UNIVERSITY OF NOVI SAD

FACULTY OF TECHNICAL SCIENCES
NOVI SAD

Prediction based Adaptive Duty Cycle MAC Protocol for Solar Energy Harvesting Wireless Sensor Networks

DOCTORAL DISSERTATION

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Novi Sad, 2023

УНИВЕРЗИТЕТ У НОВОМ САДУ

ФАКУЛТЕТ ТЕХНИЧКИХ НАУКА У НОВОМ САДУ

МАС протокол адаптивног фактора испуне заснован на предвиђању у бежичним сензорским мрежама са прикупљањем соларне енергије

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Нови Сад, 2023

УНИВЕРЗИТЕТ У НОВОМ САДУ **ОБРАЗАЦ – 5а**
ФАКУЛТЕТ ТЕХНИЧКИХ НАУКА

КЉУЧНА ДОКУМЕНТАЦИЈСКА ИНФОРМАЦИЈА[1]

Врста рада:	Докторска дисертација
Име и презиме аутора:	Сохаил
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Језик публикације (писмо):	енглески
Физички опис рада:	Унети број: Страница - 117 Поглавља - 5 Референци - 120 Табела - 8 Слика - 58
Научна област:	Електротехничко и рачунарско инжењерство
Ужа научна област (научна дисциплина):	Електроника и телекомуникације
Кључне речи / предметна одредница:	Машинско учење, предвиђање соларне енергије, протокол контроле приступа средњем нивоу, бежичне сензорске мреже за прикупљање енергије
Резиме на језику рада:	Сакупљање амбијенталне енергије омогућило је развој бежичних сензорских мрежа (EH-WSN) за прикупљање енергије. Међутим, у овим мрежама, неизвесност у стопи жетве услед динамичних временских услова поставља нове изазове. Стога, ово покреће развој решења која су свесна прикупљања енергије. Раније су развијени многи MAC протоколи за EH-WSN, који нуде различите карактеристике засноване на доступној прикупљеној енергији за подршку различитим апликацијама. Ипак, оптимизација перформанси MAC-а укључивањем предвиђеног будућег уноса енергије је релативно нова у EH-WSN-овима. Стога, ова теза представља протокол адаптивног радног циклуса за контролу приступа медијуму (MAC) заснован на предвиђању заснованом на машинском учењу за бежичне WSN мреже за прикупљање соларне енергије. Развијени протокол укључује информације о тренутној и будућој прикупљеној енергији користећи математичке формулације за побољшање перформанси мреже. На тај начин, предложени MAC протокол ефикасно се бави примарним циљевима WSN-а за прикупљање соларне енергије: обезбеђивање дугорочне одрживости мреже и ефикасно коришћење прикупљене енергије за побољшање перформанси апликације под динамички променљивим условима прикупљања енергије.

[1] Аутор докторске дисертације потписао је и приложио следеће Обрасце:
5б – Изјава о ауторству;
5в – Изјава о истоветности штампане и електронске верзије и о личним подацима;
5г – Изјава о коришћењу.
Ове Изјаве се чувају на факултету у штампаном и електронском облику и не кориче се са тезом.

Датум прихватања теме од стране надлежног већа:	30.06.2022
Датум одбране: (Попуњава одговарајућа служба)	
Чланови комисије: (титула, име, презиме, звање, институција)	Председник: Др Дејан Вукобратовић, Редовни Професор, Факултет техничких наука, Нови Сад Члан: Др Небојша Дончов, Редовни Професор Електронски факултет, Ниш Члан: Др Стеван Станковски, Редовни Професор Факултет техничких наука, Нови Сад Члан: Др Иван Мезеи, Ванредни Професор, Факултет техничких наука, Нови Сад Члан, ментор: Др Горан Стојановић, Редовни Професор Факултет техничких наука, Нови Сад
Напомена:	

UNIVERSITY OF NOVI SAD
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KEY WORD DOCUMENTATION[2]

Document type:	Doctoral dissertation
Author:	Sohail
Supervisor (title, first name, last name, position, institution)	Prof. Dr Goran Stojanović, Full Professor, University of Novi Sad, Faculty of Technical Sciences
Thesis title:	Prediction based Adaptive Duty Cycle MAC Protocol for Solar Energy Harvesting Wireless Sensor Networks
Language of text (script):	English
Physical description:	Pages - 117 Chapters - 05 References - 120 Tables - 08 Illustrations -58
Scientific field:	Electrical and computer engineering
Scientific subfield	Electronics and telecommunications
Subject, Key words:	Machine learning, solar energy prediction, Medium Access Control Protocol, Energy Harvesting Wireless Sensor Networks
Abstract in English language:	Harvesting ambient energy has enabled the development of energy-harvesting wireless sensor networks (EH-WSNs). However, in these networks, the uncertainty in harvesting rate due to dynamic weather conditions raises new challenges. Therefore, this drives the development of energy harvesting-aware solutions. Formerly, many MAC protocols have been developed for EH-WSNs, which offer various features based on available harvested energy to support different applications. Nevertheless, optimizing MAC performance by incorporating predicted future energy intake is relatively new in EH-WSNs. Therefore, this thesis presents a machine learning prediction based adaptive duty cycle medium access control (MAC) protocol for solar energy harvesting wireless sensor networks WSNs. The developed protocol incorporates information about the current and future harvested energy using mathematical formulations to improve network performance. By doing so, the proposed MAC protocol effectively addresses the primary goals of solar energy harvesting WSNs: ensuring long-term network sustainability and efficient utilization of harvested energy to enhance the application performance under dynamically changing energy harvesting conditions.
Accepted on Scientific Board on:	30.06.2022
Defended: (Filled by the faculty service)	

[2] The author of doctoral dissertation has signed the following Statements:
5б – Statement on the authority,
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The paper and e-versions of Statements are held at he faculty and are not included into the printed thesis.

Thesis Defend Board: (title, first name, last name, position, institution)	President: Dr. Dejan Vukobratović, Full Professor, Faculty of Technical Sciences, Novi Sad Member: Dr. Nebojša Dončov, Full Professor, Faculty of Electronics, Niš Member: Dr. Stevan Stankovski, Full professor, Faculty of Technical Sciences, Novi Sad Member: Dr. Ivan Mezei, Associate Professor, Faculty of Technical Sciences, Novi Sad Member, Mentor: Dr. Goran Stojanović, Full Professor, Faculty of Technical Sciences, Novi Sad
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This research work was supported by the AQUASENSE project, which has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No. 813680.

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Acknowledgments

The completion of this thesis marks the end of my long journey that has lasted three and a half years. First, I would like to express my gratitude to my family members for their love and support throughout this journey. Furthermore, I am deeply grateful to my advisor, Prof. Dr. Goran Stojanović, for his invaluable guidance, trust, and supervision. It has been a great experience working with him, and I look forward to continuing our collaboration in the future.

I would like to express my sincere gratitude to Prof. Dr. Stevan Stankovski, Prof. Dr. Varun Jeoti, and Dr. Micheal Drieberg for their valuable insights and suggestions on my work. I would also like to thank Prof. Dejan Vukobratović for giving me the chance to meet and collaborate with some of his team members, which has been an enriching experience. I extend a very special thanks to Dr. Vladimir Todorovic for providing me with an excellent working environment in IDEAlab.

I would like to express my gratitude to the AQUASENSE project, which received funding from the European Commission, for providing me with an excellent opportunity to work with a multidisciplinary team from academia and industry. It was a rewarding experience collaborating with researchers from diverse backgrounds and cultures. I extend my thanks to all members, particularly the early-stage AQUASENSE project researchers, for the memorable moments we shared during the project.

I would like to thank Dr. Milan Radovanović for providing me with all the assistance during this journey. Additionally, I am grateful to the members of the STRENTEX project, including Dr. Sanja Kojić, Dr. Kishore Bingi, Nenad Zoric, Dr. Bojana Bajic, and Milivoj Paroski, for their support throughout this journey. Finally, I would like to express my gratitude to the Faculty of Technical Sciences at the University of Novi Sad for hosting me as an MSCA early-stage researcher.

List of Publications and Awards

Journal Publications:

Sohail Sarang, Goran M Stojanović, Micheal Drieberg, Stevan Stankovski, Kishore Bingi, Varun Jeoti, "Machine Learning Prediction based Adaptive Duty Cycle MAC Protocol for Solar Energy Harvesting Wireless Sensor Networks", IEEE Access, vol. 11, pp. 17536–17554, 2023.

Sohail Sarang, Goran M. Stojanović, Stevan Stankovski, Željen Trpovski, Micheal Drieberg, "Energy-Efficient Asynchronous QoS MAC Protocol for Wireless Sensor Networks", Wireless Communications and Mobile Computing, vol. 2020, pp.1-13, 2020.

Radomir Prodanović, Dejan Rančić, Ivan Vulić, Nenad Zorić, Dušan Bogićević, Gordana Ostojić, **Sohail Sarang**, Stevan Stankovski, "Wireless sensor network in agriculture: Model of cyber security", Sensors, 20, no. 23, pp.1-22,2020.

Akhil Chandran Mukkattu Kuniyil, Janez Zavašnik, Željka Cvejić, **Sohail Sarang**, Mitar Simić, Vladimir V Srdić, Goran M Stojanović, "Performances and Biosensing Mechanisms of Interdigitated Capacitive Sensors Based on the Hetero-mixture of SnO_2 and In_2O_3 , Sensors, 20, no.21, pp.1-13, 2020.

Radomir Prodanović, **Sohail Sarang**, Dejan Rančić, Ivan Vulić, Goran M Stojanović, Stevan Stankovski, Gordana Ostojić, Igor Baranovski, Dušan Maksović, Trustworthy Wireless Sensor Networks for Monitoring Humidity and Moisture Environments, Sensors, 21, no.11, pp.1-24, 2021.

Kasyap Suresh, Varun Jeoti, Micheal Drieberg, Socheatra Soeung, Asif Iqbal, Goran M Stojanović, **Sohail Sarang**, "Simultaneous detection of multiple surface acoustic wave sensor-tags for water quality monitoring utilizing cellular code-reuse approach", IEEE Internet of Things Journal (Early Access), pp.1-16, 2021.

Akhil Chandran MK, Branimir Bajac, Gregor Filipič, Željka Cvejić, Vladimir Srdić, Milan Radovanović, Mitar Simić, Sohail Sarang, Goran Stojanović, "Synthesis and Characterization of Tin Oxide Nanopowder and Its Application to Sensing Different Pathogens", Sensors and Materials, 33, no.5, pp. 513–527, 2021.

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Prioritized-Data and Multi-Hop Routing for Wireless Sensor Networks", Sensors, 22, no. 7, pp. 1-25, 2022.

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Trinh C Nguyen, Hai-Chau Le, **Sohail Sarang**, Micheal Drieberg, and Thu-Hang T Nguyen, "Priority and Traffic-Aware Contention-Based Medium Access Control Scheme for Multievent Wireless Sensor Networks", IEEE Access, no. 10, pp. 87361-87373, 2022.

Guruswamy, Selvakumar, Milica Pojić, Jayashree Subramanian, Jasna Mastilović, **Sohail Sarang**, Arumugam Subbanagounder, Goran Stojanović, and Varun Jeoti. "Toward Better Food Security Using Concepts from Industry 5.0." Sensors 22, no. 21, pp. 1-24, 2022.

Conference Publications:

Sohail Sarang, Goran M Stojanović, Micheal Drieberg, Stevan Stankovski and Varun Jeoti "Energy Neutral Operation based Adaptive Duty Cycle MAC Protocol for Solar Energy Harvesting Wireless Sensor Networks" accepted in 2022 IEEE 95th Vehicular Technology Conference: VTC2022-Spring, Helsinki, Finland 19 - 22 June 2022, pp. 1-6.

Book Publications:

Sohail Sarang, Goran M. Stojanović, and Stevan Stankovski," Wireless Sensor Networks based Water Quality Monitoring", book chapter *submitted* to an edited book related to water quality monitoring (To be appeared soon).

Awards:

Marie Skłodowska-Curie Early-Stage Researcher in European Commission H2020 funded project AQUASENSE, H2020-MSCA-ITN-2018, 2018-2022.

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Abstract

Harvesting ambient energy has enabled the development of energy-harvesting wireless sensor networks (EH-WSNs). However, in these networks, the uncertainty in harvesting rate due to dynamic weather conditions raises new challenges. Therefore, this drives the development of energy harvesting-aware solutions. Formerly, many MAC protocols have been developed for EH-WSNs, which offer various features based on available harvested energy to support different applications. Nevertheless, optimizing MAC performance by incorporating predicted future energy intake is relatively new in EH-WSNs. Furthermore, existing MAC protocols do not fully harness the high harvested energy to perform aggressively despite sufficient energy resources. In addition, their performance evaluation has not been tested using different metrics under dynamic harvesting conditions. Therefore, this thesis proposes a new prediction-based adaptive duty cycle MAC protocol, called PADC-MAC, that incorporates current and future harvested energy information using the mathematical formulation to improve network performance. Furthermore, a machine learning model, namely nonlinear autoregressive (NAR) neural network is employed that achieves good prediction accuracy under dynamic harvesting scenarios. As a result, it enables the receiver node to perform more aggressively by increasing its duty cycle when there is a sufficient inflow of incoming harvested energy to achieve higher network performance. In addition, PADC-MAC uses a self-adaptation technique by which the receiver node shares its next duty cycle with all sender nodes, which helps sender nodes wake up slightly before the receiver for data transmission and reduces energy consumption in idle listening. The performance of PADC-MAC is evaluated for single-hop network scenario using GreenCastalia in terms of packet delay, network throughput, packet delivery ratio, energy consumption per bit, receiver energy consumption, and total network energy consumption using realistic harvesting data for 96 consecutive hours in both high and low solar harvesting conditions. The simulation results show that PADC-MAC reduces the average end-to-end (ETE) delay of the highest priority packets and all packets, energy consumption per bit, and total energy consumption by more than 10.7%, 7.8%, 81%, and 76.4%, respectively, when compared to three state-of-the-art protocols for EH-WSNs.

List of Abbreviations

WSNs	Wireless Sensor Networks
MAC	Medium Access Control
ML	Machine Learning
EH-WSN	Energy Harvesting WSNs
IoT	Internet of Things
BS	Base Station
BP-WSNs	Battery Powered WSNs
RF	Radio Frequency
QoS	Quality of Service
PDR	Packet Delivery Ratio
AI	Artificial Intelligence
QPPD	QoS protocol for Prioritized Data
QAEE	QoS-aware Energy-efficient
EEM	Enhanced Energy Management
NREL	National Renewable Energy Laboratory
PADC	Prediction based Adaptive Duty Cycle
NARNET	Nonlinear Autoregressive Neural Network
ENO	Energy Neutral Operation
EWMA	Exponentially Weighted Moving Average
ANN	Artificial Neural Network
CSMA	Carrier Sense Multiple Access
WD	Wireless Device
M2M	Machine to Machine
CW	Contention Window
ACK	Acknowledgment
CSMA/CA	Carrier-sense Multiple Access with Collision Avoidance
TDMA	Time Division Multiple Access
CCA	Clear Channel Assessment

PU	Primary User
SU	Secondary User
SIFS	Short Inter-Frame Space
WB	Wake-up Beacon
SA	Source Address
TxB	Tx-beacons
FC	Frame Control
FCS	Frame Check Sequence
NAV	Network Allocation Vector
SS	Selected Sender
DA	Destination Address
MAE	Mean Absolute Error

List of Symbols

Eth	Threshold Energy
n_{est}	Estimated number of active nodes
T_w	Waiting Timer
d_c	Duty Cycle
P_4	Urgent
P_3	Most Important
P_2	Important
P_1	Normal
E_{max}	Maximum Energy
$HE_{current}$	Harvesting power
E_c	Energy consumption
P_{con}	Contention Probability
RE_{expect}	Expected Remaining Energy
$RE_{current}$	Remaining Energy
$E_{Predict}$	Predicted Energy
S_p	Predicted Solar Irradiance
P_s	Solar Panel Size
P_e	Panel Efficiency
d_s	Timeslot Slot Duration
n_s	Number of Listening Slots
n_{ds}	Data Receiving slots
N_s	Number of Sender Nodes
e_S	Energy Consumed in Switching of Radio States
e_l	Energy Consumed in Listening to the Channel
e_B	Energy Consumed in Sending WB Beacon
e_w	Energy Consumed in Waiting for TxB beacons
e_{slp}	Energy Consumed in Sleep State

e_{RB}	Energy Consumed in Sending Rx beacon
e_d	Energy Consumed in Receiving the data packet
e_{ack}	Energy Consumed in Sending ACK packet
T_{sleep}	Sleep Time
T_{listen}	Listen Time
E_T	Total Energy Consumed by the Node
n	Number of Ratio States
p	Power Consumption rate
S	Realistic Solar Irradiance
z	Number of Simulation Hours
E_h	Harvested Energy
ETE	End-To-End
D_{queu}	Queuing Delay
D_{trans}	Transmission Delay
D_{prop}	Propagation Delay
D_{proc}	Processing Delay
NP_{PktR}	Total Number of Data Packets Received
NP_{PktT}	Total Number of Data Packets Transmitted
N_{Th}	Network Throughput
L_{Pkt}	Packet Size in Bits
T_s	Simulation Time
E	Energy Consumption per Bit
E_{total}	Total Energy Consumed in Network
E_{TR}	Energy Consumption of Receiver Node
E_{TS}	Energy Consumption of Sender Node
R	Correlation Coefficient
S_t	Realistic Solar Irradiance During Timeslot t
$\check{S}_t$	Predicted Solar Irradiance During Timeslot t

Chapter 1

Introduction

This chapter presents an overview of battery-powered and energy harvesting Wireless sensor networks (EH-WSNs). Next, it briefly discusses medium access control (MAC) protocols, energy prediction, and machine learning (ML) in EH-WSNs. It is followed by problem formulation, research hypotheses and objectives, the scope of work, contributions, and assumptions adopted in this research. Finally, the thesis outline is presented.

1.1 Overview of Battery Powered and Energy Harvesting WSNs

Nowadays, Internet of Things (IoT) is gaining strong attention in many applications, including healthcare and smart cities [1]. Wireless sensor network (WSN) plays an important role in IoT and is widely used in different applications, such as environmental monitoring, agriculture, industrial process monitoring, and others [2-4]. Conventionally, WSNs consist of several sensing nodes powered by small non-rechargeable batteries that have the ability to collect the data and and send it to the sink node, called battery-powered WSNs (BP-WSNs). However, these nodes have limited battery capacity and thus need to be replaced regularly, which hinders their operation and network performance. Therefore, energy efficiency remains critical to ensuring the sustainable operation of nodes [4]. For instance, schemes developed in [4, 5] improve energy efficiency to enhance the lifetime.

In recent years, energy harvesting techniques have gained intense attention to power sensor nodes using outdoor energy sources such as solar, wind, mechanical, radio frequency (RF), and thermal. Therefore, integrating these sources with WSNs has motivated researchers to develop energy harvesting WSNs (EH-WSNs), where, nodes can harvest energy from the surrounding environment. This helps to mitigate the energy issue faced by conventional WSNs and reduce the negative environmental impact and cost of battery replacements. Furthermore, energy harvesting enables nodes to schedule tasks such as prioritization, duty cycle, and sensing, according to harvested energy profile to maximize the network performance.

1.2 MAC Protocol, Energy Harvesting Prediction, and Machine Learning

The medium access control (MAC) protocol regulates the access of a common medium among the sensor nodes. The MAC protocols for EH-WSNs aim to optimize the network performance using harvested energy efficiently. Formerly, numerous MAC protocols have been designed for applications such as agriculture and monitoring [6] [7]. For instance, quality of service (QoS) ensures the performance level to the user that includes performance metrics: delay, throughput, packet delivery ratio (PDR), and energy consumption [7]. Moreover, these protocols incorporated the harvested energy information into settings for duty cycle, access probability, traffic load, relay node selection, and sensing interval to enhance network performance.

In certain circumstances, for example, harvesting energy varies significantly according to the weather, which may hinder the execution of ongoing tasks and node operation. Thus, it is essential to know about the future incoming energy to avoid disruption in the node's operation during periods of energy scarcity. Furthermore, knowing the future harvested energy, the node can further optimize the performance as in the case when it has a higher energy value than required for the task execution. However, among available harvesting sources, solar is the most significant energy source and has the greatest potential for harvesting energy [8]. Furthermore, solar energy can be forecasted based on the past energy pattern.

ML is a part of Artificial Intelligence (AI) that involves computer algorithms to learn automatically from data without being explicitly programmed [9]. It has gained significant attention in academia and industry and is considered a vital tool in developing automated IoT applications. For example, ML techniques, i.e., regression, have been employed in WSN to address the issues of energy harvesting, MAC protocols, transmission overhead, routing, and others. ML algorithms have also been widely incorporated to predict solar harvesting, which leads to developing harvesting-aware solutions, such as communication protocols [10].

1.3 Problem Statement and Research Hypothesis

Previously, various MAC protocols have been designed for EH-WSNs, which utilized harvested energy to optimize the performance. However, most of the existing MAC protocols devise a duty cycling mechanism according to the current harvesting energy without considering the nature of incoming harvested energy. Thus, dynamic harvesting conditions may affect ongoing node operation and degrade network performance. In certain circumstances, for example, on a typical sunny day, these protocols may not be able to increase the duty cycle of the node aggressively and since the next day may turn out to be a rainy day. Therefore, data packets suffer long delays despite sufficient energy resources. In addition, these protocols do not plan how to optimize performance when the harvested energy value is more than or equal to the energy required for the task execution. Furthermore, most available protocols have not been tested using actual solar irradiance. Also, their performance evaluation did not include all essential QoS performance metrics such as end-to-end (ETE) delay, PDR, network throughput, energy consumption per bit, receiver energy consumption, and total network energy consumption [7].

The following are the hypothesis:

- A novel and realistic adaptive MAC protocol can be developed for EH-WSNs that can utilize the current energy level and incoming harvested energy to enhance the network performance under dynamic harvesting conditions.

- ML algorithm can be incorporated to predict harvesting energy, and adjust the duty cycle based on the expected energy to improve the performance.

- Using forecasted energy, the node can increase its duty cycle aggressively when it has a higher energy value than needed for the task execution to further optimize the performance.

1.4 Research Objectives

The research objectives are:

- To develop a novel and realistic adaptive MAC Protocol for EH-WSNs that regulates the duty cycle of the receiver based on the current energy and incoming harvested energy.
- To employ an energy prediction model to improve MAC performance by incorporating incoming energy intake to optimize the network performance.
- To comprehensively evaluate the proposed protocol under a realistic scenario using actual harvesting rates in terms of ETE delay, network throughput, PDR, energy consumption per bit, receiver energy consumption, and total network energy consumption and comparison with three well-known MAC protocols, namely QoS protocol for Prioritized Data (QPPD-MAC) [11], QoS-aware Energy-efficient (QAEE-MAC) [12] and Enhanced Energy Management (EEM-MAC) [13].

1.5 Scope of Work

This work includes the development of a prediction-based adaptive MAC protocol for in EH-WSNs. Furthermore, a machine learning algorithm will be developed to predict hourly incoming harvested energy. Finally, the comprehensive performance will be evaluated using the GreenCastalia simulator under dynamic harvesting conditions. In the simulation, actual solar irradiance data provided by NREL [14], parameters from a commercially available TelosB sensor node [15], solar panel [16], and CC2420 radio [17] will be used to demonstrate the protocol performance in more realistic scenarios. Moreover, the detailed performance comparison will be conducted with three widely used protocols for EH-WSNs.

1.6 Research Contributions

The research contributions are as follows:

- The proposed Prediction based Adaptive Duty Cycle MAC (PADC-MAC) protocol introduces a numerical formula to adjust the duty cycle based on predicted incoming harvested energy.

- ML model is developed to predict the incoming harvesting energy, which enables the receiver node to perform more aggressively when it has a sufficient inflow of incoming harvested energy to improve the performance.

- A technique by which the receiver shares its next duty cycle with all sender nodes and as a result energy efficiency improves in the network.
- The performance of PADC-MAC is evaluated for single-hop network scenario in the GreenCastalia simulator for four consecutive days, i.e., 96 hours of simulation using actual harvesting rates under high and low solar irradiance conditions.
- The performance of PADC-MAC is compared with QPPD-MAC [11], QAEE-MAC [12], and EEM-MAC [13].
- The results indicate that the PADC-MAC provides better performance in terms of ETE delay, energy consumption per bit, and total network energy consumption when compared to three state-of-the-art MAC protocols for EH-WSNs.

1.7 Assumptions

The research assumptions that have been adopted in this research are:

- The network consists of energy harvesting nodes that are static.
- The factors such as dust and shadows do not affect the harvesting rate.
- The receiver's initial duty cycle and storage levels are 50% and 45%, respectively.
- The network consists of a receiver and multiple sender nodes are randomly positioned. Both the receiver and sender nodes can communicate with each other directly.
- The sender node has unlimited energy.

- The node turns off its radio when its battery energy is lesser than the threshold energy (E_{th}) i.e. 10% and goes into the sleep state.

1.8 Thesis Outline

The remainder of this thesis is structured as follows:

Chapter 2 presents a comprehensive literature review on EH-WSNs, the structure of BP-WSN and EH-WSN sensor node, energy harvesting sources, and design alternatives. Furthermore, energy prediction and existing models are described. Then, ML algorithms and their applications in EH-WSNs are explained in detail. Moreover, a detailed literature review of MAC protocols for EH-WSNS and their classification is undertaken that use available harvesting energy to optimize network performance which includes the design features based on current harvesting energy, such as duty cycle adjustment.

Chapter 3 describes the proposed PADC-MAC for EH-WSNs. First, it provides a communication overview of the proposed MAC. In addition, it presents the nonlinear autoregressive neural network (NARNET) model to predict incoming harvested energy. Then, using the mathematical formulation, the duty cycle adjustment is performed according to current and incoming harvested energy levels. Next, the self-adaptation technique is explained. It is followed by the presentation of an energy consumption model, MAC performance metrics, network simulation, and set up in GreenCastalia.

Chapter 4 provides the prediction performance of the developed NARNET model. Then, it presents the performance evaluation of PADC-MAC using GreenCastalia and results in comparison with three well known MAC protocols. Finally, the performance is evaluated in terms of ETE delay, network throughput, PDR, energy consumption per bit, receiver energy consumption, and total network energy consumption under dynamic solar harvesting conditions.

Chapter 5 concludes the thesis with future work.

Chapter 2

Literature Review

This chapter reviews the basic aspects of WSNs and EH-WSNs. In addition, the structure of the sensor node in BP-WSN and EH-WSN is presented. Then, types of communication, energy harvesting sources, and design alternatives are discussed in detail. Furthermore, the importance of energy prediction in EH-WSNs is described. It is then followed by ML algorithms in EH-WSNs. Moreover, MAC protocols for EH-WSNs and their classification are explained in detail. Finally, the summary of receiver-initiated MAC protocols and their limitations is given. In these protocols, the available harvesting energy is used to optimize network performance, including the design features based on current harvesting energy, such as duty cycle adjustment. Finally, limitations of existing MAC protocols are provided.

2.1 Wireless Sensors Networks

Currently, IoT is playing a key role in various applications such as building automation, smart home, wearable devices and many others [18-20]. WSN is an essential component of the IoT [21-23] and have many advantages such self-organizing abilities, scalability, ease of deployment and others [9]. In addition, it involves a large number of low-cost, and small-in-size sensor nodes. These sensors have the ability to sense, gather and send the information [24, 25]. The sink node gathers the data from the nodes and provides a gateway service to manage the data remotely, as shown in Figure 2.1. The key applications of WSNs include smart cities and healthcare, industrial process and environment monitoring and others [2, 26, 27]. In each application, sensors generate different data types and offer unique features that require distinctive solutions. For example, in forest monitoring, if a node detects any unusual data, e.g., alarm, smoke, temperature, it sends the acquired data immediately to the sink and gateway for further decisions to mitigate the forest fires. In this case, timely collection and transmission of the data packets are crucial.

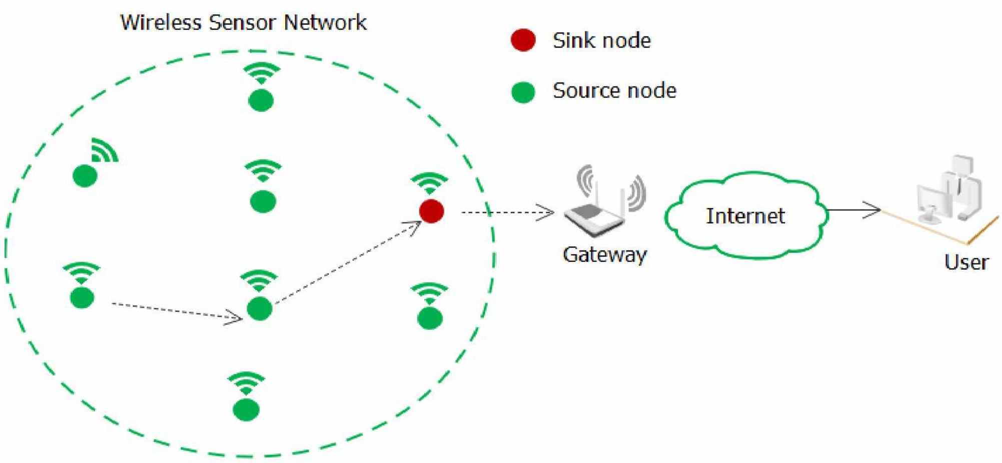

Figure 2.1: Structure of WSN

Hence, reliability and packet delay are essential. Furthermore, energy efficiency also plays an important role that will enable nodes to operate longer [7]. Furthermore, nodes follow single hop and multi-hop approaches to communicate in WSNs. In single hop, nodes have the ability to transmit data directly to the sink, resulting in less time to send a data packet. Therefore, it is a widely used and well-known communication type [28]. On the other hand, a multi-hop network consists of many nodes located far from the sink and as result, they cannot send data directly to the sink. Thus, they require relay node(s) to send data to the sink. Figure 2.2 and Figure 2.3 show single-hop and multi-hop communication scenarios in WSNs, respectively.

