CP (See Figure 3.2), the devices in the specified $\mathrm{SG_i}$are eligible to compete using the CSMA/CA method, to obtain access to the channel and transmit data during $\mathrm{TDMA_{slots}}$, also known as transmission periods ($\mathrm{TP_{transmission}}$). However, when the network does not experience any channel collisions or failure, all the other devices can compete and obtain access to the channel as a normal IEEE 802.15.4 without an adaptable sleep mode.

In this thesis, a hybrid MAC protocol is proposed in which a specified group of devices are permitted to enter the CP at a specific $\mathrm{TDMA_{slot}}$, rather than all the devices. Figure 3.2 shows the modified superframe structure for the proposed model, which is compatible with the traditional IEEE 802.15.4. As such, the proposed hybrid protocol can significantly reduce network collisions and improve performance. It uses a superframe architecture, where network beacons are periodically broadcast by the PAN coordinator to bind each superframe. The network beacons are used to describe the architecture of the superframes, and to synchronise as well as scheduling the attached devices by sending an ST message (see Figure 3.3-a).

The superframe of the proposed protocol is, firstly, divided into 16 equal sized $\mathrm{TDMA_{slots}}$ by the PAN coordinator, in a similar way to the IEEE 802.15.4 standard. Each $\mathrm{TDMA_{slots}}$ is allocated to a specific $\mathrm{SG_i}$. A device that wishes to access the channel can only compete with other devices in the same $\mathrm{SG_i}$ using a CSMA/CA mechanism (see Figure 3.3-a). However, there is an exception to this rule, which is that the device can enter the contention period with other subgroups when the channel has not suffered from any previous failure or collision. This mechanism has the dual advantage of offering efficient utilisation of the channel in low-density networks, and reducing the number of collisions by following the ST message with high-density networks.

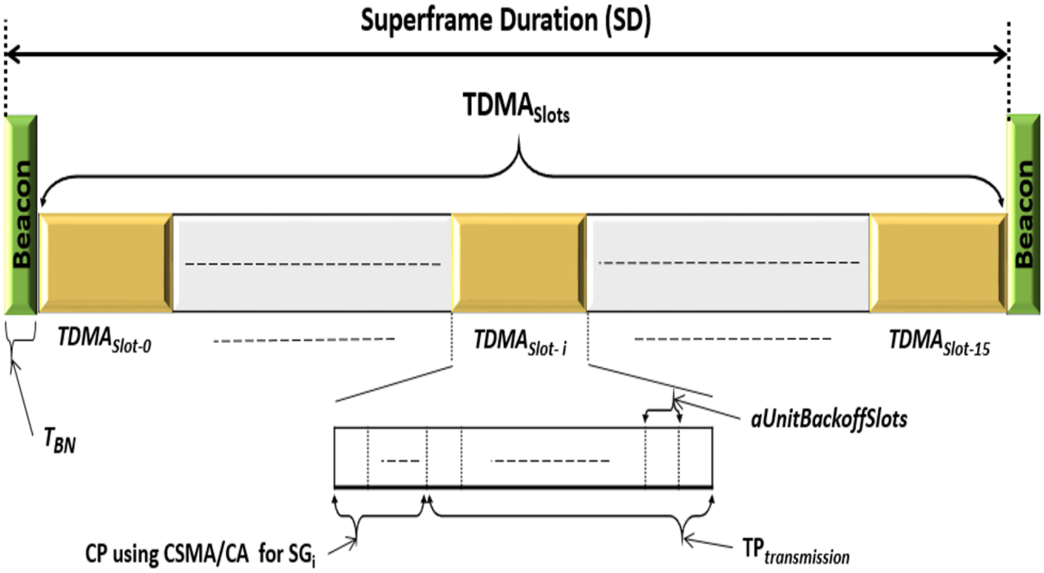


Fig. 3.2. The proposed superframe structure that shows the CP and TP periods while $\mathrm{TDMA_{slots}} = 16$

3.3.2 Frame Structure

The present IEEE 802.15.4 protocol is based on a simple time unit called a UnitBackoffslots period (BP) and three random based variables: back-off exponent (BE), contention window (CW), and number of back-off stages (NBF). The proposed protocol introduces other substantial variables, which are the length of sleep period ($\mathrm{LS_i}$), and the number of $\mathrm{SG_i}$ of the devices (NG). Furthermore, each device dynamically calculates its sleep period according to the information from the ST message (See section 3.4.1).

3.3.3 Methodology

The proposed protocol is designed according to the specifications of IoT networks and the transmission process for the proposed HSW-802.15.4 protocol is shown in Figure 3.3-b. In the proposed protocol, the MAC layer firstly initialises the following vari-

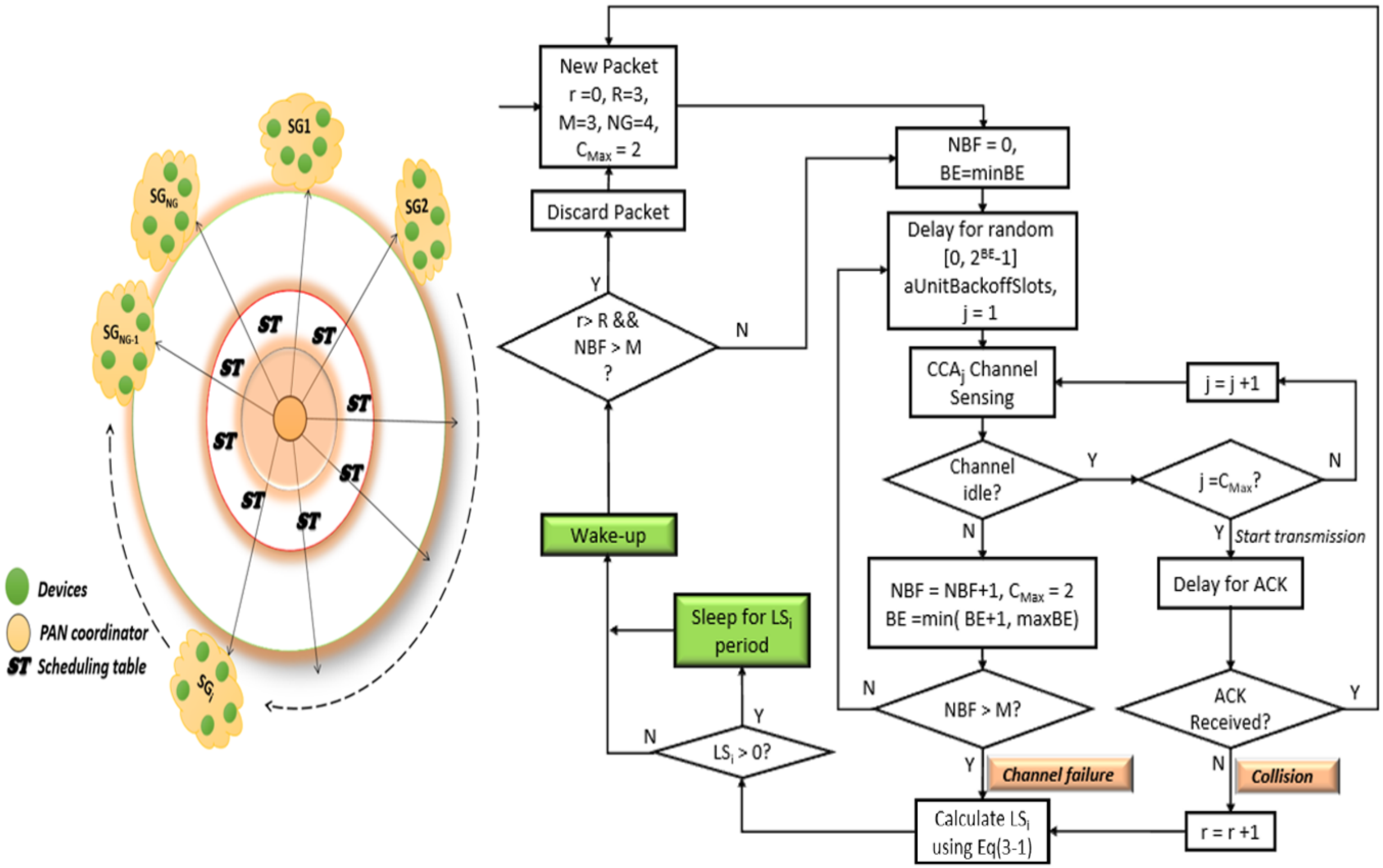


Figure a

Figure b

Fig. 3.3. a- Network star topology with SG_{is}, b- Transmission process for the proposed HSW-802.15.4

ables: contention window, back-off exponent (BE = MinBE), macMaxCSMABackoff ($M = 2$), number of back-offs counter (NBF = 0), maximum frame retries ($R = 3$), retransmission counter ($r = 0$), maximum number of CCAs ($\mathrm{C}_{\mathrm{Max}} = 2$), CCAs counter ($i = 0$), and number of SG = NG.

The device then waits for a random back-off number (BF) in the range $[0; 2^{BE} - 1]$ multiplied by the time of the BP. When the back-off counter reaches zero, the device senses the channel using clear channel assessment (CCA). If two successive CCAs are idle, the device initiates the transmission, whilst if is busy, the MAC layer will increase the value of both NBF and BE by one up to a maximum value of M and MaxBE, respectively. If the channel access is successful, the device starts transferring its packet and waits for acknowledgement (ACK). If the device receives the ACK, the transmission has succeeded and if not, a collision is detected and the devices involved should increase the variable r up to the value R. If the channel experiences a channel failure or a collision, the device calculates the length of the sleep period LS_{i} and either continues trying to access the channel, if it belongs to a permitted SG_{i} and $\mathrm{LS}_{\mathrm{i}} = 0$ or turns to sleep mode, according to the ST and the calculated LS_{i} (see equation 3.1). After the LS_{i} period, the device, depending on its NBF and r, decides either to discard its packet and generate a new one or to retransmit its packet by reinitialising the NBF = 0, BE = minBE, $r = 0$, and $i = 0$. The parameters used for the proposed protocol are listed in Table 3.1, which are the same as the default IEEE 802.15.4 MAC parameters.

3.4 HSW-802.15.4 Analytical Model and Notations

This section describes the analytical model for the proposed HSW-802.15.4 MAC protocol-based schedule sleep extension. The main aim of this protocol is to save power and prolong the overall lifespan of the IoT network. The energy consumption of the IEEE 802.15.4 standard is primarily influenced by the probability of channel access failure or collisions, and MAC parameters. Hence, the proposed HSW-802.15.4

Table 3.1
The parameters used by the HSW-802.15.4

Parameters	Values
Number of backoff stages (NBF)	0 ... 5
MinBE and MaxBE	3 and 5, respectively
Backoff Exponent (BE)	0 ...3
Contention period (CW)	2
Number of sleep stages ($\mathrm{K_i}$)	0 ... NG
Number of $\mathrm{SG_i}$ (NG)	1 ... 16
Maximum frame retransmission (R)	3
Total packet size ($\mathrm{PCK_L}$)	127 byte
Data Rate (DR)	250 kbit/sec
$\mathrm{TDMA_{slot}}i$ length	60 ms
Transmission power ($\mathrm{PW_{tx}}$)	30 mW
Receiving power ($\mathrm{PW_{Rx}}$)	40 mW
Idle power ($\mathrm{PW_{idle}}$)	0.8 mW
Channel sensing power ($\mathrm{PW_{CCA}}$)	40 mW
Sleep power ($\mathrm{PW_{SL}}$)	0.16 μW

protocol employs a strategy to force some groups of nodes to sleep for a calculated $\mathrm{LS_i}$ period, whenever there are channel collisions or channel failure.

Using this method, the proposed protocol becomes more adaptable and flexible as it dynamically adapts the sleep nodes, working with both high and low-density networks. The behaviour of this new adaptable protocol can be easily observed in a high-density network by allowing more nodes to sleep with different periods. The main benefit of this lies in a substantial reduction in the probability of channel failure and collisions. The following subsections in this chapter explain the sleep period calculation used by each device, and the three-dimension Markov model, which is based on a dynamic sleep mode. Additionally, the influence of performance metrics and MAC parameters on overall network operations are also analysed.

3.4.1 Dynamic Sleep/Wake-up Period Calculation

In this section, the grouping method that divides the nodes into $\mathrm{SG_s}$, whilst dynamically allowing the $\mathrm{SG_s}$ to calculate and enter the Sleep/Wake-up periods, is described. In each specified $\mathrm{TDMA_{slot}}$, only one SG is permitted to compete for channel access (See Figure 3.4). The aim of this technique is to distribute the active nodes evenly among the $\mathrm{TDMA_{slots}}$ and reduce the power consumed by each node as it attempts to access the channel. This is because, depending on the node density in the network, a collision may be more likely to occur at one $\mathrm{TDMA_{slot}}$ than at others. Hence, when the device in the subgroup ($\mathrm{SG_i}$) experiences a channel failure or collision, it calculates the length of its sleep period ($\mathrm{LS_i}$) as follows:

$$\mathrm{LS_i} = \begin{cases} \mathrm{Y_i} \times \mathrm{N_{BP}} & \text{if } \mathrm{Y_i} \leq \mathrm{K_i} \\ \mathrm{K_i} \times \mathrm{N_{BP}} & \text{if } \mathrm{Y_i} > \mathrm{K_i} \end{cases} \tag{3.1}$$

where, $\mathrm{K_i}$ refers to the number of sleeping $\mathrm{TDMA_{slots}}$ allocated to the $\mathrm{SG_i}$ that is initially identified by the PAN coordinator (see Figure 3.1), while $\mathrm{Y_i}$ is calculated as

$$\mathrm{Y_i} = |\mathrm{SG_i} - ((\mathrm{Slot_{seq}} \mod \mathrm{NG}) + 1)| \tag{3.2}$$

where, $\mathrm{SG_i}$ is the subgroup i of devices to which the current device belongs. $\mathrm{N_{BP}}$ refers to the number of BPs in each $\mathrm{TDMA_{slot}}$. $\mathrm{Slot_{seq}}$ is the sequence of the current $\mathrm{TDMA_{slot}}$ and lies between 0 and 15. NG represents the number of subgroups. Furthermore, the ratio of the active and sleep nodes is adjusted by adding the calculated number of sleep $\mathrm{TDMA_{slots}}$ to the model based on $\mathrm{LS_i}$.

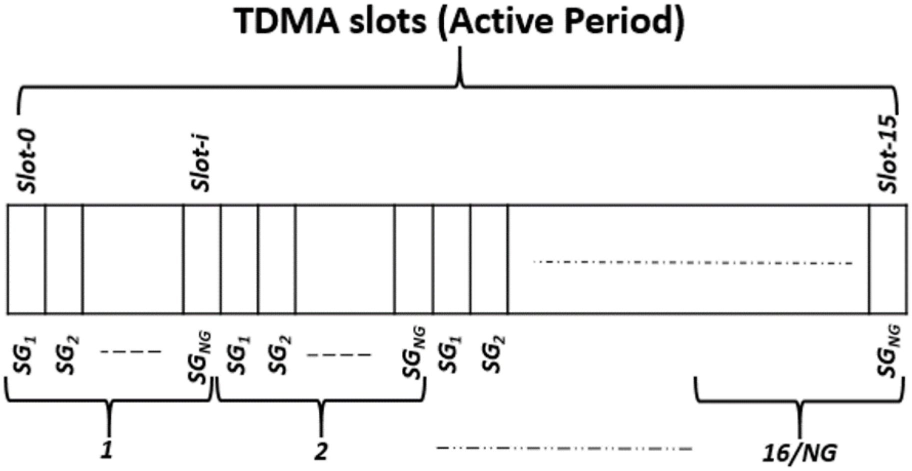


Fig. 3.4. Subgroups separation among time slots

It is worth noting that the sleep period identification process is similar to the random process used to identify the BF, which depends on the previous stage only and not on any others. In fact, the only difference between BF and LS_i is that the former is selected randomly, whilst the value of the latter is calculated according to Equation (3.1).

3.4.2 Markov Model

This subsection describes the analytical model for the proposed adaptive hybrid MAC protocol-based synchronised sleep mode. For the purposes of the analysis, a saturated network with beacon enabled and retry restrictions for each packet transmission is considered. The behaviour of the proposed HSW-802.15.4-based schedule sleep is modelled using a Markov model that takes into consideration the probabilities of collision and failure. Figure 3.5 shows the Markov model-based sleep mechanism of the HSW-802.15.4.

The analysis is split into two distinct steps, the aim of which is to identify a set of equations that exclusively describes the functionality of the network. During the first

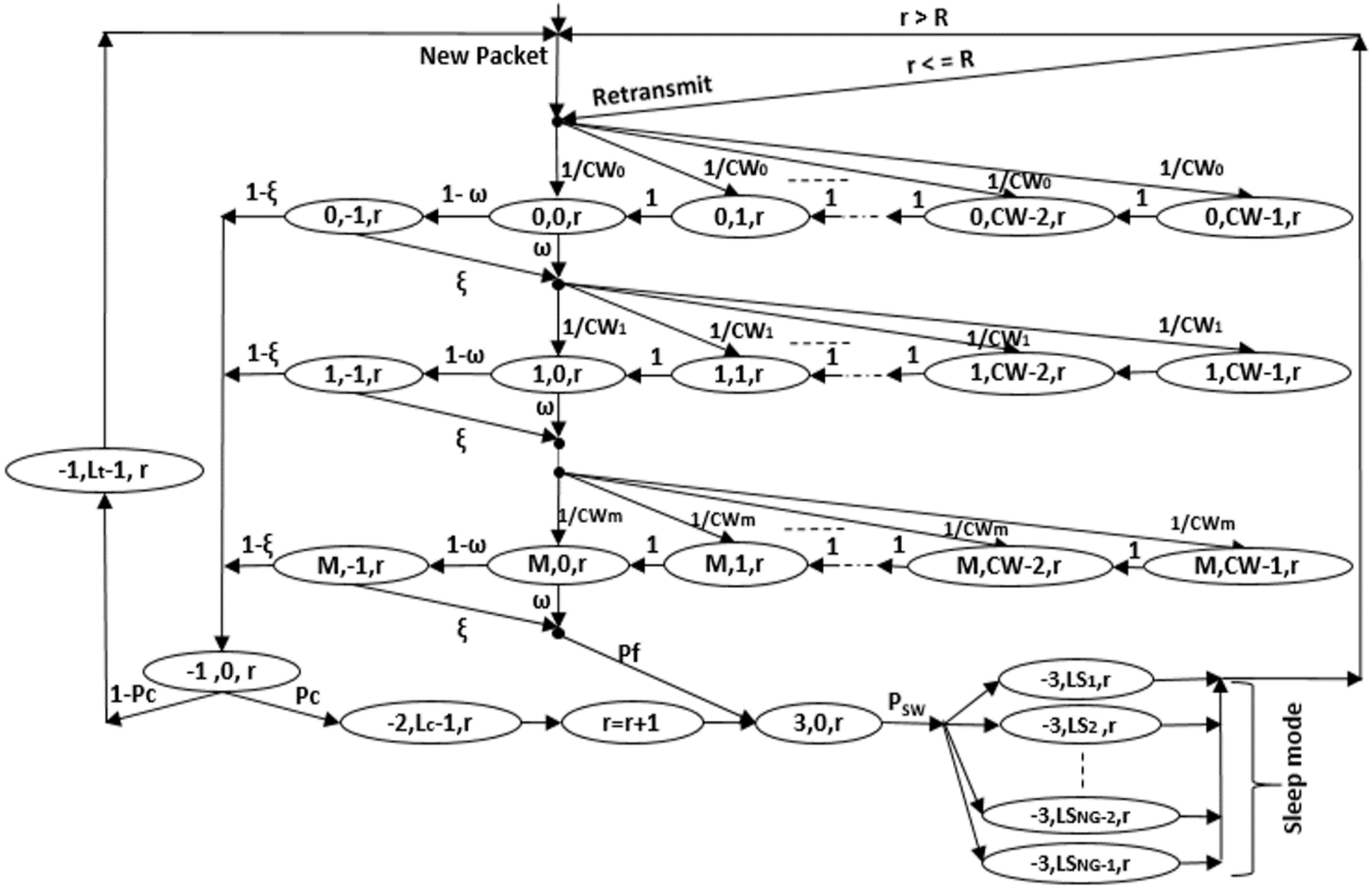


Fig. 3.5. Markov model for the proposed HSW-802.15.4

step, the actions of a single device are modelled using a three-dimensional markov chain to obtain the stationary probability (Θ) of the device attempting to access the channel for the first CCA within a given time slot. The per user Markov chains are then coupled to derive an extra set of equations to solve the system model. A significant assumption made during this coupling, is that the probability of sensing the carrier channel is constant and independent of other devices. Three stochastic processes describe the different states of the device during the transmission of a packet, namely: the back-off stage $G_b(t)$, the state of the back-off counter $G_c(t)$, and the state of the retransmission $G_r(t)$.