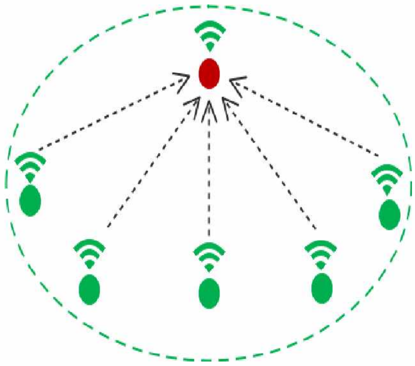

Figure 2.2: Single-hop WSNs [28]

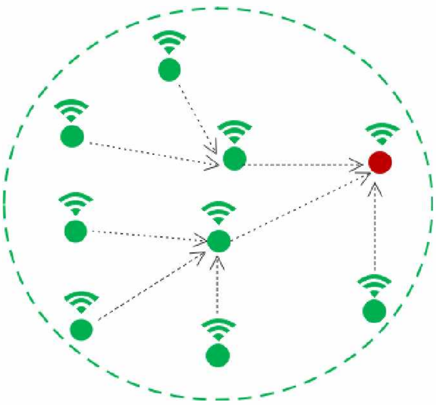

Figure 2.3: Multi-hop WSNs [28]

The energy efficiency plays a significant role in WSNs. Therefore, in terms of energy source, these networks can further be categorized as battery-powered WSNs (BP-WSNs) and EH-WSNs.

2.1.1 BP-WSNs

The architecture of a BP-WSNs node is shown in Figure 2.4 [29]. A sensor node comprises four components: a sensor unit, microcontroller, power storage, and transceiver. The sensor unit is responsible for sensing the physical phenomenon, e.g., temperature and humidity parameters. The microcontroller and transceiver are used to process and transmit data, respectively. The node uses a small battery as an energy source to power up its components. The alkaline batteries are widely used; however, the battery level decreases with time. Hence, energy efficiency is essential in BP-WSNs to prolong the network lifetime [30, 31]. Moreover, in these networks, there is always a tradeoff between lifetime extension and network performance [5]. Additionally, nodes are equipped with batteries with a limited capacity [32-35], which require frequent replacement, increase maintenance costs, and negatively impact the environment.

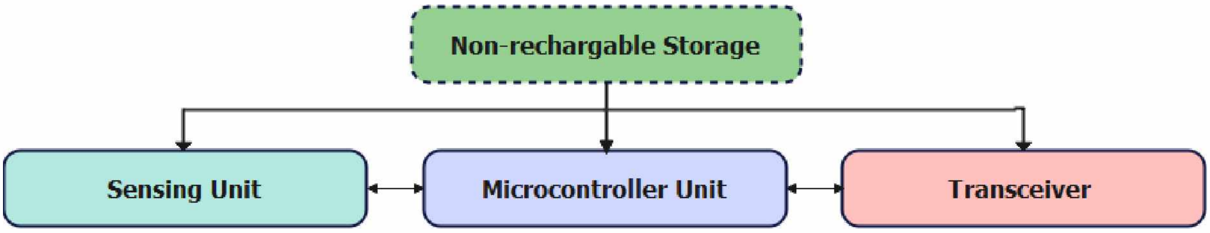

Figure 2.4: General architecture of a BP-WSN node [26]

2.2 Energy Harvesting WSNs

2.2.1 Role of EH Techniques in EH-WSNs

EH techniques enable the development of EH-WSNs and drive the following key benefits

- EH technique is an alternative energy source that enables nodes to collect energy from the external environment.
- It helps to overcome energy issues, i.e., limited battery capacity.
- It minimizes human intervention, time, and cost incurred by frequent site visits for maintenance and replacement of batteries.
- It helps nodes to reduce the dependency on external battery power, thus contributing positively to our environment.
- It enables the node to replenish energy from the surrounding environment and sustain its operation for a more extended period.
- It allows nodes to schedule tasks, for instance duty cycle, prioritization, and sensing time according to harvested energy profile to maximize the network performance.

2.2.2 Structure of EH-WSN Sensors Node

Recently, energy harvesting technology has allowed nodes to harvest energy from the external sources such as solar, wind, mechanical, radio frequency (RF), and thermal that can significantly prolong the WSN lifetime. Figure 2.5 shows the structure of an energy harvesting node that includes two components: *energy harvesting device* and *power management module* [29]. The former is utilized to extract energy from the surrounding environment and the latter is incorporated to use the harvested energy efficiently. These two additional components work together and enable the node to collect sufficient energy for future use to sustain its operation and also to improve network performance when sufficient energy resources are available. Figure 2.6 shows a comparison of energy characteristics in BP-WSNs and EH-WSNs. In BP-WSNs, the battery capacity declines over time, and the sensor node can only function until its battery energy is depleted.

On the other hand, in EH-WSNs, node harvests energy using external sources and store it using device, i.e., a rechargeable battery. Hence, it helps the sensor node to operate for a much longer time. Furthermore, the node sustains its operation perpetually if the current energy, $HE_{current}$ is the same or more than the needed energy, E_c. This is known as the energy neutral operation (ENO), as given in Figure 2.7 [36].

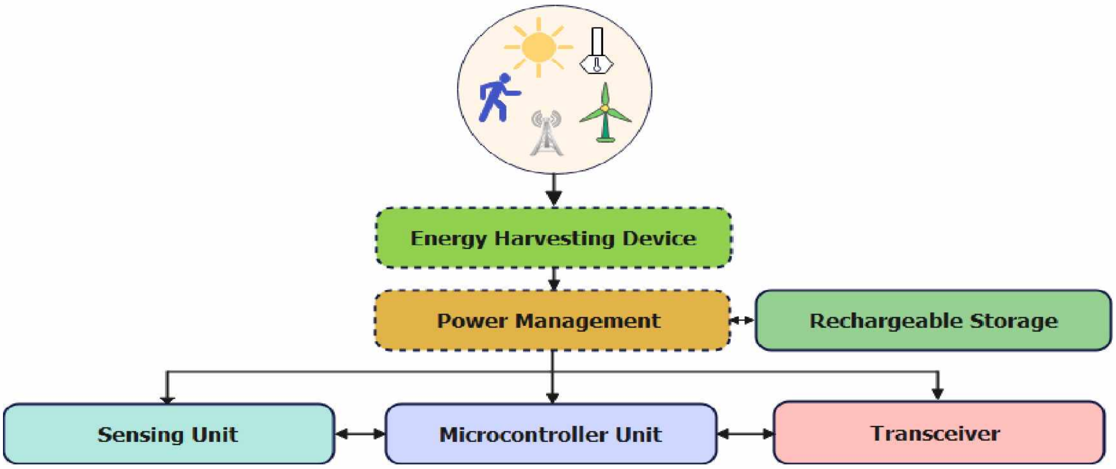

Figure 2.5: Structure of energy harvesting WSN node [29, 37]

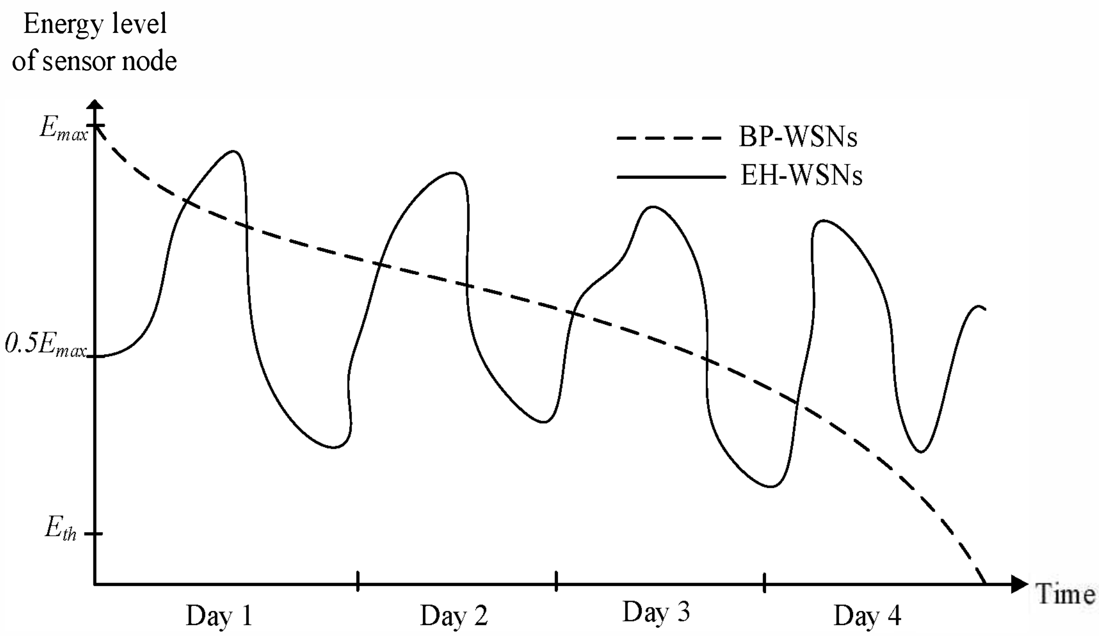

Figure 2.6: BP-WSNs vs. EH-WSNs [36]

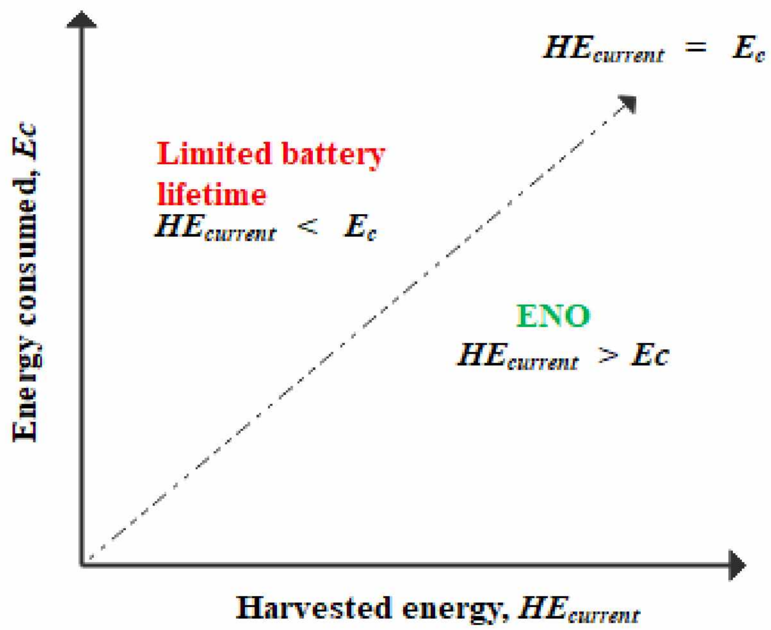

Figure 2.7: ENO [13, 36]

2.2.3 Energy harvesting sources

Harvesting energy from the surrounding environment is a promising solution that can help to reduce the energy issue faced by BP-WSNs [38]. Different energy harvesting sources are available with varying power densities, as shown in Figure 2.8 and Table 2.1. However, in this subsection, the most promising energy harvesting sources will be highlighted [39].

- **Photovoltaic or Solar harvesting:** Solar power harvesting is widely used due to its availability. It provides high conversion efficiency and power density, making it suitable for EH-WSNs applications. The main disadvantage is non-availability during bad weather conditions and night [40]. Nevertheless, it is a preferred source for powering nodes and has been widely used in the literature. In this approach, a solar cell is used to absorb energy from natural (sun) or artificial (fluorescent) lights, and its output power depends upon the source used: sun or fluorescent. Moreover, storage mechanisms, e.g., rechargeable batteries, usually employ storage energy to support ongoing node operation during the absence of harvesting energy, for example at night-time when sunlight is not available.

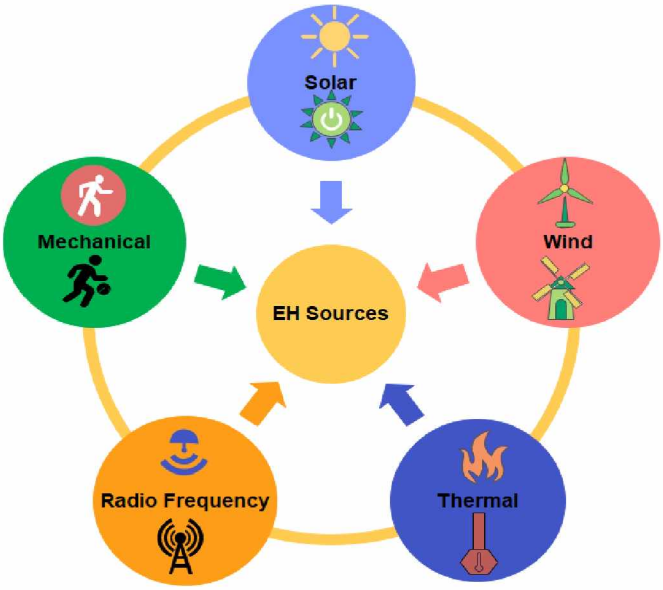

Figure 2.8: Energy harvesting sources [41]

- **Mechanical harvesting:** Mechanical or vibrational energy is produced due to the motion of objects, pressure, and human activity. The mechanical harvesting sources are piezoelectric, electrostatic, and electromagnetic. The piezoelectric is cost-effective, lightweight, and provides higher power density when compared to other mechanical sources [42]. However, it is always a challenge to integrate piezoelectric devices into small devices.

- **RF harvesting**: RF harvesting provides a promising solution to power up nodes by converting electromagnetic waves into electricity [40]. In this technique, the node harvests energy from RF signals that are radiated from sources such as TV, radio, Wi-Fi, radar, and others. However, the energy radiating from these sources decreases rapidly as the signal spreads further, leading to energy loss. Thus, it requires information about the harvester distance and direction from the RF source to get the maximum harvesting energy.

- **Thermal harvesting**: Thermal harvesting generates electric energy based on the temperature difference between two junctions of the same metals or semiconductors [43]. This is because some metals respond differently to the temperature difference, resulting in heat flow through the thermoelectric generator. In thermal harvesting, one thermocouple provides very low output power. Hence, multiple arrangements of thermocouples will be required to increase the power level.
- **Wind harvesting:** This technique converts airflow (e.g., wind) into electrical

energy. For that, the wind turbine is used [44]. In addition, miniature wind power harvesting devices such as microWindbelt are used to power nodes. However, the size of wind power harvesters has been a challenge for sensor applications, and it is still an ongoing research. In addition, the output power also depends on the wind speed and weather conditions.

Table 2.1: Characteristics of most promising and widely used energy harvesting techniques [41, 45-47]

Energy harvesting source	**Energy harvester**	**Power density**
Sun radiation	Solar cell	100 mW/cm^2 (direct sun) 100 μW/cm^2 (illuminated office)
Mechanical	Piezoelectric Electrostatic Electromagnetic	330 μW/cm^3 (shoe inserts) 50 μW/cm^3 - 100 μW/cm^3 1 μW/cm^3 – 4 μW/cm^3
Radio frequency	Wireless energy harvester	0.0002-1 μW/cm^2
Thermal	Thermocouple	40-50 μW/cm^2
Wind	MicroWindbelt	380 μW/cm^3 (5 m/s)

2.2.4 Harvesting Design alternatives

Harvesting design alternatives can be classified into *harvest-store-consume* and *harvest-consume* [48].

- **Harvest-store-consume:** This design alternative is extensively used in EH-WSNs. It uses rechargeable device to store the energy for future use as shown in Figure 2.9. Some harvesting systems face the challenge of energy uncertainty due to dynamic weather conditions. Thus, it allows sensor nodes to store energy and use it in low energy harvesting conditions, for instance, when solar energy is unavailable at night. On the other hand, in high energy harvesting scenario, for example, on a sunny day, the node can harvest an adequate amount of energy that can be used effectively by creating smart energy allocation schemes to enhance the performance.
- **Harvest-consume:** In this design alternative, harvesting energy is

immediately used to power the sensor node without any energy storage device as depicted in Figure 2. 10. However, the harvested energy from some sources is time-variant, intermittent and depends on the surrounding conditions. Hence, keeping the node operational in a low harvesting scenario may not be possible. Furthermore, when the harvesting rate exceeds the energy consumption rate, the additional harvested energy, may be wasted.

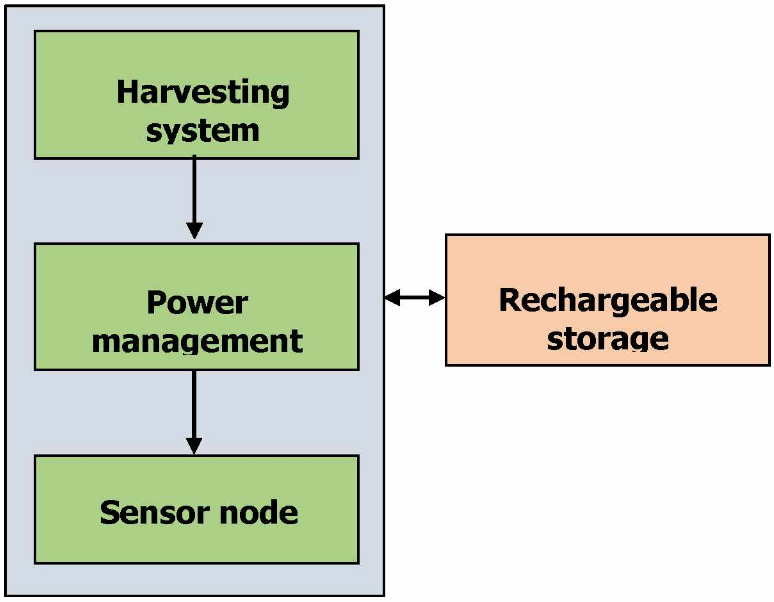

Figure 2.9: Harvest-store-consume [48]

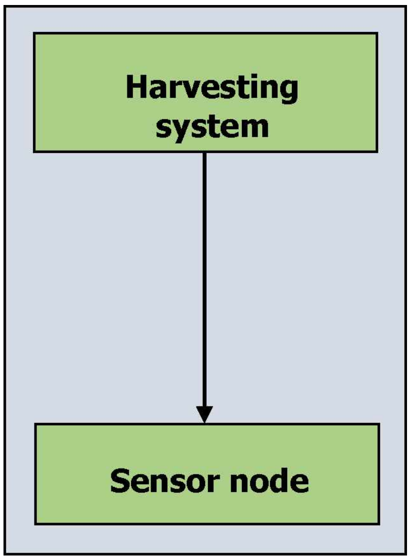

Figure 2.10: Harvest-consume [48]

2.2.5 Energy Prediction in EH-WSNs

The uncertainty in harvesting power due to dynamic conditions raises new challenges in making reliable and smart energy allocation strategies. For instance, solar harvesting nodes face significant changes in the harvesting power over time due to varying weather conditions. This drives the development of new schemes which may provide sufficient information about the future energy intake to avoid any disruption in current node operation and allocate future tasks accordingly [49]. By estimating the future harvested energy, node can exploit the expected available energy at best by making smart energy allocation strategies to enhance the performance when sufficient energy is available. Furthermore, this information can also help nodes to schedule their current operation in such a way so that operations can be sustained during periods of energy scarcity. In the literature, there are various prediction models that have been developed to estimate future energy availability in from solar energy harvesting.Table 2.2 shows some of the solar energy-based prediction models that consider different approaches. They can be used to predict the future harvested energy which can be employed to implement harvesting-aware solutions, such as communication protocols, dynamic load adaptation using smart energy allocation techniques, and others [10].

EWMA [50] assumes that the energy available at a particular day slot is similar to the previous days. The model maintains the history of available energy in the previous

Table 2.2: Schemes for predicting harvested energy in Solar EH-WSNs

Year	Method	Input Parameters
2007	EWMA [50]	Previous samples
2009	WCMA [51]	Previous samples, weather conditions
2012	Pro-Energy [52]	Previous samples and select most similar profile
2016	QLSEP [8]	Previous samples: considered the average energy increase/decrease in the most recent slots.
2021	Enhanced-Pro [10]	Previous samples used various and select the most similar profile for prediction, select the most similar profile

days as a weighted average, which is used to predict energy for the next time slot. Therefore, EWMA provides good prediction results for long-term seasonal conditions. Another scheme, called WCMA [51] addresses the shortcomings of EWMA. It takes the harvested energy of the previous days and weather conditions of the current day as well as previous days. Specifically, a matrix is used to store energy intake values. QLSEP [8] addresses the shortcomings of EWMA that is suitable for long-term seasonal conditions. It considers past energy profiles as well weather variations to forecast energy intake in a particular slot. Pro-Energy [52] considers the previous day's energy profiles as other models to predict future energy intake. It stores energy intake values of past days (sunny, cloudy, rainy) and incorporates past values to estimate the energy intake in the next slot. Enhanced-Pro [10] is the extension of the Pro-Energy by considering real-life solar traces to predict future intake. The model introduces a tuning factor and fine adjustment index to improve prediction accuracy. It uses past energy profiles as Pro-Energy to find correlation coefficient factors with the current harvested energy profile in the current slot. However, most of these models do not perform well when sudden changes occur in weather conditions and provide significant errors when employed in different weather conditions (e.g., sunny, partially sunny, consecutive cloudy days). In addition, they involve multiple parameters such as weighting in Pro-Energy [52], and tuning and adjustment index factors in Enhanced-Pro [10], which increase complexity, processing time, and energy cost. Furthermore, the effectiveness of these models at the MAC layer, that can help in designing adaptive schemes based on predicted energy to optimize the network performance, has only received limited consideration [10].

2.3 Machine Learning

Artificial Intelligence enables automation of tasks that are typically done manually by huma ns. Machine learning (ML) is a part of AI that involves computer algorithms that learn automatically from data or experience without being explicitly programmed [9]. It has gained significant attention in industry and academia and is considered a vital tool in developing automated IoT applications [53, 54]. The advancement in ML models provides substantial benefits, such as making the computing process more reliable and analyzing more complex data quickly and efficiently [9]. Hence, it has gained applications in various fields, such as engineering, computing, medicine, and security [55]. Generally, three steps are involved in solving a problem using ML. First is data gathering, which is data acquisition tasks, and labeling. Second, data preparation or feature extraction involves raw data processing and conversion into meaningful form before training and testing data. Then, the ML model selecting and its training and testing.

ML techniques based on learning styles have been explained and classified into supervised, unsupervised, semi-supervised, and reinforcement learning, as shown in Figure 2.11 [9]. Supervised learning is the most important and extensively used approach in ML. This learning takes input and output data known as a labeled set to build the system model that finds a relation between them. This type of learning is widely adopted in EH-WSNs and addresses various issues such as data aggregation, MAC and energy harvesting [56-58]. On the other hand, the unsupervised learning approach does not provide output associated with the inputs. Instead, it tries to extract the relationship between the data and classifies them into different groups based on the similarity between the input data sets. This approach contributes to WSNs in addressing various issues such as clustering, routing, and anomaly detection [59-61]. Semi-supervised learning shares features of both supervised and unsupervised learning. It works on labeled and unlabeled data and aims to reduce their weaknesses [19]. In addition, it covers issues such as localization and fault detection [62, 63]. Lastly, reinforcement learning involves an agent that learns by interacting with its environment. The agent gathers information that helps to learn and take the best possible action that maximizes its rewards. The Q-learning technique is an example of reinforcement learning [8].

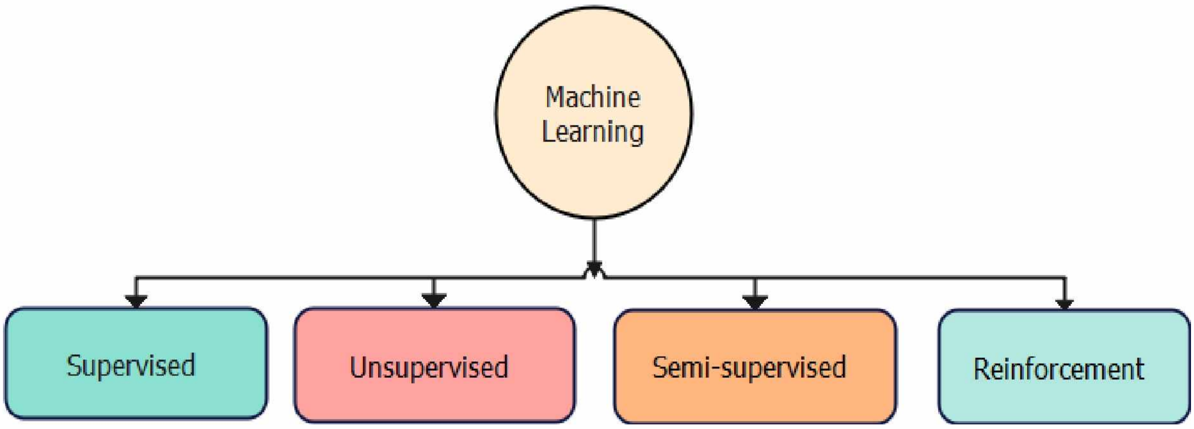

Figure 2.11: Classification of ML models [9]

2.3.1 Machine Learning in EH-WSNs

ML techniques have been widely used to solve various challenges such as MAC, QoS, routing, localization, data integrity and fault detection, synchronization, and data aggregation [64]. For example, it can help optimize MAC protocols to enhance network performance [9]. Moreover, in EH-WSNs, nodes can use ML algorithms to predict the energy intake at a given time slot [65] [66]. For instance, ML models such as regression and Q-learning have been used to forecast future energy in WSNs [8, 56]. Similarly, reinforcement learning-based energy management has been introduced that maintains nodes' energy harvesting and energy consumption [67]. Authors in [68] compared Artificial neural network (ANN) based ML models' that take different parameters such as rain, time, wind, atmospheric pressure, dew point, and azimuth angle to forecast daily solar intensity. In [69], the authors have developed a model that takes relative humidity, temperature, pressure and cloud formation data to predict the hourly solar irradiance. In [70], the authors compare the performance of multi-layer perceptron neural networks and support vector machine to predict the global solar radiation using various combinations of input variables such as ambient temperature, sunshine duration, and extraterrestrial global solar radiation.

2.4 Medium Access Control Protocol

In WSNs, the MAC protocol is responsible for providing access to the shared medium among sensor nodes, and it consumes most of the energy. These MAC protocols can be categorized into three classes: contention-free, contention-based, and hybrid protocols as shown in Figure 2.12 [48, 71]. The contention-free protocols assign variable or fixed time slots to each sensor node for data transmission [72]. This allows nodes to access the channel in the allocated time slots, and as a result, collisions in the network are reduced.

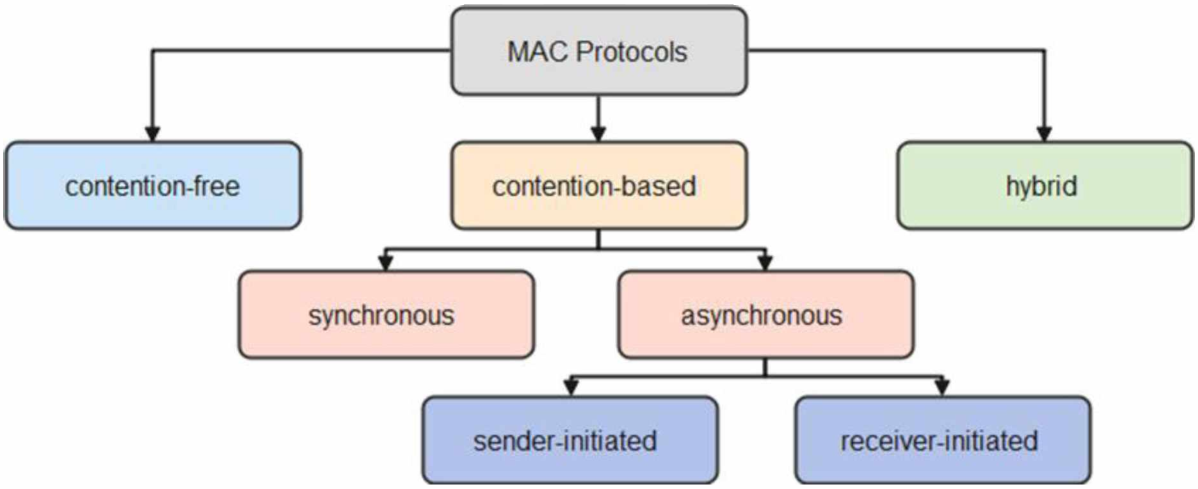

Figure 2.12: Classification of MAC protocols [71]

The contention-based protocols avoid time slots overhead for packet transmission among nodes and allow them to access the medium randomly. Thus, the risk of collision may increase, which can be avoided by employing different mechanisms i.e., CSMA. These protocols can be further classified as synchronous or asynchronous [73]. In synchronous such as S-MAC [74], T-MAC [75], DW-MAC [76], DSMAC [77], SMACS [78], and PQMAC [79], nodes are required to follow a common listening time in a virtual cluster, where nodes can exchange the data packets. Consequently, protocols conserve energy by reducing idle listening in the network. However, the tight synchronization requires additional overhead that leads to limitations in terms of adaptability, scalability, robustness and others. Furthermore, these protocols need synchronization among sensor nodes for data transmission which do not allow node to operate on a duty cycle of their choice, which hampers their ability to adapt to dynamic energy harvesting conditions.