The integer time (t) matches the beginning of the time slot and is declared as the delay stages (when $G_b(t) \in (0, \ldots$,NBF) or the transmission stage ($G_r(t) = -1$). Furthermore, the stages ($G_b(t) = -2, -3$) introduce the collision stage and the sleep/wake-up stage, respectively. The $G_c(t)$ stage represents the delay counter of the device for a random duration between (0 and $CWi-1$). The values ($G_c(t) = -1, -2$) reflect to the first CCA and second CCA, respectively. The parameters M and R, in turn, are set to the values macMaxCSMABackoffs and macMaxFrameRetries. All other MAC parameters are shown in Table 3.1. The probability ω refers to the likelihood of the channel assessment finding the channel busy during CCA1, whilst the probability ξ pertains to channel assessment of finding the channel busy during CCA2. The stages $(-1, k, j), (-2, k, j)$ and $(-3, k, j)$ characterise the transmission state, the packet collision state and the dynamic sleep state, respectively. The parameters L_s and L_c denote the durations of packet transmission and packet collision, respectively. The transition probabilities for the proposed three-dimensional Markov model can therefore be derived as follows:

$$P(i, j, r | i, j+1, r) = 1, \qquad \text{for } j \geq 0 \qquad (3.3)$$

$$P(i,j,r|i-1,0,r) = \frac{\omega+\xi-\omega\xi}{\mathrm{CW}_i}, \qquad \text{for } i \leq M \tag{3.4}$$

$$P(0,j,0|i,0,r) = \frac{1-\omega-\xi+\omega\xi}{\mathrm{CW}_0}, \qquad \text{for } i \leq M, r < R \tag{3.5}$$

$$P(0,j,r|i,0,r-1) = \frac{(1-\omega-\xi+\omega\xi)\mathrm{P_{SW}}}{\mathrm{CW}_0}, \qquad \text{for } r < R \tag{3.6}$$

$$\begin{aligned} P(0,j,0|M,0,r) = \Bigg[&\frac{1-\omega-\xi+\omega\xi}{\mathrm{CW}_0} + \frac{(1-\omega-\xi+\omega\xi)\mathrm{P_{SW}}}{\mathrm{CW}_0} \\ &+ \frac{(\omega+\xi-\omega\xi)\mathrm{P_{SW}}}{\mathrm{CW}_0}\Bigg], \quad \text{for } r = R \end{aligned} \tag{3.7}$$

where $\mathrm{P_{SW}}$ shows the probability that the device is in the sleep stage and equivalent to:

$$\mathrm{P_{SW}} = L_c P_c + P_f \tag{3.8}$$

The values of P_f and P_c are calculated in section 3.6.1 and Equation 3.18, respectively. Equations (3.3 - 3.5) are similar to the Equations represented by [37], whereas Equations (3.6 and 3.7) have been added to represent the proposed sleep/wake-up model. Furthermore, Equation (3.3) represents the delay counter for a random number of slots. Equation (3.4) provides the probability that the device picks a state in the next delay stage due to sensing the channel is busy during either the first or the second CCA, with probabilities ω and ξ, respectively. Equation (3.5) refers to the probability of successfully sending the packet without collision after sensing the channel is idle for both CCAs and ($r < R$). Equation (3.6) denotes the packet being sent for retransmission due to collision. In this case, the device should calculate the LS_i before retransmitting it under the condition of ($r < R$). Equation (3.7) defines the probability of beginning a new transmission when the device is in the final delay stage. This is either due to sending the packet successfully; sending it with a collision after sensing the channel is idle for both CCAs, whereby the device needs to calculate $\mathrm{LS_i}$ before starting a new transmission; or channel access failure during either CCA1 or CCA2, which means the device needs to calculate the LS_i at a specific $\mathrm{TDMA_{slot}}$.

The steady state probability for the proposed Markov model is denoted by $b_{i,j,r} = P\{(G_b(t), G_c(t), G_r(t)) = (i, j, r)\}$, where $i \in \{-3, M\}$, and $j \in \{-1, \max(\mathrm{CW}_i - 1, L_t - 1, L_c - 1, \mathrm{LS_i} - 1)\}$, and $r \in \{0, R\}$.

$$b_{i,j,r} = \frac{\mathrm{CW_i} - j}{\mathrm{CW_i}} b_{i,0,r} \tag{3.9}$$

$$b_{i,0,r} = (\omega + (1 - \omega)\xi)^i b_{0,0,r} \tag{3.10}$$

$$b_{0,0,r} = [\mathrm{P_{SW}}(1 - (\omega + \xi - \omega\xi)^{M+1})]^r b_{0,0,0} \tag{3.11}$$

From Equation (3.9), for $i = M$ and $r = R, b_{0,0,0}$ is located from the following

$$\sum_{i=0}^{M-1} \sum_{j=0}^{\mathrm{CW_i}-1} \sum_{r=0}^{R-1} b_{i,j,r} + \sum_{i=0}^{M-1} \sum_{r=0}^{R-1} b_{i,0,r} + \sum_{i=0}^{M-1} \sum_{r=0}^{R-1} b_{i,-1,r} + \sum_{j=0}^{L_t-1} \sum_{r=0}^{R-1} b_{-1,j,r} + \sum_{j=0}^{L_c-1} \sum_{r=0}^{R-1} b_{-2,j,r} + \sum_{j=0}^{\mathrm{NG}-1} \sum_{r=0}^{R-1} b_{-3,j,r} = 1 \tag{3.12}$$

Next each expression in Equation (3.12) is derived separately according to Equations (3.9),(3.10) and (3.11). Furthermore, the delay line CW_i is started with $\mathrm{CW}_0 = 2^{\mathrm{MinBE}}$ and $\mathrm{CW_{Max}} = 2^{\mathrm{MaxBE}}$, where the fist part of Equation 3.12 has been analysed according to the condition of i, which is as follows,

1- when $0 \leq i \leq (\mathrm{MaxBE} - \mathrm{MinBE} = \mathrm{Dif})$

2- when $\mathrm{Dif} \leq i \leq M$

to get,

$$\sum_{i=0}^{M-1}\sum_{j=0}^{\mathrm{CW_i}-1}\sum_{r=0}^{R-1} b_{i,j,r} = \frac{b_{0,0,0}}{2}\Bigg[\Gamma + \Psi \times \Bigg(\mathrm{CW}_0 \frac{1-(2(\omega+\xi-\omega\xi))^{\mathrm{Dif}+1}}{1-2(\omega+\xi-\omega\xi)} + \mathrm{CW}_0 2^{\mathrm{Dif}} \frac{1-(\omega+\xi-\omega\xi)^{M-1}}{1-\omega-\xi+\omega\xi}\Bigg)\Bigg] \quad (3.13)$$

and

$$\sum_{i=0}^{M-1}\sum_{r=0}^{R-1} b_{i,0,r} + \sum_{i=0}^{M-1}\sum_{r=0}^{R-1} b_{i,-1,r} + \sum_{j=0}^{L_t-1}\sum_{r=0}^{R-1} b_{-1,j,r} + \sum_{j=0}^{L_c-1}\sum_{r=0}^{R-1} b_{-2,j,r} = \Gamma \times \Big((2-\omega) + (1-\omega-\xi+\omega\xi)(L_t(1-P_c)+P_cL_c)\Big) b_{0,0,0}, \quad (3.14)$$

where

$$\Psi = \frac{1-(\mathrm{P_{SW}}(1-(\omega+\xi-\omega\xi)^{M+1}))^{R+1}}{1-\mathrm{P_{SW}}(1-(\omega+\xi-\omega\xi)^{M+1})}, \quad (3.15)$$

and Γ is equivalent to

$$\Gamma = \Psi \times \frac{1-(\omega+\xi-\omega\xi)^{M+1}}{1-\omega-\xi+\omega\xi} \quad (3.16)$$

For simplicity, we assume in the analysis that each $\mathrm{SG_i}$ has a fixed value of sleep period (LS). Then the last expression of Equation (3.12) is expressed as

$$\sum_{j=0}^{\mathrm{NG}-1}\sum_{r=0}^{R-1} b_{-3,j,r} = \frac{\mathrm{LS}\times\mathrm{NG}+\mathrm{LS}}{2}\sum_{r=0}^{R-1} b_{-3,0,r} = \frac{\mathrm{LS}\times\mathrm{NG}+\mathrm{LS}}{2} \times \Big([L_cP_c + (1-L_cP_c)(\omega+\xi-\omega\xi)^{M+1}] \times \Psi\Big) b_{0,0,0}, \quad (3.17)$$

where P_c, which is the probability of more than one node that sense an idle channel and start their transmission at the same time, is given by

$$P_c = 1 - \frac{N\Theta(1-\Theta)^{N-1}}{1-(1-\Theta)^N} \tag{3.18}$$

where Θ, which the probability of the device starts sensing the channel, is equivalent to

$$\Theta = \sum_{i=0}^{M-1}\sum_{r=0}^{R-1} b_{i,0,r}, \tag{3.19}$$

and after analysing Equation 3.19 the value of Θ will be represented by $(\Gamma \times b_{0,0,0})$.

3.5 HSW-802.15.4 Model Validation

To confirm the accuracy of the proposed analytical model, extensive simulations of the IEEE 802.15.4 based-contention formulation are compared with the proposed model and included in the results. The simulation model attempts to imitate, as closely as possible, the actual transmission process based on the CSMA/CA of each device (see Appendix-A for more details about the simulation algorithm). In general, the CSMA/CA allows all the devices to compete for channel access as a single group rather than as multiple ones. Hence, only NG=1 will be considered when validating the accuracy of the proposed model; however, all other NG values have been provided to show the improvement in the proposed model over the traditional IEEE 802.15.4-based CSMA/CA protocol. The values of the parameters used to implement both the analytical model and the simulation runs are listed in Table 3.1, which are the same for all the simulations in this chapter and are identical to the default values of the IEEE 802.15.4 standard.

In Figure 3.6, the analytical model is compared to the simulation results, with one value of NG (NG = 1), to validate the accuracy of the proposed model. This is because the proposed analytical model behaves identically to the traditional IEEE

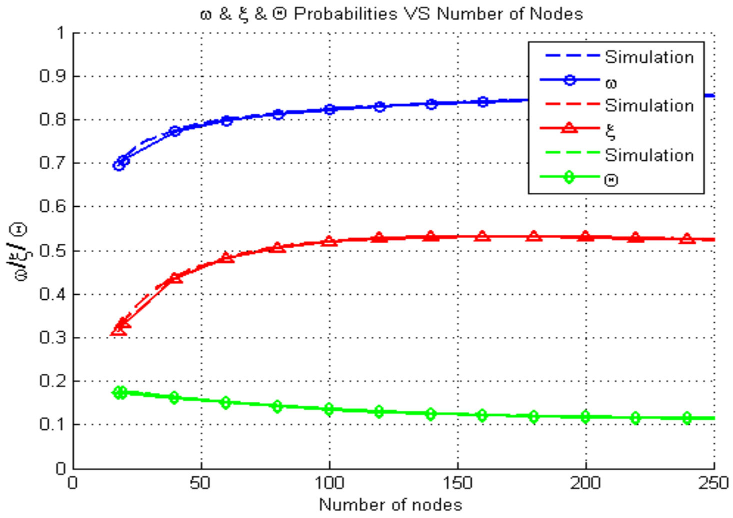


Fig. 3.6. This figure shows the validation of the proposed Markov model by comparing the numerical results of ω, ξ and Θ with the results obtained from the simulation when NG =1

802.15.4 standard when NG = 1, which means there is no sleep mode and all the devices compete to access the channel as one group.

The figure presents the validation for the derived expressions ξ, ω and Θ when compared to the simulation results. As shown, the values of the analytical prediction results are accurate and very close to those of the simulation results. Additionally, when the number of devices is increased, the values of ω and ξ increase, whilst the value of Θ decreases. Thus, there is an increase in the number of collisions and channel failures when the number of devices is increased.

Figure 3.7 displays ω probability against the number of devices. The value of ω has been tested when NG = 1, 4 and 8, and MaxBE = 3 and 5 This figure shows that, during the channel sensing process, the HSW-802.15.4 performs the same, or better, when NG = 4 or 8, and MaxBE = 3, than when NG = 1 and MaxBE = 5. This means that the value of NG with lower power consumption due to sleep mode can compensate the MaxBE when the device consumes more power, especially in a

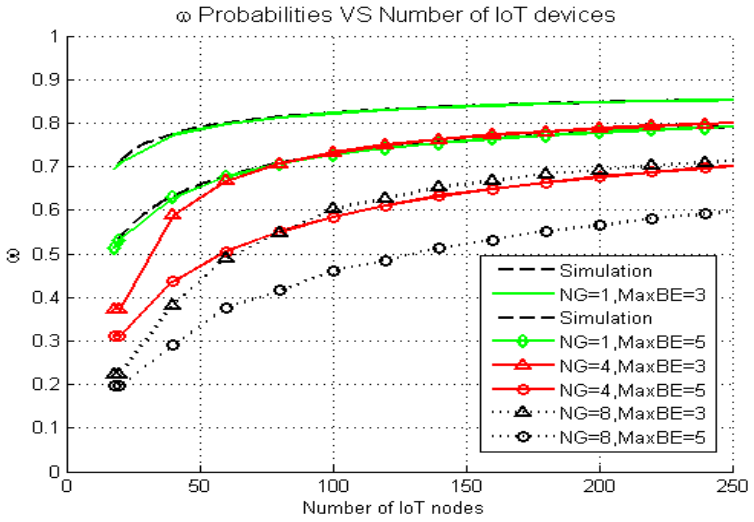


Fig. 3.7. ω validation for the proposed HSW-802.15.4 when MaxBE= 3 and 5 and with different values of NG

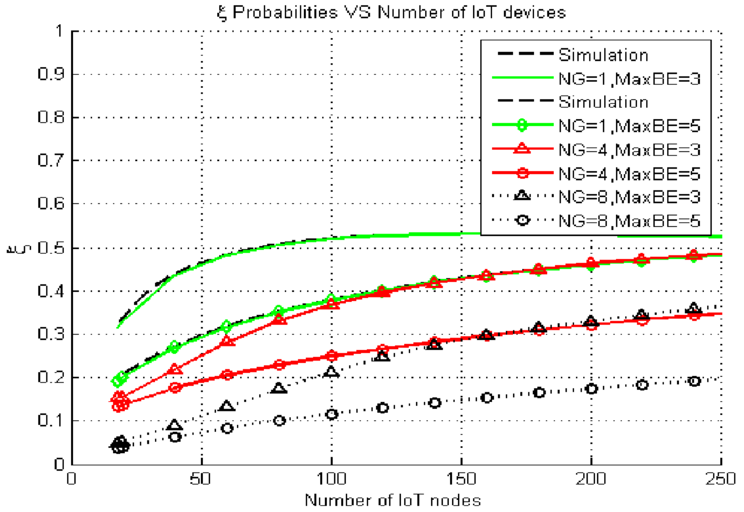


Fig. 3.8. ξ validation for the proposed HSW-802.15.4 with different values of NG

high-density network. Figure 3.8 also shows the effect of the NG and MaxBE on channel sensing for the second CCA with the probability ξ.

3.6 Metrics Results

In this section, the analytical model is used to describe numerically the performance of the HSW-802.15.4 model and the results from this are compared to those of the IEEE 802.15.4 standard in terms of: failure probability (P_f), throughput (S), channel utilisation (ρ), and power consumption (P_W). The performance of the proposed protocol has been examined with different numbers of subgroups (NG $=1; 2; 3; 4; 8$ and 16). It should be noted that the proposed HSW-802.15.4 behaves identically to the IEEE 802.15.4 standard when NG = 1.

3.6.1 Failure Probability

Failure probability (P_f) refers to the probability of a packet being discarded as the result of either channel access failure (CAF) or retransmission limits (RL). According to the Markov model in Figure 3.5, the P_f can be mathematically represented as follows:

$$\begin{aligned} P_f &= \mathrm{P}_{\mathrm{RL}} + \mathrm{P}_{\mathrm{CAF}} \\ &= \Big[(\mathrm{P}_{\mathrm{SW}}(1-(\omega+\xi-\omega\xi)^{M+1}))^{R+1} + \\ &\qquad \Psi \times (\omega+\xi-\omega\xi)^{M+1}\Big] b_{0,0,0} \end{aligned} \tag{3.20}$$

where, the $\mathrm{P}_{\mathrm{CAF}}$ and P_{RL} are the probabilities of the packet getting discarded due to CAF and RL, respectively.

Figure 3.9 shows the P_f against the number of devices with different values of NG and it is clear from the figure that failure probabilities decrease with higher values. This justifies the effectiveness of the proposed sleep/wakeup protocol, especially when the network begins to suffer from a higher number of collisions or channel failure. When the number of subgroups increases, the number of sleep devices also increases,

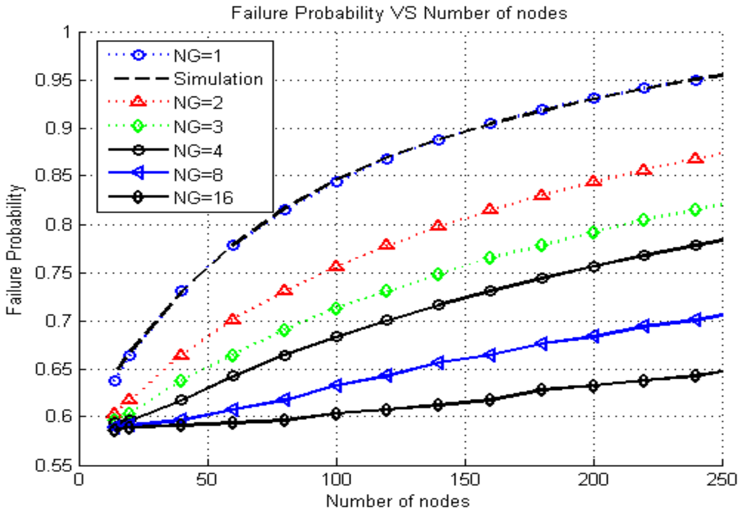


Fig. 3.9. Probability of failure P_F with different values of NG and with MAC parameters: MaxBE=5 and $M = 3$

which leads to a decrease in the number of contending devices during the CP and consequently, the number of collisions fall and channel failure is more likely to be avoided.

3.6.2 Throughput

The throughput ($S(bit/sec)$) is defined as the aggregated amount of data that is successfully transmitted during a time specified. Successful transmission means that the device needs to sense the channel successfully for both CCAs and then, send the packet without channel failure or collision. The S can be mathematically represented as follows:

$$S = \mathrm{DR} \times \varphi \tag{3.21}$$

where φ is calculated as follows:

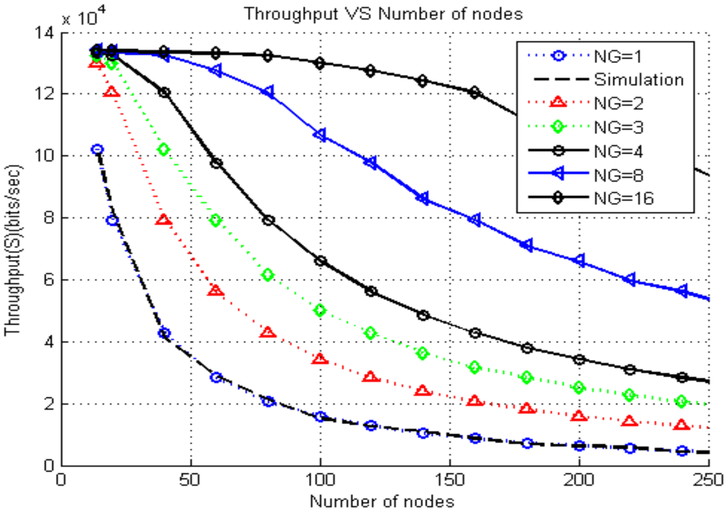


Fig. 3.10. Average throughput S with different values of NG and with MAC parameters: MaxBE=5 and $M = 3$

$$\varphi = \Theta(1-\omega)(1-\xi)(1-\mathrm{P_{SW}}) \tag{3.22}$$

where, DR represents the data rate (see Table 3.1). The throughput generated using the proposed model is explored using different values of NG.

Figure 3.10 shows the throughput against different numbers of devices when NG = 1, 2, 3, 4, 8 and 16. It shows that the throughput is increased when NG is increased. However, the throughput starts decreasing with all values of NG when the number of devices increases, which is because the number of collisions starts to increase when there are more devices. To compensate, the proposed protocol expands to cover a larger number of devices in the network. In conclusion, there is an inverse relationship between the throughput and the number of devices, and vice versa depending on NG.

3.6.3 Channel Utilisation

The channel utilisation (ρ) for one superframe is defined as the summation of the time during the successful transmission of packets to the total time of that superframe. The ρ in the simulation can be mathematically evaluated as:

$$\rho = \frac{(\sum_{i=1}^{N_s} \mathrm{TDMA_{slot}}i - \mathrm{T_{BN}}) \times \varphi}{\sum_{i=1}^{N_s} \mathrm{TDMA_{slot}}i + \mathrm{T_{BN}}} \tag{3.23}$$

where N_s represents the number of $\mathrm{TDMA_{slots}}$, $\mathrm{T_{BN}}$ refers to the beacon notification interval. The value of T_{BN}, in the results, is taken as equivalent to at least one $\mathrm{PCK_L}$. $\mathrm{PCK_L}$ refers to the total length of the packet including overhead and payload (see Table 3.1). Then, $\mathrm{T_{BN}}$ is estimated as

$$\mathrm{T_{BN}} = \lceil \frac{\mathrm{PCK_L}}{\mathrm{DR}} \rceil \tag{3.24}$$

Figure 3.11 investigates ρ in terms of the number of devices using different values of NG. As shown in the figure, the proposed HSW-802.15.4 provides a better ρ when NG = 2, 3, 4, 8 or 16. Moreover, the value of ρ is high when the number of devices is less than 50, from there it starts decreasing when the number of devices is increased. Finally, the figure also shows that the proposed protocol means that ρ remains high, even with a higher number of devices, which indicates the effectiveness of the proposed protocol in a higher network density. Furthermore, the value of ρ stays high for a longer time when NG is increased.

3.6.4 Power Consumption

In this subsection, the average energy consumed by a device attempting to transmit a single bit using the proposed HSW-802.15.4 protocol is considered. Using the IEEE 802.15.4 power parameters listed in Table 3.1, the power consumed in idle, channel sensing, transmission, receiving and sleep modes is denoted by $\mathrm{PW_{idle}}$, $\mathrm{PW_{CCA}}$,

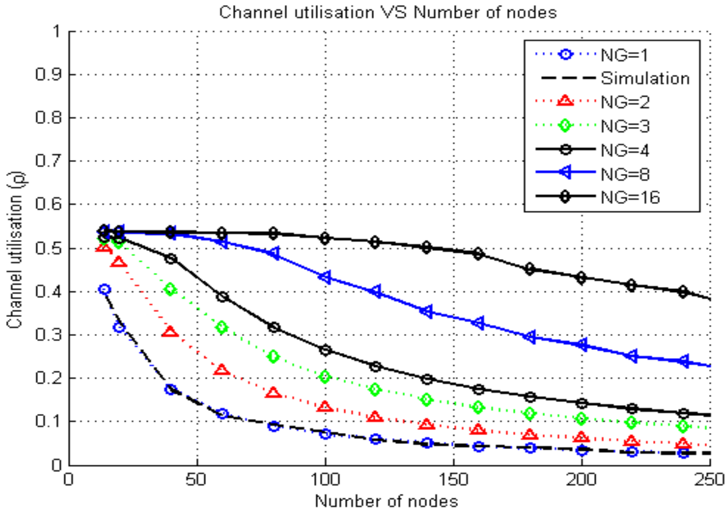


Fig. 3.11. Channel utilisation ρ with different values of NG and with MAC parameters: MaxBE=5 and $M = 3$

$\mathrm{PW}_{\mathrm{Tx}}$, $\mathrm{PW}_{\mathrm{Rx}}$, and $\mathrm{PW}_{\mathrm{SL}}$, respectively. Furthermore, taking into consideration the Markov probabilities of the proposed protocol, the mean energy $\mathrm{E}_{\mathrm{Tot}}$ can be obtained as follows:

$$\begin{aligned}\mathrm{E}_{\mathrm{Tot}} = {} & \mathrm{PW}_{\mathrm{idle}}\mathrm{P}_{\mathrm{idle}} + \mathrm{PW}_{\mathrm{CCA}}\mathrm{P}_{\mathrm{CCA}} \\ & + \mathrm{PW}_{\mathrm{Tx}}\mathrm{P}_{\mathrm{Tx}} + \mathrm{PW}_{\mathrm{Rx}}\mathrm{P}_{\mathrm{Rx}} + \mathrm{PW}_{\mathrm{SL}}\mathrm{P}_{\mathrm{SL}}\end{aligned} \quad (3.25)$$

where P_{SL} is given in Equation (3.17). $\mathrm{P}_{\mathrm{idle}}$ is the probability of the device being idle either at the backoff, or at the time of waiting for the ACK ($\mathrm{L}_{\text{ACK-out}}$), and can be calculated as follows:

$$\begin{aligned}\mathrm{P_{idle}} &= \sum_{i=0}^{M-1}\sum_{j=0}^{\mathrm{CW_i}-1}\sum_{r=0}^{R-1} b_{i,j,r} + \sum_{j=0}^{\mathrm{L_{ACK\text{-}out}}-1}\sum_{r=0}^{R-1} b_{-1,j,r} \\ &= b_{0,0,0} \times \Bigg[\frac{1}{2}\Bigg(\Gamma + \Psi \times \Bigg(\mathrm{CW_0}\frac{1-(2(\omega+\xi-\omega\xi))^{\mathrm{Dif}+1}}{1-2(\omega+\xi-\omega\xi)} \\ &+ \mathrm{CW_0}2^{\mathrm{Dif}}\frac{1-(\omega+\xi-\omega\xi)^{M-1}}{1-\omega-\xi+\omega\xi}\Bigg)\Bigg) + \Bigg(\Gamma \times (\mathrm{L_{ACK}}(1-\omega-\xi+\omega\xi))\Bigg)\Bigg] \end{aligned} \tag{3.26}$$

$\mathrm{P_{CCA}}$ is the probability of channel sensing for two consecutive CCAs, and it is calculated as follows:

$$\mathrm{P_{CCA}} = \Theta + (1-\omega)\Theta \tag{3.27}$$

and $\mathrm{P_{Tx}}$ is the transmission probability and calculated as:

$$\mathrm{P_{Tx}} = \frac{\mathrm{PCK_L}}{\mathrm{DR}} \times (1-(1-\Theta)^N)(1-\omega)(1-\xi) \tag{3.28}$$

$\mathrm{P_{Rx}}$ is the probability of successfully receiving the ACK after a transmission and it is given as follow:

$$\mathrm{P_{Rx}} = \sum_{j=0}^{\mathrm{L_{ACK}}-1}\sum_{r=0}^{R-1} b_{-1,j,r} \tag{3.29}$$

Figure 3.12 compares the energy consumed by the HSW-802.15.4 MAC for the following values of NG: 1, 2, 3, 4, 8, and 16. This shows that average energy depletion has been improved by 40% to 60% with the proposed protocol depending on the number of devices and NG. This is because the devices avoid the high-energy depletion caused by attempting to access the channel and thus, there is no energy lost in idle stages waiting for the channel state to be detected, or when receiving unwanted packets due to collisions or channel overhead. Instead, the devices in the proposed protocol spend more time in a low energy sleep stage when network density is high and the NG is increased, which results in a decrease in the number of competing devices depleting their energy in successful transmission or reception.

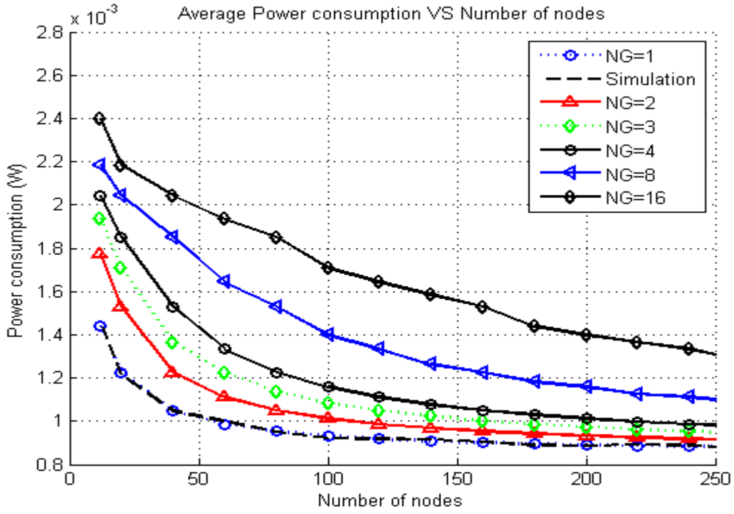


Fig. 3.12. The average power consumption with different values of NG and MaxBE=5 as a function of saturated network

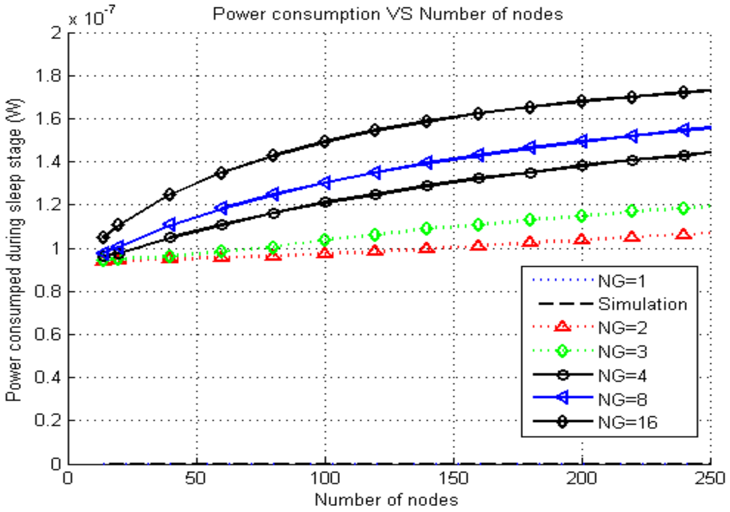


Fig. 3.13. Power consumption during the sleep stage with different values of NG and with MAC parameters: MaxBE=5 and $M = 3$

Figure 3.13 shows the energy consumed by the devices during the sleep stage. This shows that the device spends more energy on the sleep stage when the NG value is increased. Energy consumption is, therefore, increased when the network density (number of devices) is increased. Furthermore, there is no energy consumption when NG = 1, because there is no sleep stage, while the highest energy consumption occurs when NG = 16. Thus, this figure illustrates why there is efficient utilisation of overall energy consumption as the device consumes its energy during the sleep stage or in successful transmission and channel access, rather than in idle stages or higher energy depletion stages, such as collision or channel failure.

3.7 Contributions

The proposed model automates the network, thereby enabling it to work flexibly with low and high-density networks. Additionally, it has the advantage of avoiding a costly channel access pattern by reducing the number of collisions occurring due to a high density of devices. To implement the proposed sleep model, the PAN coordinator, during the beacon frames, produces a ST, which contains information related to the sleep/wake-up periods and the nodes that are related to each individual group. Furthermore, to save energy, each individual device has to calculate and switch to a sleep/wakeup period. This occurs during the channel access attempts and according to the information in the ST, reduces the number of collisions or channel failures. Moreover, this information enables a certain group of devices to compete for entering the transmission period. In contrast, other groups are forced to enter the sleep mode and each is allocated a different $\mathrm{LS}_{\mathrm{is}}$. Furthermore, the proposed hybrid protocol-based adaptable sleep model can be theoretically displayed using a three-dimensional Markov chain and then, compared to the original IEEE 802.15.4. Hence, this chapter makes the following contributions to current knowledge:

- It provides a dynamic hybrid MAC protocol for high density IoT communications by proposing a scheduler sleep/wakeup mode called HSW-802.15.4. This mode has been designed to be activated only after the device experiences a high collision rate and/or channel failure situation;

- It develops a frame structure scheme for the proposed protocol, which offers enhanced exploitation of the $\text{TDMA}_{\text{slots}}$ and compatibility with the IEEE 802.15.4 standard;
- It provides a comprehensive analytical evaluation using a three-dimensional Markov model that predicts the performance of the proposed hybrid protocol-based dynamic sleep mode;
- It evaluates and verifies the performance of the proposed model for small and high-density networks by comparing it with the traditional IEEE 802.15.4 standard.

3.8 Summary

Advances in the development of low powered sensors has meant they can now provide solutions to IoT networks that suffer from restricted power supply and a lack of resource facilities. In this chapter, a hybrid TDMA-CSMA/CA MAC protocol for high density IoT networks has been proposed that efficiently utilises the energy of the nodes and dynamically adapts the sleep/wake-up periods according to the variance in the network loads. This hybrid protocol first schedules the $\text{TDMA}_{\text{slots}}$, and then allocates each slot to a group of devices that compete for the medium using the CSMA/CA. This case is different from the traditional CSMA/CA-TDMA hybrid protocol, in which all the devices compete to access the channel, following which, each successful device is allocated an individual time slot. At the commencement of each superframe, the base station broadcasts a scheduler table, which includes network grouping information that is used by the IoT devices to categorise themselves into wake-up and sleep groups. To reduce the number of collisions or channel access failures, this information permits only one group to compete for each $\text{TDMA}_{\text{slot}}$. A three-dimensional Markov model is used to develop a per user stochastic behaviour for the proposed hybrid MAC protocol-based adaptable sleep mode. The simulation results demonstrate the effectiveness of the proposed protocol, which improves the network throughput and enhances energy conservation by 30% - 40% more than the IEEE 802.15.4-based MAC protocol.

Chapter 4: Clustering Algorithm for Random Diversification of IoT Node Density

4.1 Introduction

Cluster-based hierarchical routing protocols have been broadly accepted as highly energy efficient and prolonging the lifetime of the network [81]. However, the node density, random diversification of node density in the sensing area, residual energy and communication cost are all regarded as crucial metrics in the formulation of clusters, because they can limit the appropriateness of the clusters for an efficient network. As IoT becomes increasingly complex and dense, researchers have proposed the use of bio-inspired techniques in the formulation of routing protocols, which mimic the biological behaviours of swarm intelligent (SI) animals and improve network lifetime, such as the cases of PSO and ACO [87]. The WOA [9] is a another new meta-heuristic algorithm inspired by the intelligent and foraging behaviour displayed by humpback whales when hunting their prey.

Optimisation-based bio-heuristic techniques share a mutual property irrespective of their originality, whereby the search progress is separated into two stages, namely, exploration and exploitation. The exploration stage comprises mechanisms that are globally discovered in the search field, namely, bubble-net attack mechanisim, in which the design of the search improvement has to be randomised as much as possible. The exploitation stage is defined, in particular, as the progress of exploring the promising area of the search field [9]. The WOA has produced results which indicate that it performs better and is more competitive than other optimisation algorithms, such as the PSO [9]. In fact, this improvement has made it possible to achieve balance between the exploration and exploitation stages.

The organisation of this chapter is as follows. Sections 4.2 and 4.3 introduce the exploration of PSO and WOA , whilst Sections 4.4 and 4.5 discuss the effect of random distribution of node density on overall network performance and the architecture concept of the IoT based on SDN, respectively. Section 4.6 introduces the proposed clustering protocol based on WOA, SDN and cloud. Section 4.7 evaluates the performance of the proposed protocol. Section 4.8 introduces the contributions relating to this chapter, and finally, this chapter ends with a brief summary in section 4.9.

4.2 Particle Swarm Optimisation

The PSO process is initiated by generating a group of random particles, each particle (p) is a D dimension vector, which is evaluated by a objective function. Whilest, the optimal resolution of PSO is gained after specific number of progressions known as iterations. Throughout the iterative progressions, each particle in the swarm follows the global best ($\mathrm{G_{best}}$) and its personal best ($\mathrm{P_{best}}$). Moreover, during each progression, the position and the velocity of each indiviual particle are updated as the following formula [8]:

$$\mathrm{v_{id}}(t+1) = \varsigma \times \mathrm{v_{id}}(t) + c_1\partial_1(\mathrm{p_{id}} - \mathrm{x_{id}}(t)) + c_2\partial_2(\mathrm{p_{gd}} - \mathrm{x_{id}}(t)) \tag{4.1}$$

$$\mathrm{x_{id}}(t+1) = \mathrm{x_{id}}(t) + \mathrm{v_{id}}(t) \tag{4.2}$$

where v and x are the velocity and position of the particle. The c_1, c_2, and ς parameters are presented in Table 4.1, which control the influence of the current particle by the preceding one. The values of ∂_1 and ∂_2 are random numbers between 0 and

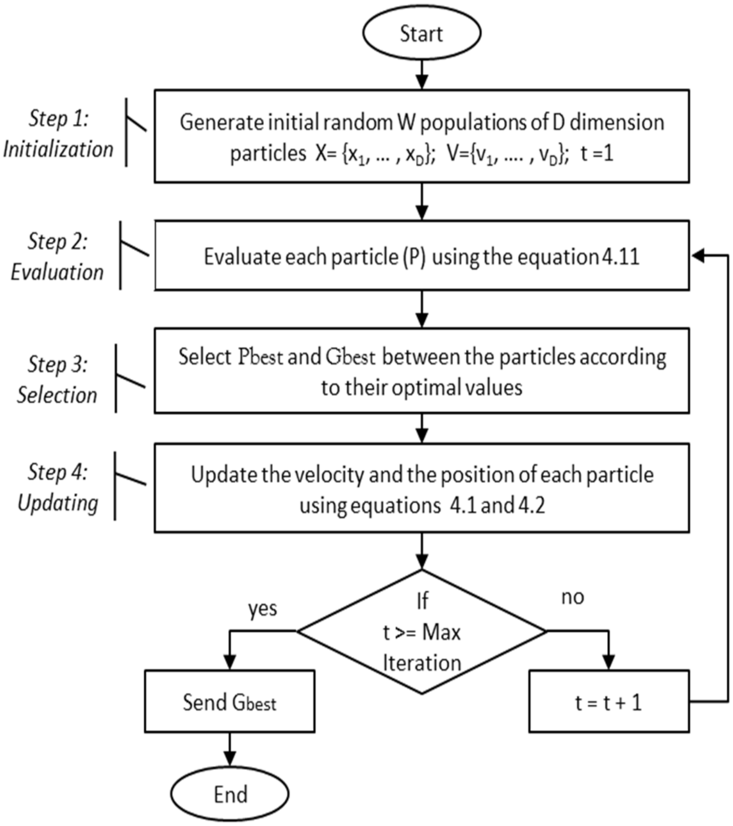


Fig. 4.1. The steps of selecting the optimal set of CHs using PSO

1, while $\mathrm{p_{id}}$ and $\mathrm{p_{gd}}$ are particle's best position and global position. Moreover, the steps of implementing the clustering-based PSO are presented in Figure 4.1 and listed below:

1. Generate W initial group of particles with random numbers. These numbers in each particle represent the IDs for a candidate group of CHs.

2. Evaluate the cost of each particle using the fitness function presented in equation 4.11.

3. Choose the values of $\mathrm{G_{best}}$ and $\mathrm{P_{best}}$ for each particle.

4. Modify the position and velocity values using equations 4.1 and 4.2.

5. Limit the modified value of position according to the NCH values.
6. Repeat steps 2 to 5 until reaching the maximum iteration.
7. Provide the values of G_{best} as the optimal set of CHs.

4.3 Whale Optimisation Algorithm

The WOA is a new bio-inspired meta-heuristic that mimics the bubble-net hunting and foraging behaviour of humpback whales. Humpback whales are considered to be very intelligent animals because, similarly to humans, they have common cells in their brains called spindle cells. The most exciting thing about these whales is their special intelligent bubble-net hunting technique. Figure 4.2 shows the humpback hunting behaviour. It has been discovered that this whale hunts its prey by encircling and making peculiar bubbles around it in a spiral or 9 shaped pattern (as shown in Figure 4.2). Further details about these hunting behaviours are discussed in [104]. In this study, the 9-shaped bubble-net feeding scheme is mathematically demonstrated in order to accomplish the WOA.