In the asynchronous approach, nodes do not require synchronization; consequently, each node can wake up and sleep independently [80]. Thus, nodes require a rendezvous point for data communication. Comparisons suggest that asynchronous schemes are more energy-efficient than synchronous [81, 82]. The asynchronous protocols are further divided into sender-initiated and receiver-initiated protocols. The sender-initiated protocols such as B-MAC [81], X-MAC [83] use preamble sampling or low power listening techniques to establish a communication link between the receiver and sender nodes. These protocols shift the burden to the sender side to initiate the communication, where the node having a data packet transmits a preamble before sending its actual data packet. The receiver upon waking up detects the preamble and waits for the actual data packet. In this scheme, the preamble transmission requires a longer time; thus, the sender node holding a data packet must wait until the channel becomes free, which causes an increase in packet delay and a decrease in network throughput [80]. On the other hand, the receiver-initiated protocols such as DWT-MAC [84], RI-MAC [80] and RICER [85] have been proposed. For example, DWT-MAC [84] considers QoS and reduces the delay for the highest priority packet in BP-WSNs. In receiver-initiated protocols, the receiver starts the communication by broadcasting a wake-up beacon which indicates to all senders that it is ready to receive data packets. The sender node having a data packet turns on its radio and wait for the wake-up beacon. After receiving the beacon, it transmits the data packet and waits for the acknowledgment packet. Therefore, the receiver-initiated protocols perform better in terms of energy efficiency than sender-initiated protocols [80], [86].

2.4.1 MAC Protocols for Energy Harvesting WSNs

The MAC protocols for EH-WSNs aim to optimize the performance using harvested energy [87]. Previously, numerous MAC protocols have been proposed that incorporate harvested energy to formulate different tasks such as duty cycle and access probability. These protocols can be divided into sink-initiated, sender-initiated, and receiver-initiated approaches, as shown in Figure 2.13.

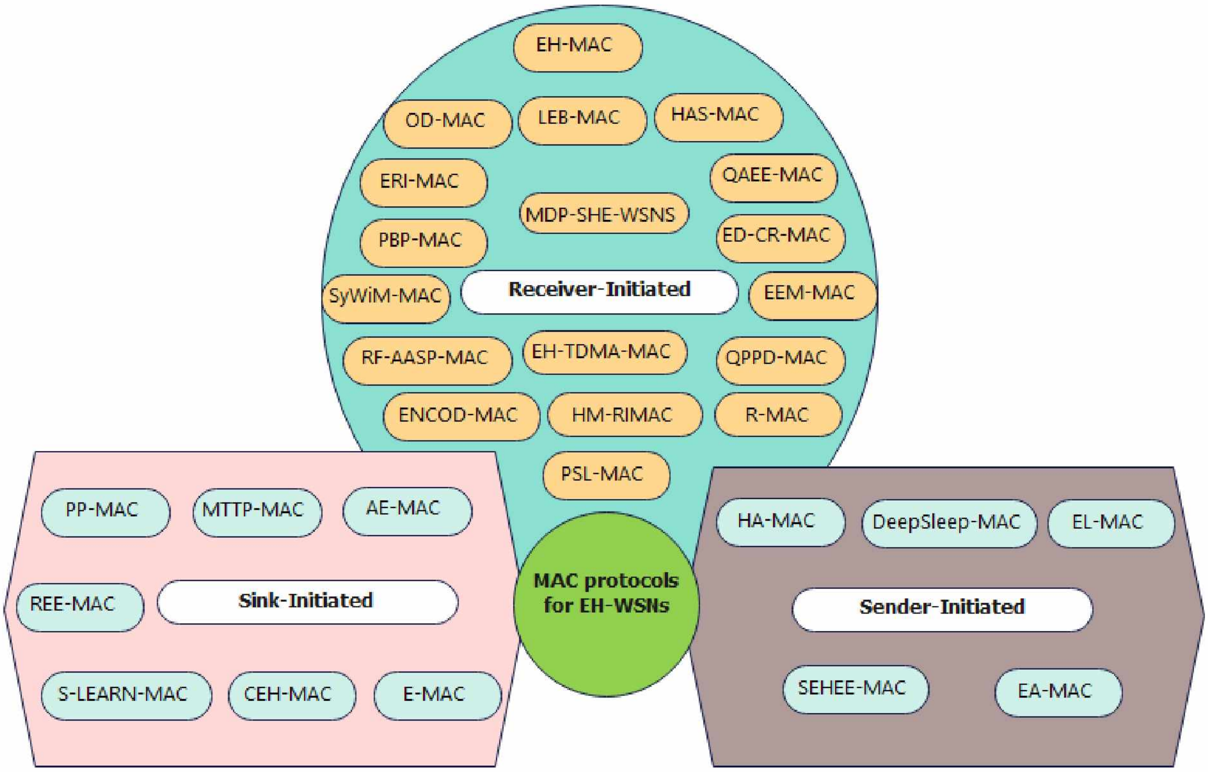

Figure 2.13: MAC protocols for energy harvesting WSNs [48]

2.4.1.1 Sender-initiated MAC protocols for EH-WSNs

HA-MAC [88] follows a superframe structure that consists of a beacon and random access slots. The network consists of a coordinator node and multiple sender nodes named wireless devices (WDs). At the beginning of the superframe, the coordinator broadcasts a beacon containing information about synchronization and the number of random-access slots, as shown in Figure 2.14. Using this information, each WD randomly selects random access slots and starts energy harvesting until it has access, then transmits the data packet. As a result, the developed protocol achieves good network throughput. However, its performance evaluation does not focus on other important parameters such as delay, PDR, and energy efficiency. In addition, it does not support individual duty cycle of the node and does not utilize the current harvesting rate to adjust the node's operation.

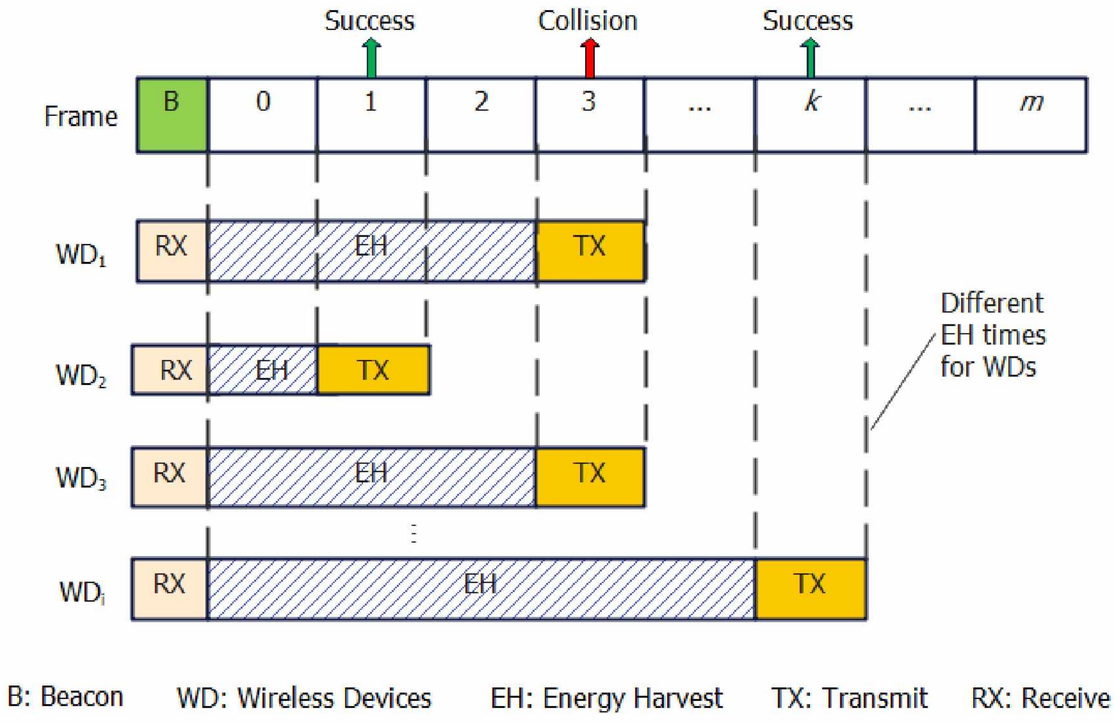

Figure 2.14: Communication overview of HA-MAC [88]

DeepSleep-MAC [89] supports M2M energy harvesting communication. It supports low-energy nodes by allowing them to access the medium faster than other high-energy nodes. It is accomplished by allocating a shorter contention window (CW) size to low-energy nodes. Furthermore, it incorporates an algorithm that reduces the number of active nodes to limit the medium access attempts and lower channel contention. Moreover, this approach also reduces collision in the network. However, higher energy nodes need to wait for longer to access the medium, increasing packet delay and energy consumption. In addition, its performance evaluation is conducted using a constant harvesting rate, which is unrealistic. Moreover, its performance is not evaluated under dynamic harvesting conditions and does not include essential parameters such as delay, PDR, and energy efficiency.

EL-MAC [90] aims to support low-energy nodes by providing them access to the medium. The network comprises two types of users: primary users (sink) with high energy and secondary users (nodes) with low energy. The communication is based on a superframe, divided into three periods: sensing, contention, and transmission. At first, the sink node broadcasts a superframe that indicates that the sink is ready to accept the packets. On the other hand, after receiving the superframe, the node starts channel sensing. If the channel is free, the node contends for medium access according to its energy level. The protocol provides a higher priority to low-energy nodes by assigning it shorter CW, thus, reducing the number of contending nodes. Nevertheless, the sender node with sufficient energy resources must wait until the low-energy nodes complete data transmission, resulting in data packets experiencing long delays. In addition, nodes must follow the frame structure and need to wait until the transmission period starts. Furthermore, the performance is not measured using realistic harvesting conditions.

SEHEE-MAC [90] introduces a slotted preamble technique that controls the sensor's radio—resulting in significant energy savings by extending sleep time. It supports the duty cycle of the node and enables low-energy nodes to go sleep and conserve energy. The sender nodes initiate the communication by sensing the channel. If it is free, the node sends a small preamble indicating the need for communication, and it keeps sending the preamble until the receiver wakes up. On the other hand, if the channel is busy, the node calculates the backoff interval and senses the medium when the backoff expires. On the other hand, the intended receiver receives the preamble and replies with a short ACK that indicates a request to send the data packet. After obtaining the ACK, the intended sender node transmits the packet. After successful transmission, each node checks its residual energy and adjusts the slotted preamble interval accordingly. However, its performance evaluation is conducted on a very small scale and is not compared with the energy harvesting MAC protocol. Furthermore, sender nodes must wait until the receiver wakes up, which increases energy consumption in the network. Moreover, it does not incorporate current and incoming harvested energy to adjust the node's operation.

EA-MAC [91] adjusts the duty cycle and backoff times according to the energy harvesting conditions, and considers fairness among the nodes. This is because nodes that are randomly distributed have different locations in the network. It employs energy adaptive duty cycle and contention algorithms to adjust sensor nodes' duty cycle and backoff time according to their harvested energy level and harvesting rates, respectively. The results show that EA-MAC achieves good network throughput and fairness among sensor nodes. However, its performance is not compared with any other energy harvesting protocol and does not include other essential parameters such as delay and packet loss.

2.4.1.2 Sink-initiated MAC protocols for EH-WSNs

PP-MAC [92] aims to improve network throughput and provides good scalability. It regulates the contention probability value corresponding to the harvesting rate, number of nodes, and packet collision. Initially, the sink wake-up periodically to transmit a polling packet, including a contention probability, P_{con}. After receiving the polling packet, the sender generates a random number, y between 0 and 1 and sends the data packet if $y \leq P_{con.}$ Otherwise, it remains active, waits for the next polling packet, and goes into a charging state. The Additive Increase Multiplicative Decrease technique is used to adjust the value of P_{con} according to the number of active nodes, response type, and packet collision. However, the sender nodes holding data must wait for the appropriate value of P_{con} to perform data transmission, resulting in longer delays and increasing energy consumption due to idle listening. In addition, its performance evaluation does not include a realistic harvesting rate and any plan to use the excess harvested energy to adjust the node's operation.

MTTP-MAC [93] depends solely on energy harvesting sources. It employs a tier-based hierarchy model to support multi-hop scenarios. Each tier consists of a set of nodes arranged in a group form and located at different distances from the sink node. The sink node wakes up periodically and broadcasts a polling packet to tier-1 that contains P_{con} and tier number. Then, the node in tier-1 further sends the polling packet and waits for the data packet. The communication overview of MTTP-MAC is given in 2.15. Its performance has been validated in an indoor environment using commercial-off-the-shelf nodes. However, its performance has not been compared with any other protocols. In addition, it does not use an external source for storage, which may lead to energy waste without taking advantage of it in high harvesting conditions. Furthermore, a higher number of tiers will further increase overhead and complexity.

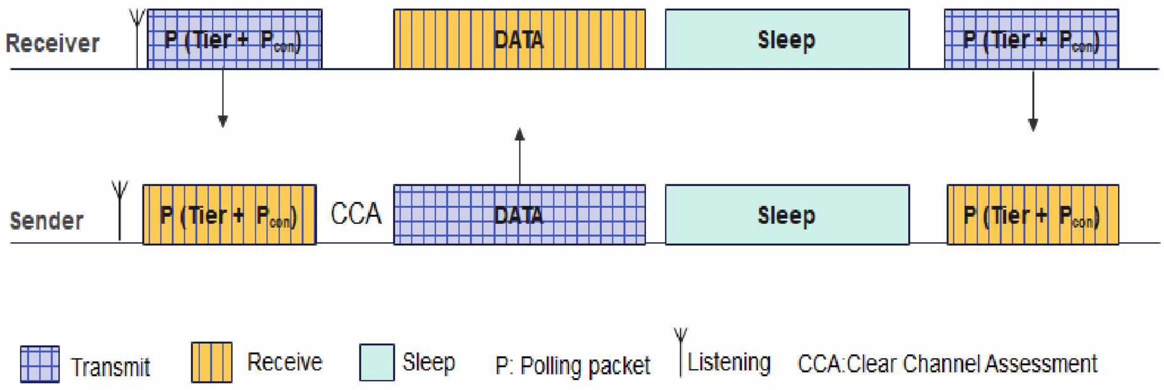

Figure 2.15: Communication overview of MTTP-MAC [93]

AE-MAC [94] assigns contention priorities based on energy level of each node. The network consists of a base station (sink) and multiple sender nodes. Initially, the sink broadcasts a superframe that includes periods of notification, harvesting, contention, and data transmission. The notification indicates the starting period of the frame, and then nodes prepare for energy harvesting in the harvesting period. Sender nodes then update the sink about their energy levels. Next, sender nodes hold packets and contend for the medium in contention period by sending transmission requests. Afterward, the designated sender sends the data packet to the sink nodes and listens to the channel for ACK. However, it allows nodes to harvest for a limited time with a constant harvesting rate, which is unrealistic. In addition, its performance does not consider the current harvesting rate to adjust the node's operation and does not incorporate dynamic harvesting conditions.

REE-MAC [95] aims to reduce control packet overheads involved in scheduling node operation and to achieve good fairness among sensor nodes. It employs a dual superframe structures. In the first frame, the power transmitting unit, called the coordinator, transfers power to the receiving nodes in their dedicated timeslots. Then, sender nodes use the harvested energy to exchange data packets. Furthermore, this frame is further divided into timeslots assigned to receiving nodes based on their estimated residual energy. On the other hand, the second superframe is compose of beacon and data transmission periods. However, the protocol does not support the individual duty cycle of the node. In addition, nodes must wait for their timeslots to harvest energy and send data packets, which increases packet delay. Also, nodes can only harvest energy in their dedicated timeslots and follow the superframe structure for data transmission. Lastly, the performance is evaluated at a constant harvesting rate, which is unrealistic.

E-MAC [96] enables high-energy nodes to transfer the data while allowing low-energy nodes to harvest energy from RF sources to increase their energy level. It incorporates the residual energy to adjust the duty cycle of the node while considering QoS requirements. It enables the sink node to increase the duty cycle when sufficient energy is available. Furthermore, it assigns the time slots to sender nodes by considering their energy levels and amount of data traffic. The results indicate that it improves data transmission and the lifetime of IoT devices. However, its performance evaluation does not consider realistic harvesting conditions and comparison with other energy harvesting MAC protocols.

S-LEARN-MAC [97] developed a scheduling algorithm to handle energy harvesting and data transmission activities accordingly. It creates schedules for each node by specifying its timeslot for data transmission to avoid collision. Furthermore, it allows nodes to reuse the same antenna for both the transmitter and harvester to reduce cost. When the sender node is busy in data transmission, other nodes use that time to harvest energy from the RF source. The results show that it achieves good network throughput and packet delivery ratio. However, its performance evaluation is not evaluated using realistic harvesting conditions. In addition, it does not provide any plan for utilizing the excess harvested energy more efficiently to improve network performance.

CEH-MAC [98] exploits the energy information to adjust the idle time of intermediate nodes and allow them to harvest the necessary energy to carry out the cooperation phase. It introduces a charging time that allows intermediate nodes to harvest enough energy. The sink node sets the charging time value, which considers the node's energy level. Furthermore, it also incorporates the expected duration of the cooperation phase that depends on channel conditions and the number of relay nodes. As a result, it achieves better delay, throughput, and energy efficiency. However, its performance is not evaluated using a dynamic harvesting rate and is not compared with other energy harvesting MAC protocols.

2.4.1.3 Receiver-Initiated MAC protocols for EH-WSNs

EH-MAC [99] incorporates energy harvesting rate in regulating the contention probability, which determines whether to send the packet or not. It aims to achieve better throughput while considering dynamic harvesting conditions. Initially, the receiver begins the communication by sending a wake-up packet that contains P_{con}, as shown Figure 2.16. Additionally, it employs two approaches called Estimated Number of Active Neighbors and Additive Increase Multiplicative Decrease to adjust the P_{con} values. The results show it achieves better throughput and scalability in multi-hop scenarios. However, it results in a higher latency. In addition, the dynamic harvesting condition algorithm may take longer to adjust P_{con}. Furthermore, its performance is not assessed under realistic harvesting conditions and does not include essential parameters such as delay, PDR, and energy efficiency.

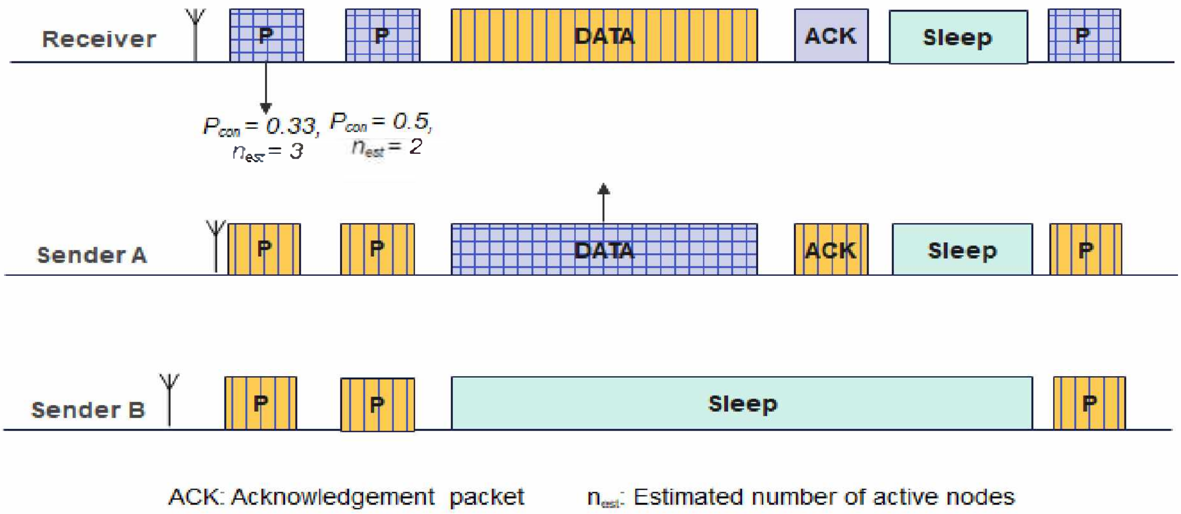

Figure 2.16: Communication overview of EH-MAC [99]

OD-MAC [36] offers on-demand communication, where the receiver wakes up and broadcasts the beacon to initiate the communication. It adjusts the wake-up beacon and sensing interval based on harvested energy. The protocol aims to support the individual duty cycle of the nodes according to their energy profiles. Therefore, it enables them to increase network performance when sufficient energy resources are available. The communication of OD-MAC is shown in Figure 2.17. The receiver wakes up periodically to broadcast the beacon indicating that the receiver is ready to receive the incoming packet. The receiver adjusts the beacon frequency according to the receiver's energy level. On the other hand, the sender nodes set their sensing interval according to their energy level to gather more data packets. In addition, the protocol introduces a technique called opportunistic forwarding to minimize idle listening for wake-up beacon. However, the OD-MAC protocol does not offer packet ACK and retransmission features, which are essential for some critical applications. In addition, it adjusts beacon frequency without knowledge of upcoming energy, which may degrade network performance under dynamic harvesting conditions. In addition, its performance has not been evaluated and compared with any other protocol using realistic harvesting conditions.

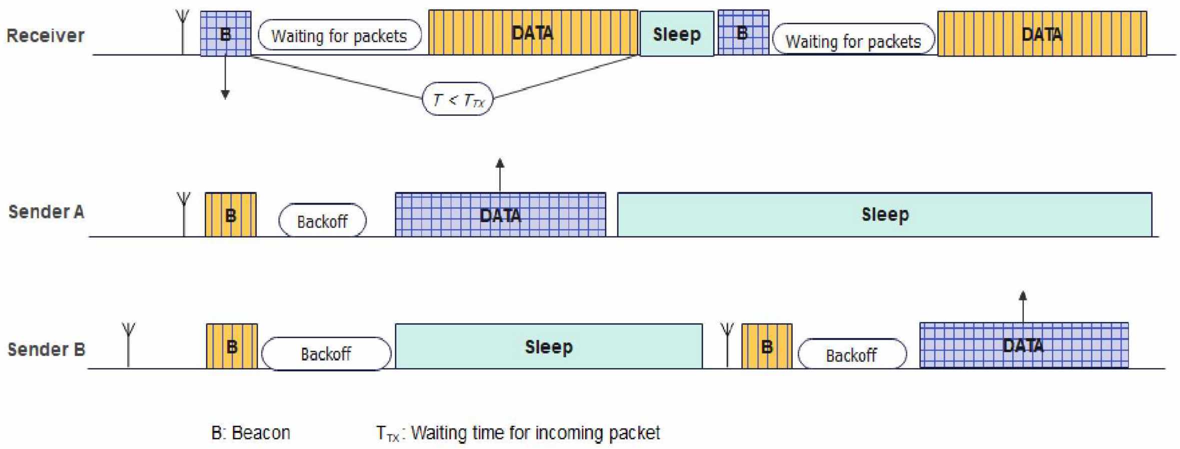

Figure 2.17: Communication overview of OD-MAC [36]

LEB-MAC [100] aims to achieve energy and load balancing state among nodes. Figure 2.18 shows the communication overview of LEB-MAC. The receiver begins communication by sending a wake-up beacon periodically and then waits for the data packet from the sender nodes. Sometimes the beacon transmitted by the receiver also contains the next schedule that helps senders to synchronize. Furthermore, it employs a technique that enables nodes to distribute the load according to energy levels. For instance, the node with a higher energy level accommodates more data packets compared to a low-profile energy node. Furthermore, it introduces a collision resolution mechanism to avoid collisions when multiple senders contend for the channel simultaneously. However, in this protocol, sender nodes competing for the first time must wait a long time, increasing packet delay and energy consumption. In addition, it does not provide any plan for utilizing the surplus harvested energy more efficiently to improve network performance.

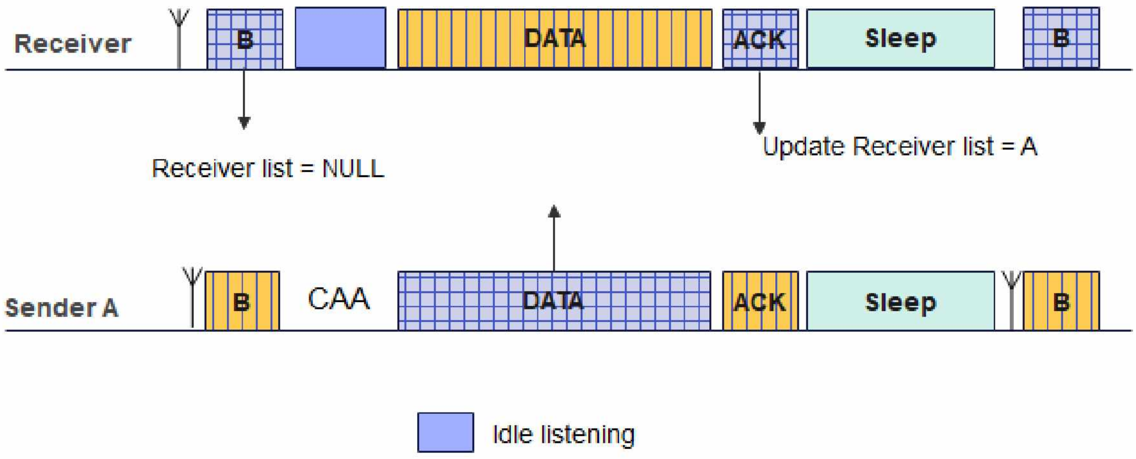

Figure 2.18: Communication overview of LEB-MAC [100]

MDP-SHE-WSNS [101] introduces a transmission policy that enables the node to make three decisions according to its energy level: decrease, maintain or increase. It allows the node to transfer more data packets considering its energy level. In the network, each node adjusts the duty cycle and takes the rewards as the amount of data transferred. As a result, it achieves good performance in network throughput under different scenarios. However, it does not employ any prediction model to estimate an increase in harvested energy level. Furthermore, its performance is not evaluated using dynamic harvesting conditions and does not include other parameters such as delay, PDR, and energy efficiency.

ERI-MAC [102] utilizes packet concatenation technique in which several small packets are combined to form the super packet. This appraoch helps to reduce packet overheads and improves the energy efficiency. The communication overview of ERI-MAC is given in Figure 2.19. At first, the receiver transmits a beacon containing its address and then waits for a short period to determine if there is any incoming packet. On the other hand, the sender nodes that have packets keep in a listening state and wait for the beacon. After receiving a beacon from the receiver, the sender nodes start contending for the medium and send data packets. After successful packet transmission, the sender gets ACK and goes to sleep. The motivation behind the packet concatenation scheme is that the data packet is usually small in size. Thus, the sending process for small data packets involves the exchange of control packet, which increase packet overhead, energy consumption, and channel contention. Therefore, sending multiple data packets that are usually destined to the same receiver using a packet concatenation scheme increases energy efficiency and reduces packet overhead and channel contention. However, it is primarily designed to address the application that generates small size and similar type of data packets. Thus, it is not suitable for application that generates packet with large size and different priority level. In addition, it takes longer to fill the super packet in low traffic conditions, resulting in data packets already in queue suffering longer delays until they reach their destination. Furthermore, the performance evaluation is conducted using a fixed harvesting rate, which is unrealistic and not compared with any other energy harvesting protocol.

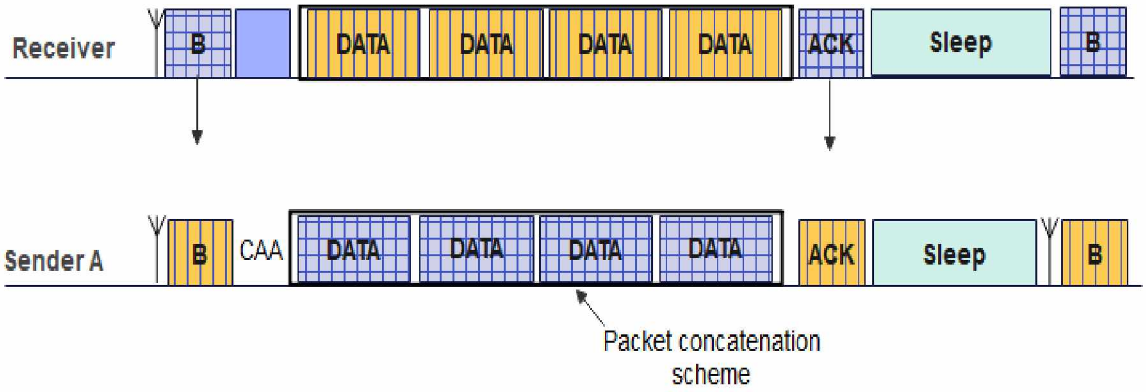

Figure 2.19: Communication overview of ERI-MAC [102]

HAS-MAC [103] is a hybrid communication scheme that utilizes the features of asynchronous and synchronous MAC protocols. It enables the sensor node to switch between asynchronous and synchronous approaches. Furthermore, it adjusts the working schedule of the node according to its energy level. In this scheme, the asynchronous part is used for sharing the working schedule with neighbor nodes. In the synchronous part, the sender nodes analyze the node's working schedule and send the data packet to its neighbor node. The results show that it achieves good delay reduction compared to the other two schemes. However, sender nodes need to know the working schedule of their neighboring nodes to perform data transmission. Furthermore, it does not include details about energy harvesting conditions, i.e., harvesting rate. Moreover, it does not have a plan to utilize the excess and future harvested energy to improve the performance. In addition, the performance evaluation does not include other essential parameters such as throughput, PDR, and energy efficiency.

In [12], the authors developed a priority-based MAC protocol named QAEE-MAC. The protocol takes advantage of packet priority and enables the receiver node to select the sender node based on the highest packet priority. In this protocol, the receiver periodically wakes up and broadcasts a beacon that indicates that it is available to accept incoming data packets. Then, it waits a short time to receive data packets from the sender nodes, as shown in Figure 2.20. On the other hand, sender nodes holding data packets send TX beacon that includes packet priority. After receiving TX beacon(s), the receiver chooses the sender based on the received Tx beacon with the highest priority and then broadcasts the Rx beacon, enabling sender nodes to know who the selected sender is. After that, the selected sender sends the data packet to the receiver. The protocol performs well in terms of delay for the highest priority packet. However, its performance does not include PDR and throughput, which are primary concerns supporting QoS in EH-WSNs. In addition, its performance has not been compared with any other protocol and not tested using realistic energy harvesting conditions. Furthermore, it does not provide any mechanism to incorporate the excess harvested energy to improve the performance.

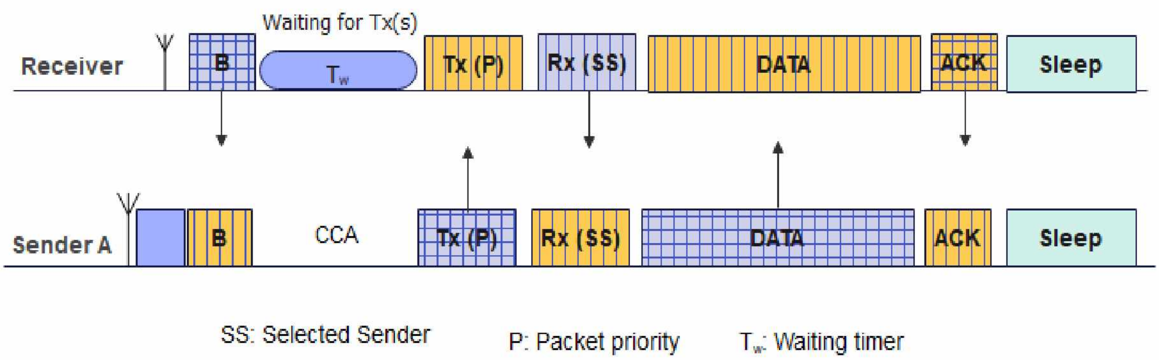

Figure 2.20: Communication overview of QAEE-MAC [12]

ED-CR [104] presents two schemes that considers residual energy and an assumed energy increase to improve network performance. First, the authors have implemented an exponential decision graph to adjust the duty cycle based on energy level. Second, it accounts for the prospective increase in energy to reduce the duty cycle further. As a result, it achieves better performance than DSP and RI-MAC (non-energy harvesting MAC) in terms of delay, energy consumption, and PDR. However, its performance is evaluated on a very small scale, for instance, a total simulation of 60 seconds. Furthermore, it assumes a future increase in energy without employing any prediction scheme under dynamic energy harvesting; hence inappropriate for the evaluation. In addition, its performance is not compared with any energy harvesting MAC protocol.

In [105], the authors proposed the PBP-MAC protocol that supports multi-hop data transmission and assigns a priority to relay nodes based on residual energy and current harvesting rate. The network is composed of multiple sender nodes and each node access the wireless medium with different access probabilities, which depend on residual energy and energy harvesting rate. A node with a high energy level performs more aggressively and supports neighboring nodes by accepting and forwarding more data packets. The communication overview of priority-based pipelined-forwarding MAC is given in Figure 2.21. Initially, a node broadcasts a beacon that is available to relay incoming packets. On the other hand, the node that holds the data packet keeps listening to the medium for the beacon. After accepting the beacon, it sends a data packet and then listens to the channel for the ACK. After receiving the data packet, the relay node sends an ACK packet that other neighbor nodes can also hear. At this point, the non-relay node starts computing its priority corresponding to the current energy level and energy harvesting rate to become the next relay node. Then, it sends a beacon after a backoff value is assigned according to the priority value. If the node has a higher priority value, it sets a smaller backoff value, resulting in a higher probability of a node becoming a relay node. It achieves a good energy balance among nodes and increased network lifetime. However, its performance has not been evaluated and compared with any other protocol in terms of delay, network throughput, PDR, and energy efficiency. Furthermore, its performance evaluation has not considered realistic harvesting conditions. Moreover, it does not provide any mechanism to utilize the excess harvesting energy to enhance the performance in high harvesting scenarios.

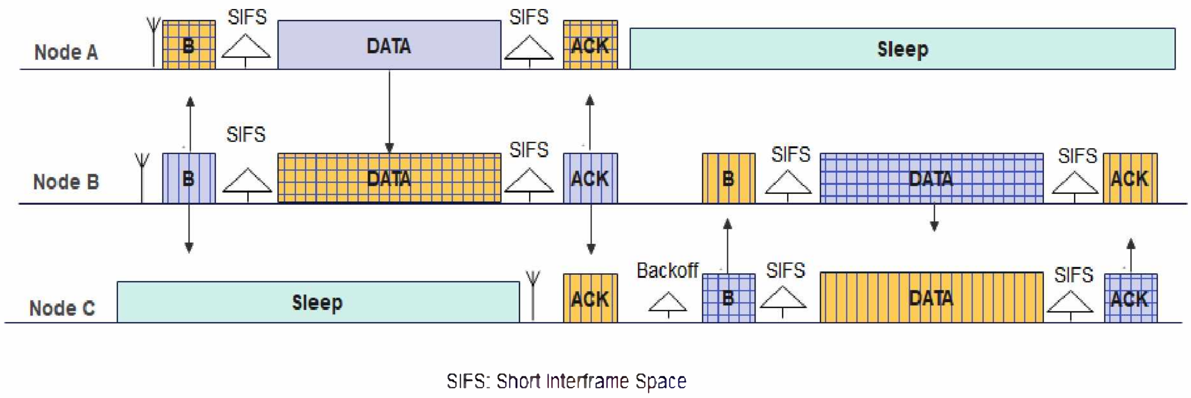

Figure 2.21: Communication overview of PBP-MAC [105]

SyWiM-MAC [106] aims to improve the QoS in the network. Whenever the sender node has data, it waits for the wake-up beacon from the receiver. Once the beacon is received, it transmits the data after Clear Channel Assessment (CCA). The receiver confirms the reception of the data packet by sending an ACK packet. The protocol incorporates timing offset to maintain synchronization between nodes. However, if sender nodes operate at different times, then timing offset will occur, resulting in nodes having to wait for a longer time for synchronization to perform data transmission. Thus, it introduces a technique that helps nodes find the correct timing offset and enables them to update the next wake-up interval to reduce idle listening. However, it does not support the individual duty cycle of the node under harvesting and is unable to optimize performance when sufficient energy resources are available. In addition, the performance evaluation does not incorporate realistic harvesting conditions.

R-MAC [107] aims to achieve energy balance among nodes. The network comprises multiple clusters, each consisting of multiple sender nodes distributed randomly. The cluster head is selected based on residual energy level or the size of data queue lengths. The secondary users (SUs) perform data sensing and periodically send the gathered data to the primary user (PU) during its allotted time slot. It is assumed that each node can harvest energy from the RF source. Furthermore, it introduces extra timeslots in which cluster head and sender nodes can harvest energy. It keeps changing the number of harvesting slots in each superframe to optimize harvested energy while maintaining the network throughput and delay within acceptable limits. However, R-MAC does not provide any mechanism to utilize the excess harvested energy. In addition, a higher number of timeslots for harvesting energy may lead to a higher delay in the network. In addition, its performance evaluation does not consider other important parameters such as network throughput and energy efficiency.

EH-TDMA-MAC [108] follows the superframe structure that consists of a specific number of slots. At first, the receiver initiates the communication by broadcasting a small packet named ping that allows sender nodes to synchronize and perform data transmission. The communication overview of EH-TDMA-MAC is given in Figure 2.22. The receiver also checks its power level before sending a ping packet. On the other hand, sender nodes hold data packets, wait for ping packets, and send them in their dedicated timeslot. This help to reduce packet collision. However, it does not provide ACK of the received data packet, which is essential for data reliability. Furthermore, its performance is not tested using dynamic harvesting rates. Moreover, it does not utilize surplus harvested energy to enhance the performance.

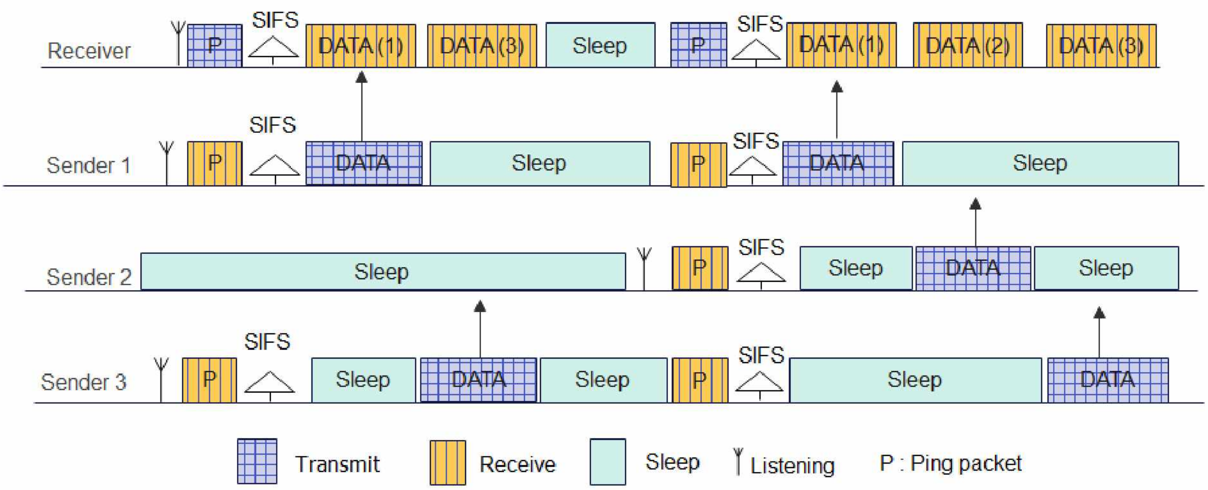

Figure 2.22: Communication overview of EH-TDMA-MAC [108]

EEM-MAC [13] supports the individual duty cycle and allows it to regulate the duty cycle based on remaining energy while ensuring a balance between the energy harvesting and energy consumption of the node. Initially, the receiver broadcasts the beacon that announces that it is ready to accept the packet. Then, the sender that holds data packets, senses the medium, and sends the packet. On the other hand, the receiver sends an acknowledged beacon, R, that indicates the successful reception of the data packet and invites other senders to transfer the data packet. Then, it waits for a short time, and if there is no incoming data packet, it goes to sleep. Figure 2.23

describes the communication overview of EEM-MAC. It supports two modes of duty cycle. First is the static mode duty cycle, defined by the user or administrator. Second is the dynamic duty cycle, which is set according to the harvested and remaining energy level. Thus, the nodes with high energy profiles wake up more frequently and relay more data packets. Furthermore, it improves performance in terms of latency, throughput, and PDR than other protocols. However, the dynamic duty cycle mode does not consider future energy intake, which may degrade network performance in low harvesting conditions. Furthermore, its performance has not been evaluated using dynamic harvesting under different scenarios.

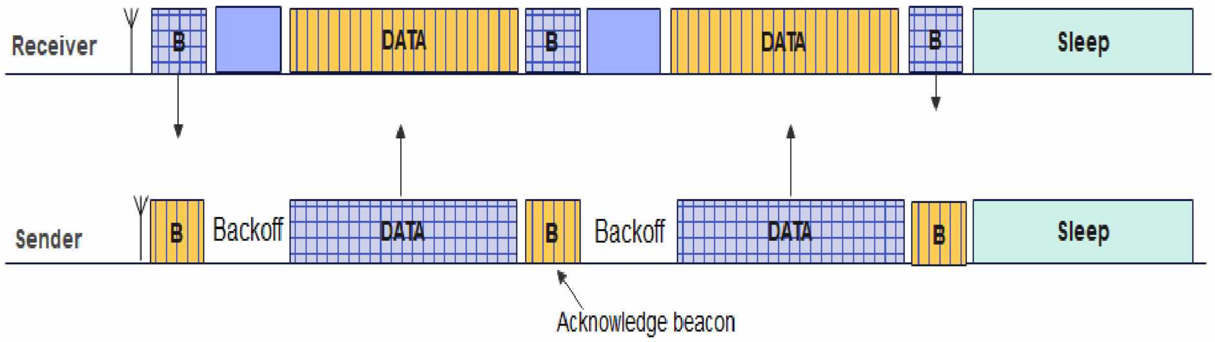

Figure 2.23: Communication overview of EEM-MAC [13]

RF-AASP-MAC [109] uses a technique to adjust the sleeping period according to traffic conditions, residual, and available RF energy. It helps to reduce the contention level and improves network throughput. Furthermore, the sink node counts the number of incoming packets in the current beacon interval to estimate the traffic conditions and compare it with total received packets in the last beacon interval to find the variations. This scheme enables nodes to use two antennas: one for harvesting RF energy and the other for data transmission. As a result, the protocol achieves good energy efficiency while satisfying QoS requirements in the network. However, its performance is not tested under dynamic harvesting conditions and is not compared with energy harvesting MAC schemes.

In ENCOD-MAC [110], the receiver seeks to operate close to the ENO condition and sets the duty cycle based on the harvested energy to improve network performance. It introduces a duty cycle adjustment scheme by which the receiver checks its energy level and harvesting energy, and assigns the duty cycle more aggressively when sufficient energy resources are available under dynamic harvesting scenarios. Furthermore, it also incorporates the packet's priority and reduces the delay for the highest-priority packet. However, the receiver node does not consider incoming harvested energy in duty cycle adjustment, which may affect ongoing node operation and degrade network performance in dynamic harvesting conditions. Furthermore, data packets suffer longer delays despite sufficient energy resources. In addition, its performance evaluation does not include other parameters such as energy efficiency and network throughput, which are primary concerns of QoS.

QPPD-MAC [11] supports QoS by assigning multi-priority to the data packets. It helps the highest priority packet by canceling the waiting timer to reduce the delay. Figure 2.24 presents the communication overview of QPPD-MAC. Furthermore, it adjusts the receiver duty cycle based on the remaining energy level. As a result, the receiver node wakes up frequently when its energy level is high. Moreover, its performance is evaluated using realistic harvesting rates under low and high irradiance scenarios. However, it adjusts the receiver's duty cycle without prior knowledge about the future available energy, leading to the following limitations. First, it does not plan how to utilize the incoming harvested to help further improve performance when sufficient energy resources are available. Second, it does not consider the high variability of energy intake over time, which may lead to power outages in the future. In addition, sender nodes must wait for the receiver wake-up beacon, consuming a considerable amount of energy in idle listening.

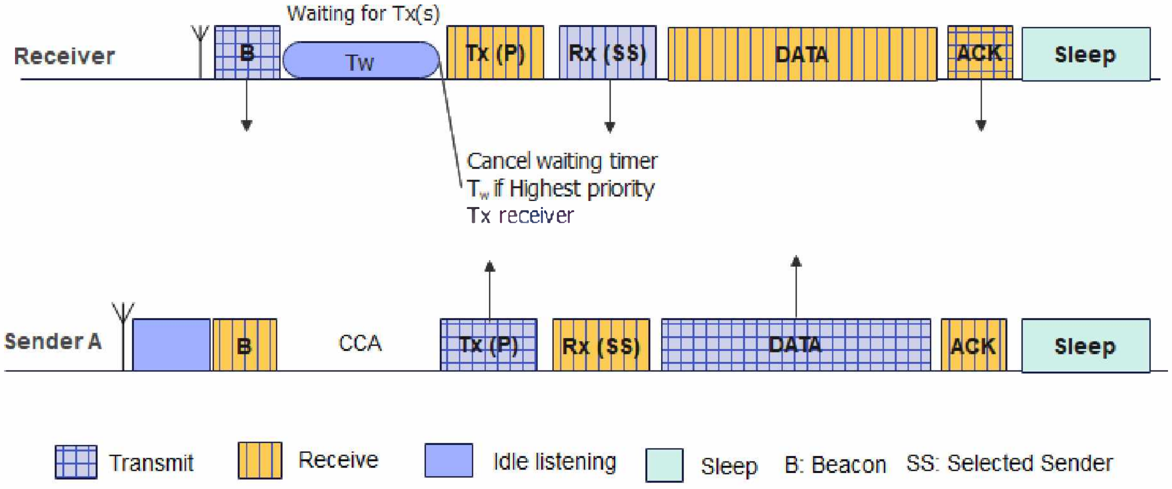

Figure 2.24: Communication overview of QPPD-MAC [11]

PSL-MAC [111] aims to address the data accumulation problem and improve the data transmission rate in EH-WSNs. The network consists of multiple nodes with different harvesting rates due to dynamic environmental conditions. Thus, low-energy nodes that serve as relay nodes face energy issues and cannot send stored packets to the next hop. As a result, this may lead to packet loss in the network. To deal with this problem, the proposed MAC introduces two techniques. First, the data transmission mechanism is introduced by which the sending node knows the number of request packets received by the receiving node. This enables it to start data transmission or go to the sleep state for charging. Second, the node holds data packets and waits for the request packet in the data processing mechanism. If it does not receive any request in a predefined time or fails to find the next-hop node, it increases the transmission power, broadcasts an emergency beacon, and waits for the suppression packet. After obtaining the suppression packet for the next-hop node, it sends the accumulated data with increased transmission power. After successful transmission, it reinstates the original transmission power. However, its performance does not provide any mechanism to use the excess and incoming harvested energy to enhance the performance. In addition, its performance is not evaluated under dynamic harvesting conditions using realistic harvesting rates.

HM-RIMAC [6] is proposed for the smart agriculture application that enables nodes to adjust their wake-up and sleep time according to energy level. It assumes that nodes are in the sleep state and then listens to the channel when enough energy is available. It employs a multi-layer approach in which nodes are distributed in different layers. The sender nodes listen for the receiver beacon and contend for the channel to transfer the data packet. If the channel is free, it sends the data packet and waits for the ACK. Otherwise, it follows a backoff algorithm and senses the channel when backoff time expires. The results show that it reduces packet collision and delay, and achieves good network throughput. However, it does not provide any plan to use the excess harvested energy. Furthermore, its performance is not evaluated using realistic harvesting conditions under dynamic harvesting conditions and is not compared with the energy harvesting MAC protocol.

2.4.2 Summary of Receiver-initiated MAC protocols

Many MAC protocols have been developed for EH-WSNs, focusing on applications such as agriculture and healthcare monitoring and employing different harvesting strategies and design alternatives, as shown in Table 2.3. Moreover, these protocols have used the receiver-initiated approach. These MAC protocols have incorporated the stored energy to dynamically adjust the parameters such as duty cycle, access probability, traffic load, relay node selection, and sensing interval to enhance network performance. For example, EH-MAC [99] incorporates energy harvesting rate in altering the contention probability, which determines whether to send the packet or not. OD-MAC [36] offers on-demand communication and its receiver broadcasts the beacon and waits to receive the packets from the nodes. It varies the wake-up beacon interval based on energy profile. LEB-MAC [100] achieve the energy and load balancing state among nodes. In MDP-SHE-WSNS [101], nodes send data packets by considering the energy level. ERI-MAC [102] uses a packet concatenation technique to improve energy efficiency by decreasing packet overheads. HAS-MAC [103] adjusts the working schedule of the node according to its energy level. In QAEE-MAC [12], the receiver adjusts medium access based on the energy state and support the priority data transmission. ED-CR [104] considers residual energy and accounts for prospective increase in energy level to adjust the duty cycle of the node according to its energy level. PBP-MAC [105] assigns a priority to relay nodes based on residual energy and current harvesting rate. SyWiM-MAC [106] aims to use Wake-up Variation Reduction Power Manager support, developed for nodes powered by periodic energy sources. R-MAC [107] selects the cluster head based on residual energy level or the size of data queue lengths. EH-TDMA-MAC [108] adjusts wake-up schedules according to available energy. EEM-MAC [13] regulates the duty cycle according to the remaining energy level. RF-AASP-MAC [109] adjusts the sleeping period according to traffic conditions and residual energy. In ENCOD-MAC [110], the receiver operates close to the ENO condition and sets the duty cycle based on harvested energy to improve network performance. QPPD-MAC [11] considers priority packets and adjusts the duty cycle based on different energy levels. PSL-MAC [111] employs a data accumulation processing mechanism and helps low-energy relay nodes to forward data packets.

HM-RIMAC [6] enables nodes to adjust their wake-up and sleep time according to energy level, and the node starts listening when enough energy is available.

However, most of the available receiver-initiated MAC protocols do not consider the incoming harvested energy in devising task scheduling, such as duty cycle adjustment and contention probability, as given in Table 2.3. Thus, it may hinder the execution of ongoing tasks and node operation during periods of energy scarcity. As a result, it can lead to an overall degradation in network performance. Furthermore, in high energy harvesting conditions, these protocols do not incorporate the upcoming harvested energy, which can be estimated using the energy prediction model to make smart energy allocation strategies and improve the performance. In addition, most available protocols do not plan how to optimize performance when the harvested energy value is more than or equal to the energy needed for the task execution. Moreover, their performance evaluation does not include all essential parameters such as ETE delay, PDR, network throughput, energy consumption per bit, receiver energy consumption, and total network energy consumption, which are of primary concern in QoS [7], as shown in Table 2.4. Furthermore, most available protocols do not consider realistic harvesting conditions in their performance evaluations. Hence, there is a great need to propose a more realistic energy prediction-based MAC protocol that can adapt to dynamic energy harvesting conditions and use smart energy allocation approaches to improve the performance.

Table 2.3: Summary of techniques used in MAC protocols for EH-WSNs

MAC Protocol and Year	EH Technique	Design Alternative	ENO Consideration	Incorporate Predicted Energy	Support Packet Priority	Energy Management Technique	Application Support	Validation
HA-MAC [88] (2019)	RF	Harvest-store-consume	✗	✗	✗	Adjust random access slots	Generic application	Simulation
DeepSleep-MAC [89] (2015)	Generic appraoch	Harvest-store-consume	✗	✗	✗	Energy-aware and controlled access	M2M communication	Simulation
EL-MAC [90] (2014)	Generic appraoch	Harvest-store-consume	✗	✗	✗	Adaptive CW	Cognitive radio network	Simulation
SEHEE-MAC [112] (2011)	Solar	Harvest-store-consume	✗	✗	✗	Adaptive slotted preamble schedule	Generic application	Simulation
EA-MAC [91] (2011)	RF	Harvest-store-consume	✗	✗	✗	Adaptive duty cycle and Contention algorithm	Monitoring application	Simulation
PP-MAC [92] (2011)	Generic approach	Harvest - consume	✗	✗	✗	Adaptive CW	Monitoring application	Simulation
MTTP-MAC [93] (2011)	Solar	Harvest - consume	✗	✗	✗	Grouping strategy	Generic application	Testbeds
AE-MAC [94] (2015)	Generic appraoch	Harvest-store-consume	✗	✗	✗	Adaptive contention priority	M2M communication	Simulation
REE-MAC [95] (2021)	RF	Harvest-store-consume	✗	✗	✗	Adjust charging priorities based on energy	Generic application	Simulation
E-MAC [96] (2021)	RF	Harvest-store-consume	✗	✗	✗	Adaptive duty cycle	Generic application	Simulation

Table 2.3. continued

MAC Protocol and Year	EH Technique	Design Alternative	ENO Consideration	Incorporate Predicted Energy	Support Packet Priority	Energy Management Technique	Application Support	Validation
S-LEARN-MAC [97] (2016)	RF	Harvest-store-consume	✗	✗	✗	Adaptive transmission schedule	Generic application	Simulation
CEH-MAC [98] (2015)	Generic appraoch	Harvest-store-consume	✗	✗	✗	Energy-aware relay node	Healthcare application	Simulation
EH-MAC [99] (2012)	Generic approach	Harvest - consume	✗	✗	✗	Adaptive contention probability	Event Driven application	Simulation
OD-MAC [36] (2011)	Generic appraoch	Harvest-store-consume	✓	✗	✗	Opportunistic forwarding	Delay sensitive applications	Simulation
LEB-MAC [100] (2014)	Solar	Harvest-store-consume	✗	✗	✗	Fuzzy logic	Generic application	Simulation
MDP-SHE-WSNS [101] (2021)	Solar	Harvest-store-consume	✗	✓	✗	Adaptive duty cycle	Generic application	Simulation
ERI-MAC [102] (2014)	Generic appraoch	Harvest-store-consume	✓	✗	✗	Queuing mechanism	Application that generates small size packets	Simulation
HAS-MAC [103] (2021)	Solar	Harvest-store-consume	✗	✗	✗	Wake-up and sleep scheduling	Generic application	Simulation
QAEE-MAC [12] (2012)	Generic appraoch	Harvest-store-consume	✗	✗	✓	Adaptive CW	Urgent/Critical data	Analytical computation
ED-CR [104] (2014)	Generic appraoch	Harvest-store-consume	✗	✓	✗	Wake-up/sleep schedule	Generic application	Simulation

Table 2.3. continued

MAC Protocol and Year	EH Technique	Design Alternative	ENO Consideration	Incorporate Predicted Energy	Support Packet Priority	Energy Management Technique	Application Support	Validation
PBP-MAC [105] (2019)	Generic appraoch	Harvest-store-consume	✗	✗	✗	Selection of relay node	Generic application	Simulation
SyWiM-MAC [106] (2015)	Solar	Harvest-store-consume	✓	✗	✗	Wake-up variation reduction power management	Monitoring application	Simulation and testbeds
R-MAC [107] (2021)	RF	Harvest-store-consume	✗	✗	✗	Adaptive time slots for energy harvesting	Generic application	Simulation
EH-TDMA-MAC [108] (2016)	Generic appraoch	Harvest-store-consume	✗	✗	✗	Adaptive wake-up time	Generic application	Simulation
EEM-MAC [13] (2019)	Generic appraoch	Harvest-store-consume	✗	✗	✗	Wake-up and sleep scheduling	Application with periodic traffic Simulation	Simulation
RF-AASP-MAC [109] (2016)	RF	Harvest-store-consume	✗	✗	✗	Differentiated Contention Window	Generic application	Simulation
ENCOD-MAC [110] (2022)	Solar	Harvest-store-consume	✗	✗	✓	Adaptive duty cycle	Urgent/Critical data	Simulation
QPPD-MAC [11] (2018)	Solar	Harvest-store-consume	✗	✗	✓	Adaptive duty cycle	Application with multi-priority data packets	Simulation
PSL-MAC [111] (2022)	Solar	Harvest-store-consume	✗	✗	✗	Accumulated Data Processing mechanism	Generic application	Simulation
HM-RIMAC [6] (2020)	Solar	Harvest-store-consume	✗	✗	✗	Adaptive transmission schedule	Agriculture monitoring	Simulation

Table 2.4: List of performance metrics used in performance evaluation

Protocol	Channel Access Scheme	Initiation Process	Delay	Energy Consumption per Bit	Throughput	PDR	Total energy Consumption	Performance comparison with EH-MAC
HA-MAC [88] (2019)	Slotted ALOHA	Sender-initiated	✗	✗	✓	✗	✗	✓
DeepSleep-MAC [89] (2015)	CSMA	Sender-initiated	✗	✓	✗	✗	✗	✓
EL-MAC [90] (2014)	CSMA	Sender-initiated	✗	✓	✓	✗	✗	✓
SEHEE-MAC [112] (2011)	CSMA	Sender-initiated	✗	✓	✗	✗	✓	✗
EA-MAC [91] (2011)	CSMA/CA	Sender-initiated	✗	✓	✓	✗	✗	✗
PP-MAC [92] (2011)	Polling	Sink-initiated	✓	✗	✓	✗	✗	✓
MTTP-MAC [93] (2011)	Polling	Sink-initiated	✗	✗	✓	✗	✗	✗
AE-MAC [94] (2015)	CSMA	Sink-initiated	✓	✗	✓	✗	✗	✗
REE-MAC [95] (2021)	TDMA	Sink-initiated	✗	✗	✓	✗	✓	✓
E-MAC [96] (2021)	CSMS/CA	Sink-initiated	✗	✗	✓	✗	✗	✗
S-LEARN-MAC [97] (2016)	CSMA	Sink-initiated	✗	✗	✓	✓	✗	✓
CEH-MAC [98] (2015)	CSMA/CA	Sink-initiated	✓	✓	✓	✗	✗	✗
EH-MAC [99] (2012)	Polling	Receiver-initiated	✗	✗	✓	✗	✗	✓
OD-MAC [36] (2011)	CSMA	Receiver-initiated	✓	✗	✗	✗	✗	✗
LEB-MAC [100] (2014)	CSMA	Receiver-initiated	✓	✗	✗	✓	✗	✓

Table 2.4. continued

Protocol	**Channel Access Scheme**	**Initiation Process**	**Delay**	**Energy Consumption per Bit**	**Throughput**	**PDR**	**Total energy Consumption**	**Performance comparison with EH-MAC**
MDP-SHE-WSNS [101] (2021)	CSMA	Receiver-initiated	X	X	✓	X	X	✓
ERI-MAC [102] (2014)	CSMA	Receiver-initiated	✓	✓	X	X	X	X
HAS-MAC [103] (2021)	CSMS/CA	Receiver-initiated	✓	X	X	X	X	✓
QAEE-MAC [12] (2012)	CSMA	Receiver-initiated	✓	X	X	X	✓	X
ED-CR [104] (2014)	CSMA	Receiver-initiated	✓	X	X	✓	✓	X
PBP-MAC [105] (2019)	CSMA	Receiver-initiated	X	X	X	X	✓	X
SyWiM-MAC [106] (2015)	CSMA	Receiver-initiated	✓	X	✓	X	X	✓
R-MAC [107] (2021)	TDMA	Receiver-initiated	✓	X	✓	X	✓	✓
EH-TDMA-MAC [108] (2016)	TDMA	Receiver-initiated	X	✓	✓	X	X	✓
EEM-MAC [13] (2019)	CSMA/CA	Receiver-initiated	✓	X	✓	✓	X	✓
RF-AASP-MAC [109] (2014)	CSMA	Receiver-initiated	✓	✓	✓	X	X	X
ENCOD-MAC [110] (2022)	CSMA	Receiver-initiated	✓	X	✓	✓	X	✓
QPPD-MAC [11] (2018)	CSMA	Receiver-initiated	✓	✓	✓	✓	X	✓
PSL-MAC [111] (2022)	CSMA	Receiver-initiated	X	X	✓	✓	X	✓
HM-RIMAC [6] (2020)	CSMA	Receiver-initiated	✓	X	✓	✓	✓	X

2.5 Summary

In this chapter, we reviewed the basic design features and composition of the sensor node in EH-WSNs. Then, the sensor communication, energy harvesting sources, and harvesting design alternatives have been discussed in detail. Furthermore, the importance of energy prediction and the role of ML in EH-WSNs have been explained. Then, MAC protocols for EH-WSNS are described. Moreover, a detailed study on MAC protocols for EH-WSNs with respect to the initiation process has been undertaken. It includes the design features based on harvested energy, such as duty cycle adjustment and selection of relay node. The summaries of both the techniques and performance evaluation metrics used in existing MAC protocols are given. Finally, this chapter summarizes the existing receiver-initiated MAC protocols and their limitations.