The cost results from Mirjalili et al. [9] indicate that the algorithm is both competitive and effective when compared to other well-known meta-heuristic ones, such as PSO, ACO, and GA. This is due to the efficient position updating technique of the search agents performed by the WOA, which results in optimal exploration compared to other meta-heuristic algorithms. This feature allows the search agents to reposition around each other in a random manner during the early stages. However, in the rest of the iterations, the search agents keep moving around themselves in a spiral path, with a high level of exploitation and convergence towards the best solution (best search agent) achieved so far. These two phases, namely exploitation and convergence, render the WOA more likely to avoid the local optima throughout the progress of iterations. On the other hand, the PSO and other meta-heuristic algorithms use only one formula or phase in order to modify the value of the search

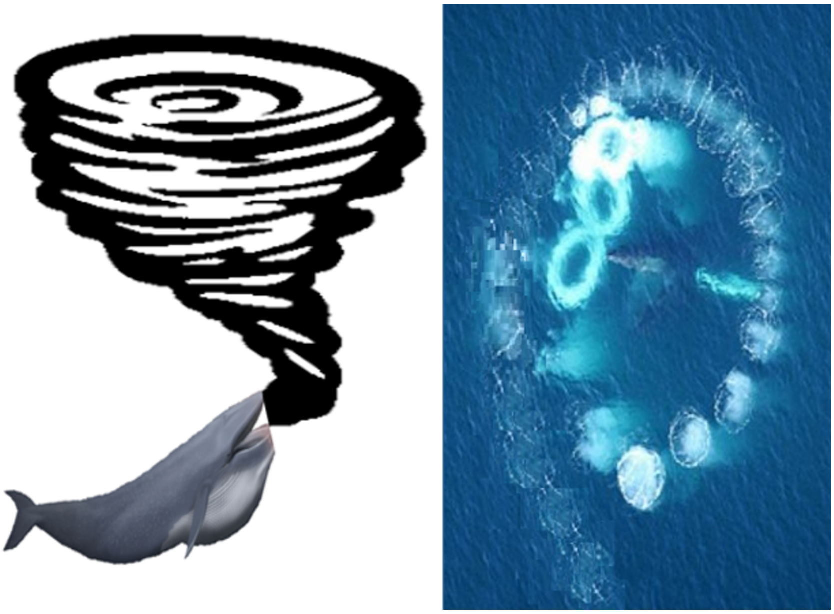


Fig. 4.2. The hunting scheme of humpback whales

agents, which increases the possibility of the optimal solution being trapped in the local optima.

4.3.1 Mathematical Model

The mathematical model of WOA consists of three discrete phases: prey encircling phase, exploitation phase and exploration phase.

4.3.1.1 Prey Encircling Phase

WOA begins with the humpback whales (search agents) encircling the prey (optimal agent). They then identify the current and best available solution as the desired prey. After identifying the optimal search agent, all other search agents attempt to upgrade their positions in the direction of the optimal solution as follows [9]:

$$\overrightarrow{D} = |\overrightarrow{C_1}.\overrightarrow{Y^*}(t) - \overrightarrow{Y}(t)| \tag{4.3}$$

$$\overrightarrow{Y}(t+1) = \overrightarrow{Y^*}(t) - \overrightarrow{C_2}.\overrightarrow{D} \tag{4.4}$$

where $\overrightarrow{C_1}$ and $\overrightarrow{C_2}$ are the coefficient of vectors, t refers to the iteration number. $\overrightarrow{Y^*}$ and $\overrightarrow{Y}$ vectors refer to the best agent position vector and the position vector, respectively. However, in each iteration, $\overrightarrow{Y^*}$ should be upgraded if there is a better solution. Furthermore, vectors $\overrightarrow{C_1}$ and $\overrightarrow{C_2}$ are identified as follows [9]:

$$\overrightarrow{C_1} = 2\overrightarrow{r_1} \tag{4.5}$$

$$\overrightarrow{C_2} = 2\overrightarrow{a}.\overrightarrow{r_1} - \overrightarrow{a} \tag{4.6}$$

where $\overrightarrow{r_1}$ is a random vector in [0, 1], $\overrightarrow{a}$ is a vector that is linearly reduced during the iteration process from 2 to 0.

4.3.1.2 Exploitation Phase (Bubble-Net Attacking Method)

The mathematical model of the bubble-net attacking method uses the following two approaches:

- Shrinking encircling approach: In this mechanism, the value of $\overrightarrow{C_2}$ is randomly chosen between [-1, 1]; therefore, the new position of a search agent will be anywhere between the agents' position and the position of the recent optimal agent.
- Spiral upgrading position approach: This mechanism starts by computing the distance between the agent ($\overrightarrow{Y}(t)$) and the optimal agent ($\overrightarrow{Y^*}(t)$). It then

imitates the spiral shaped movement of the humpback whales using Equation (4.7) [9]

$$\overrightarrow{Y}(t+1) = \overrightarrow{\mathrm{Dis}}.e^{\varrho\ell}.\cos(2\pi\ell) + \overrightarrow{Y^{*}} \tag{4.7}$$

where $\overrightarrow{\mathrm{Dis}} = |\overrightarrow{Y^{*}}(t) - \overrightarrow{Y}(t)|$ refers to the distance, ϱ is the spiral constant and ℓ is a random number between [-1, 1]. Furthermore, WOA updates the position of the search agent using a 50% level of probability to select between the shrinking encircling approach and the spiral mechanism as follows [9]:

$$\overrightarrow{Y}(t+1) = \begin{cases} \overrightarrow{Y^{*}}(t) - \overrightarrow{C_2}.\overrightarrow{D} & \text{if } p < 0.5 \\ \overrightarrow{\mathrm{Dis}}.e^{\varrho\ell}.\cos(2\pi\ell) + \overrightarrow{Y^{*}} & \text{if } p \geq 0.5 \end{cases} \tag{4.8}$$

where p is a random number between [0; 1]

4.3.1.3 Exploration Phase (Search for Prey)

In this phase, a randomly selected search agent (act as the optimal search agent) is followed by the other search agents to update their positions, as opposed to the optimal search agent chosen previously. Furthermore, WOA uses a random number between -1 and 1 with $\overrightarrow{C_2}$ to enable the search agents to explore far away from the reference agent. The mathematical model of this phase is as follows [9]:

$$\overrightarrow{D} = |\overrightarrow{C_1}.\overrightarrow{Y_{\mathrm{rand}}} - \overrightarrow{Y}(t)| \tag{4.9}$$

$$\overrightarrow{Y}(t+1) = \overrightarrow{Y_{\mathrm{rand}}} - \overrightarrow{C_2}.\overrightarrow{D} \tag{4.10}$$

where $\overrightarrow{Y_{\mathrm{rand}}}$ vector is a random search agent selected between the set populations.

4.4 Node Diversification in the Geographical Area

Grouping network devices into smaller clusters enhances network performance by efficiently utilising the node resources, such as batteries, memory, processing units, and communication capabilities. Generally, in IoT applications, some of the devices can be installed manually in a uniform manner, such as building monitoring and surveillance applications, but most are distributed in a stochastic manner in order to cover geographical areas, such as battlefields and forests. A random deployment of the groups of nodes in the field results in an insufficient cluster formulation. Additionally, it negatively influences the overall network performance and causes an incongruous balancing of the load in each cluster and of the CHs in the geographical area. The efficient clusters, that minimise the transmission distance by the nodes and balance the energy depletion among all CHs, can be formulated by dividing the sensing area by the SDN controller into multiple VZs. This division has the advantage of considering both the CHs deployment and the random deployment of node density in the sensing area during the cluster construction process.

Figure 4.3 shows an example from a Google map of about 200m×200m of Brunel University London buildings. The geographical area in this example has been divided into four VZs and the random diversification of the node density can be clearly seen from this example. The first VZ is a park with a smaller than expected number of IoT devices, whereas the other zones, particularly zone four, have a high density of buildings with a larger than expected number of devices. Hence, in order to ensure that the network performs as expected, here, dividing the sensing area into multiple VZs is proposed using the SDN controller and working with each zone separately during the CH selection process.

4.5 IoT-Based SDN Architecture

The SDN is a technique in networking architecture that facilitates network administration through an efficient methodology, which is implemented by decoupling

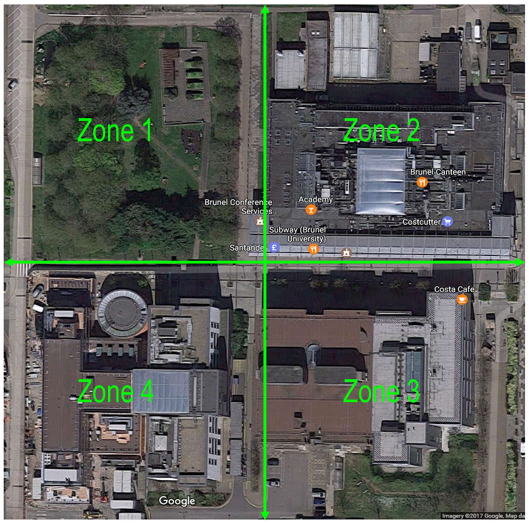


Fig. 4.3. An example explains the random diversification of node density

the control plane from the data plane [10]. The architecture of the SDN technology consists of three layers, namely: application layer, control layer and physical layer. The application layer includes many applications, such as business applications, web application and database servers. The control layer typically houses the SDN controller itself, whereas the SDN devices reside in the physical layer. These devices represent the data plane in SDN architecture and contain only a bare minimum of software that enables communication between the SDN router/switch and the SDN controller [105].

Hence, SDN architecture has the advantage of reducing the cost of the IoT control network that relies on expensive and embedded control circuits and software, when compared to legacy IoT networks. Furthermore, it offers networking vendors the ability of the flexibility, extensibility and writing up the control software into the SDN controller. Additionally, the centralised network control based on SDN architecture is better suited to modern cloud applications and its resources, which can be effectively utilised by the controller to make decisions, such as those about protocols [11].

4.6 Proposed Routing Model

The novelty of this chapter can be summarised as providing a new clustering algorithm that considers, during the cluster formulation process, the node density (presented in Equation 4.14) and the random diversification of node density in the geographical area (considered when dividing the sensing area by the SDN controller into four VZs. The rest of this section describes the proposed CC-WOA protocol. All the nodes are assumed as being static, and their coordinates are sent to the cloud by the Graphical Position System (GPS) to be used by the SDN controller during the CH selection process.

4.6.1 Network Model

The proposed protocol balances the number of the CHs according to the distribution of the node density in the geographical area. As shown in Figure 4.4, the protocol offers a pure separation between the control plane and the data plane using the concept of SDN. Moreover, the proposed IoT structure consists of three main layers: infrastructure layer, control layer, and application layer. The infrastructure layer consists of a wide variety of nodes that only perform packet forwarding. The SDN controller is situated in the control layer and accomplishes network decisions, such as those relating to protocols. The application layer is positioned over the cloud to be used for business purposes. Moreover, the SDN controller uses cloud resources such as the storage and data centres to accomplish complex calculations or to store data.

The SDN controller, in this thesis, logically divides the sensing area into four VZ, which means that the nodes are also separated into four sub-groups (SG), according to their coordinates (see Figure 4.5). This division has the advantage of balancing the number of CHs in the geographical area, whilst another advantage is that a zone with a higher node density is allocated more CHs than one with a lower density. The

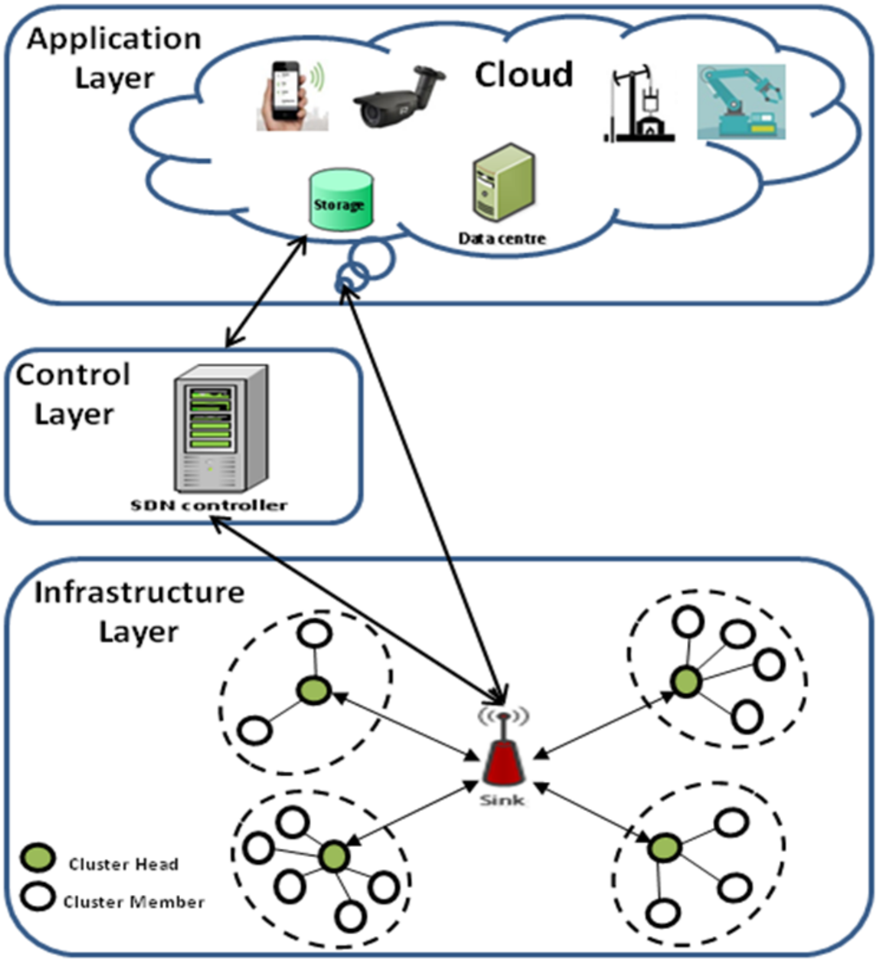


Fig. 4.4. Network architecture based SDN concept

SDN controller then implements the WOA for each SGi to define the optimal set of CHs in VZi.

4.6.2 Clustering-Based WOA

For each VZ, WOA begins with a random set of solutions, with referring to the ID of a specific set of CHs. Then, at each iteration, the search agents (solutions) upgrade their positions following either a randomly selected search agent (solution)

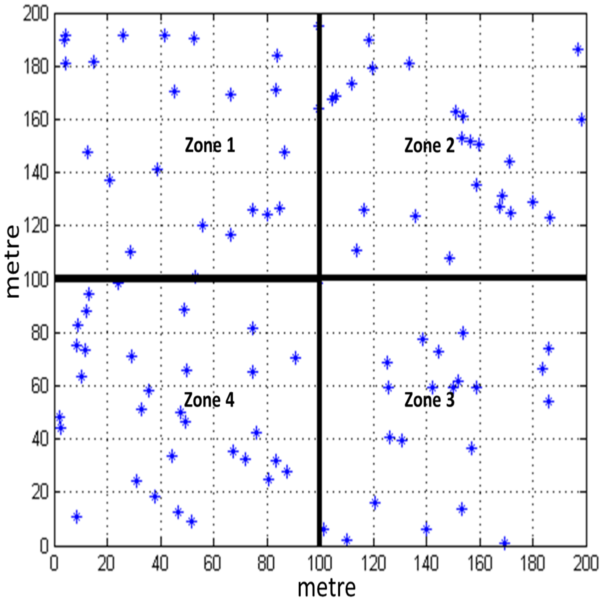


Fig. 4.5. Virtual zones by the SDN controller and the random distribution of node density

or the optimal solution acquired earlier. The solutions are then evaluated and the cost of the following function is minimised:

$$\text{cost} = \alpha f_1 + \beta f_2 + \tau f_3 \tag{4.11}$$

$$f_1 = \frac{\sum_{i=1}^{\text{SG}} E_{(n_i)}}{\sum_{j=1}^{K} E_{(\text{CH}_{p,j})}} \tag{4.12}$$

$$f_2 = \sum_{j=1}^{K} \frac{\sum_{i=1}^{\text{NC}_{p,j}} \text{dis}_{(n_i,\text{CH}_{p,j})}}{\text{NC}_{p,j}} + \frac{\sum_{j=1}^{K} \text{dis}_{(\text{CH}_{p,j},\text{BS})}}{K} \tag{4.13}$$

$$f_3 = \frac{\text{SG}}{\sum_{j=1}^{K} \text{CMs}_{(j,\text{CH}_j)}} \tag{4.14}$$

where coefficients α, β and τ are shown in Table 4.1. K refers to the number of CHs, as shown in Table 4.2. The function f_1 in Equation (4.12) chooses the set of CHs with the maximum energy level. The function f_2 in Equation (4.13) includes the communication cost between CHs to CMs, and the CHs to the sink. Moreover, the node density is processed by Equation (4.14), which chooses the set of CHs covering the highest number of nodes. The SDN controller uses the information contained in the nodes which is stored at the cloud in the CHs selection process, as shown in the following steps (see Algorithm 1):

1. Division phase:
    (a) Divide the sensing area into four VZ.
    (b) Define the nodes into SG.
2. Initialisation phase:
    (a) Initialise W random vectors of search agents (sets of CHs' IDs).
    (b) Initialise values for $\overrightarrow{C_1}, \overrightarrow{C_2}, \overrightarrow{a}$ and Max_{itr}.
3. Evaluation phase:
    (a) Evaluate the search agents using Equation (4.11).
    (b) Assign the best search agent (set of CHs) as an optimal agent.
4. Updating phase:
    (a) Update the parameters $\overrightarrow{a}, \overrightarrow{C_1}, \overrightarrow{C_2}, r_1, \ell$ and p using Equations (4.5) and (4.6).
    (b) Apply exploitation and exploration to the search agents using Equations (4.8) and (4.10) according to the values of $\overrightarrow{C_2}$ and p.
    (c) Limit the variation in the search agent values according to the CHs' IDs.
5. Repeat steps 3 and 4 until the maximum number of repetitions is reached or it matches the termination criteria.

6. Repeat steps 2 and 5 until the optimal solutions for all the VZ are defined.

The SDN controller sends the optimal set of CHs with their CMs as a set-up table to the sink to be forwarded to the nodes. Following this, each CM turns its radio on or off according to the TDMA scheduled by their CH. It is worth mentioning that virtual zones do not affect the cluster formulation process, where the nodes are connected to the closest CH chosen by the SDN controller in the set-up table.

4.6.3 Radio Model

The first order radio model in [18] is used to calculate the energy dissipation in the proposed protocol. This model examines the node's energy exhaustion in transmission (E_{TX}), reception (E_{RX}) and data aggregation (E_{DA}). The energy dissipated by the node to transmit or receive s bits is defined as follows:

$$\mathrm{E}_{\mathrm{amp}} = \begin{cases} \varepsilon_{\mathrm{FS}} d^2 & \text{if } d < d_0 \\ \varepsilon_{\mathrm{TR}} d^4 & \text{if } d \geq d_0 \end{cases} \tag{4.15}$$

$$\mathrm{E}_{\mathrm{TX}}(s, d) = s\mathrm{E}_{\mathrm{elec}} + s\mathrm{E}_{\mathrm{amp}} \tag{4.16}$$

$$\mathrm{E}_{\mathrm{RX}}(s, d) = s\mathrm{E}_{\mathrm{elec}} \tag{4.17}$$

where d is a distance between two nodes, E_{TX} and E_{RX} the energy dissipated in transmission and reception respectively, and d_0, E_{FS}, E_{DA} and $\mathrm{E}_{\mathrm{elec}}$ are defined in Table 4.2.

Algorithm 1 CC-WOA For Each Round

```
procedure CLUSTERS FORMULATION
    Separate the nodes into four SG according to their VZ
    for each SG do
        Initialise W random populations (search agents)
        Evaluate each search agent ($\overrightarrow{Y_i}$) using Equations (4.11)-(4.14)
        $\overrightarrow{Y^*} \leftarrow$ best search agent, $Max_{itr} \leftarrow$ Maximum number of iterations
        $t \leftarrow 0$
        while $t < Max_{itr}$ do
            for each search agent ($\overrightarrow{Y_i}$) do
                Update $\overrightarrow{C_1}$,$\overrightarrow{C_2}$,$\overrightarrow{a}$, $\ell$, and $p$
                if $p < 0.5$ then
                    if $|A| < 1$ then
                        Update $\overrightarrow{Y_i}$ using Equation (4.8)
                    else
                        Select random search agent($Y_{\text{rand}}$)
                        Update $\overrightarrow{Y_i}$ using Equations (4.9)-(4.10)
                    end if
                else
                    Update $\overrightarrow{Y_i}$ using Equation (4.8)
                end if
            end for
            Check if $\overrightarrow{Y_i}$ past the search space limit and adjust it
            Calculate the fitness of $\overrightarrow{Y_i}$ , Update $\overrightarrow{Y^*}$ if there is a better solution
            $t \leftarrow t + 1$
        end while
    Return $\overrightarrow{Y^*}$ as optimal set of CHs for each VZ
    end for
    Send the set-up table (the set of CHs and the CMs)
end procedure
```

Table 4.1
WOA and PSO parameters

Parameter	Value
population size (W)	50
Maximum number of iterations ($\mathrm{Max}_{\mathrm{itr}}$)	400
Spiral constant (ϱ)	1.5
Energy parameter (α)	0.4
Distance parameter (β)	0.3
Density parameter (τ)	0.3
Inertia weight (ς)	0.8
Learning factors $c_1 = c_2$	2

Table 4.2
Radio simulation parameters

Parameter	Value
Energy dissipated per bit ($\mathrm{E}_{\mathrm{elec}}$)	50 nJ/b
Amplifier energy for free space ($\varepsilon_{\mathrm{FS}}$)	10 pJ/b/m2
Amplifier energy for transmitter ($\varepsilon_{\mathrm{TR}}$)	0.0013 pJ/bit/m4
Energy for data aggregation (E_{DA})	5 nJ/bit
Transmission distance threshold (d_0)	$\sqrt{\frac{\varepsilon_{\mathrm{FS}}}{\varepsilon_{\mathrm{TR}}}}$
Packet size	4000 bit
Number of CH_s (K)	$10\% \times N$

4.7 Simulation and Results

4.7.1 Network Set-up

The network comprises 100 heterogeneous stationary nodes randomly distributed in an area of 200m×200m. The initial energy that is assigned randomly to each node lies between 0.4 J and 1 J. Moreover, the network is examined with a single centralised sink node that has unlimited resources in terms of storage, processing and power supply. However, other WOA and radio simulation parameters are seen in Table 4.1 and Table 4.2 respectively.

4.7.2 Performance and Results

The simulation is accomplished using MATLAB. The efficacy of the proposed CC-WOA protocol is shown by comparing it to other traditional clustering protocols, including LEACH, SEP and an optimised clustering protocol, i.e. PSO-C, in terms of network lifetime, remaining energy and throughput.

Figure 4.6 improves the performance efficiency of the WOA-based clustering algorithm by comparing it with the state-of-the-art PSO-based clustering algorithm. Furthermore, both algorithms have been examined under the same cost function used in [14]. Compared to the PSO based clustering, the overall network lifetime using WOA-based clustering has been expanded by about 12%. This expansion in

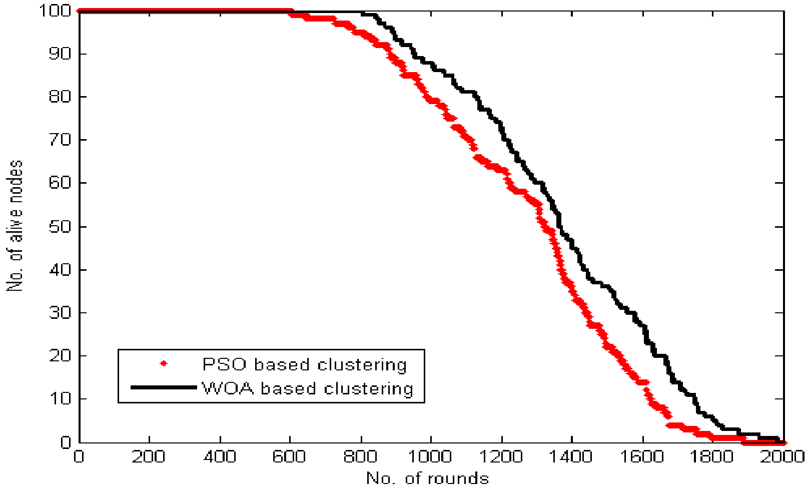


Fig. 4.6. WOA performance evaluation compared to the performance of PSO using the same fitness function presented by [14]

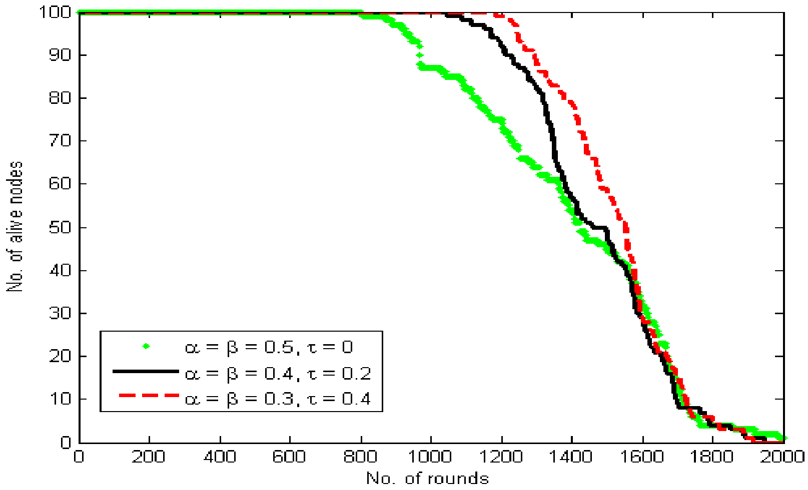


Fig. 4.7. The effect of node density on network lifetime using WOA with different values of $\alpha, \beta and \tau$

network lifetime is a result of the effective position updating technique of the search agents and the high balance between the exploration and exploitation techniques of the WOA compared to the PSO algorithm. These techniques enable the WOA to construct better cluster solutions as opposed to the PSO, ultimately enhancing the overall network lifetime.

Figure 4.7 shows the effect of the node density in Equation (4.14) on the overall network lifetime. The cost function in Equation (4.11) contains three optimisation constraints: the energy weight (α), the communication cost weight (β), and the node density weight (τ). The figure displays the network lifetime in three individual cases, each case with different values attributed to the optimisation constraints. The first case shows the results when $\alpha = \beta = 0.5$, while $\tau = 0$; the second case shows an enhancement in the network lifetime because of the consideration of node density with the weight values of $\alpha = \beta = 0.4$ and $\tau = 0.2$; the third case shows an enhancement in the network lifetime when the weight value for $\tau = 0.4$, which is higher than the 0.3 of both α and β.

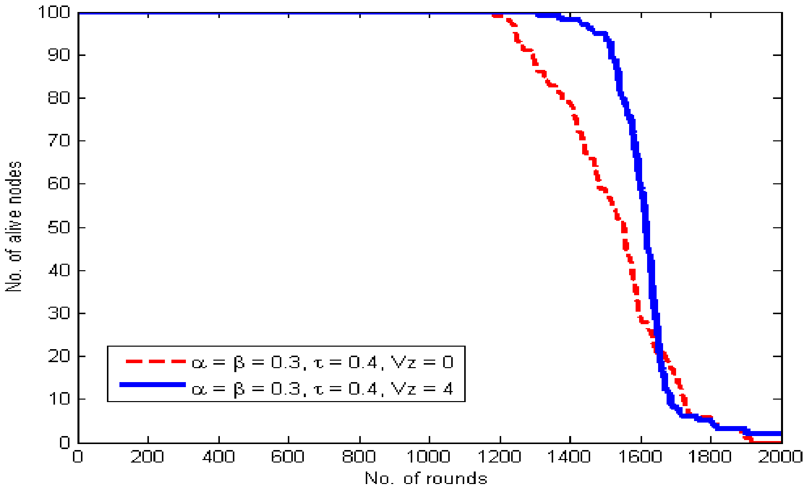


Fig. 4.8. The effect of VZs applied by the SDN controller on the network lifetime using WOA and the same values of $\alpha, \beta and \tau$

Figure 4.8 shows the number of live nodes against the rounds with different values of VZs. It is clear from the figure that the network lifetime increases when the number of the VZs implemented by the SDN controller is increased, which illustrates the effect of the SDN controller. Additionally, it is worth noting that the SDN controller implements the virtual zones division process only during the CHs selection procedure; however, the division process does not affect the progression of the cluster formulation. Furthermore, the effect of the number of the VZs implemented by the SDN controller varied as a function of different parameters, such as the number of nodes in the network, the network size, the random distribution of node density, the number of CHs in the network, and the node communication capability. Therefore, the figure shows the results for just two values for VZ (0 and 4) in order to recognise the effect of the SDN controller.

Figure 4.9 displays the simulation results of the CC-WOA's network lifetime compared to other protocols. It is clear from the figure that the overall network lifetime in the proposed clustering protocol has increased compared to other clustering

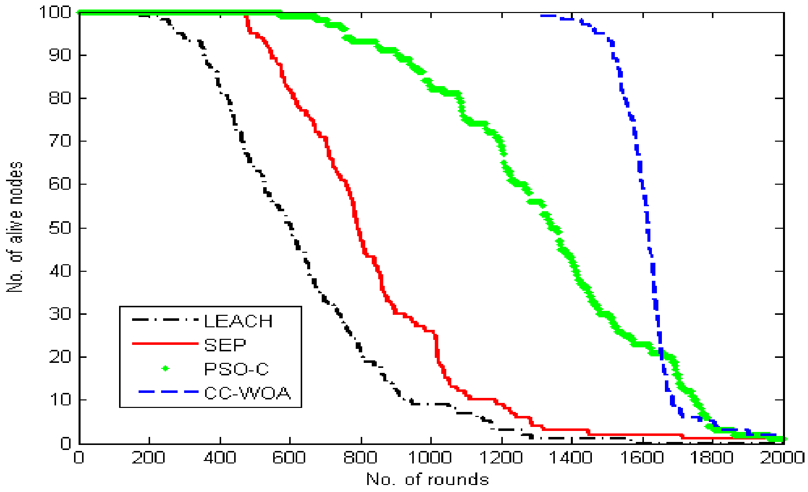


Fig. 4.9. Network lifetime of CC-WOA compared to other clustering algorithms

protocols. This is due to its consideration of the remaining energy, the communication cost and the covered nodes by the WOA, as well as the division of the sensing area by the SDN controller into VZs.

Figure 4.10 illustrates the packets sent to the sink during the simulation rounds. The total number of packets received by the sink throughout the simulation time has improved by approximately 55% compared to traditional clustering protocols, and 20% compared to the optimisation based clustering protocol. This is due to the improvement in the network lifetime of the proposed protocol in comparison to other protocols.

Figure 4.11 shows the energy remaining during this time. The proposed protocol shows an efficient distribution of energy dissipation among all the nodes in each time-period which increases the overall network lifetime. This efficient distribution is due to the consideration of both the coverage area and the division of the sensing area into four VZ.

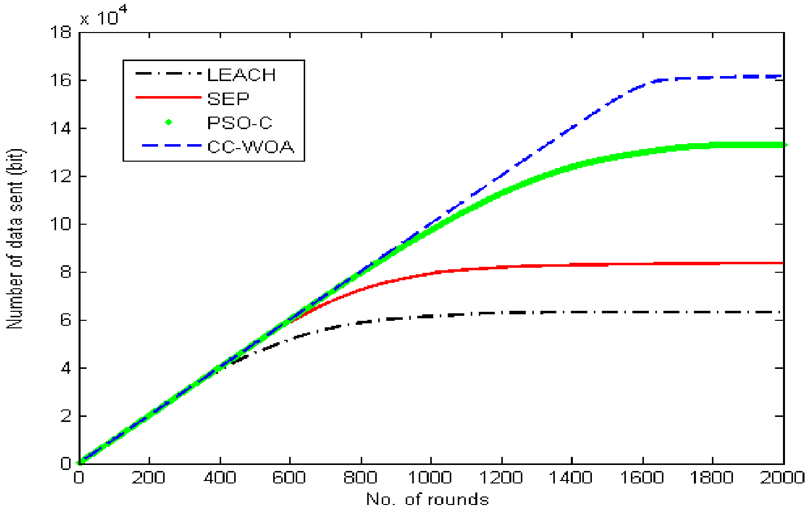


Fig. 4.10. Number of data sent (in bit) to the sink using CC-WOA and compared to other clustering algorithms

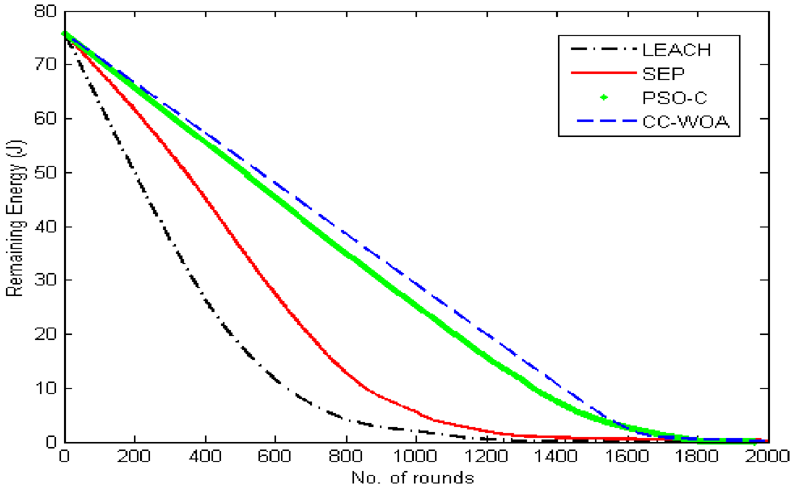


Fig. 4.11. Remaining energy in (J) of CC-WOA compared to other clustering algorithms

The number of cluster heads over simulation rounds is given in Figures 4.12, 4.13 and 4.14. The CC-WOA protocol has a stable number of cluster heads over the

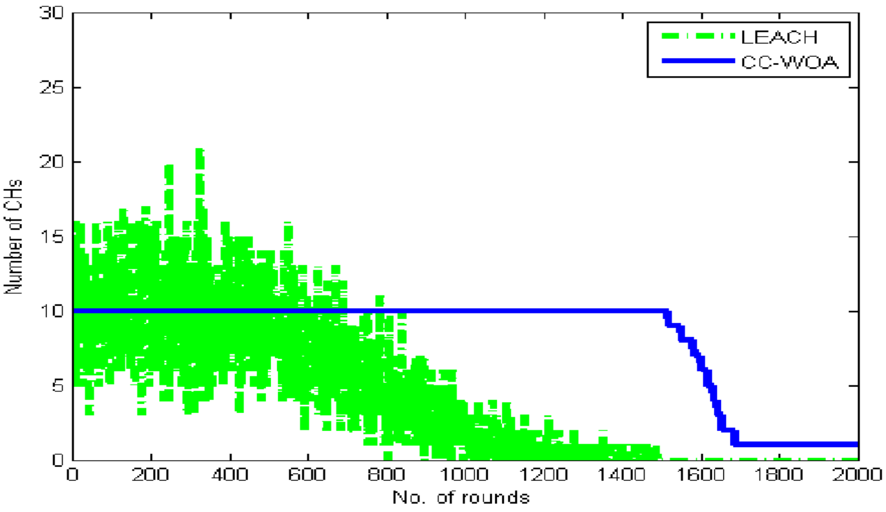


Fig. 4.12. The CHs comparison between CC-WOA and LEACH

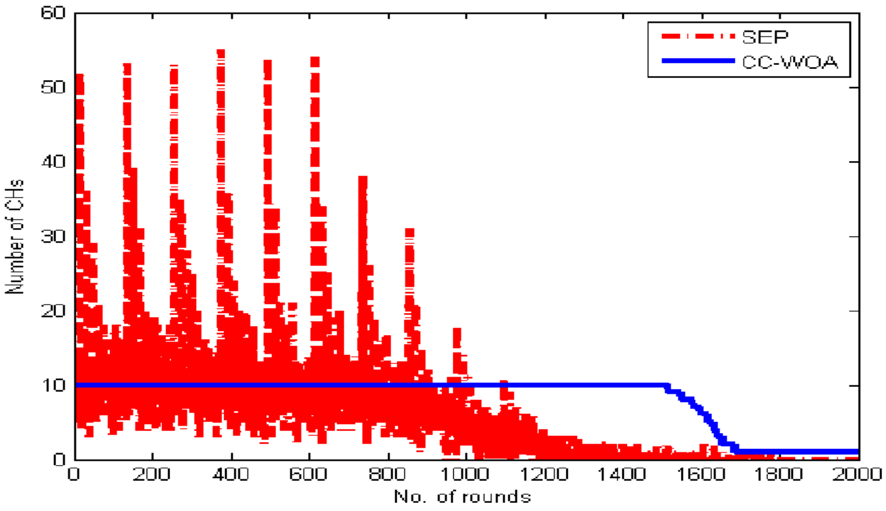


Fig. 4.13. The CHs comparison between CC-WOA and SEP

simulation rounds compared to other protocols (LEACH and SEP). This is because it determines the number of CHs as a percentage from the total number of nodes. Conversely, the random rotation of cluster heads occurs in LEACH and SEP based on probability rather than when certain criteria are met. Furthermore, in comparison

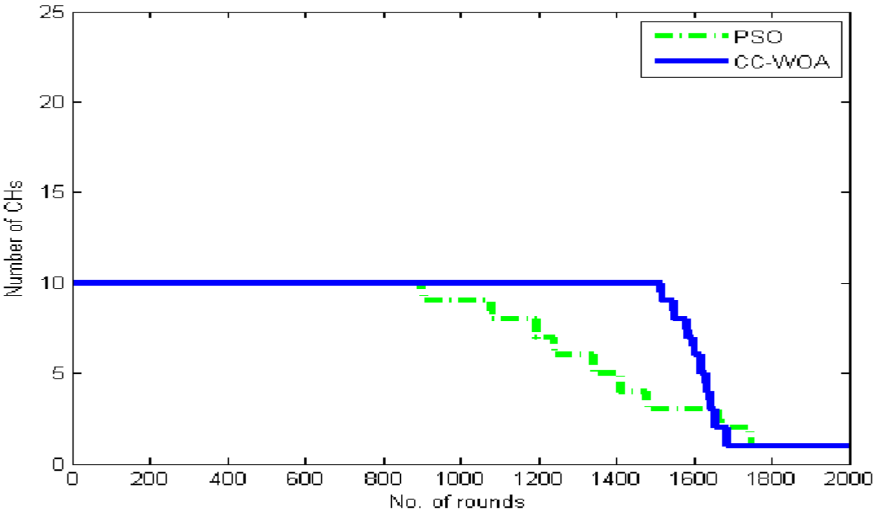


Fig. 4.14. The CHs comparison between CC-WOA and PSO-C

with the number of CHs using the PSO-C, Figure 4.14 shows that the number of CHs using the CC-WOA stays higher for longer period of time. This is because of using an efficient WOA and the consideration of the random distribution of node density by the SDN controller during the CHs selection process.

4.8 Contributions

In this chapter, a centralised clustering algorithm is proposed, based on the WOA and called CC-WOA for use in heterogeneous, randomly distributed and dense IoT networks. It combines SDN and clustering techniques with a WOA algorithm that enhances the performance of the IoT network. CC-WOA consists of two main phases: set-up and transmission. At the set-up phase, the SDN controller assumes that the network area is divided into VZs to balance the number of CHs in relation to the node density and the geographical area. It then uses the WOA to define the optimal set of CHs for cluster formulation. In the transmission phase, the CMs send their data to the CHs according to the TDMA scheduled by the corresponding SDN controller. Accordingly, the following objectives are pursued:

- Proposing a novel clustering algorithm based on an efficient fitness function using the WOA;
- Developing a routing protocol under the SDN concept that takes into consideration the node density in two positions: before the selection of CHs by dividing the sensing area into VZs, and then, during the selection of CHs by the WOA;
- Evaluating the effectiveness of the proposed protocol in terms of network lifetime, throughput and other influential metrics by comparing it with others.

4.9 Summary

The recent advent of SDN and intelligent networks has prompted the researcher to conduct further investigations into the high-density WSN. WSNs exhibit inherent issues that limit their performance, such as sensor resource restrictions that affect the power supply, memory, processing units and communications capabilities thereof. This thesis proposes new clustering, using a WOA based on the concept of SDN. The proposed protocol considers both sensor resource restrictions and the random diversification of node density in the geographical area. It begins by dividing the sensing area by the SDN controller into VZs in order to balance the number of CHs according to the node density in each VZ; it then uses the WOA, which considers residual energy, communication cost and node density, in order to define the optimal set of CHs. The simulation results indicate the efficiency of the WOA in cluster formulation by comparing it with other types of swarm-based optimisation clustering. Additionally, the results indicate that the proposed protocol has improved the network lifetime and resulted in an efficient dissipation of energy. Furthermore, it has increased the number of packets sent to the sink by approximately 55% compared to traditional protocols, and by about 20% compared to an optimisation-based routing protocol.