Chapter 3

Research Methodology

This chapter presents a novel and more realistic prediction-based receiver-initiated MAC protocol, called PADC-MAC. First, the communication overview of the proposed MAC is given in detail. Furthermore, it presents the prediction model, named NARNET model, which uses the actual solar irradiance data measured by National Renewable Energy Laboratory (NREL) for 19 consecutive months to predict the incoming harvested energy. Then, PADC-MAC proposes a mathematical formula that sets the receiver duty cycle corresponding to the current and incoming harvested energy obtained using the prediction model. Next, the self-adaptation technique is explained. It is then presented with an energy consumption model, MAC performance metrics, network simulation, and setup in GreenCastalia.

3.1 Proposed PADC-MAC protocol

The development of receiver-initiated PADC-MAC protocol is described in this section. The aim is to develop an adaptive duty cycle MAC Protocol for EH-WSNs that can incorporate current and future energy intake to optimize the network performance and ensure sustainable operation under dynamic harvesting conditions. The essential parts of PADC-MAC are: basic communication overview and traffic differentiation, an energy prediction model, adaptive duty cycle management, and a self-adaptation technique.

3.1.1 Basic Communication Overview and Traffic Differentiation

The essential communication between the receiver and three senders is shown in Figure 3.1. Initially, the receiver wakes up and broadcasts a wake-up beacon (WB). It indicates that it is ready to receive the packets from senders. Furthermore, it contains source address (SA) and duty cycle (d_c), as given in Figure 3.2. After broadcasting WB, it initiates a waiting timer (T_w) and waits for the Tx beacon from senders. The time taken by the node to switch its radio state and process the packet is called short interframe space ($SIFS$).

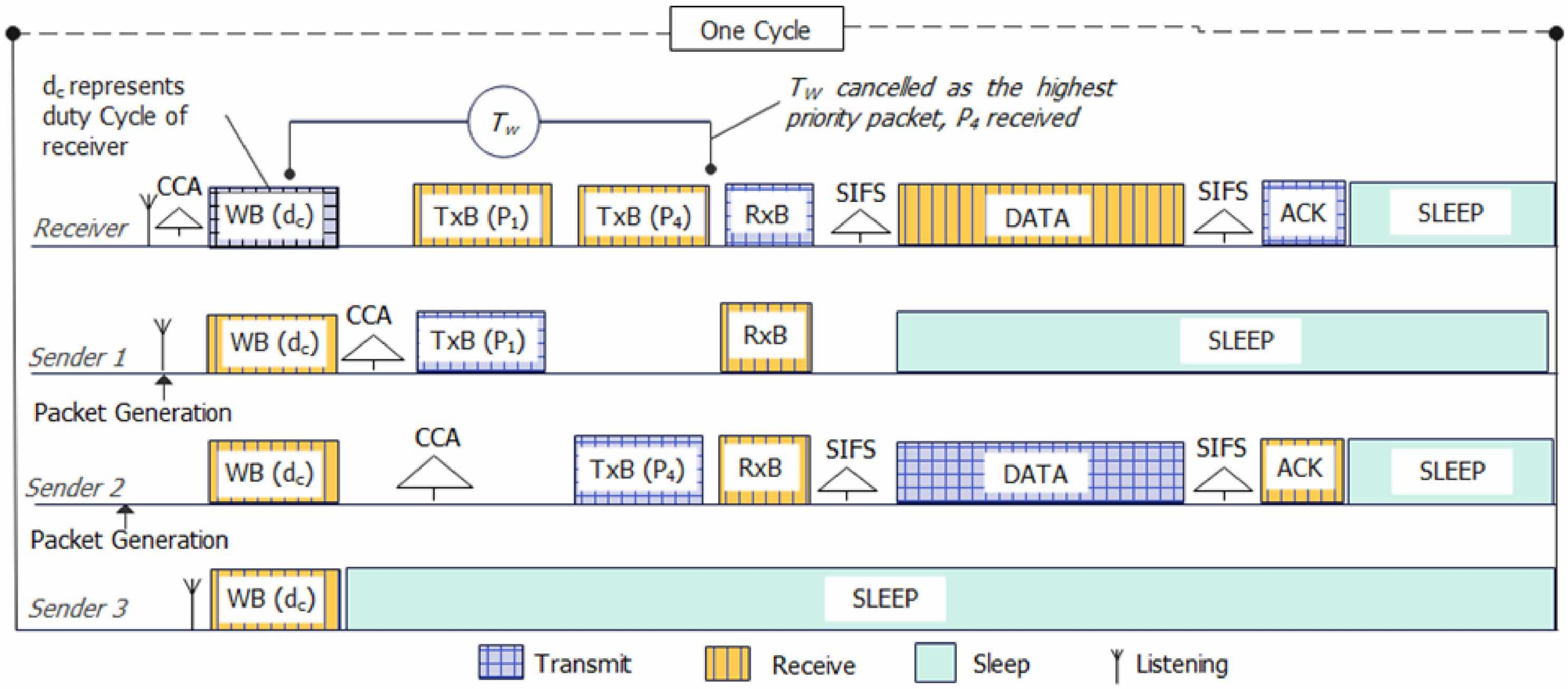

Figure 3.1: Communication overview of PADC-MAC protocol. The receiver initiates the communication by broadcasting WB. On the other side, *Sender* 1 and 2 send Tx-beacons (TxB) containing their packet priorities.

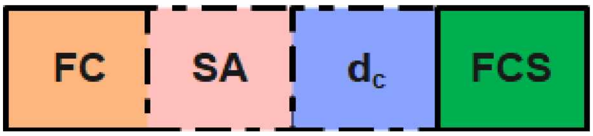

Figure 3.2: Frame structure of WB

PADC-MAC offers traffic differentiation to support applications that generate packets with different urgency (e.g., fire alert vs. periodic temperature measurement). Thus, it allows sender nodes to assign four priority levels to data packets as normal (P_1), important (P_2), most important (P_3), and urgent (P_4). The priority assigned corresponds to the data type defined in Table 3.1. Upon the reception of WB, the senders perform clear channel assessment (CCA) and transmit Tx beacons that include the packet priority, as given in Figure 3.3, using p-persistent CSMA technique that includes packet priority. In contrast, the receiver receives Tx-beacon(s) and selects the sender according to the received highest priority Tx beacon. Then, it cancels T_w accordingly. After that, it broadcasts the Rx beacon that includes, addresses of selected sender (SS) and source, and network allocation vector (NAV), as given in Figure 3.4. After receiving the Rx beacon, the chosen node transmits the data packet to the receiver and waits for the acknowledgment (ACK) packet while other nodes sleep to conserve energy. Furthermore, the flowchart of the receiver and sender nodes are given in Figure 3.5 and Figure 3.6, respectively. The Frame Check Sequence (FCS) and Frame Control (FC) are fields from IEEE 802.15.4 standard.

Table 3.1 Priority level

Data type	Priority	Example
Urgent	P_4	Emergency alarm
Most important	P_3	Real time
Important	P_2	On-demand
Normal	P_1	Periodic

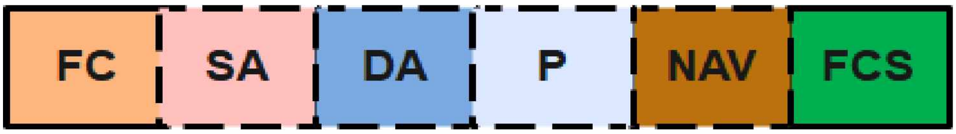

Figure 3.3: Frame structure of Tx-Beacon. DA and P represent destination address and priority value, respectively.

Figure 3.4: Frame structure of Rx-Beacon

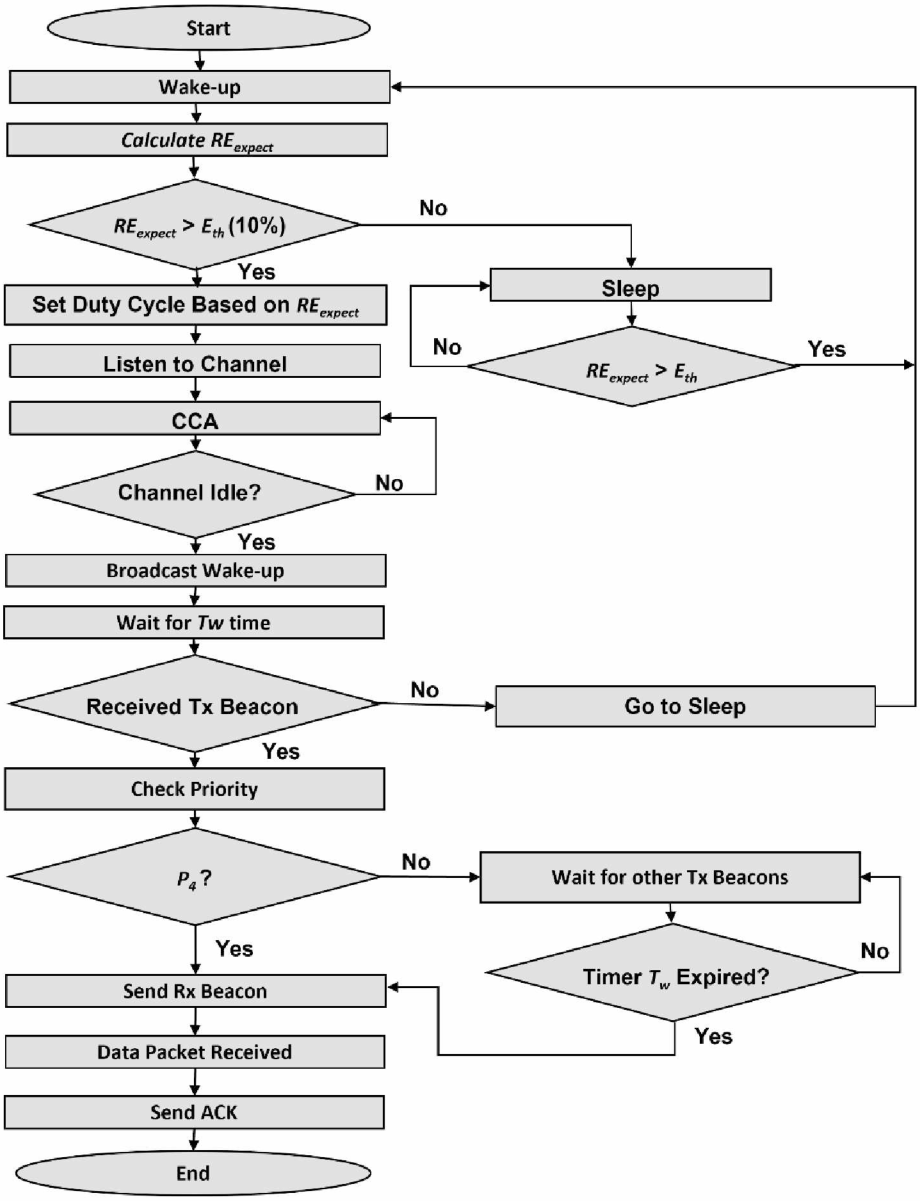

Figure 3.5: Flowchart of the receiver node

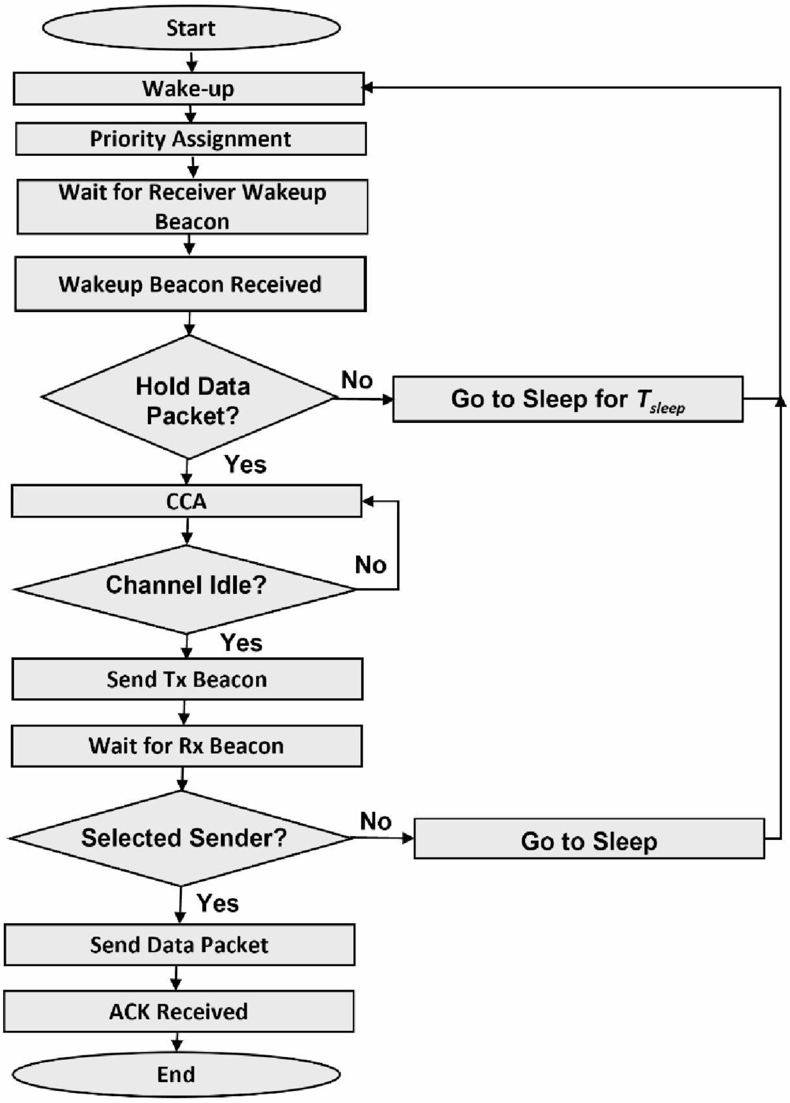

Figure 3.6: Flowchart of the sender node

3.1.2 Energy Prediction Model

Energy harvesting rate varies significantly over time due to dynamic weather and seasonal changes. Hence, there is a need to deal with the dramatic changes in harvesting energy and devise efficient energy allocation strategies to optimize network performance. Therefore, this section will develop an energy prediction model to forecast expected solar energy intake in the near future and incorporate it with the proposed PADC-MAC to proactively plan the available energy resources to enhance the performance. Therefore, the ANN model, namely the nonlinear autoregressive neural network (NARNET), is developed that uses the past solar irradiance data to predict future harvested energy accurately. The energy prediction mechanism involves data preparation and model development.

The data preparation involves raw data processing and conversion into meaningful form before training and testing data. It begins with collecting actual solar irradiance data from National Renewable Energy Laboratory (NREL), which provides high-resolution open-source irradiance data. The data contains 13862 samples of hourly solar irradiance for 19 months from April 1, 2010, to October 31, 2011, which incorporates both summer and winter data. These datasets are divided into 80% for training and 20% for testing to validate the model performance.

The structure of the proposed prediction model is given in Figure 3.7. The model comprises of an input layer, a hidden layer, and an output layer. The hidden layer consists of ten nodes and uses *tansig* activation function to transform data into the output layer. The number of hidden layer nodes is chosen as 10 through the trial-and-error procedure to obtain good accuracy while considering model complexity and computation time. Furthermore, the hidden layer takes the weight and bias parameters to manage neurons. In this perspective, the learning aims to find optimal weight values that provide the minimum error. For that, the model incorporates the Levenberg–Marquardt algorithm for weight adaptation. The output layer involves one node and uses pure linear (*purelin*) activation to forecast the energy in the next slot. The performance of the model is computed using Mean Absolute Error (MAE). Table 3.2 describes notations used in the model structure. The NARNET model can be written using Eq. (3.1) [113].

$$y(t) = h\big(y(t-1), y(t-2), .., y(t-p)\big) + \epsilon(t) \tag{3.1}$$

where $y(t)$ represents the predicted value of data series y at time t using p past values. The function $h(*)$ is unknown in advance, and is approximated through the optimization of weights and neuron bias, and $\epsilon(t)$ indicates the error obtained from the model at time t.

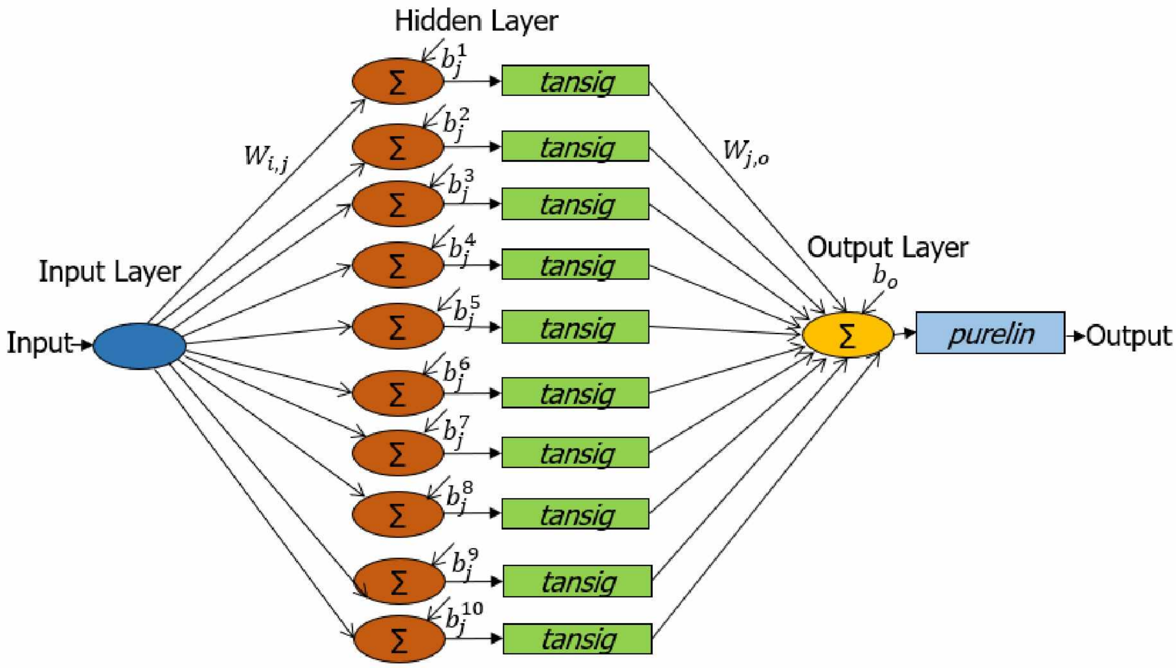

Figure 3.7: Structure of proposed neural network model with ten hidden layer nodes

Table 3.2: Notations used in the structure of the neural network

Notation	Description
$W_{i,j}$	Weights between input node i and hidden node j
b_j	Bias at hidden node j
tansig	Tangent sigmoid activation function
$W_{j,o}$	Weights between hidden node j and output node o
b_o	Bias at output node o
purelin	Pure linear activation function

3.1.3 Adaptive Duty Cycle Mechanism

The dynamic energy harvesting conditions lead to uncertainty in the available energy, which drives the development of an adaptive duty cycle mechanism to ensure sustainable operation, specifically in energy-constrained environments. Furthermore, increasing the duty cycle when energy is abundant improves the network performance. In addition to the adaptable duty cycle, the node incorporates an additional feature that allows it to consider the incoming harvested energy to enhance the network performance further. This feature addresses the energy's unpredictable nature and enables nodes to use this knowledge to plan the available energy resources. Therefore, PADC-MAC supports the adaptive duty cycle (d_c) of the receiver and sets its d_c according to the current energy level and the predicted energy in the next slot as follows

$$RE_{expect} = RE_{current} + E_{Predict} \tag{3. 2}$$

where RE_{expect} , $RE_{current}$ and $E_{Predict}$ are the total expected remaining energy, current remaining energy level, and predicted energy. These values are given in joules and computed at the beginning of the slot.

The RE_{expect} in percentage is given as follows

$$RE_{expect\ (\%)} = \frac{RE_{expect}}{E_{max}} \times 100 \tag{3. 3}$$

where E_{max} denotes the maximum battery capacity in joules. The predicted energy $E_{Predict}$ is computed as follows

$$E_{Predict} = S_p \times P_s \times P_e \times d_s \tag{3. 4}$$

where S_p, P_s , P_e and d_s denote predicted solar irradiance (W/m^2) obtained from the prediction model, solar panel size (m^2), panel efficiency, and duration of a timeslot in second. When RE_{expect} is above 30% and $E_{Predict}$ value is equal or greater than the maximum required energy in an hour. Then, the receiver node increases its duty cycle to a maximum value, i.e., 1, to enhance the network performance.

Table 3.3 shows the d_c value according to different RE_{expect} ranges and $E_{Predict}$.

Table 3.3: Duty cycle adjustment based on RE_{expect} and $E_{Predict}$

RE_{expect} **and** $E_{Predict}$	d_c
50% ≤ RE_{expect} ≤ 100%	1
RE_{expect} ≥ 30% and $E_{Predict}$ ≥ E_c	1
10% ≤ RE_{expect} < 50%	0.11-0.55 (using Eq.(3.5))
0 < RE_{expect} < 10%	0.05

In case when RE_{expect} ranges between 10% to 50%, the d_c value is between 0.11 to 0.55 computed as follows

$$d_c = \frac{RE_{expect} - E_{th} + 10\%}{E_{max} - E_{th}} \tag{3. 5}$$

where E_{th} is threshold energy (10% of E_{max}) and is applied to ensure that the battery of node does not exhaust completely.

In Table 3.3, E_c denotes the energy consumption of a node when it operates at the maximum duty cycle, i.e., 1, continuously for one hour, and is computed as follows

$$E_c = (n_s \times (e_S + e_l + e_B + e_w + e_{slp})) + (n_{ds} \times N_s \times (e_{RB} + e_d + e_{ack})) \tag{3. 6}$$

where n_s represents the number of listening slots in one hour in which no data transmission is performed. n_{ds} denotes the number of slots in which the receiver node received data packets from N_s sender nodes. e_S, e_l, e_B, e_w, and e_{slp} represent energy spent by the receiver switching its radio states, listening to the channel, sending WB beacon, waiting for TxB, and in sleeping state. e_{RB}, e_d, and e_{ack} denote energy consumed in sending the Rx beacon, receiving a data packet, and transmitting an ACK packet.

The computed d_c value can be employed to define the sleep duration (T_{sleep}) of the node as shown in the following equation

$$T_{sleep} = \frac{T_{listen} \times (1 - d_c)}{d_c} \tag{3. 7}$$

where T_{listen} represents the total listening time.

3.1.3 Self-adaptation Technique

The receiver node periodically wakes up to accept incoming packets from sender nodes. However, the sender node with data packet uses significant amount of energy in idle listening for WB. To deal with the issue, the protocol utilizes a self-adaptation technique by which the receiver shares its duty cycle through a wake-up beacon with all senders. Upon the reception of a WB, a node checks its buffer before sensing the medium. In case nodes do not have data packets in their buffers, they adjust their sleeping time according to the received duty cycle of the receiver and wake up slightly before the receiver at the beginning of the next cycle to perform data transmission. The formula to compute T_{sleep} of the sender is as follows

$$T_{sleep} = (T_{listen} - (T_{WB} + T_{CCA}) + \frac{T_{listen} \times (1 - d_c)}{d_c}) \quad (3.8)$$

The proposed self-adaptation technique allows the sender node to conserve energy by decreasing idle listening. For example, consider a scenario where *Sender 1* (S_1) and *Sender 2* (S_2) receive WB from the receiver node that contains its duty cycle, as shown in Figure 3.8. After receiving WB, S_2 performs data transmission. However, since S_1 does not hold the data packet, thus, it goes to sleep following the duty cycle of the receiver to conserve energy. Then, S_1 wake-up slightly prior to the receiver in the next cycle. It is essential to mention that if multiple senders send Tx beacons with the same priority, i.e., P_1, then the receiver considers the node based on the first arrived Tx beacon.

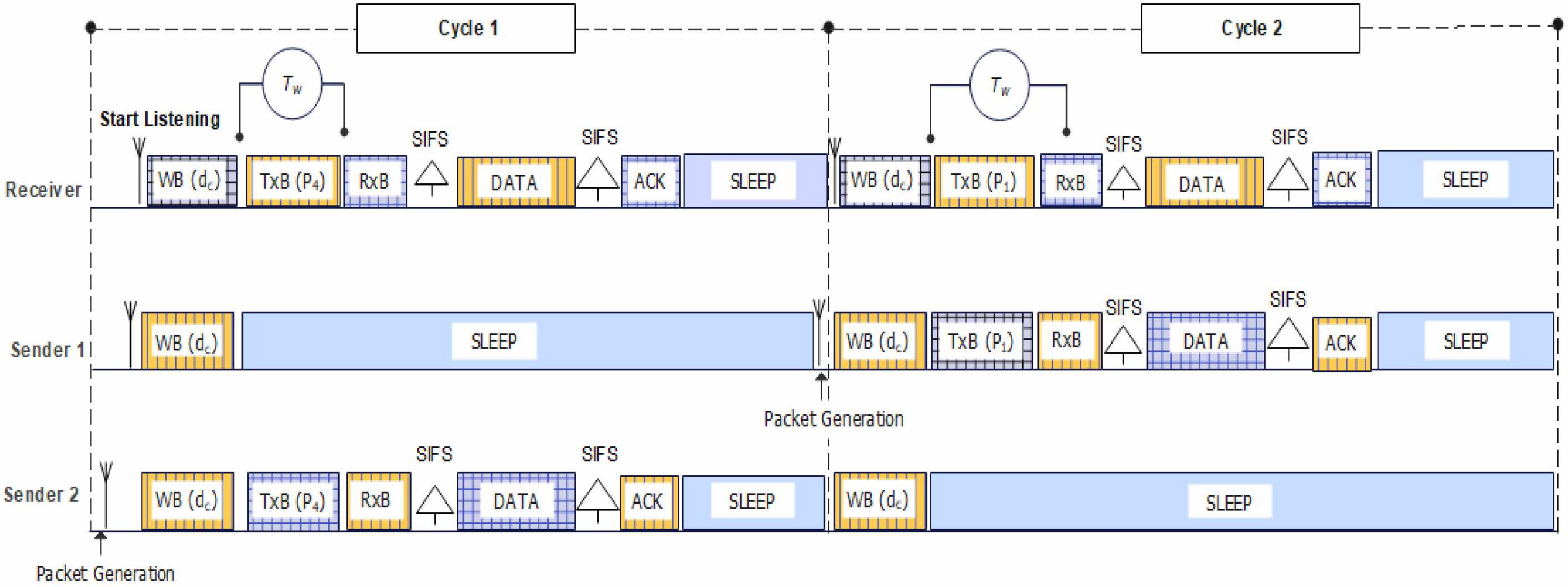

Figure 3.8: Data transmission using the self-adaptation technique

3.2 Energy Model

The energy model accounts for the total energy consumed (E_T) and harvested energy (E_h) by the node. The energy consumption, E_T of a node is as follows

$$E_T = \sum_{i=0}^{n} P_i \times t_i \tag{3.9}$$

where p, t, and n denotes power consumption rate of radio state i, time spent in state i and the number of states, respectively. For example, radio CC2420 has four states: sleep, transmission, reception, and idle listening, consuming power of 1.4 mW, 46.2 mW, 62 mW, and 62 mW, respectively. When the node turns ON its radio for transmitting or receiving a packet, the energy is subtracted from the battery. The model also accounts for energy consumption when the node stays in the listening and sleep states.