Chapter 5: Routing Protocol for Large Scale IoT Networks

5.1 Introduction

In general, WSNs are considered a resource that enables the accomplishment of the IoT [2]. Moreover, the deployment of the IoT devices is usually random and unbalanced, taking place within a harsh and large-scale environment, which makes the replacement of any device's battery a nigh on impossible task [2]. The use of a static sink only covers a small-scale network region and thus, mobile sink routing algorithms for WSN become indispensable for extending the life of the network [86]. However, the technique used by a mobile sink to roam across the network to gather data has suffered from delay issues. Consequently, the scheduling of MS and efficient path determination are perceived as the key research challenges.

Therefore, in order to tackle these challenges, AI, which require a global view and a centralised control of the entire network, are involved in the IoT monitoring system. However, centralised network monitoring using the SDN controller and global network optimisation are deemed substantial challenges in the IoT, as each device follows an independent routing protocol to forward their data to other devices or to the sink [106] [107]. This independent protocol leads to unbalanced cluster construction, which can shorten the lifetime of the entire network. Hence, it is necessary to design an energy efficient routing protocol that properly balances the load between the devices and is suitable for both small and large-scale environments, thus improving the lifespan of the entire IoT network.

The remainder of this chapter is organised as follows. Section 5.5 briefly reviews the contributions related to this chapter and Section 5.2 describes the formulation of the problem presented in this chapter. The methodology for the proposed mobile sink-based protocol using optimisation approaches is illustrated in Section 5.3, with the shortest path determination using a GA also being introduced in this section. In Section 5.4, the obtained simulation results and validation are discussed. Finally, Section 5.6 presents a chapter summary.

5.2 Problem Formulation

The key aim of this research is to develop an energy efficient routing protocol for large scale networks. However, the WSN nodes suffer from sensor resource restrictions in terms of processing units, battery, communication capability and memory. Hence, a clustering technique is used for the data aggregation process to conserve energy. The cluster formulation process begins by electing the set of CHs responsible for collecting the data from the CMs and forwarding them to the sink, which can be either static or mobile. Consequently, the CHs deplete their energy more rapidly than the cluster members due to: the unbalanced cluster formulation that forces one CH to spend more power than others, performing the data aggregation, and sending these data to the sink from a greater distance than the CMs. Furthermore, in a large-scale network, it is practically impossible to cover the entire region using a static sink. Additionally, the use of such a sink in large scale networks leads to high energy exhaustion among the CHs and increases the hot spot problem due to the connection to the sink.

One effective solution to reduce the energy spent by the CHs is to use the MS. However, its execution in the IoT network presents many challenges, such as: determination of the MS's optimal path and collection points, synchronisation between the MS and the CHs, and protocol overheads for route discovery by the CHs when forwarding their data to the sink. In this chapter, an energy efficient routing protocol for large scale IoT networks is proposed that considers the above issues, with the aim of reducing the overall energy consumed by the nodes and thus, prolonging the overall network lifespan. The proposed protocol involves using a centralised architecture based on the SDN and cloud technologies to reduce network complexity, thereby effectively mitigating the overheads generated by the nodes in the route identification procedure. Furthermore, the SDN controller uses optimisation algorithms to define a load balanced set of clusters that considers the impact of the $\mathrm{MS}_{\mathrm{Opath}}$ during the CH selection process. In addition to this, the proposed protocol offers a synchronisation technique between the MS and the CHs that allows the latter to sleep whenever possible and thus, reduces the energy consumed by them.

5.3 Proposed Scheduling Protocol-Based Optimisation Algorithms

The novelty of this chapter is the suggestion of a new routing protocol that works efficiently in large scale IoT network. This novel protocol is implemented by proposing a load balanced clustering algorithm and a new technique to collect the data from the large scale network using novel S_{DG} and $\mathrm{MS}_{\mathrm{Opath}}$. The proposed approach is divided into four related phases: cluster formation, S_{DG} determination, $\mathrm{MS}_{\mathrm{Opath}}$ identification and network scheduling with the MS. The following assumptions are made prior to the simulation of the proposed protocol:

1. The sensor nodes are the same in terms of having the same computational and sensing capabilities, but differ in that they have two levels of initial energy;
2. Each sensor node has a chance to transmit its location based on the GPS using long range transmission.

5.3.1 Network Architecture

The network is designed in such a way as to reduce the average energy consumed by the CMs and CHs. The protocol is implemented using optimisation algorithms and new technologies, including SDN and the cloud. As shown in Figure 5.1, the proposed OMS-LB architecture can be organised into three main layers: the infrastructure layer, the processing layer and the application layer. The infrastructure layer is comparable to the data-plane layer in the SDN construction and includes two sub-layers: the data gathering sub-layer and the sensing sub-layer. The data are first collected at the sink or gateway and either sent to the cloud to be stored and used by specific applications, or processed and then sent to the SDN controller to make routing decisions.

The SDN controller is executed over the cloud and has the responsibilities of: cluster construction using PSO and a GA, $\mathrm{S_{DG}}$ determination using PSO, $\mathrm{MS_{Opath}}$ identification using a GA, and network scheduling. The use of OMS-LB construction has a crucial impact in that it reduces network complexity. Furthermore, the positioning of the SDN controller over the cloud provides vital benefits by employing its resources for data processing or storage. For instance, the SDN controller uses the data-centre in the cloud as a huge computational resource, for such as the implementation of the optimisation algorithms outlined in this chapter. The development of the OMS-LB provides efficient mapping and fairness in the allocation of CHs as well as the sink nodes, such that there is no congestion at the sink and redundant paths are provided for it in the event of sink node failure.

5.3.2 Cluster Formulation

The suggested protocol employs cloud resources using a centralised SDN controller to find an optimal routing protocol for IoT networks. This work provides an energy efficient routing protocol by combining the impact of the moving cost of the MS to collect the data with the cluster formulation process, such that the energy consumed

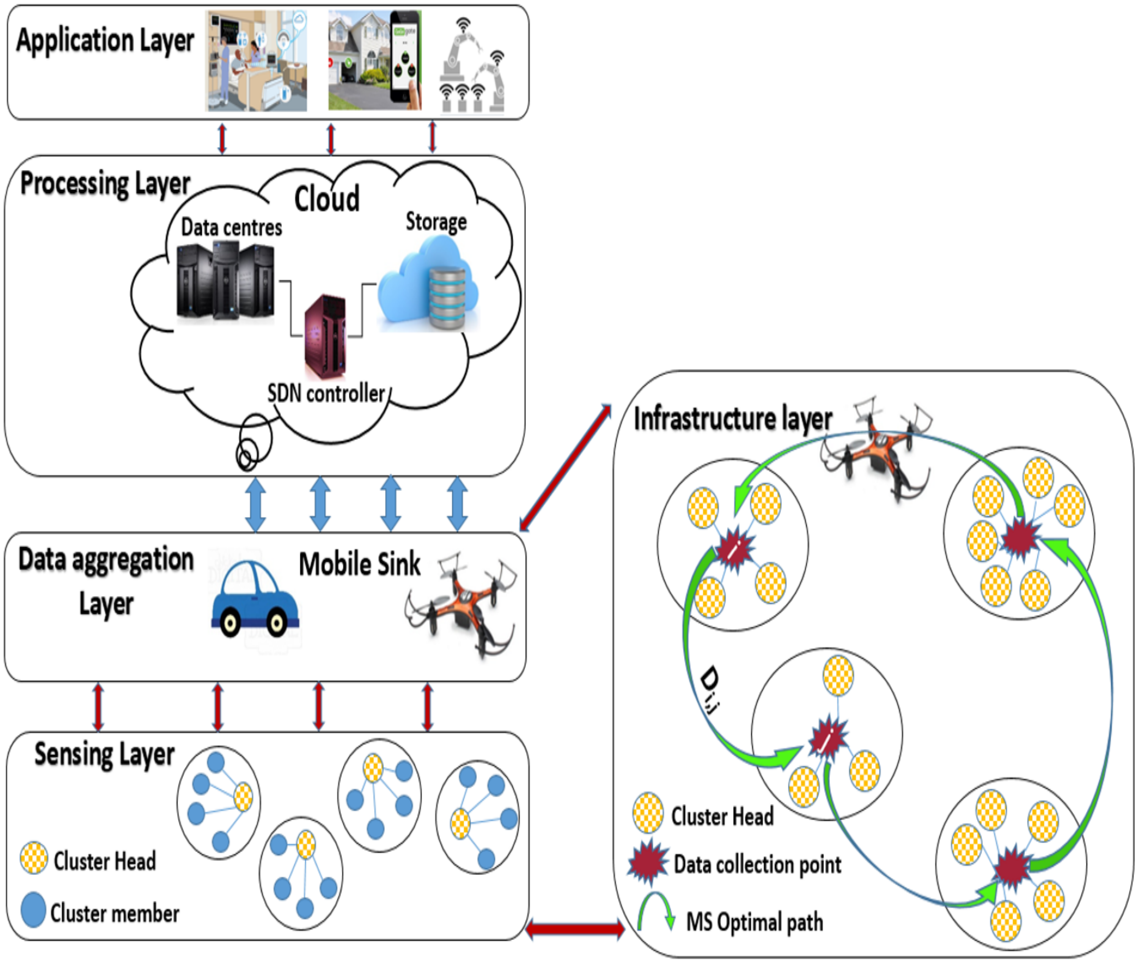


Fig. 5.1. Routing structure-based SDN and MS

when sending data over the entire network is reduced. The cluster construction is handled by the SDN controller, which constructs the clustering table (CT) using a load-balanced PSO algorithm. For the first round, the controller builds the CT using only the information on the device coordinates. For subsequent rounds, the controller exploits the information collected on the remaining energy and distances to choose the best set of CHs, then constructing the CT. Subsequently, the controller sends the CT to the MS, with the former scheduling information about the clusters, the set of CHs and the CMs belonging to each cluster (see Figure 5.1). The MS then broadcasts the CT to all the devices, and each inspects it to determine whether it is a CM or CH.

As shown in Figure 5.2, the PSO starts by generating a set of random particles (NP), with each particle (p) being an D dimension vector evaluated by a fitness function. However, the perfect solution for PSO is only achieved after a certain number of iterative evolutions. Throughout these, each particle in the swarm tracks the global best ($\mathrm{G}_{\mathrm{best}}$) and its personal best ($\mathrm{P}_{\mathrm{best}}$). In this work, the controller computes the average energy of all the devices that are alive at each round and memorises those with an energy level greater than average as candidates to be CHs, in a matrix known as NCH. Moreover, PSO maximises the cost of the following function:

$$\mathrm{cost} = \alpha f_1 + \beta f_2 + \eta f_3 + \gamma f_4 \tag{5.1}$$

$$f_1 = \frac{\sum_{j=1}^{K} E_{(\mathrm{CH}_{p,j})}}{\sum_{i=1}^{N} E_{(n_i)}} \tag{5.2}$$

$$f_2 = \sum_{j=1}^{K} \frac{\mathrm{NA}_r}{\sum_{i=1}^{\mathrm{NC}_{p,j}} \mathrm{dis}_{(n_i,\mathrm{CH}_{p,j})}} \tag{5.3}$$

$$f_3 = \frac{(\mathrm{LB}_{\mathrm{avg}})^2}{\sum_{j=1}^{K} (\mathrm{NC}_{(p,j)} - \mathrm{LB}_{\mathrm{avg}})^2 + \delta} \tag{5.4}$$

$$\mathrm{LB}_{\mathrm{avg}} = \frac{(\mathrm{NA}_r - K)}{K} \tag{5.5}$$

$$f_4 = \frac{\mathrm{S}_{\mathrm{DG}}}{\mathrm{MS}_{\mathrm{Opath}}} \tag{5.6}$$

where coefficients α, β, η and γ are constants and presented in Table 5.1. The function f_1 identifies the set of CHs with a higher energy level. The function f_2 selects clusters with minimal communication costs between CH and CMs. The function f_3 selects the set of clusters with a maximum load-balancing rate. The constant δ in Equation (5.4) provides a method of escape from the local maximum throughout the progression of the PSO. Furthermore, load balancing in the IoT is distinct as a uniform distribution of load among the CHs; hence, in this chapter, the SDN controller processes load balancing by choosing a well-balanced set of clusters using Equation 5.4. The value $\mathrm{LB}_{\mathrm{avg}}$ is the mean number of CMs belonging to each cluster, and NA_r is the total number of devices alive during round r. The function f_4 comprises the minimum movement cost of the MS. The value S_{DG} is the optimal set of the data gathering points discussed in Section 5.3.3, and $\mathrm{MS}_{\mathrm{Opath}}$ refers to the selection of the optimal path for the MS with minimum distances (see Section 5.3.4). As shown in Figure 5.2, on determining the routing protocol the cluster formulation in the proposed protocol combines with the impact of the optimal MS movement.

5.3.3 Data Aggregation Points

The (S_{DG}) in the proposed protocol are defined using the PSO algorithm (as shown in Figure 5.2). Initially, the number of S_{DG} in this work is equal to (DG x K), where DG is the percentage of S_{DG} selected between 0 and 1, whilst K is the number of CHs. Furthermore, the optimal S_{DG} is defined using PSO by maximising the cost of the following fitness functions:

$$\mathrm{cost} = \Phi f_{\mathrm{dg1}} + \psi f_{\mathrm{dg2}} + \mu f_{\mathrm{dg3}} \tag{5.7}$$

$$f_{\mathrm{dg1}} = \sum_{i=1}^{\mathrm{S}_{\mathrm{DG}}} \frac{\sum_{j=1}^{K_i} \mathrm{CHs}_{(i,j)}}{\mathrm{S}_{\mathrm{DG}}} \tag{5.8}$$

$$f_{\mathrm{dg2}} = \sum_{i=1}^{\mathrm{S}_{\mathrm{DG}}} \frac{K}{\sum_{j=1}^{K_i} \mathrm{dis}_{(\mathrm{CH}_{p,j},\mathrm{S}_{\mathrm{DGi}})}} \tag{5.9}$$

$$f_{\mathrm{dg3}} = \frac{\mathrm{S_{DG}}}{\text{optimal distance}} \tag{5.10}$$

where, Φ, ψ and μ are shown in Table 5.1. The function f_{dg1} chooses the $\mathrm{S_{DG}}$ that covers the maximum number of CHs. Furthermore, the function f_{dg2} selects the $\mathrm{S_{DG}}$ containing the shortest distances between the CHs and their data collection points, whilst the function f_{dg3} selects the $\mathrm{S_{DG}}$ with the shortest path for the MS. Moreover, the shortest path found in the last iteration is used in Equation 5.6 as $\mathrm{MS_{Opath}}$. However, the shortest path is identified using the GA (explained in Section 5.3.4) and has the advantages of reducing the delay, which also restricts the energy consumed by the CHs when waiting for the MS. In addition, each CH is connected to the closest $\mathrm{S_{DG}}$, whilst the proposed algorithm has been designed such that the maximum average distance between a CH and the closest $\mathrm{S_{DGi}}$ (named as $\mathrm{CH_{avd}}$) is no greater than the threshold (T_h)(see Figure 5.2). However, if the distance is more than T_h, an extra collection point should be added to the routing design to satisfy a higher level of energy conservation by the CHs.

5.3.4 Optimal Mobile Sink Path Determination

In this chapter, one of the problems to be solved is how to determine the best route (path) for the MS in the search space. Once the SDN controller identifies the optimal $\mathrm{S_{DG}}$ using PSO, it executes the GA-based algorithm to evaluate the $\mathrm{MS_{Opath}}$, which passes across all the data aggregation points for $\mathrm{S_{DGs}}$ only and collects data from the CHs to the mobile sink using a one-hop transmission. The GA is a heuristic search algorithm based on the principles of natural selection and is used to resolve optimisation problems [108]. It develops finite length strings of alphabet known as chromosomes, which are sets of nominee solutions to the search problem, with these alphabets being also known as genes [109]. The set of chromosomes represents a set

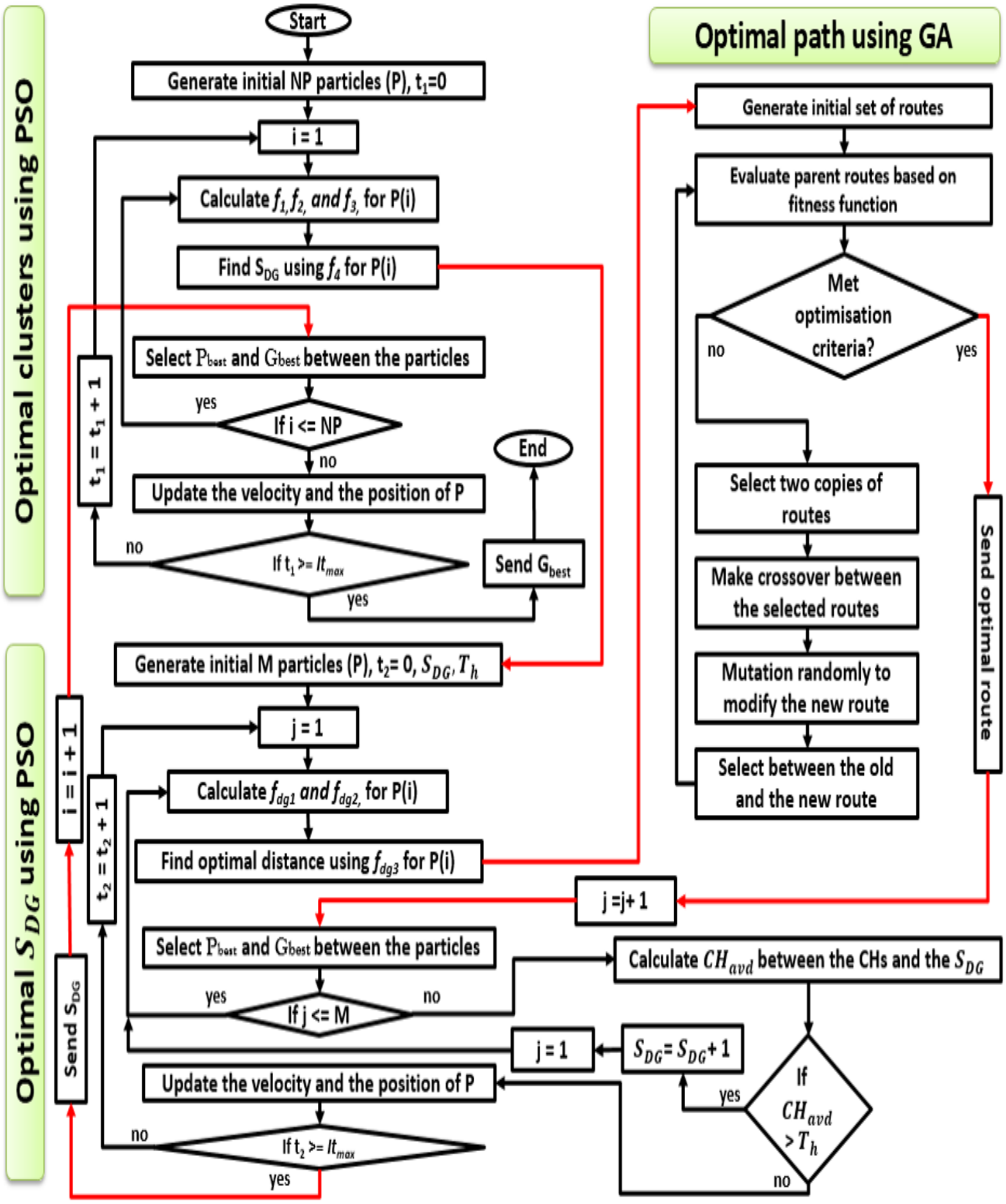


Fig. 5.2. Flowchart of cluster formulation based optimisation algorithms

of paths, and the genes in each represent the position of $\mathrm{S_{DG}}$, as defined in Section 5.3.3.

The objective function of the GA is based on the shortest path passing through all the $\mathrm{S_{DG}}$ positions, one beginning from the position nearest to the start point and returning there without visiting the same node twice (see Figure 5.1). The process of the GA is described in Figure 5.2. Once the set of populations is encoded into a set of chromosomes, the fitness function distinguishes good resolutions from bad ones. The process of can be summarised as the following steps:

1. Initialisation: initialising sets of populations for different routes, which are generated randomly as nominee solutions in the search space;
2. Evaluation: evaluating the nominee solutions of parent routes using the fitness function;
3. Selection: selecting two copies of nominee routes with higher fitness values and this is known as survival-of-the-best between the candidate solutions;
4. Recombination: forming a crossover between the selected candidates to create a better solution;
5. Mutation: modifying the route randomly using the GA;
6. Replacement: selecting the best route between the old and that newly generated;
7. Repeat steps 2 to 6 until the optimisation criteria is met.

5.3.5 Network Scheduling

Network scheduling is one of the key challenges in the design protocols of WSNs. Without network scheduling, the devices deplete higher energy when accessing the channel or waiting for a chance to send their data. In this thesis, a network scheduling technique arranged by the SDN controller is proposed in the form of a network

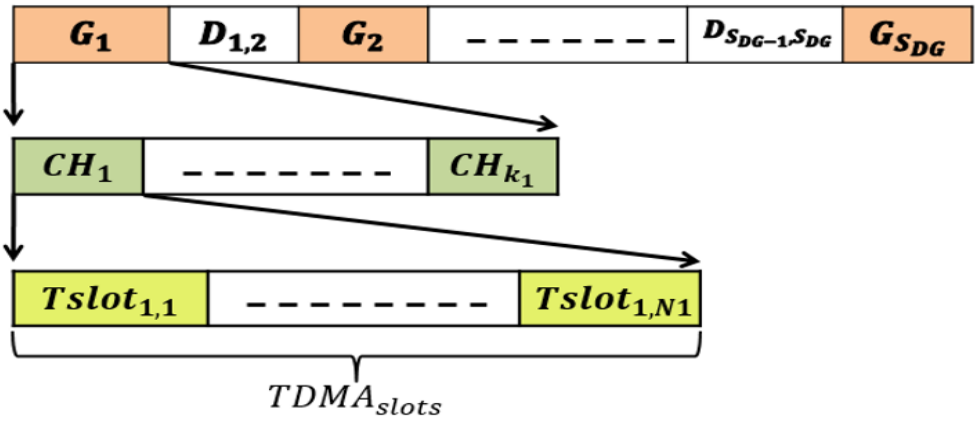


Fig. 5.3. Network scheduling message

scheduling message (NSM). This message is used to schedule the sleep/wakeup period of the CHs, according to the arrival time of the MS. Furthermore, the data transmission period is also structured by the SDN controller using TDMA scheduling. Additionally, regarding the TDMA scheduler, all the CMs send their residual energy, ID, and data to their predetermined CH during their definite time slot and shut down their radio across all others to conserve energy.

Figure 5.3 depicts the structure of the proposed scheduling technique, where each device in the network has its own time slot in which to send its data. Furthermore, all the CMs and CHs can turn their radio off to conserve energy, if the MS has not yet arrived; however, according to NSM, the devices can turn their radio ON once it has. The total delay in the network can be calculated according to Figure 5.3 as follows:

$$\text{Delay} = \sum_{i=1}^{\text{SDG}} G_i + D_{i,i+1} \tag{5.11}$$

where G_i represents the time spent by the MS at $\mathrm{S_{DGi}}$ to collect the data from K_i

number of CHs, which belong to the aggregating point i. Furthermore, G_i is calculated as follows:

$$G_i = \sum_{j=1}^{K_i} \sum_{L=1}^{N_j} \mathrm{T}_{\mathrm{slot}(j,L)} \tag{5.12}$$

where N_j is the number of nodes connected to CH_j and is identified by the SDN controller during the generation of the TDMA schedule. $\mathrm{T}_{\mathrm{slot}(j,L)}$ represents the time slot used by the device L to send its data to CH_j. The Value $D_{i,i+1}$, in Equation 5.11, considers the delay by the MS in moving from $\mathrm{S}_{\mathrm{DGi}}$ to $\mathrm{S}_{\mathrm{DGi+1}}$ (see Figure 5.1), and is calculated as follows:

$$D_{i,i+1} = \frac{\mathrm{Dis}_{i,i+1}}{\mathrm{V}_{\mathrm{MS}}} \tag{5.13}$$

where $\mathrm{Dis}_{i,i+1}$ is the Euclidean distance between $\mathrm{S}_{\mathrm{DGi}}$ and $\mathrm{S}_{\mathrm{DGi+1}}$, and V_{MS} is the velocity of the MS.

5.3.6 Radio Model

The first order radio model proposed in [18] is used in this work. Each device can waste its energy in amplification ($\mathrm{E}_{\mathrm{amp}}$), reception ($\mathrm{E}_{\mathrm{RX}}$), transmission ($\mathrm{E}_{\mathrm{TX}}$), and data aggregation (E_{DA}). Additionally, the $\mathrm{E}_{\mathrm{amp}}$ is expressed by Equation (4.15) to attain evident levels of Signal-to-Noise Ratio (SNR) in transmitting a single bit over a distance d. Whilst, the required energy to transmit or receive s bits over a distance (d) is given in equations 4.16 and 4.17, respectively. Moreover, all other radio parameters are presented in Table 4.2.

Table 5.1
PSO, GA and network parameters

Parameter	Value	Definition
N	200	Number of nodes
S_{PAO}	40 particles	Swarm size
W_{GA}	100	GA population size
PSO $\mathrm{It}_{\mathrm{max}}$	400	Maximum number of iterations
GA $\mathrm{It}_{\mathrm{max}}$	5000	Maximum number of iterations
α	0.2	Energy parameter
$\beta = \psi$	0.3	Distance parameters
η	0.2	Land balancing parameter
γ	0.3	$\mathrm{MS}_{\mathrm{Opath}}$ weight parameter
δ	1	Load balancing constant
Φ	0.3	number of CHs covered parameter
μ	0.4	route length parameter
C_r	0.8	GA crossover parameter
M_u	0.05	GA mutation parameter
Packet	4000 bit	Data message size
V_{MS}	3 m/sec	Velocity of the MS

5.4 Performance Evaluation Results

5.4.1 Network Set-up

The proposed network model consists of N stationary IoT nodes, which are location aware and randomly deployed in a X, Y square metres network field. In this work, there is consideration of the results of two cases aimed at improving the scalability of the proposed protocol, which are: network size 200 m × 200 m, and network size 700 m × 700 m. Additionally, the network considers two degrees of node heterogeneity, these being: 50 percent of advanced nodes and 50 percent of normal nodes. The normal nodes have $0.5J$ of initial energy and the advanced ones have $1J$, while the sink (static or mobile) is presumed to be resource sufficient. The traditional network based static sink is situated at the centre of the network. Moreover, at each round, the number of CHs (K) is set to be 10 percent of all the live nodes ($\mathrm{NA_r}$) and the number of $\mathrm{S_{DG}}$ is initially set to be 50 percent of K. Moreover, the number of $\mathrm{S_{DG}}$ continues to increase until it satisfies the average destination criteria stipulated in function 5.7. All the relevant simulation parameters are listed in Table 5.1.

5.4.2 Performance Evaluation

The proposed approach is extensively simulated using MATLAB software to evaluate the performance of the proposed clustering technique and the $\mathrm{MS_{Opath}}$-based GA. In this thesis, a load-balanced clustering technique with $\mathrm{MS_{Opath}}$ for IoT networks called OMS-LB is proposed. To improve the efficiency of the proposed clustering technique-based optimisation, the OMS-LB protocol was compared to two well-known cluster-based routing protocols with a static sink: LEACH and PSO-C.

Furthermore, to improve the effectiveness of the proposed OMS-LB, it was first compared with the centralised clustering algorithm-based load balancing without the use of the MS, namely, CLBCA. Then, it was compared to the MIEEPB-based MS and the random move determination for the MS-based load balancing, called RM-LB, using the same proposed clustering algorithm in CLBCA to identify the optimal set of CHs. Network lifespan is defined as the number of nodes alive over time (rounds) from the beginning of the transmission until the death of the last node in the network. Moreover, the network lifespan is divided into two periods: the stable period (from the beginning of transmission until the death of the first node) and the unstable one (from the death of the first node until the death of the last).

Figures 5.4 and 5.5 illustrate the network lifespan. It is clear from the figures that the suggested protocol can considerably extend the overall life of the network, partic-

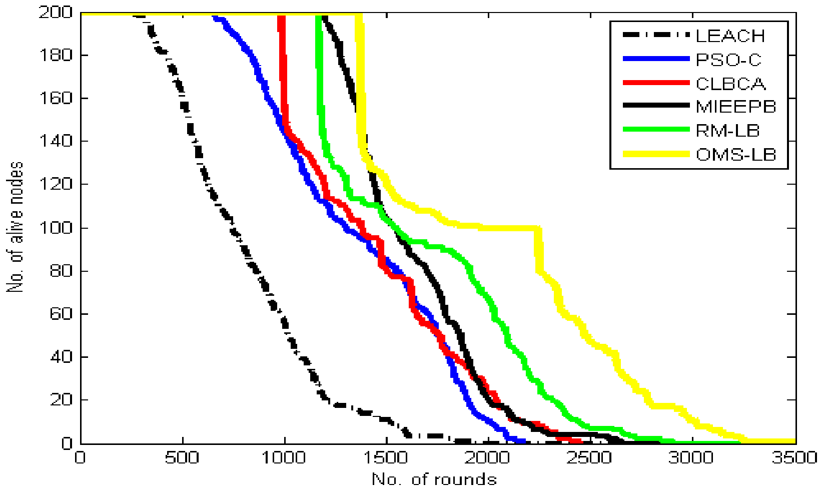


Fig. 5.4. Network lifetime when the network size = 200 m × 200 m

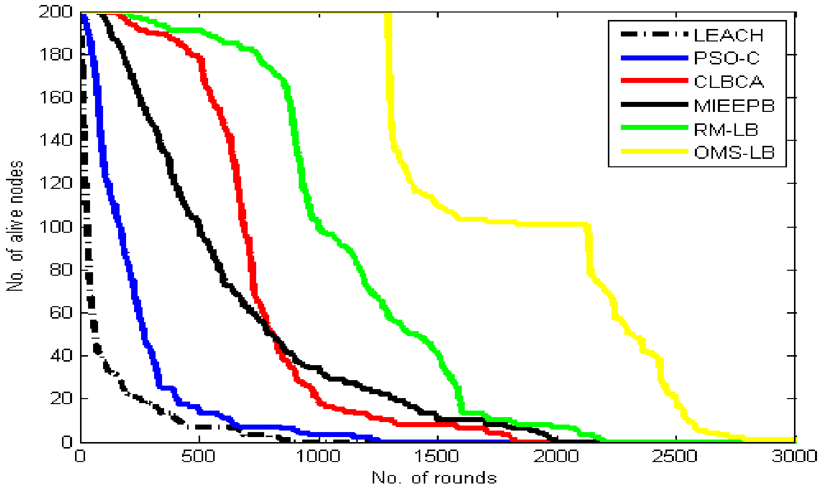


Fig. 5.5. Network lifetime when the network size = 700 m × 700 m

ularly the stability period, compared to other routing protocols. The improvement in network lifespan and the long stability period justify the attention of load-balancing, S_{DG}, network scheduling and the MS_{Opath} by the PSO during the cluster construction process. Additionally, the figures show that the death of the first node of the protocol occurs at approximately rounds 1410 and 1280 for Figures 5.4 and 5.5, respectively.

The proposed protocol enhances the stability period compared to other protocols, and the curve displays a relatively steep decline. This is the outcome of fair load-balancing and consideration of the optimal route for the MS using the GA. Hence the overall network has many devices with a small amount of preliminary energy that all give out at the same interval. Figures 5.4 and 5.5 show the network lifespan for the first and second cases, respectively. It is clear from these figures that the proposed algorithm exhibits efficient energy consumption and furthermore, it works more efficiently with a large-scale network than do other protocols. The MIEEPB routing protocol uses the MS, under the assumption that the path of the MS and the number and positions of the data collection points are constant. As a consequence, the nodes will spend more energy in sending their data, especially in large scale networks. Additionally, the overall performance indicates that, compared to RM-LB, MIEEPB, CLBCA and PSO-C, the OMS-LB protocol prolonged the life of the network in the first case, by 15%, 19% 25% and 37% percent, respectively, and in the second case, by 23%, 31%, 38% and 54%.

Figures 5.6 and 5.7 display the residual energy of the IoT nodes with the simulation rounds for the first and the second case. All the protocols start with the same level of initial energy. However, the OMS-LB protocol has more residual energy than the existing protocols in both cases. This is because, firstly, the OMS-LB efficiently distributes energy consumption among all the nodes throughout each round in contrast to other protocols; hence, the entire network stays alive for an extended time. Such efficient distribution is due to the fair load balancing technique executed by the SDN controller through the cluster formulation process using Equations 5.1 and 5.7. Secondly, the determination and customisation of the $\mathrm{MS}_{\mathrm{Opath}}$ using optimisation algorithms improves data gathering across the network field and ensures that the nodes save their energy for future transmission and control duties.

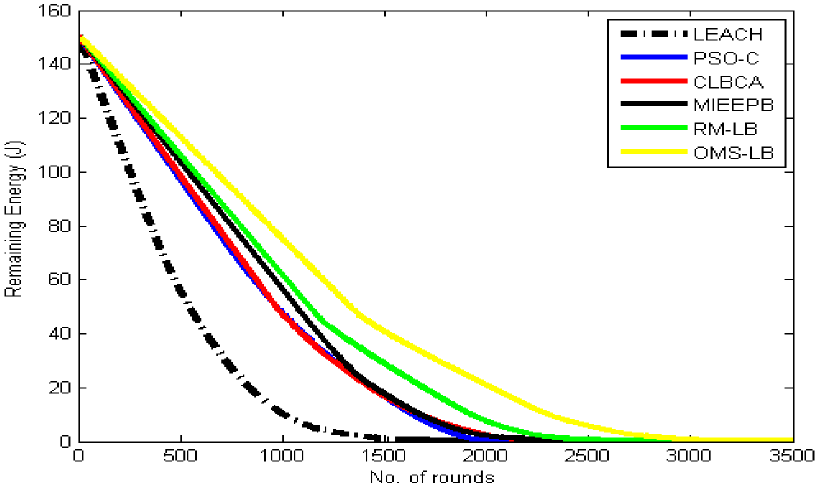


Fig. 5.6. Remaining energy when the network size = 200 m × 200 m

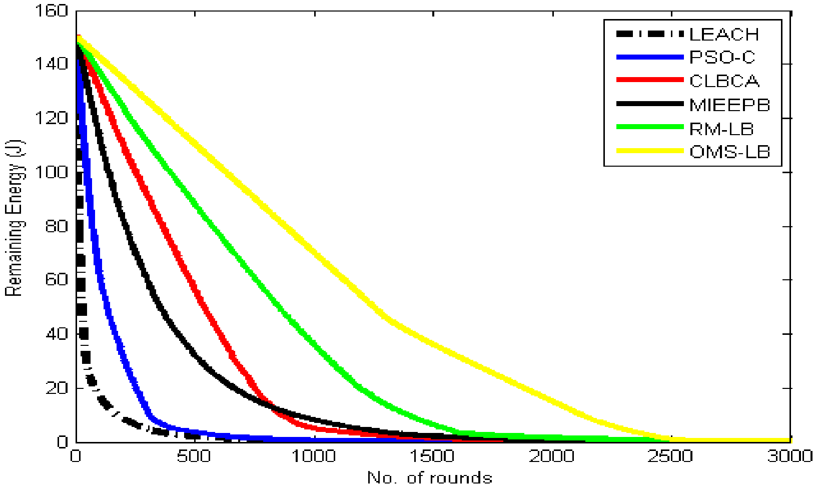


Fig. 5.7. Remaining energy when the network size = 700 m × 700 m

Fairness in energy dissipation through the network field means that the OMS-LB sends substantially more packets to the base station than other protocols, as shown in Figures 5.8 and 5.9. The overall throughput of the IoT devices is enhanced by approximately 62%, 33%, 28%, 20% and 15%, respectively, in comparison to LEACH,

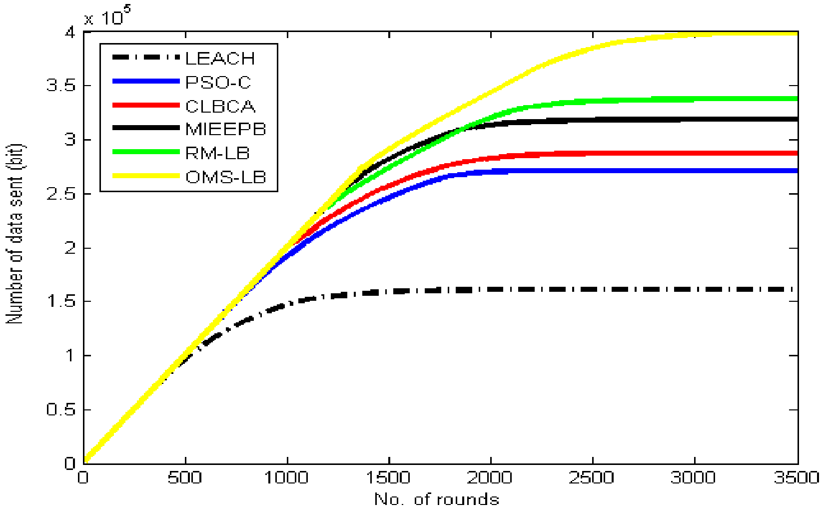


Fig. 5.8. Volume of data sent when the network size = 200 m × 200 m

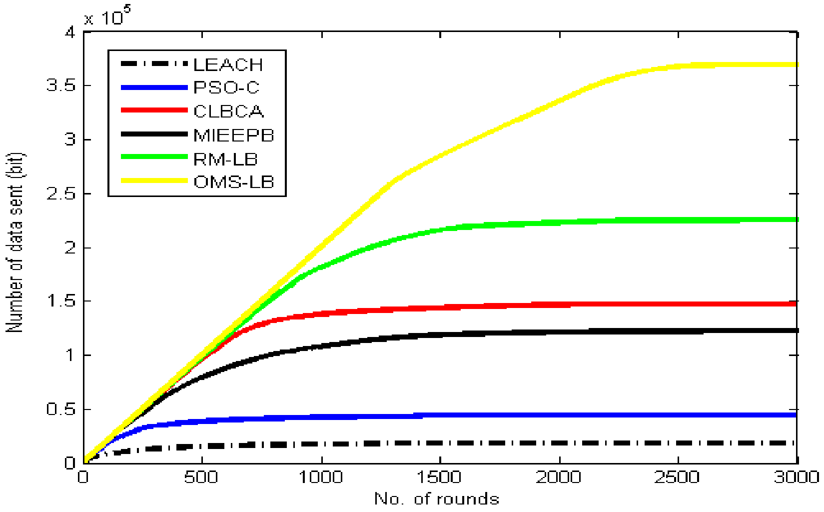


Fig. 5.9. Volume of data sent when the network size = 700 m × 700 m

PSO-C, CLBCA, MIEEPB and RM-LB for the first case and by approximately 93%, 86%, 62%, 69% and 44% for the second case with a large scale network. The OMS-LB routing protocol reduces the number of hops from the sensor nodes to the CH node and from the CHs to the S_{DG} using the PSO. This reduction in hop count will reduce

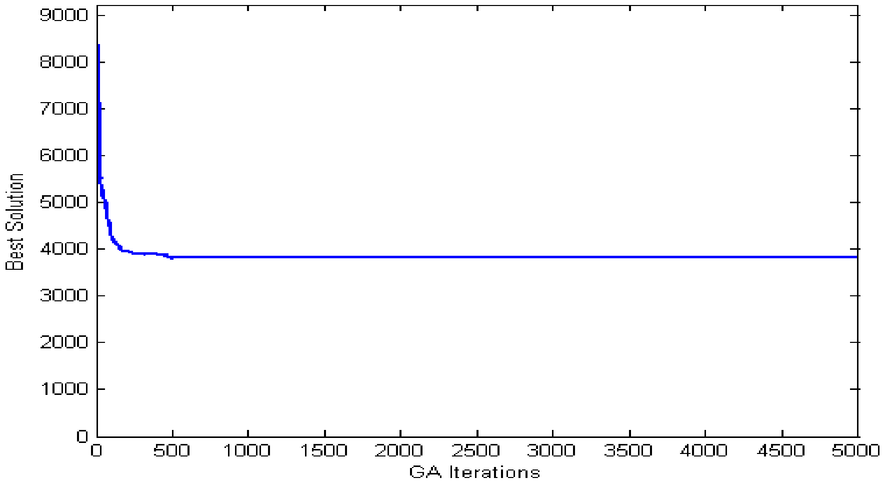


Fig. 5.10. GA convergence to find $\mathrm{MS}_{\mathrm{Opath}}$

the energy dissipation in relay nodes. Furthermore, the proposed algorithm schedules the entire network with the aid of the GA, which allows most of the sensor nodes and the CHs to conserve energy by turning their radio off. Consequently, the volume of data sent increases as the lifespan of the network increases.