The harvested energy, E_h of a node is computed using the following formula

$$E_h = \sum_{N=1}^{N=96} S \times P_s \times P_e \times d_s \tag{3. 10}$$

where N and S represent the number of simulation hours and realistic solar irradiance (W/m^2) obtained from NREL [14], respectively.

3.3 Performance Metrics

This subsection describes the metrics used in the performance evaluation of PADC-MAC.

3.3.1 Average packet delay

The ETE delay refers to the total time between the generation of the packet at the source and until its reception at the destination. It can be computed using the following equation

$$ETE\ delay = D_{queu} + D_{trans} + D_{prop} + D_{proc} \tag{3. 11}$$

where D_{proc}, D_{queu}, D_{prop}, D_{trans}, represent processing, queuing, propagation, and transmission delays, respectively.

3.3.2 Packet delivery ratio

It is defined as the the ratio of total number of packets received (NP_{PktR}) by the receiver to the number of packets transmitted by the sender nodes (NP_{PktT}). It can be computed is as follows

$$PDR = \frac{NP_{PktR}}{NP_{PktT}} \times 100\% \tag{3. 12}$$

3.3.3 Network throughput

The average network throughput (N_{Th}) is refers to the total number of data packets received by the receiver divided by the total simulation time (T_s) as shown below

$$N_{Th} = \frac{NP_{PktR} \times L_{Pkt}}{T_s} \tag{3. 13}$$

where L_{Pkt} denotes the packet size in bits.

3.3.4 Average energy consumption per bit (E)

It is defined as the total energy spent divided by the total number of data packets received, as given below

$$E = \frac{E_T}{NP_{PktR} \times L_{Pkt}} \tag{3. 14}$$

and E_T can be calculated using Eq. (3.9).

3.3.5 Total energy consumption in the network

The total energy consumption, E_{total} is the sum of energy spent by the receiver and sender nodes. It can be computed as follows

$$E_{total} = E_{TR} + (N_s \times E_{TS}) \quad (3.15)$$

where N_s, E_{TR} and E_{TS} denote the number of sender nodes, energy consumption of the receiver and sender node, respectively. E_{TR} and E_{TS} can be computed using Eq. (3.9).

3.4 Network Simulator

To evaluate the protocol performance through simulations, we implemented the protocol in GreenCastalia [114], an extension of the Castalia 3.3 simulator [115]. Castalia is widely used by the WSN research community and is based on OMNeT++4.6 [116]. It is an open-source framework and is coded in C++. Moreover, it is designed for GNU/Linux platforms. Furthermore, it enables the development and simulation of energy harvesting protocols and algorithms using realistic radio modules and wireless channels. For example, the user can define the radio model, i.e., CC2420, and add new MAC and routing protocols per application requirements. In GreenCastalia, the implementation of a sensor node follows a modular approach, and each module is connected through connections, as shown in Figure 3.9. The gates represent the modules' input and output interfaces. In the figure, the arrows indicate the relationship between one module to another, and the dashed arrow denotes a function call. Finally, the sensor node transmits the message to the wireless module for further processing. The software organization of GreenCastalia is given in Figure 3.10. The EnergySubsystem module is divided into four submodules: EnergyHarvesting, EnergyStorage, EnergyManager, and EnergyPredictor, as shown in Figure 3.11.

- **EnergyHarvesting:** It represents an energy harvesting device, such solar cell, connected to a node. It enables nodes to harvest energy with a particular efficiency from the surrounding environment to power up its components. Currently, GreenCastalia supports two models of energy harvesters (solar cell and wind-micro turbine) and allows users to use the appropriate model per application requirements. Furthermore, these harvesters can also take timestamped data obtained from a real-life deployment to simulate the realistic harvesting scenario. In this work, we feed the harvester with actual solar irradiance data collected from the NREL. In addition, parameters such as solar panel size and efficiency can be defined.

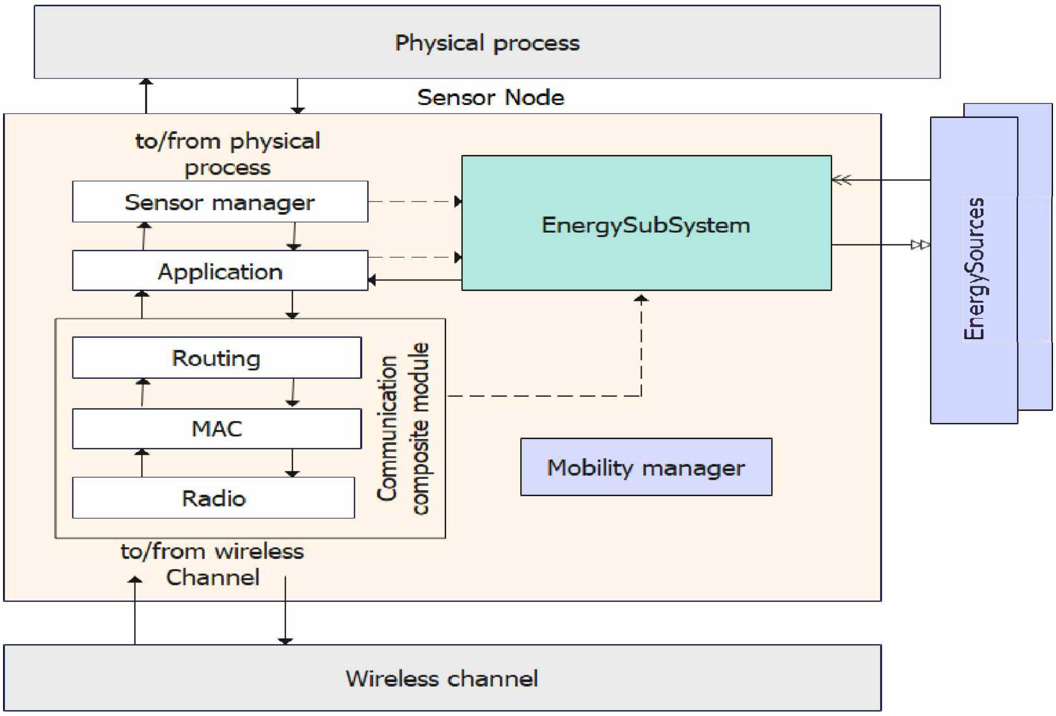

Figure 3.9: Basic structure of the GreenCastalia

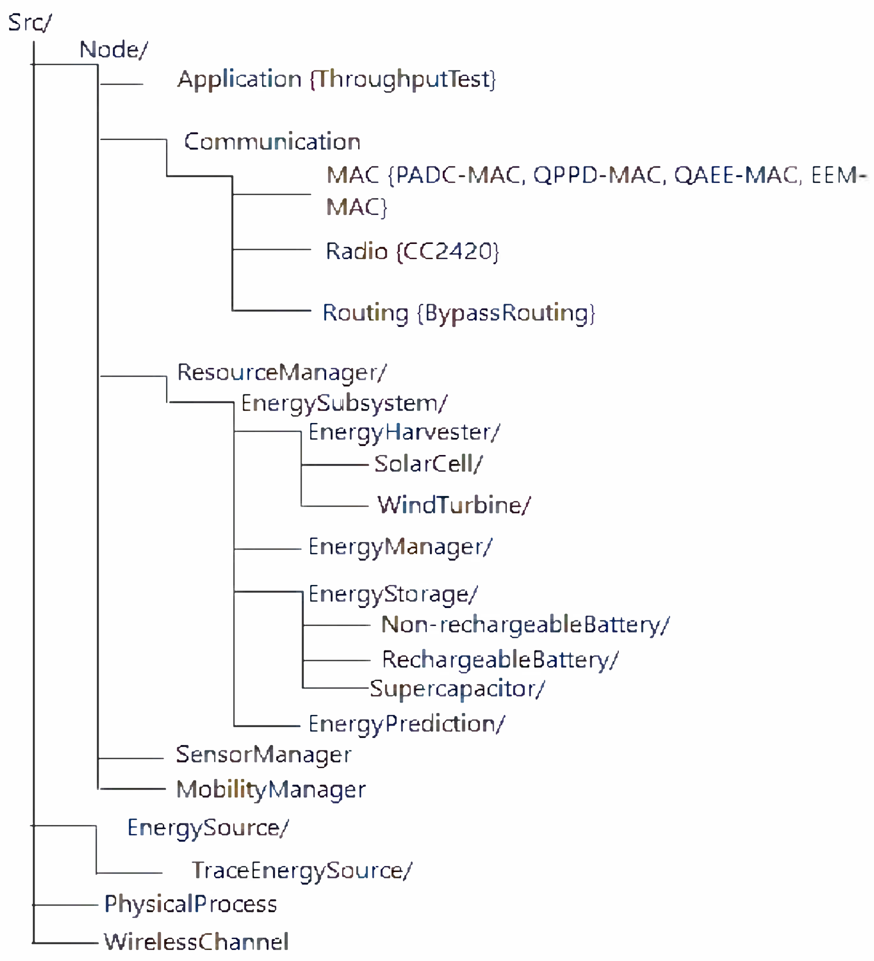

Figure 3.10: GreenCastalia organization

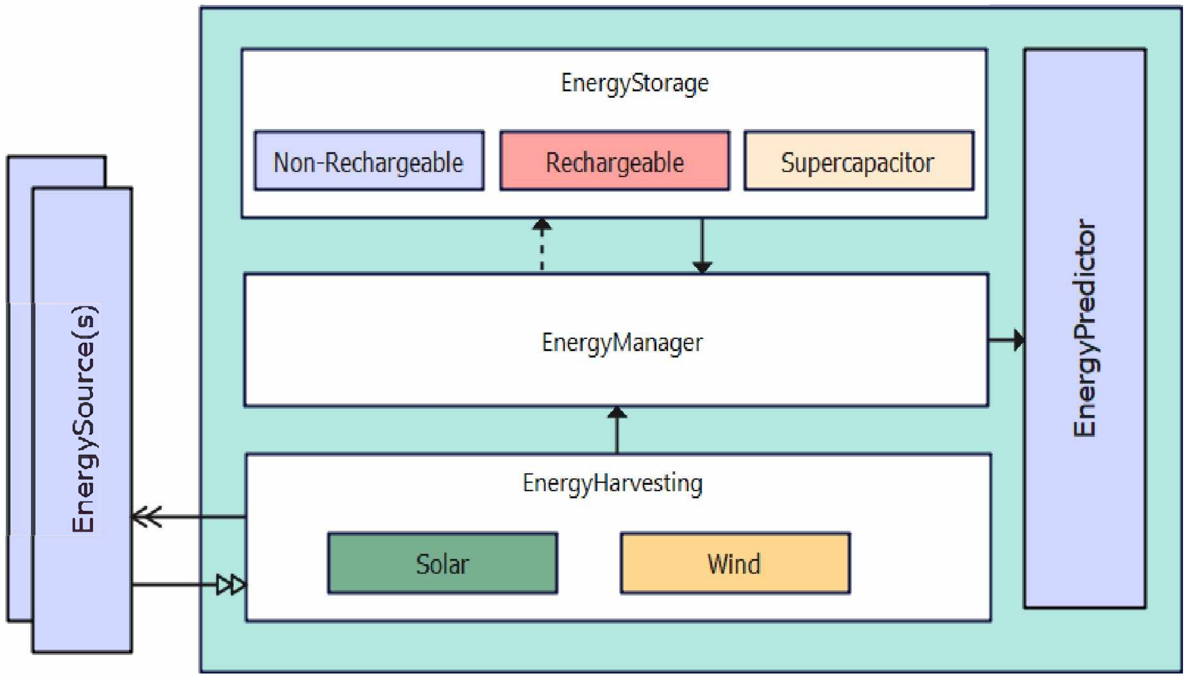

Figure 3.11: Structure of the EnergySubSystem module

- **EnergyStorage:** This represents a storage device, i.e., rechargeable battery that provides power to the node. This module contains three types of storage devices (non-rechargeable batteries, rechargeable batteries, and supercapacitors). It enables nodes to store harvested energy for future use. It allows users to choose a suitable battery model and sets parameters such as maximum capacity, initial battery capacity, and charging and discharging efficiency. In this work, a rechargeable battery is implemented with solar as an energy harvesting device.

- **EnergyManager:** Energy management is carried on by the EnergyManager module. It observes the harvested and consumed energy of the node over time. Furthermore, it holds the control logic for storage devices and manages the flow of energy from the harvesting device to storage and then to the load. It also keeps track of the battery capacity and performs periodic updates of the energy consumed by the node over time.

- **EnergyPredicter:** This module helps to design energy harvesting aware protocols and algorithms for EH-WSNs. It allows users to develop energy prediction models to forecast expected energy intake and use it to enhance the performance using smart energy allocation approaches. In this work, we proposed an offline prediction model that predicts hourly energy intake. Then, the proposed PADC-MAC uses the expected energy to set its duty cycle to optimize the performance under dynamic harvesting conditions.

3.5 Simulation Setup and Network Scenario

To evaluate the protocol performance, we implemented the PADC-MAC protocol in GreenCastalia [114]. Furthermore, to demonstrate the PADC-MAC performance, real-life solar data is utilized for four consecutive days (96 hours of simulations) from August 9-13, 2011 (high irradiance) and October 24-27, 2011 (low irradiance). The commercially available CC2420 radio module and TelosB node parameters are used. The receiver uses a solar panel of 7.7 cm2 with an efficiency of 22%. In addition, it employs a rechargeable battery with a capacity of 1500 mAh. Table 3.4 shows the simulation parameters. Moreover, it is optimized for the network that has a small number of sending nodes per receiver. This is because in a large size sensor network with single receiver, the PADC-MAC will require to increase beacon transmissions and duration of waiting timer (T_w) to accommodate all sender nodes. Resulting in, energy consumption and packet delay will increase. To address this issue, a large size sensor network can be divided into several smaller-sized networks, called clusters to achieve benefits like optimizing energy efficiency, and scalability and reduced routing delay [117, 118] at higher overhead costs [119]. In each cluster, both receiver and sender nodes can communicate with each other directly form a single-hop network. Therefore, to demonstrate the features of PADC-MAC, its performance is evaluated only using single-hop scenario and the network topology consists of a receiver and 7 sender nodes randomly located within an area of 30 m × 30 m, as shown in Figure 3.12. However, it can be extended to support the multi-hop scenario, for instance in the clustered network, the first hop is from the sender nodes to the cluster head (receiver), and it is then followed by next hops that is communication between cluster heads and eventually to the sink. This can be achieved by combining the proposed PADC-MAC and a routing scheme at the routing layer. Each sender node generates 345600 packets with a rate of 1 packet per second with a size of 33 bytes and transmits to the receiver using the p-persistent CSMA approach, where the p-value is set as $1/N_s$, where N_s represents the total number of senders. The performance of the PADC-MAC is evaluated in terms of average ETE delay for the highest priority packet and all packets, network throughput PDR, energy consumption per bit, receiver energy consumption, and total network energy consumption. For performance comparison, three well-known MAC protocols for EH-WSNS, namely QPPD-MAC, QAEE-MAC, and EEM-MAC are also implemented. In these protocols, nodes solely depend on the current energy level to keep the node operational without considering the high variability of energy intake in dynamic harvesting conditions, which may degrade their performance.

Table 3.4: Simulation parameters

Simulation time	96 hours
Data packet	33 bytes
Tx beacon	14 bytes
ACK packet	11 bytes
Rx beacon	13 bytes
Wake-up beacon	13 bytes
Physical frame overhead	6 bytes
Harvesting rate	Variable
Solar panel size	7.7 cm^2
Panel efficiency	22%
Retransmission limit	10
Data rate	250 kbps
Number of sender nodes	1 to 7
Node type	Telos Rev B
Operating voltage	2.4 V
SIFS	0.192 ms
CCA check delay	0.128 ms
T_{listen}	17ms
T_w	5 ms
Slot size	320 µs
E_{max}	12960J
E_{th}	10%
Initial battery level	45%

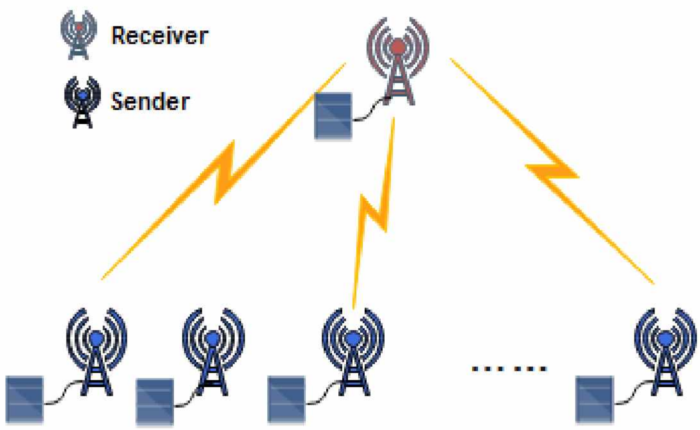

Figure 3.12: Network topology used in performance evaluation.

3.6 Summary

This chapter presents the proposed PADC-MAC in detail. First, it discusses the communication overview and traffic differentiation between the receiver and sender nodes. Then, the prediction model, named NARNET, which predicts the incoming harvested energy, is explained. Next, the duty cycle mechanism is presented, which incorporates current and future energy intake to adjust the duty cycle of the receiver using a numerical formula. It enables the node to rise the duty cycle when sufficient energy resources are available to improve the network performance. Moreover, the self-adaptation technique is described, which helps sender nodes to conserve energy in the network. Finally, performance metrics, network simulator, simulation setup, and parameters are given. The performance evaluation of the proposed prediction model and PADC-MAC protocol under dynamic harvesting conditions are shown in the next chapter.

Chapter 4

Results and Discussion

This chapter firstly presents the performance evaluation of the proposed NARNET model and its comparisons with EWMA and actual data under dynamic harvesting conditions. Secondly, the performance evaluation of the proposed PADC-MAC protocol, which incorporates energy prediction results obtained using NARNET in the GreenCastalia simulator under high and low solar harvesting conditions, is presented. Finally, simulation results in average ETE delay for the highest priority packet and all packages, packet delivery ratio, network throughput, energy consumption per bit, receiver energy consumption, and total network energy consumption are discussed and compared with QPPD-MAC, QAEE-MAC, and EEM-MAC protocols.

4.1 Performance Evaluation of the NARNET Model

The NARNET model is implemented in MATLAB R2022a to predict the hourly solar irradiance value. Thus, each day is divided into 24 timeslots. The developed model has one-dimensional solar irradiance data measured by NREL for 19 consecutive months. The data contains 13862 samples of solar irradiance from April 1, 2010, to October 31, 2011, incorporating seasonal variations. The model is trained offline using available NREL data from April 2010 to June 2011 and tested using the data from July 2011 to October 2011, which includes high and low energy harvesting scenarios. Furthermore, the performance has been compared with EWMA using different months' data, i.e., August (high harvesting) and October (low harvesting) scenarios. The prediction error is computed using MAE

$$MAE(\%) = \frac{\sum\left|S_t - \check{S}_t\right|}{\sum S_t} \times 100 \tag{4. 1}$$

where S_t and $\check{S}_t$ are actual and predicted irradiance during timeslot t, respectively.

Figure 4.1 and Figure 4.2 presents high solar irradiance and corresponding energy obtained using the solar panel, respectively. The results compare the prediction performance of the developed NARNET model with actual data and EWMA for four consecutive days, i.e., 9th to 13th August 2011. For a fair comparison, the weighting factor (α) in EWMA is set to 0.5, which provides the lowest error [120]. The results show that the proposed model closely follows the actual trend and accurately predicts the incoming irradiance with a correlation coefficient (R) of 0.98 and MAE of 11.75%. In contrast, EWMA achieves R of 0.96 and provides the MAE of 16.90%. The EWMA incorporates energy intake in current slot as well as of previous days to perform the prediction for the next slot. As a result, it fails to adapt to sudden changes in weather conditions, particularly on the first day and as a result it provides greater MAE of up to 30.47% when compared with the proposed prediction model.

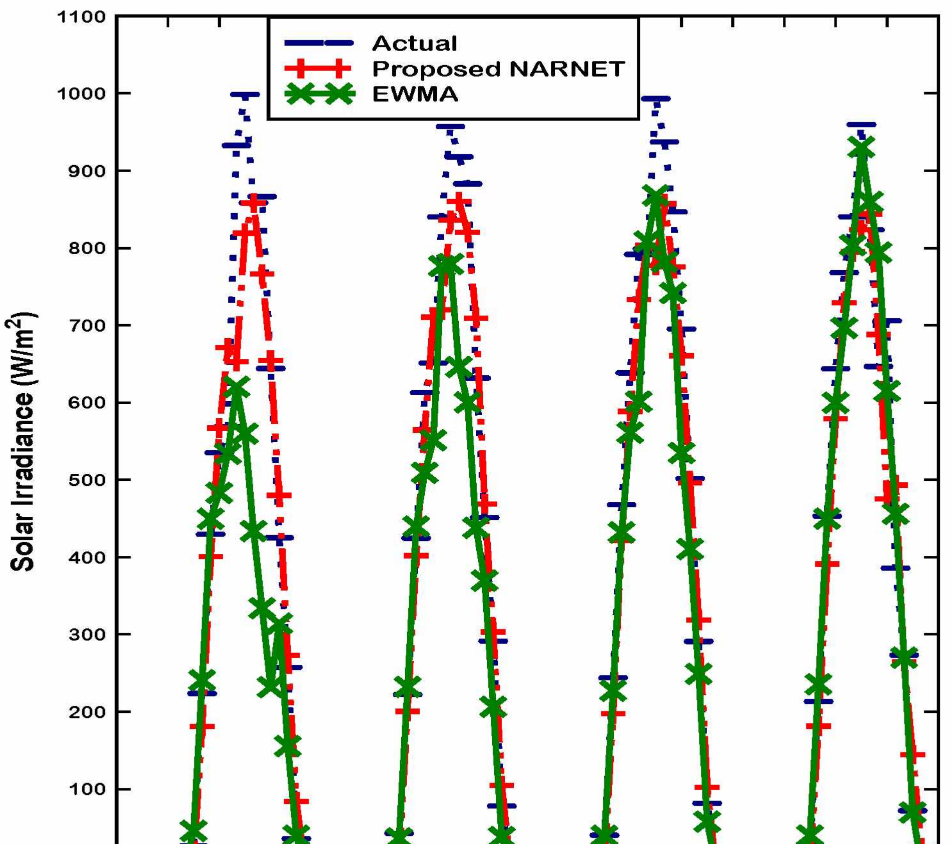

Figure 4.1: Average hourly solar irradiance data for four consecutive days, 9th to 13th August 2011, versus simulation time

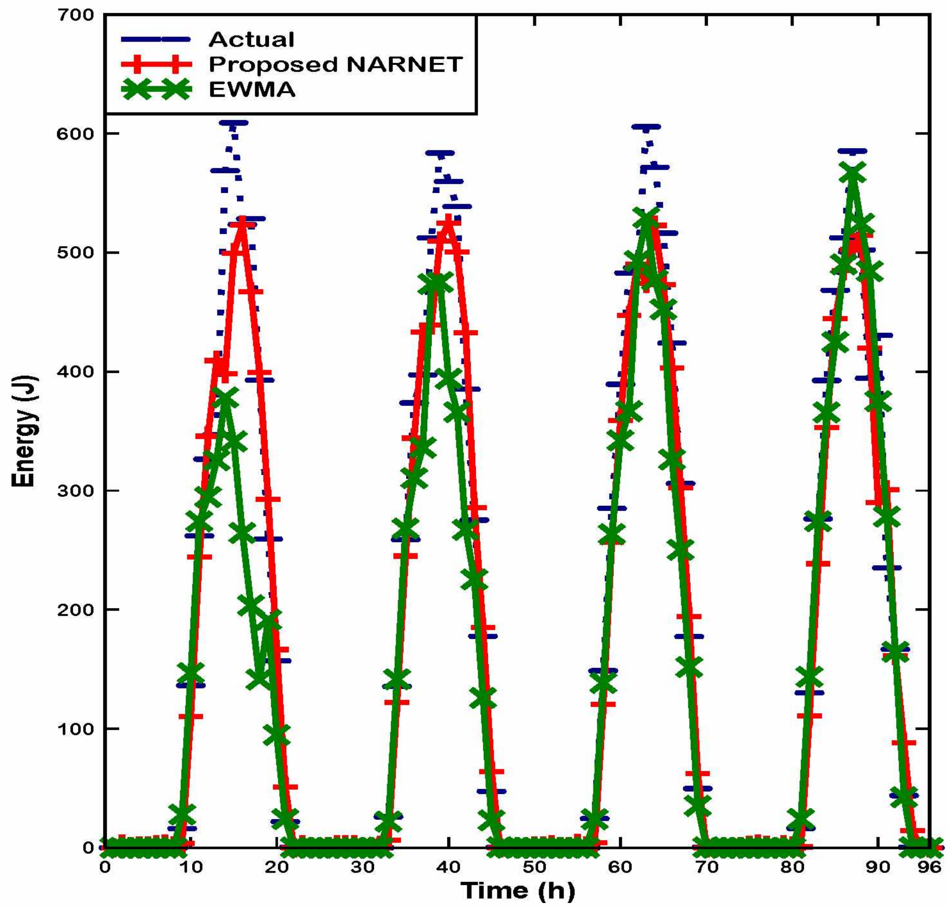

Figure 4.2: Comparison of predicted energy obtained using NARNET and EWMA with actual energy for four days consecutive days, 9th to 13th August 2011.

Figure 4.3 and Figure 4.4 present low solar irradiance data and corresponding energy for four consecutive days, i.e., 24th to 27th October 2011. The results show that the NARNET attains good agreement with the actual energy and provides R and MAE of 0.95 and 28.46%, respectively, which are marginally different than Figure 4.1. This is because weather conditions are changing consistently every day. On the other hand, sudden weather changes also degrade EWMA performance. It achieves an R of 0.82 and provides MAE of 39.48%, respectively, which is 28% more than NARNET.

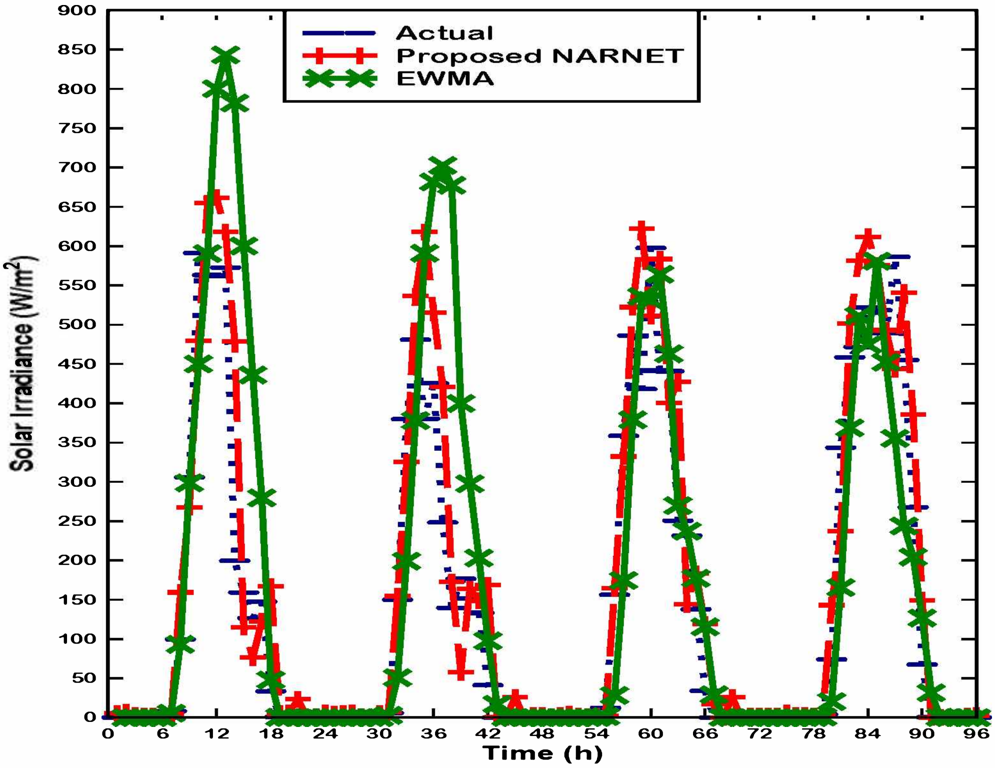

Figure 4.3: Average hourly solar irradiance data for four consecutive days, 24th to 27th October 2011, versus simulation time

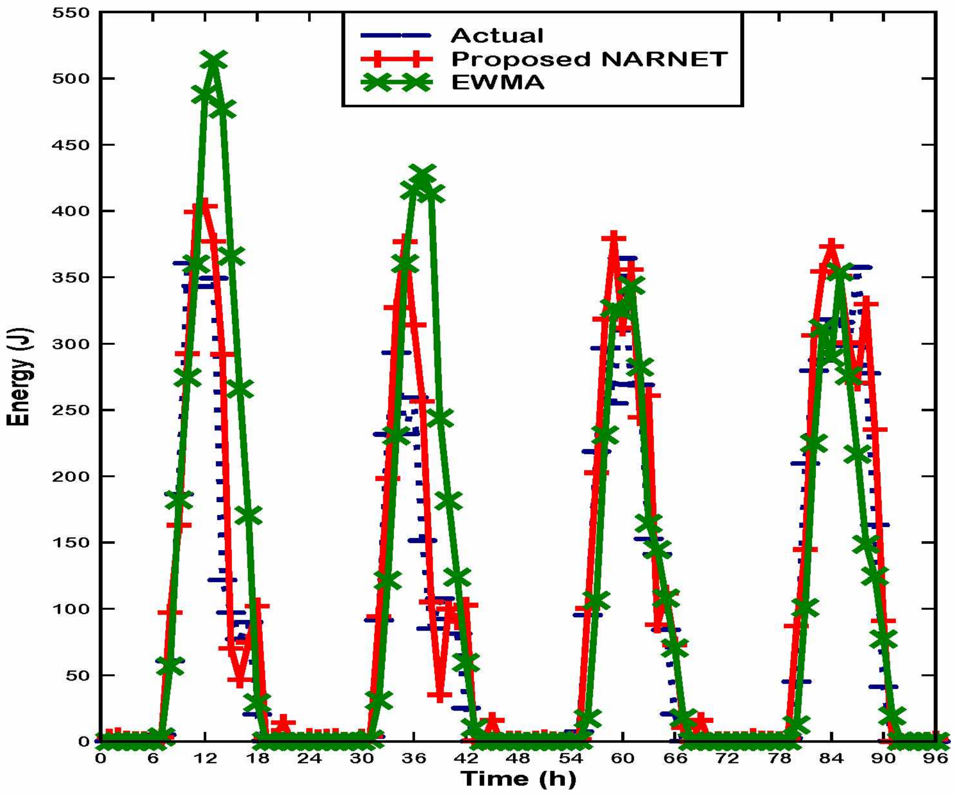

Figure 4.4: Comparison of predicted energy obtained using NARNET and EWMA with actual energy for four days consecutive days, 24th to 27th October 2011.