Figure 5.10 illustrates the convergence process of the GA-based $\mathrm{MS}_{\mathrm{Opath}}$ after a few iterations when reaching the optimal solution. The figure shows how quickly the proposed approach converges to the $\mathrm{MS}_{\mathrm{Opath}}$ when the sensing field has the maximum number of S_{DG}. Figure 5.11 displays the optimum mobile sink path in red for the proposed OMS-LB, indicating where the MS visits the S_{DG} not the the CHs to collect the data from the cluster heads. Therefore, this figure gives a clear indication of the optimum path, which passes through the minimum number of S_{DG} in the sensing area. Figure 5.12 shows the MS random path for the RM-LB, which visits each CH to collect the data from the CHs. Therefore, the route length of the RM-LB is longer than that of the proposed OMS-LB.

Figure 5.13 compares OMS-LB and RM-LB in terms of the delay. The network scales (1, 2, 3, 4, 5, 6 and 7) refer to the network fields (100 m × 100 m, 200 m ×

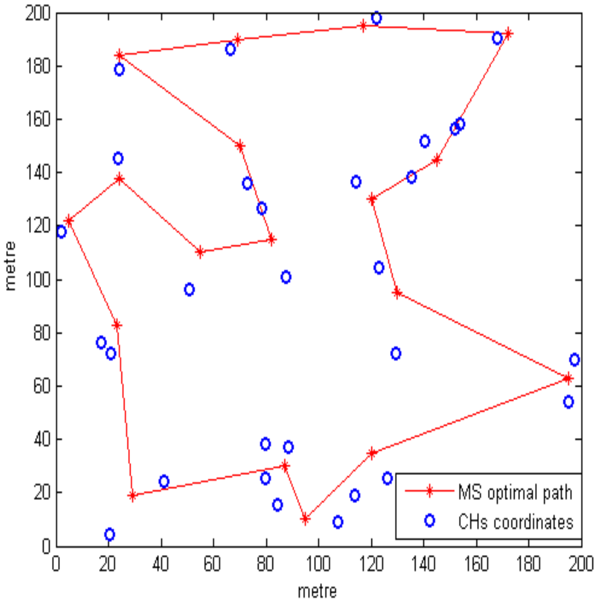


Fig. 5.11. MS_{Opath} using OMS-LB, the MS pass through the S_{DG} not the CHs

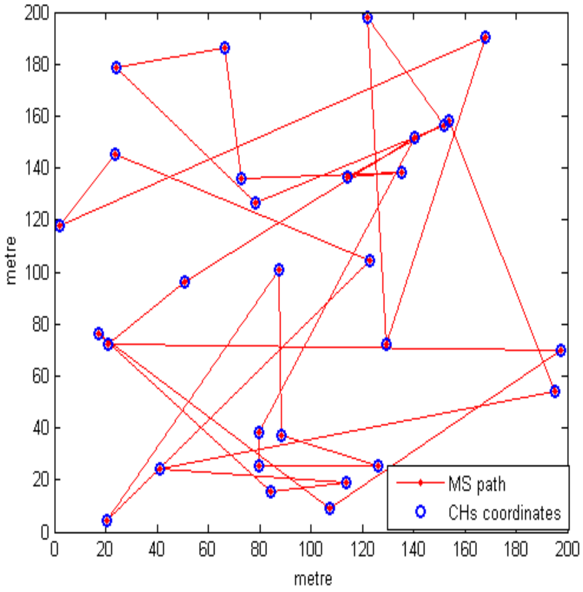


Fig. 5.12. RM-LB the MS pass through each CH in a random movement

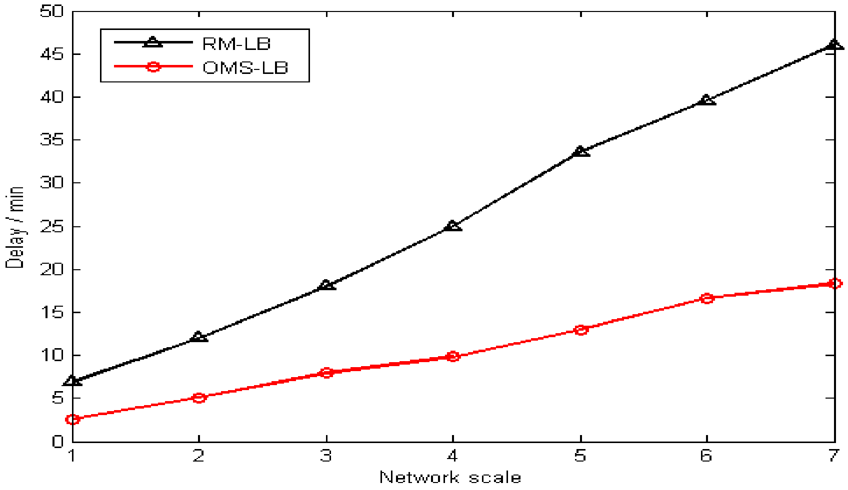


Fig. 5.13. The route delay with network scale when the MS velocity = 3 m/sec

200 m, 300 m × 300 m, 400 m × 400 m, 500 m × 500 m, 600 m × 600 m and 700 m × 700 m), respectively. It is clear from the figure that the MS delay using the proposed OMS-LB has been reduced in comparison to the RM-LB. This reduction is the result of using the PSO to identify the optimal set of S_{DG} and GA during the path determination process, whereas the RM-LB chooses the CHs positions as a collection points and move randomly to collect the data, which causes more delay and a longer MS path.

5.5 Contributions

In this chapter, a load balanced and scheduled protocol based on optimisation algorithms for large scale IoT networks, named, OMS-LB, is proposed. The protocol will use the MS to collect data across a large-scale sensing field. The main aims of this study are to provide an energy efficient procedure that will balance the workload of the IoT devices, while scheduling the MS, which drives the whole IoT network into sleep/wakeup mode, as required. Consequently, this procedure will prolong the life of the network and reduce energy dissipation in sensor nodes.

The proposed OMS-LB transfers complex protocol computations from the network devices and implements them using the SDN controller, which utilises cloud resources, such as data centres and storage in its calculations. The sensed data are gathered using a single MS and then sent to the cloud for further processing. Moreover, the load balanced set of clusters, optimal set of data aggregation points ($\mathrm{S_{DG}}$), and best path of the MS node are all determined by the SDN controller using PSO and a GA to gather the sensed data from the CHs in the sensing fields. Thereafter, the SDN controller sends the optimal set of clusters, best $\mathrm{S_{DG}}$, optimal path for the MS, and the network scheduling message (NSM) to the MS to be forwarded to the entire network. In sum, this chapter provides the following contributions.

- Developing a robust load-balancing clustering algorithm using PSO for data gathering in the IoT called C-LBCA.
- Proposing a framework construction for the SDN controller that implements the routing design through the utilisation of cloud resources. This controller is responsible for the formulation of a CT as well as determination of the $\mathrm{S_{DG}}$ and the optimal mobile sink path ($\mathrm{MS_{Opath}}$) using robust PSO and a GA (see Section 5.3). Furthermore, the suggested design construction will mitigate the functionality performed by the IoT devices.
- Determining the $\mathrm{MS_{Opath}}$ using the GA to collect the data from each $\mathrm{S_{DG}}$ at a pre-scheduled time.
- Developing an energy efficient joint model, which connects the impact of the $\mathrm{MS_{Opath}}$ determination with the cluster formulation process to define an optimised routing protocol suitable for large scale networks.
- Presenting extensive simulation results for both small and large scale IoT networks regarding network lifespans, energy dissipation along with the volume

of data sent to the sink and the $\mathrm{MS}_{\mathrm{Opath}}$, which will validate the proposed OMS-LB.

5.6 Summary

Extensive efforts have been undertaken to enhance the centralised monitoring of the large-scale IoT. Furthermore, the number of IoT devices in vast environments is increasing and a scalable routing protocol has therefore become essential. However, due to associated resource restrictions, only very small functions can be configured using the IoT nodes, principally those related to the power supply. One solution for increasing network scalability and prolonging the life of the network is to use the MS. However, determining the optimal path and S_{DG}, scheduling the entire network with the MS in an energy efficient manner and prolonging the life of the network present huge challenges, particularly in large-scale networks. This chapter therefore proposed an energy efficient routing protocol based on optimisation algorithms, i.e., PSO and GA, for large scale IoT networks under the SDN and cloud architecture. The basic premise is to exploit cloud resources such as storage and data-centre units by using a centralised SDN controller to calculate: a load-balanced CT, an optimal S_{DG}, and a $\mathrm{MS}_{\mathrm{Opath}}$. Moreover, the proposed new routing technique will prevent significant energy dissipation by the CH and by all nodes in general by scheduling the whole network. Consequently, the SDN controller essentially balances energy consumption by the network during the routing construction process as it considers both the S_{DG} and the movement of the MS. Simulation results demonstrate the effectiveness of the proposed approach by improving the network lifespan up to 54%, volume of data aggregated by the MS up to 93% and reducing the delay of the $\mathrm{MS}_{\mathrm{Opath}}$ by 61% in comparison to other approaches.

Chapter 6: Conclusions, Future Work and Research Impact

6.1 Conclusions

Three energy efficient design protocols have been suggested within this thesis. One design has considered the MAC protocols and the others have involved the routing paradigm. The first is the HSW-802.15.4 MAC protocol. This proposed protocol has enabled the IoT devices to conserve more power to access the channel, thereby prolonging the lifespan of the network regardless of the number of devices it contains by adding an adaptable sleep/wake-up extension to the mechanism of the IEEE 802.15.4 standard. This extension has permitted each device that experiences channel collision or failure calculates its sleep period, according to the information in the ST message and the $\mathrm{TDMA}_{\mathrm{slot}}$ sequence. A frame structure and a theoretical analysis-based Markov chain for the proposed protocol have also been developed. The results have shown that the proposed HSW-802.15.4 protocol can efficiently utilise the energy of the battery by 30% to 40% depending on the NG, and this has demonstrated very efficient channel utilisation with high throughput when compared to the performance of the IEEE 802.15.4 standard.

The second protocol has a CC-WOA clustering proposed, which has the advantages of enabling the IoT devices to use the their resources efficiently and to reduce the overall energy consumption. These benefits are performed by involving the impact of node density during the cluster formulation process that has been considered in two different ways, firstly by the SDN controller when dividing the sensing area into VZs, and secondly by the WOA's fitness function, which considers the number of nodes covered by the CHs. Finally, the simulation results have shown that the proposed CC-WOA protocol has minimised power consumption when compared to other traditional routing protocols.

The third contribution has presented a flexible, load balanced and scalable optimised routing protocol-based $\mathrm{MS}_{\mathrm{Opath}}$ administration for large scale IoT networks, known as OMS-LB. The OMS-LB has integrated the SDN concept in IoT and has specified the optimal set of clusters and the $\mathrm{MS}_{\mathrm{Opath}}$ for collecting the data from the large scale IoT network. Furthermore, it has presented a framework that considers the impact of the $\mathrm{MS}_{\mathrm{Opath}}$ during the cluster construction process. This framework has employed the AI to reduce the energy consumed by the CHs and to ensure that the proposed protocol is highly flexible and will work successfully with both large and small-scale networks. Moreover, the SDN controller has used a cost-effective load-balancing technique with the PSO to launch a well-balanced set of clusters that encompasses the whole network. The results have demonstrated the effectiveness of the proposed protocol in the large scale area network by comparing it to other protocols.

6.2 Future Work

On the one hand, IoT manufacturers keep employing wireless methods as communication techniques between the nodes in an increasing manner, which always consume node resources and thus, require more efficient algorithms and protocols. On the other hand, the density of the connected nodes to IoT networks is expected to get increasingly higher and these nodes ordinarily suffer from resource limitation, particularly energy, being often distributed randomly in harsh environments over large-scale areas.

Despite the many energy efficient solutions proposed in this thesis for the IoT research challenges, various other tests and adaptations need to be further investigated to improve the energy conservation, thereby delivering higher performance. Accordingly, the future work should pursue the enhancement of the current designs using emerging techniques, i.e. SDN and virtualisation. That is, there needs to be novel approaches that have the capability to provide a higher performance and eliminate the impact of the aforementioned issues. Accordingly, in the next subsections future works are discussed that offer two directions for improvement in the research area for both MAC and routing protocols.

6.2.1 MAC Protocol-Based Future Work

The IEEE 802.15.4 MAC is subject to many issues that not are considered in this thesis and need to be investigated and incorporated to improve the energy conservation of the devices, some of these being the: back-off methodology, optimal duty cycle, unreliability and the hidden node problem. Finding efficient algorithms for these issues can prevent the high energy consumed by the devices, due to data transmission, reception, collision, idle and sleep modes.

For instance, tuning the values of the maximum and minimum number of binary exponential back-off in an effective way will have a direct impact on the energy efficiency of any device. Furthermore, this is considered as a better solution, which will have a greater impact on the communication reliability than increasing the number of retransmissions, for this will require higher energy consumption. Another factor that can affect the energy consumption of any device is the efficient determination of the duty-cycle period. The duty cycle defines the length of the sleep/wake-up periods of the radio communication of the device according to the availability of data exchange. Furthermore, depending on the application constraints and specifications, some devices are allocated a fixed duty cycle (long or short period), while others require adaptable periods. These two factors can obviously affect the unreliability issue in IEEE 802.15.4 MAC. This is because the IEEE 802.15.4 MAC employs the CSMA/CA mechanism to access the channel, which is considered as being an inefficient algorithm for controlling the number of collisions, especially in high density networks. Therefore, tuning the CSMA/CA parameters, such as the back-off and duty cycle, and suggesting well-organised methods to mitigate the hidden node problem can efficiently increase the reliability of the IEEE 802.15.4.

Another important solution to conserving the energy consumed by IoT devices is the involvement of SDN technology in the MAC process and not only in the routing mechanism, which presented in this thesis. This can be implemented in different ways, such as proactively, reactively (on demand) or by mixing between them. With these approaches, the SDN controller has the responsibility of monitoring the number of network traffic collisions and deciding upon the optimal sleep/wake-up period for each device in a way that eliminates the effect of the hidden node issue. These methods can be easily combined with the proposed HSW-802.15.4 MAC protocol (suggested in chapter-3), because the SDN controller can categorise the devices into several groups and identify the TDMA time slots as well as the group associated with each. Furthermore, the involvement of such technology in the MAC protocol will facilitate the protocol updating process, according to the network requirements, such as in the case of an emergency. In this case, the device will need to be accompanied by the GPS facility in order to be able to send an emergency request, when required, to the SDN controller, which in turn will update the network with an emergent route for the requested device.

6.2.2 Routing Protocol-Based Future Work

The research on routing protocols also include many gaps that need to be considered throughout our future work by the development of new efficient algorithms. Two of these research gaps are the: development of energy efficient data gathering algorithms and ways of involving new technology in the network operation. In chapters 4 and 5, the clustering techniques were designed to collect the data using single-hop transmission techniques; however, the radio of the sensor node can only cover a short range and consumes higher energy within a wider area network. Hence, efficient clustering algorithms that consider multi-hop transitions and connectivity-quality parameters in their fitness function are required, especially with large scale networks.

One further research direction that can deliver energy efficiency within a large-scale network, is the association of multiple MS and multiple SDN controllers. However, the involvement of such technologies in the networks will be accompanied by a number of issues, which accordingly, will open up many other research inquires. Examples these are: distinguishing the paths and synchronisation of the MS as well as quantifying the optimal number, position and distribution of the controllers. The involvement of SDN technology can significantly reduce the energy depleted by the nodes due to processing and aggregation. In particular, more research in the future is essential to evaluate the trade-off between the processes implemented by the SDN controller and the nodes. Finally, investigation of SDN impact on IoT networks needs to be evaluated more in the future using different types of controllers, such as Floodlight and NOX and by hardware implementations.

6.3 Thesis Impact

This thesis proposed efficient design protocols for IoT network that have the potential capability on impacting greatly on the future of the IoT world by providing better functionality in a faster manner and at lower cost. IoT is becoming increasingly more popular and is included in many large and small life applications, such as environmental monitoring meters as well as everyday objects like coffee pots, keys, cars, smart phones, and small tracker devices. Currently, there are hundreds of millions of invisible or visible sensors that are grouped as networks and deployed for transportation, industrial, utilities and other purposes. These sensors are making it possible to develop and innovative new ways that have the ability to identify the requirements of revolutionise the world. IoT can not only improve the management of the energy, water and safety, for it can also bring people, in urban areas, in closer touch with their surroundings and avoid extinction of species. That is, this can all be achieved through fully integrated networks, remote monitoring and geolocation tracking objects.

Hence, the energy efficient design protocols, which have been presented in this thesis, can impact in a positive way the performance of the IoT networks and make them work more appropriately for both small and large-scale environments, whether they have low or high network density. The results for the case of the large-scale network have presented an increase in the volume of data sent to the MS by up to 93%, as well as an increase the network lifespan by up to 66% compared to other present IoT protocols. In addition, AI techniques employed by the SDN architecture throughout the protocol design process have been proposed and provided intelligent decisions by the controller as well as reducing network complexity with more practicality and reliability.

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Appendix A

Algorithm 2 describes the behaviour of the CSMA/CA mechanism, which is compared with the proposed numerical model in Chapter-3.

Algorithm 2 Transmission-based CSMA/CA

```
procedure TRANSMISSION ATTEMPT FOR EACH DEVICE
    N, MinBE, MaxBE, R
    $r(1:N) \leftarrow 0;$
    $NBF(1:N) \leftarrow 0;$
    $CCA(1:N) \leftarrow 2;$
    $Tx_{Succ}(1:N) \leftarrow 0;$
    $M \leftarrow (MaxBE - MinBE);$
    for each Node i do
        Initialisation of Backoff Exp.
        $CW(i,1) \leftarrow 2^{MinBE} - 1;$
        if $R > M$ then
            if $M > 0$ then
                $CW(i,2:M+1) \leftarrow 2^{(1:M)} * CW(i,1)$ ;
                $CW(i,M+1:R+1) \leftarrow CW(i,M+1)$ ;
            else
                if $M = 0$ then
                    $CW(i,2:R+1) \leftarrow CW(i,1)$ ;
                end if
            end if
        else
            $CW(i,2:M+1) \leftarrow 2^{(1:M)} * CW(i,1)$ ;
        end if
        while $(NBF(i) < M)$ & $(Tx_{Succ}(i) = 0)$ do
            BE = MinBE + NBF(i);
            Backoff-Delay(i) ← Random number in [1,..., CW(i, BE)]
            Wait for the Backoff-Delay(i)
            Note: Each node has different Backoff-Delay
```

```
28:       **if** $Backoff\text{-}Delay(i) = 0$ **then**
29:         Check First CCA(i)
30:         **if** Channel idle **then**
31:           CCA(i) $\leftarrow$ CCA(i) -1;
32:           Check the second CCA(i)
33:           **if** Another node is transmitting **then**
34:             Collision!
35:           **else**
36:             Successful Transmission
37:             $Tx_{Succ}(i) \leftarrow 1$;
38:           **end if**
39:         **else**
40:           Channel Busy
41:           $NBF(i) \leftarrow NBF(i)+1$; $CCA(i) \leftarrow 2$ ;
42:         **end if**
43:       **end if**
44:     **end while**
45:     **if** $r(i) < R$ & $Tx_{Succ}(i) = 0$ **then**
46:       r(i) $\leftarrow$ r(i) + 1; CCA(i) $\leftarrow$ 2;
47:       BE $\leftarrow$ MaxBE;
48:       Repeat the from line 25
49:     **else**
50:       **if** $Tx_{Succ}(i) = 0$ **then**
51:         Transmission Failure
52:       **end if**
53:     **end if**
54:   **end for**
55: **end procedure**
```

List of Publications

[1] T. Al-Janabi and H. Al-Raweshidy, "Effcient whale optimisation algorithm based sdn clustering for iot focused on node density," in *2017 16th Annual Mediterranean Ad Hoc Networking Workshop (Med-Hoc-Net)*, pp. 1-6, IEEE, 2017.

[2] T. Al-Janabi and H. Al-Raweshidy, "Optimised clustering algorithm-based centralised architecture for load balancing in iot network," in *2017 International Symposium on Wireless Communication Systems (ISWCS)*, pp. 269-274, IEEE, 2017.

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[4] T. Al-Janabi and H. Al-Raweshidy, "A Centralised Routing Protocol with a Scheduled Mobile Sink-Based AI for Large Scale I-IoT," in *IEEE Sensors Journal*, 2018, Accepted.