The primary objective of employing a prediction model is to optimize the network performance by allocating incoming harvested energy efficiently. Therefore, the following section describes the performance evaluation of the proposed PADC-MAC protocol, which incorporates incoming harvested energy to set the duty cycle of the receiver to enhance the performance under high and low energy harvesting conditions.

4.2 Performance Evaluation of PADC-MAC Protocol

In this subsection, the performance of the PADC-MAC protocol has been evaluated under both high and low solar energy harvesting conditions in terms of in average ETE delay for the highest priority packet and all packages, packet delivery ratio, network throughput, energy consumption per bit, receiver energy consumption, and total network energy consumption. Furthermore, the performance of the PADC-MAC has been compared with three existing protocols for EH-WSNs, namely QPPD-MAC, QAEE-MAC, and EEM-MAC.

4.2.1 High Irradiance Scenario

The remaining energy, RE_{total} of the receiver is shown in Figure 4.5. Initially, the receiver starts its operation with battery level of 45%, and the day starts at midnight. The RE_{total} declines slightly as solar energy is unavailable until sunrise (shown in the high solar irradiance scenario, Figure 4.1), and the receiver uses its stored battery energy to execute communication-related tasks. After sunrise, its values slowly increase to 62.5%, 65.7, 65.8%, and 66.1% in PADC-MAC, QPPD-MAC, QAEE-MAC, and EEM-MAC, respectively, on the first day. Then, it declines again as harvesting energy is unavailable after sunset. During the last three days, sufficient harvesting energy was available. Thus, its values reach 98.7%, 98.8%, 99.3%, and 98.8% at the end of the fourth day. It can be noticed that PADC-MAC has a lower RE_{total} values during 18h to 90h when compared to other protocols. This is because of two reasons. First, it regulates the receiver duty cycle based on its remaining energy and increases the duty cycle more aggressively to lower the delay, while maintaining and ensuring a stable level of battery energy. Resulting in, a slight decrease in RE_{total} when compared to other protocols. Furthermore, it incorporates knowledge of future energy intake (given in Figure 4.2) to optimize the network performance further. Thus, it increases its duty cycle to 1 when sufficient energy is available in the next hour and is more than the required energy, E_c. However, other protocols do not consider energy prediction and do not perform aggressively even though adequate energy is available during the daytime for all days.

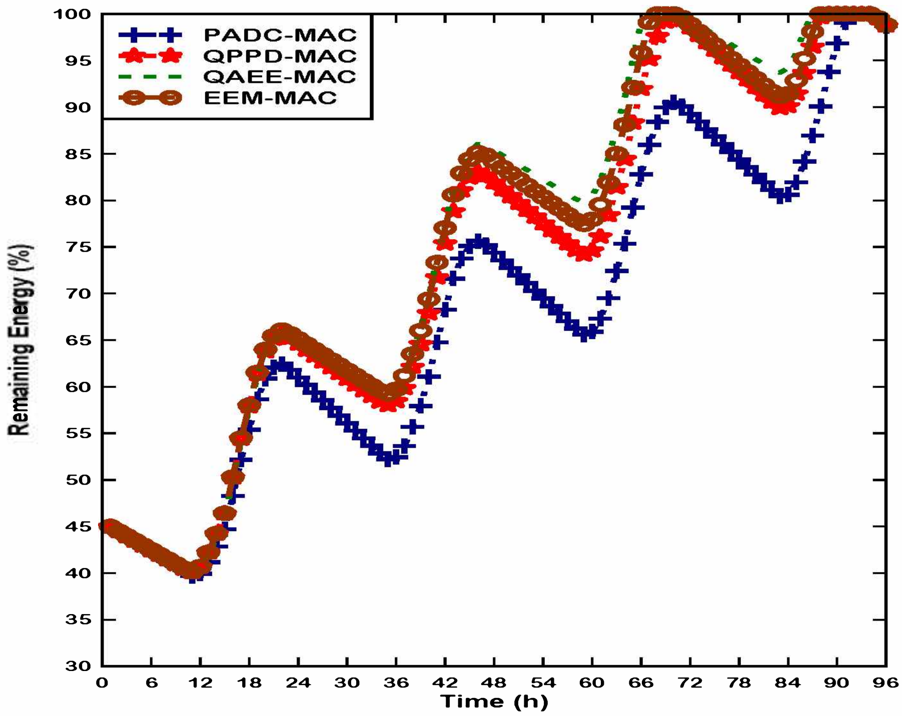

Figure 4.5: Remaining energy of the receiver

Figure 4. 6 presents the duty cycle of the receiver. Initially, PADC-MAC, QPPD-MAC, and QAEE-MAC start their operation with a duty cycle value of 50%, while its value is set to 56% in EEM-MAC. Subsequently, the duty cycle decreases to 45.5%, 45.5%, and 54.3% in PADC-MAC, QPPD-MAC, and EEM-MAC, respectively. The reason is that the receiver incorporates RE_{total} to adjust its duty cycle values, which decline slighty, as external solar energy is unavailable until sunrise. After that, in PADC-MAC, the duty cycle rises to maximum value i.e., 1 for the following three days. The reason is that the receiver battery is sufficiently charged to more than 50% for the following days, and duty cycle is increased to reduce sleep time. This helps the receiver to stay active for almost 86 hours and to minimize delay for the incoming packets. In addition, it also incorporates predicted harvesting energy in the next hour, i.e., $HE_{predicted}$ and uses this information in duty cycle adjustment to further improve the performance. In QPPD-MAC, QAEE-MAC, and EEM-MAC, the receiver becomes more conservative

despite adequate energy resources for all consecutive days; thus, they have missed the opportunity to improve their performance.

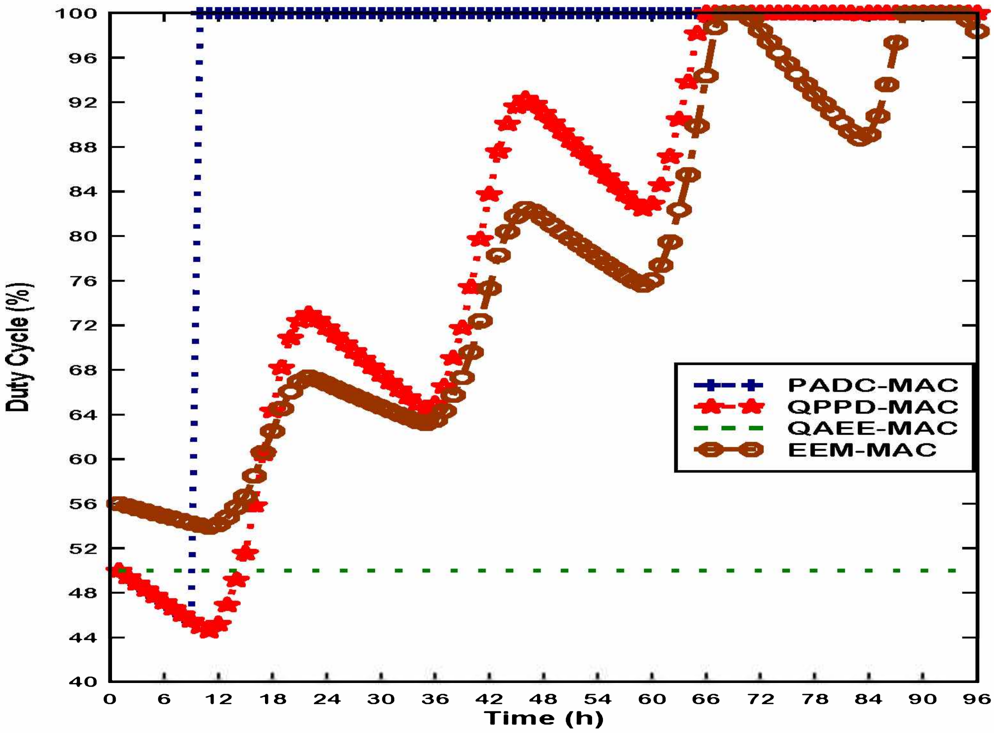

Figure 4. 6: Duty cycle of the receiver

Figure 4.7 shows the average ETE delay for the different priority packets in all protocols. The results are shown for different packet priorities (P_4, P_3, P_2, P_1) in both PADC-MAC and QPPD-MAC, (P_2, P_1) in QAEE-MAC, and the average of all packets in EEM-MAC as it does not consider packet priority. For the comparison, only delay results for the highest packet are discussed. The result indicates that PADC-MAC provides a meaningful reduction in delay of up to 13.5%, 46%, and 28% compared to QPPD-MAC, QAEE-MAC, and EEM-MAC, respectively, across all sender nodes. The reason is that both PADC-MAC and QPPD-MAC support the P_4 priority packets by shortening the waiting timer when they arrive. Furthermore, PADC-MAC uses the harvested energy more aggressively, when possible, by maximizing its duty cycle corresponding to its remaining energy level and the potential increase in energy level in the near future. Therefore, considering battery capacity and incoming harvested energy, the receiver operates on the maximum duty cycle, i.e., 1. As a result, the radio remains active most of the time, which decreases the delay for incoming packets, P_4. In contrast to PADC-MAC, QPPD-MAC, QAEE-MAC, and EEM-MAC are more energy-conservative and operate without incorporating incoming harvested energy. Thus, the data packets suffer long delays despite sufficient energy resources. It can be seen that QAEE-MAC has the highest average delay for priority packets compared to other protocols. This is because it operates on a fixed duty cycle and does not consider current harvesting to enhance the performance.

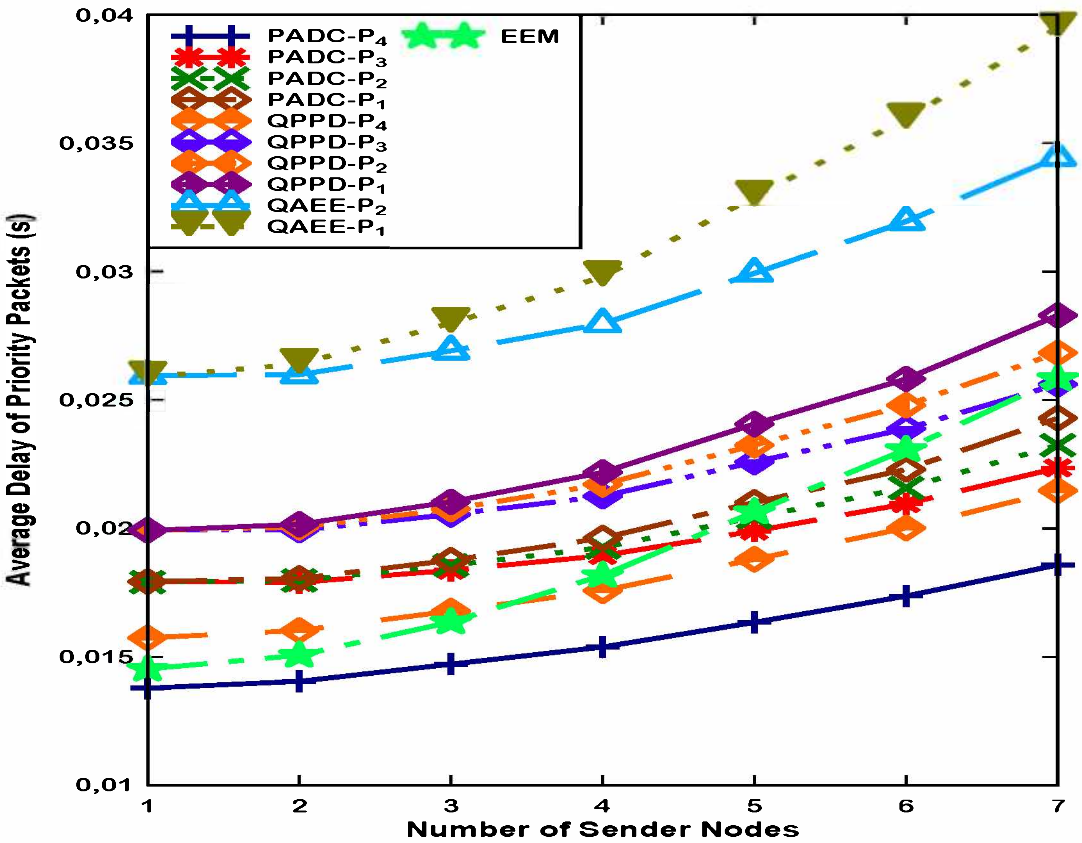

Figure 4.7: Average ETE delay for priority packets

The average ETE delay of all packets is shown in Figure 4.8. Again, PADC-MAC outperforms other protocols even in the average delay of all data packets. Furthermore, the result shows that PADC-MAC provides the lowest packet delay by up to 13.5%, 40.2%, and 14.4% compared to QPPD-MAC, QAEE-MAC, and EEM-MAC, respectively. The fact is that it increases its duty cycle based on its remaining energy level and the potential increase in energy in the near future. The result also indicates that EEM-MAC performs slightly better than PADC-MAC when the number of sender nodes is 1–4. First, it allows nodes to send their packets with no priority. Second, a few sender nodes experience low contention in accessing the medium and, as a result, lower average delay. However, EEM-MAC performance decreases compared to PADC-MAC when the number of sending nodes is 5-7. The reason is that when there are a higher number of sender nodes, nodes try to access the medium simultaneously without priority differentiation, which increases packet delay.

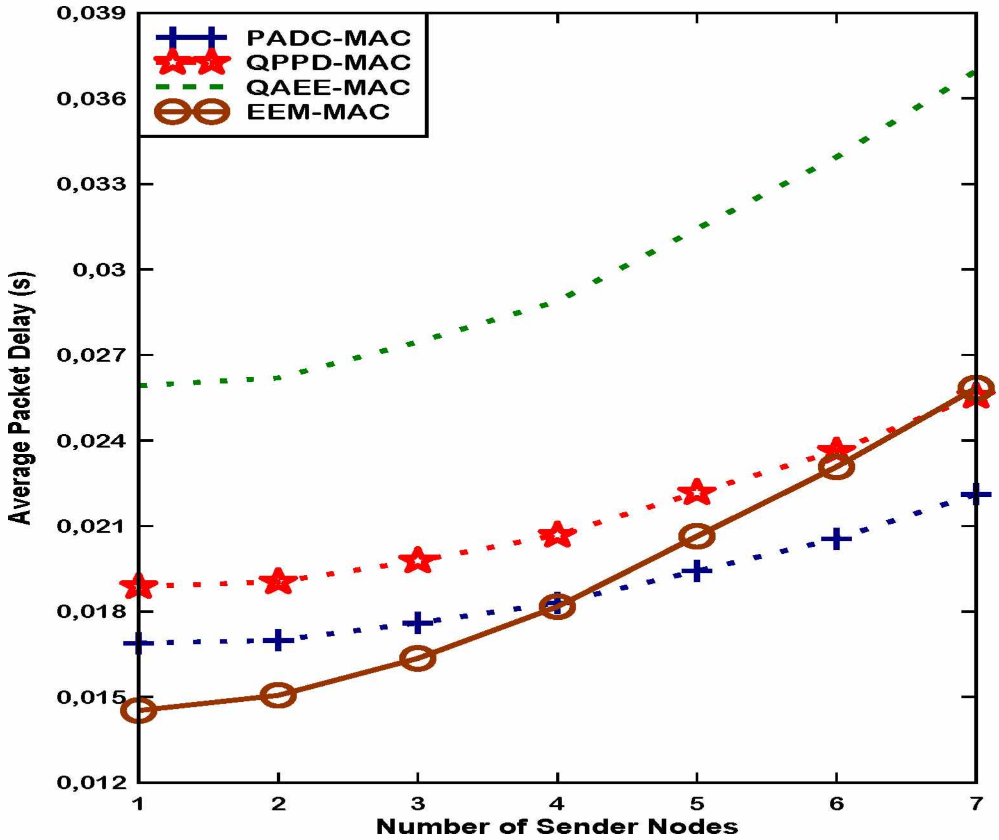

Figure 4.8: Average ETE delay of all packets

Figure 4.9 presents the PDR of all protocols. It can be noticed that all protocols achieve almost 100% PDR across all numbers of sensor nodes. This is because the receiver in all protocols has sufficient energy to maintain its operation and is available to accept the incoming packets. The average network throughput performance of all protocols is presented in Figure 4.10. The network throughput increases linearly with respect to the number of sender nodes. The result indicates the maximum value of 1568 bps when sender nodes are 7.

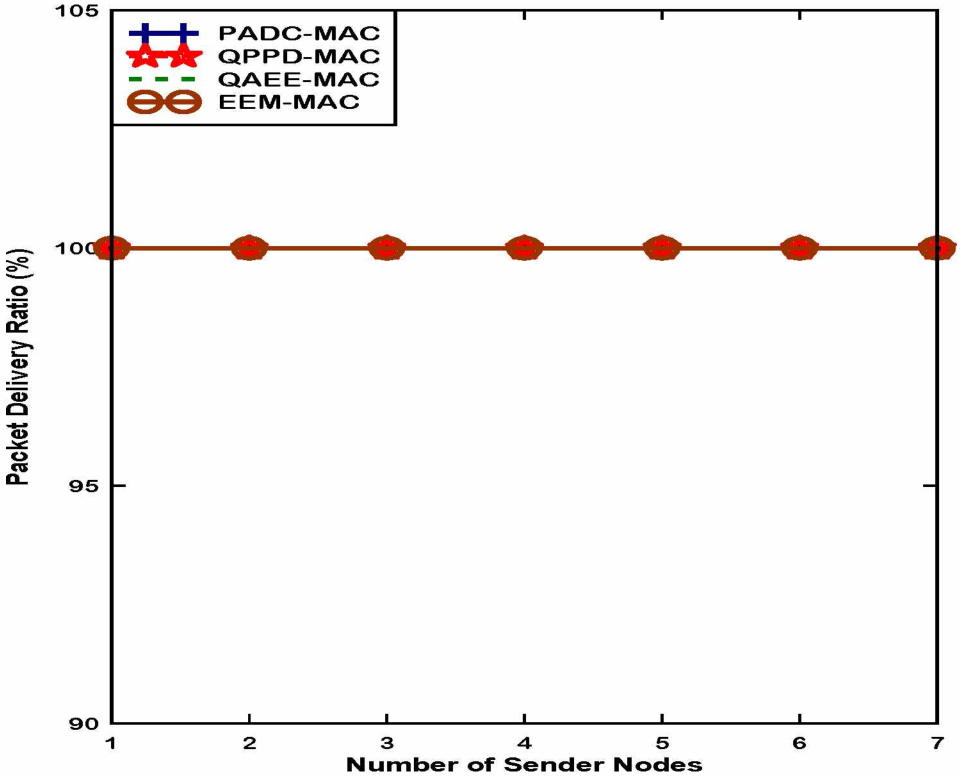

Figure 4.9: Packet delivery ratio

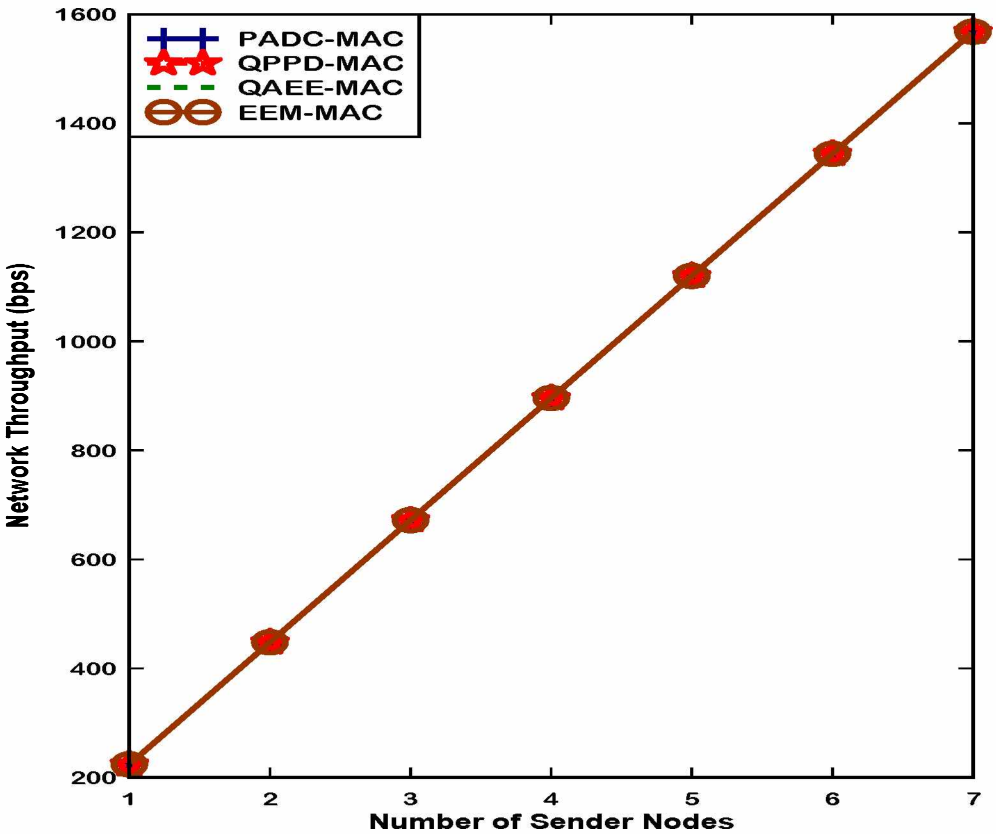

Figure 4.10: Network throughput

Figure 4.11 presents the energy consumption per bit in all three protocols. It increases linearly because more packets are transmitted at a higher number of sender nodes. In PADC-MAC, it decreases significantly by up to 81% compared to other protocols. This is because the PADC-MAC uses self-adaptation in which the receiver sha res its following wake-up schedule with all sender nodes through the wake-up beacon. After obtaining the wake-up beacon, the sender nodes that have data packets contend for the medium to perform data transmission. Other sender nodes incorporate the receiver's wake-up schedule and adjust their sleep time to wake up just before the receiver. As a result, nodes conserve energy by reducing idle listening. In other protocols, sender nodes are usually active, which leads to an increase in energy consumption due to idle listening. It can also be seen that both QPPD-MAC and QAEE-MAC have slightly lower energy consumption per bit compared to EEM-MAC when sender nodes is 7. The is because these protocols use the RX beacon that contains a NAV value. After accepting RX-beacon, the non-designated sender nodes sleep until NAV timer expires, which conserves energy.

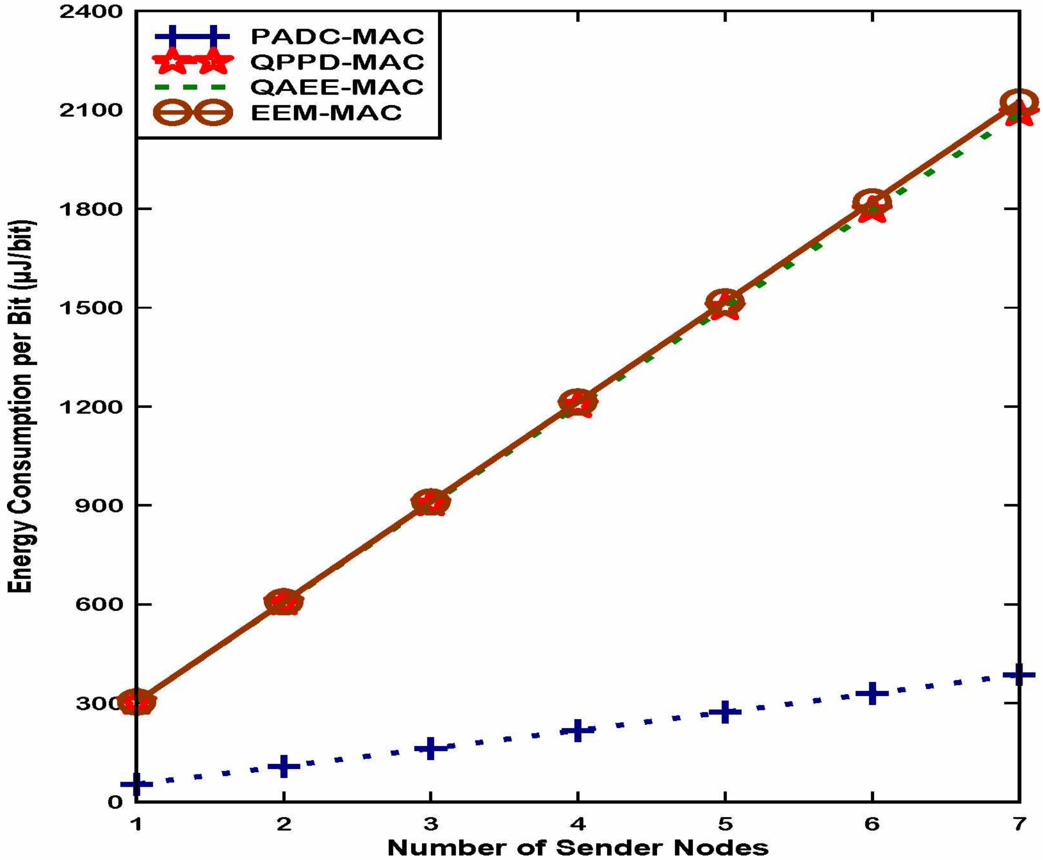

Figure 4.11: Average energy consumption per bit

The receiver energy consumption (E_r) in all protocols is given in Figure 4.12. It can be noticed the PADC-MAC consumes more energy by up to 14.7%, 50.4%, and 26% compared to QPPD-MAC, QAEE-MAC, and EEM-MAC, as expected. This is because the receiver in PADC-MAC becomes more aggressive when it has sufficient energy available and aims to use it efficiently to optimize the network performance. Thus, it increases its duty cycle by reducing sleep time according to the remaining energy level. Moreover, it also incorporates expected harvesting energy in the next hour to increase the duty cycle further. This helps reduce packet delay in the network at the cost of a slight energy consumption increase when sufficient harvesting energy is available. In other protocols, the receiver becomes more energy-conservative, resulting in lower energy consumption than PADC-MAC. However, it can also be noticed that the energy consumption in PADC-MAC, QPPD-MAC, and QAEE-MAC slightly increases with the varying number of nodes. This is because the receiver receives more packets. In addition, the receiver has to wait until it gets the highest priority packet. On the other hand, energy consumption slightly decreases in EEM-MAC for higher sender nodes. This is because EEM-MAC does not employ TX-beacon and RX-beacon, and the receiver does not wait for a particular packet. Thus, after receiving the first data, it sleeps to conserve energy.

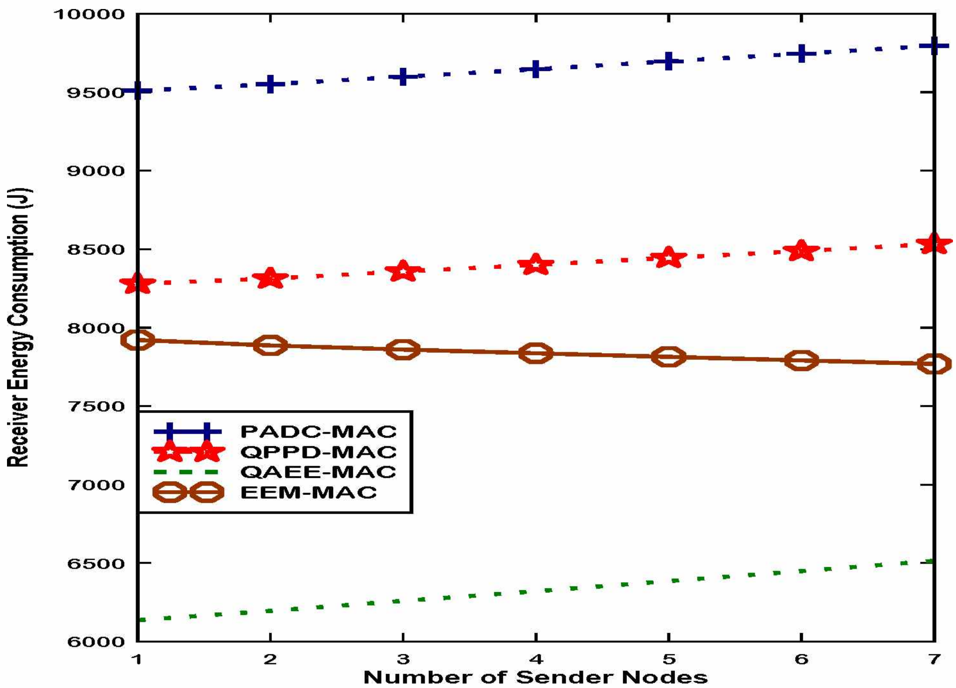

Figure 4.12: Energy consumption of the receiver

Figure 4.13 shows the total energy consumption for the different number of sender nodes. It combines the receiver's energy consumption and the sender nodes' total energy consumption. It can noticed that the PADC-MAC shows a meaningful reduction of up to 76.6%, 76.4%, and 76.9% when compared to QPPD-MAC QAEE-MAC, and EEM-MAC, respectively. This is because the PADC-MAC uses a novel self-adaptation technique by which the sender conserves energy and becomes active slightly prioir to the receiver. This leads to reducing overall energy consumption. On the other hand, QAEE-MAC provides a marginally lower value compared to QPPD-MAC and EEM-MAC. The reason is that in QAEE-MAC, the receiver energy consumption is lower than QPPD-MAC and EEM-MAC, resulting in slightly lower total energy consumption.

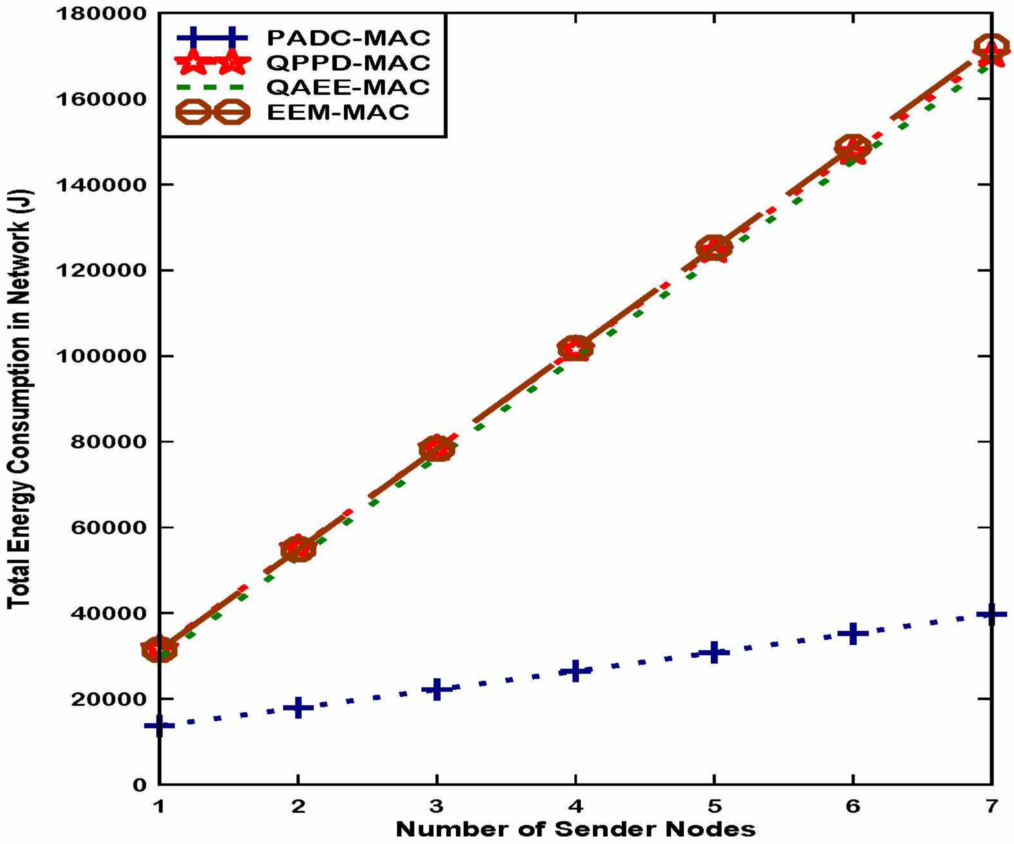

Figure 4.13: Total energy consumption

4.2.2 Low Irradiance Scenario

The remaining energy is presented in Figure 4.14. Initially, it declines as sunlight is unavailable until morning (as shown in the low solar irradiance scenario, Figure 4.3). Then, it increases until noon and reaches 46.7%, 48.8%, 48.8%, and 49.2% in PADC-MAC, QPPD-MAC, QAEE-MAC, and EEM-MAC, respectively. It follows a similar trend for the next three days. It can be noticed that its value is significantly lower than those in the high irradiance scenario. Moreover, the battery remains charged up to 49.4%, 58.9%, 60.7%, and 61.1% in PADC-MAC, QPPD-MAC, QAEE-MAC, and EEM-MAC, respectively, at the end of the last day. Moreover, these values are 49.3%, 39.9%, 38.6%, and 37.7% less than those in Figure 4.5. It can be seen that PADC-MAC has a lower value when compared to others. This is because the PADC-MAC uses its availabe energy to regulate its duty cycle more aggressive to enhance the network performance, while maintaining and ensuring a stable level of battery energy. Thus, it increases the duty cycle by considering both remaining and forecasting energy values to minimize the packet delay. As a result, the remaining energy is decreased.

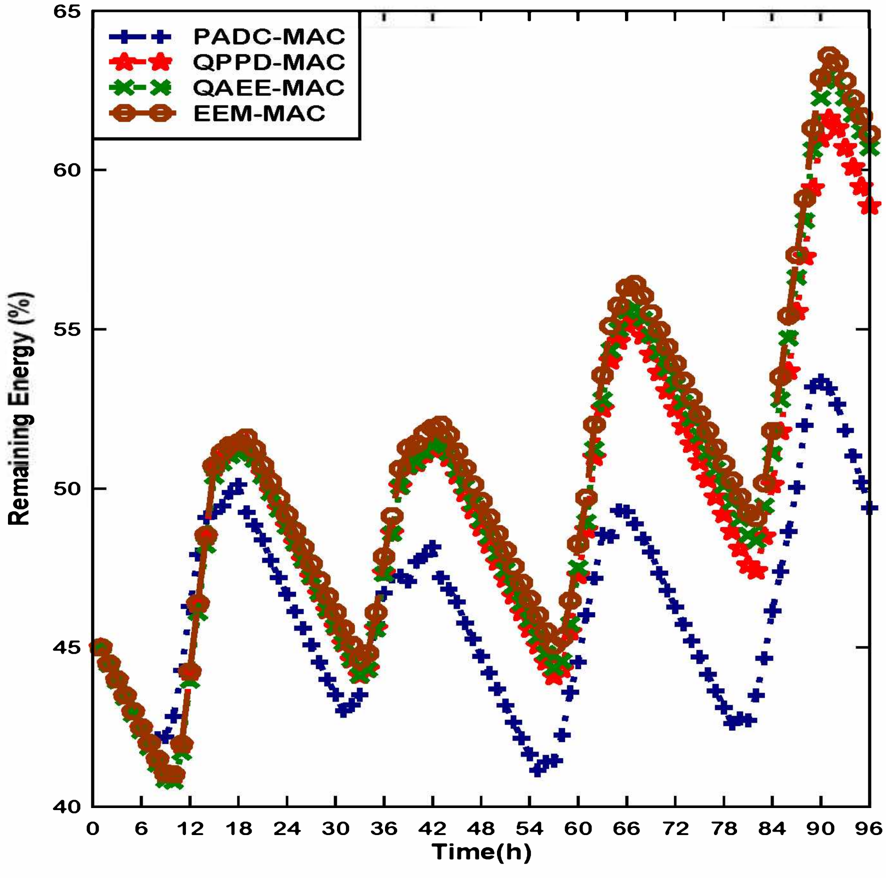

Figure 4.14: Remaining energy of the receiver

The duty cycle of the receiver in all protocols is given in Figure 4.15. The result shows significant variation in PADC-MAC compared to other protocols. In addition, its value changes abruptly to maximum, i.e., 1 in certain hours, mainly during the daytime, for almost seven times. Then, it returns suddenly and follows a continuous trend as QPPD-MAC and EEM-MAC. This is because it incorporates the remaining energy and predicted energy value as given in Figure 4.14 and Figure 4.4, respectively, to adjust the receiver duty cycle. During certain hours of the day, it meets the condition where the expected energy value is greater than the maximum required energy in an hour. This leads to increasing the duty cycle to a maximum value, i.e., 1, to enhance the network performance. Moreover, small changes in the duty cycle are due to weather conditions such as cloud cover that could suddenly appear and disappear. On the other hand, QAEE-MAC uses on a fixed duty cycle, i.e., 0.5, and thus shows a straight line.

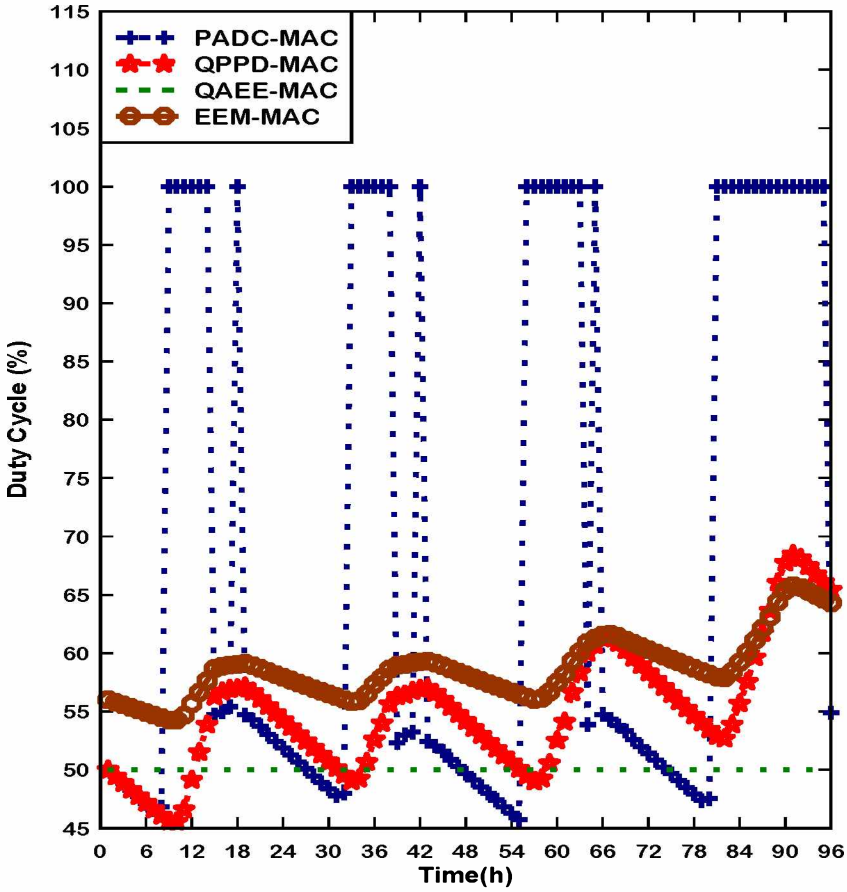

Figure 4.15: Duty cycle of the receiver versus simulation time

Figure 4.16 shows the average ETE delay for the highest priority packet. In PADC-MAC, the highest priority packet, P_4 experiences less delay by up to 10.7%, 27.8%, and 23.2% compared to P_4 in QPPD-MAC, P_2 in QAEE-MAC, and the average of all packages in EEM-MAC. This is due to the duty cycle mechanism, which allows the PADC-MAC's receiver to increase its duty cycle when sufficient energy resources are available. Thus, it wakes up frequently to collect the priority packets. As a result, it minimizes the waiting time for priority packets to reduce the delay. Nevertheless, it can be seen that PADC-MAC suffers slightly higher delays for P_3, P_2, and P_1 priority packets in comparsion to the highest priority packet of QPPD-MAC. This is because it aims to meet the requirement of transmitting the highest priority packet, P_4, faster than others priority packets. Thus, lower priority packets experience longer delays before their transmission. It can also be seen that delay increases linearly with respect to the number of sender nodes . The reason is that more sender nodes contend for a medium to transmit their packet, contributing to a higher average delay.

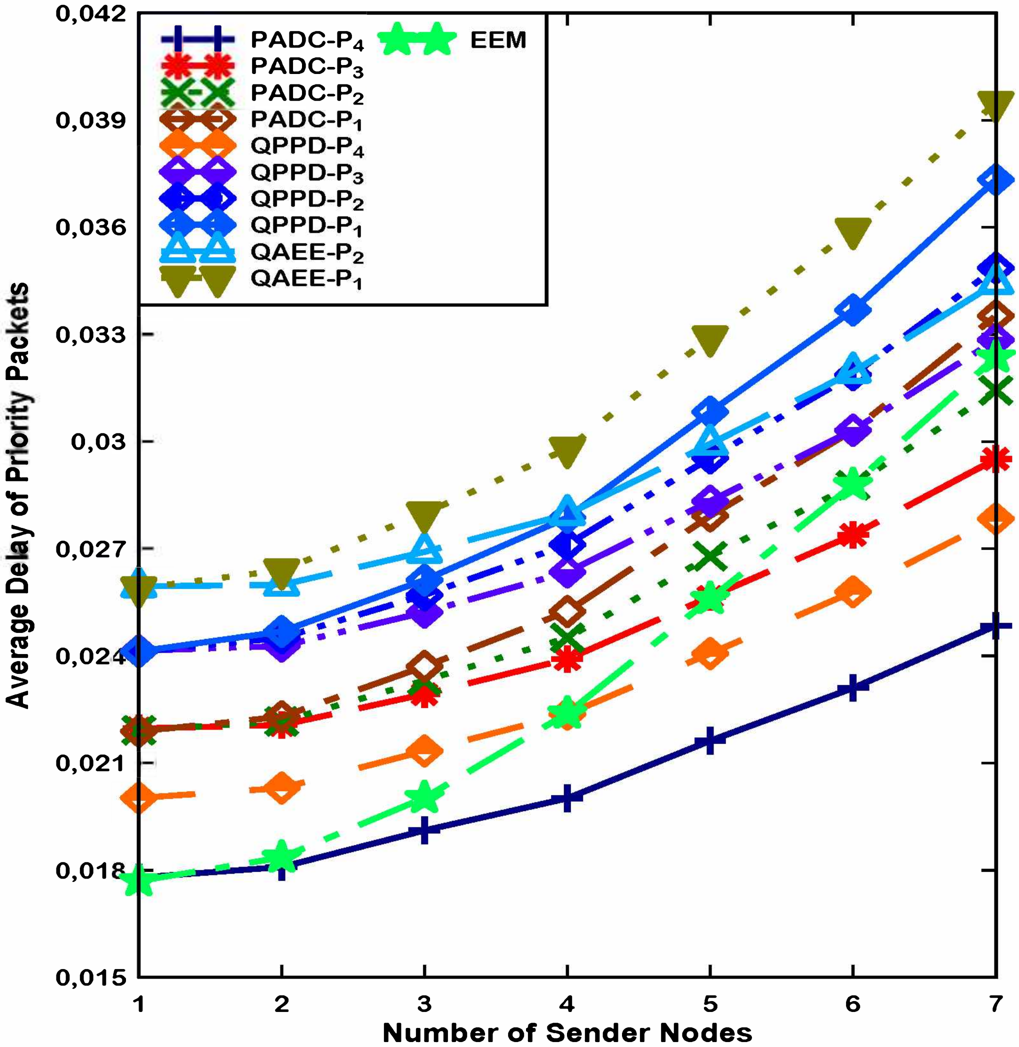

Figure 4.16: Average ETE delay for priority packets

The average ETE delay for all packets is shown in Figure 4.17. The result indicates that the PADC-MAC outperforms other protocols when the number of senders is 5-7. Furthermore, the PADC-MAC offers a meaningful reduction of up to 10.2%, 19.3%, and 7.8% compared to QPPD-MAC, QAEE-MAC, and EEM-MAC, respectively. The reason is that the receiver follows the duty cycle adjustment mechanism, which allows the receiver to increase its listening time while considering its current energy level and incoming harvested energy to reduce delay. It can also be noticed that EEM-MAC provides better performance compared to QPPD-MAC and QAEE-MAC. The reason is that the receiver of EEM-MAC has a higher duty cycle than both protocols, resulting in a lower average packet delay.

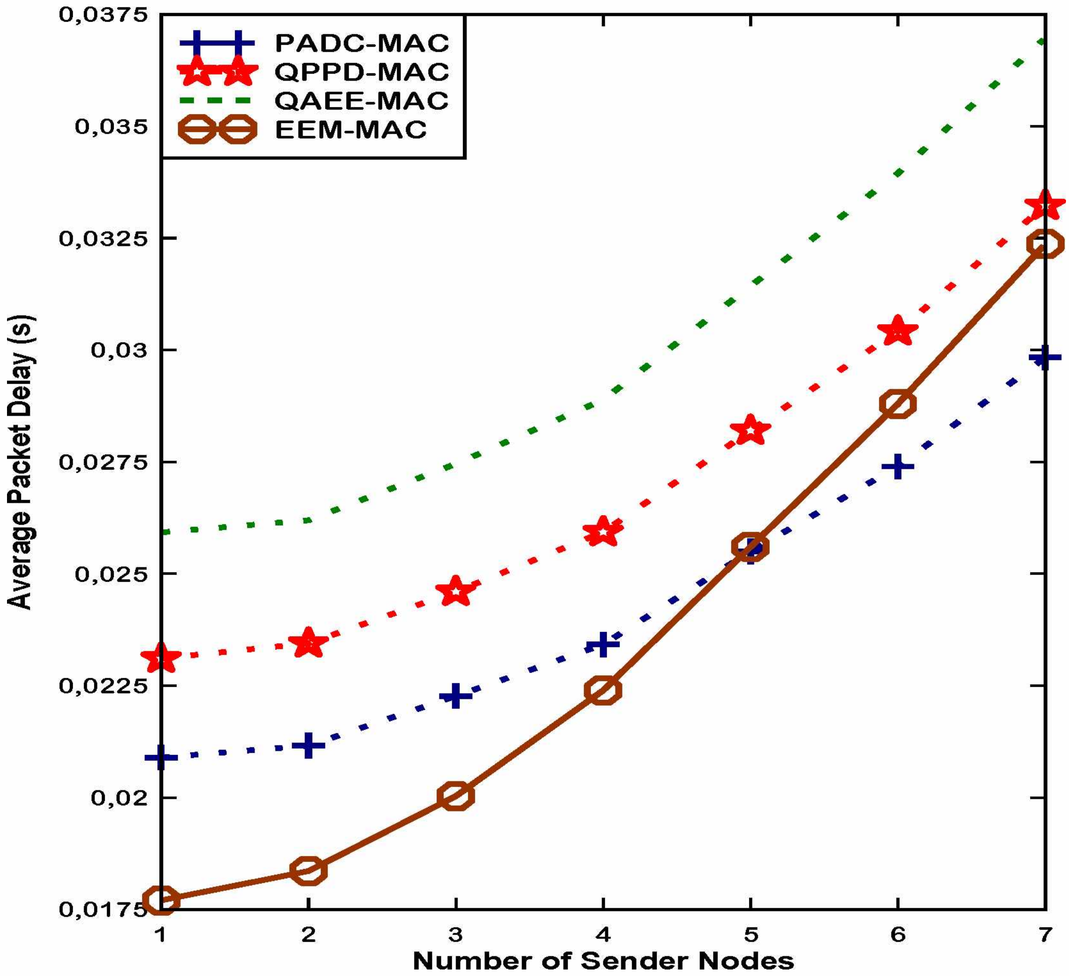

Figure 4.17: Average ETE delay of all packets

The PDR and network throughput performance of all protocols are presented in Figure 4.18 and Figure 4.19, respectively. The results show that all protocols achieve a PDR of almost 100% and network throughput of 1568 bps, the same as in high solar scenarios.

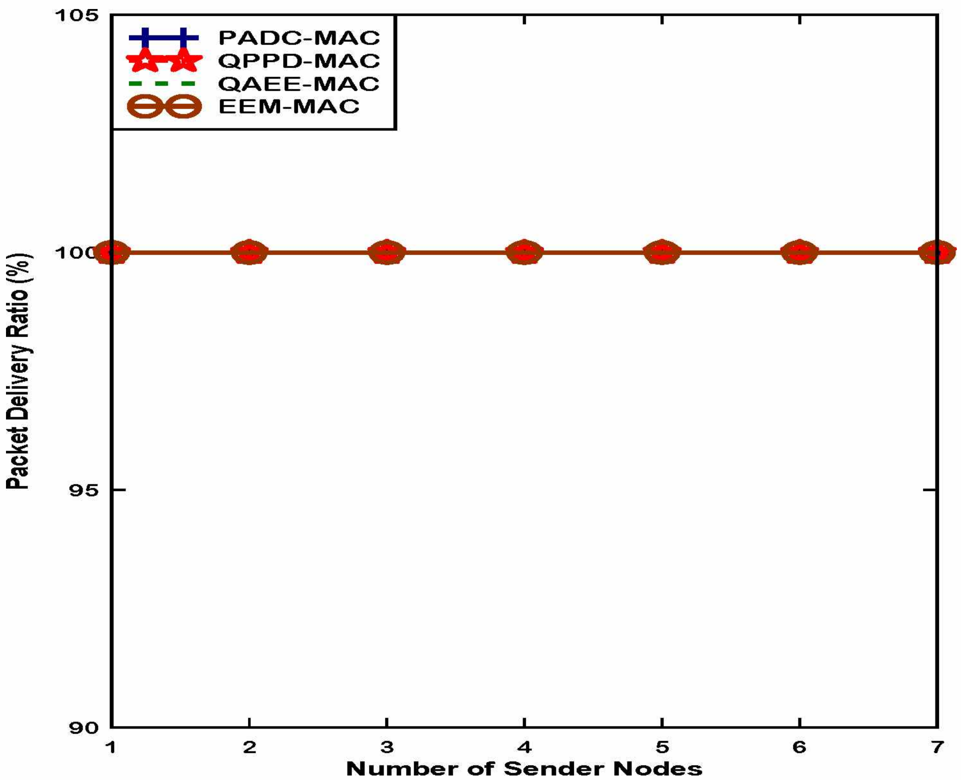

Figure 4.18: Packet delivery ratio

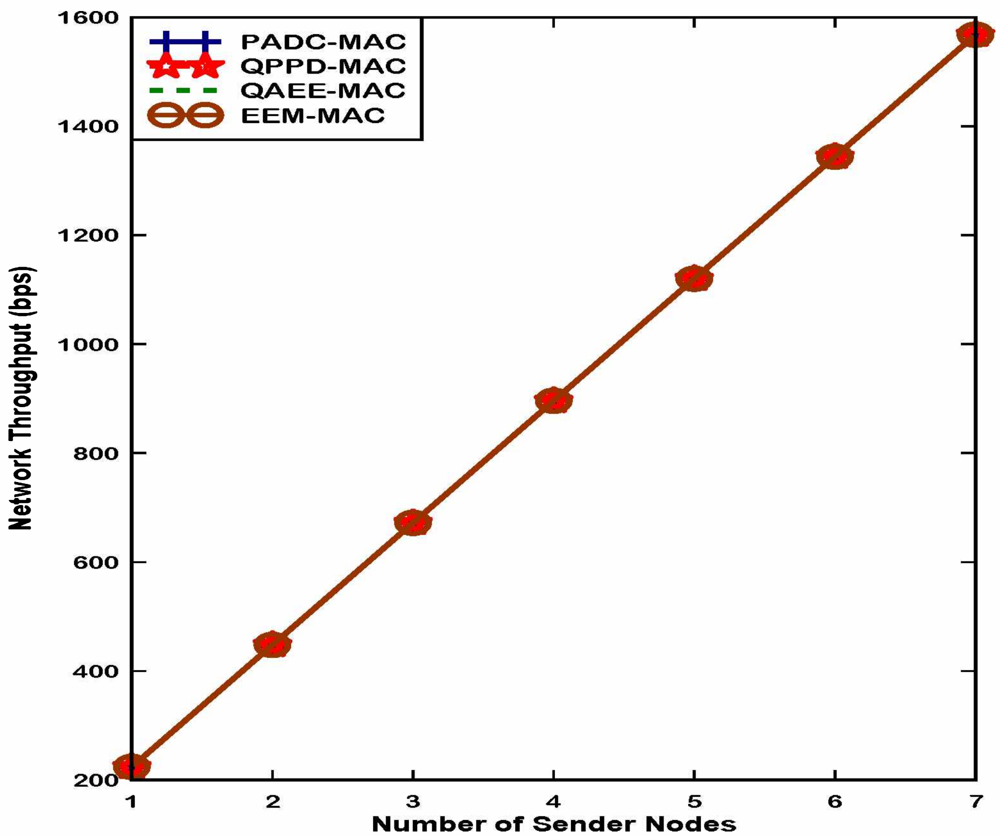

Figure 4.19: Network throughput

Figure 4.20 presents energy consumption per bit. PADC-MAC achieves better performance by up to 81.7% compared to QPPD-MAC and QAEE-MAC and up to 82% compared to EEM-MAC. The reason it that it uses a self-adaptation technique that allows senders to regulate their sleep and wake up accordingly so that they become active slightly before the receiver to conserve energy. In other protocols, the sender nodes are usually active, which increases energy consumption. It can be noticed that PADC-MAC has almost the same performance in both scenarios because the same number of packets are delivered in the networks. Moreover, QPPD-MAC and QAEE-MAC provide slightly lower values compared to EEM-MAC. This is because both protocols use RX beacon that contains NAV value. After receiving RX-beacon, the non-selected sender nodes sleep until the NAV timer expires, which conserves energy.

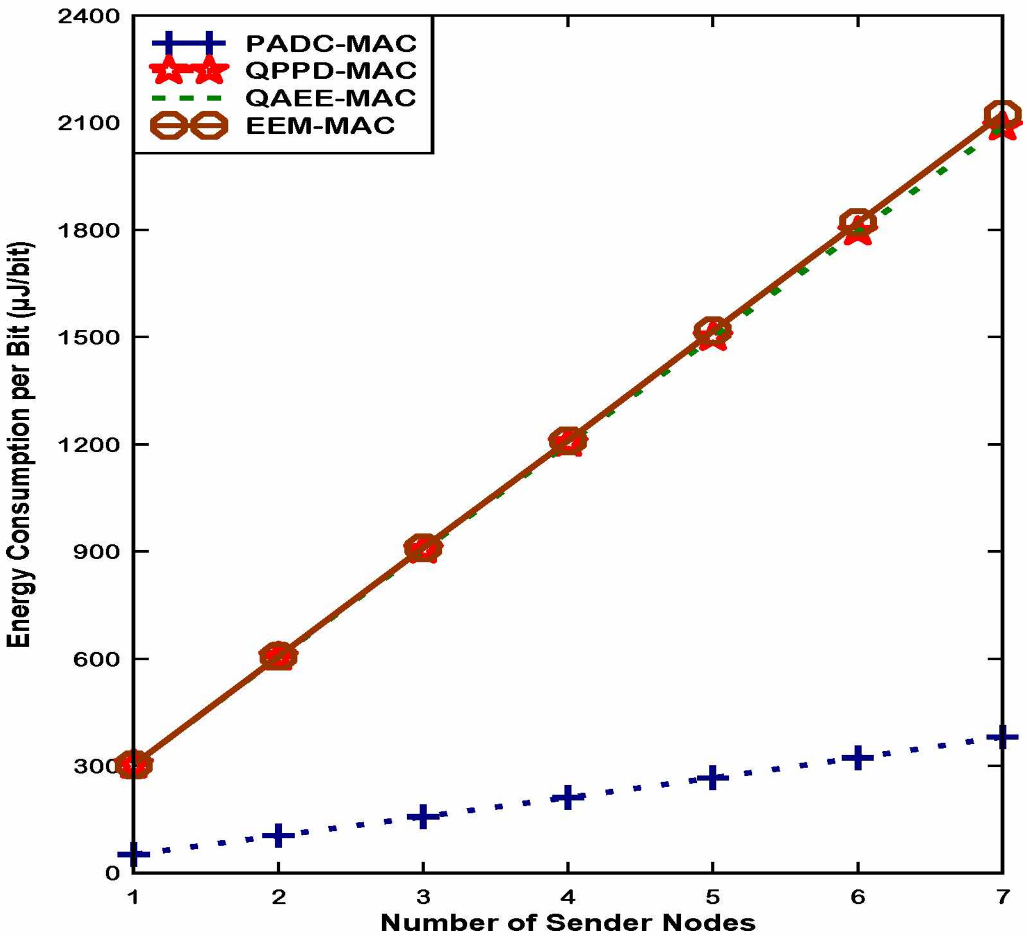

Figure 4.20: Average energy consumption per bit

Figure 4.21 presents the energy consumption of the receiver in all protocols. The results indicate that the PADC-MAC has higher energy consumption by up to 18.1%, 22.6%, and 23.6% compared to QPPD-MAC, QAEEM-MAC, and EEM-MAC, respectively, as expected. The reason is that PADC-MAC aims to optimize network performance when sufficient energy is available. Thus, it increases the duty cycle more aggressively to minimize the packet delay. As a result, it consumes higher energy. However, other protocols become more conservative even though sufficient resources are available. As a result, packets suffer longer delays.

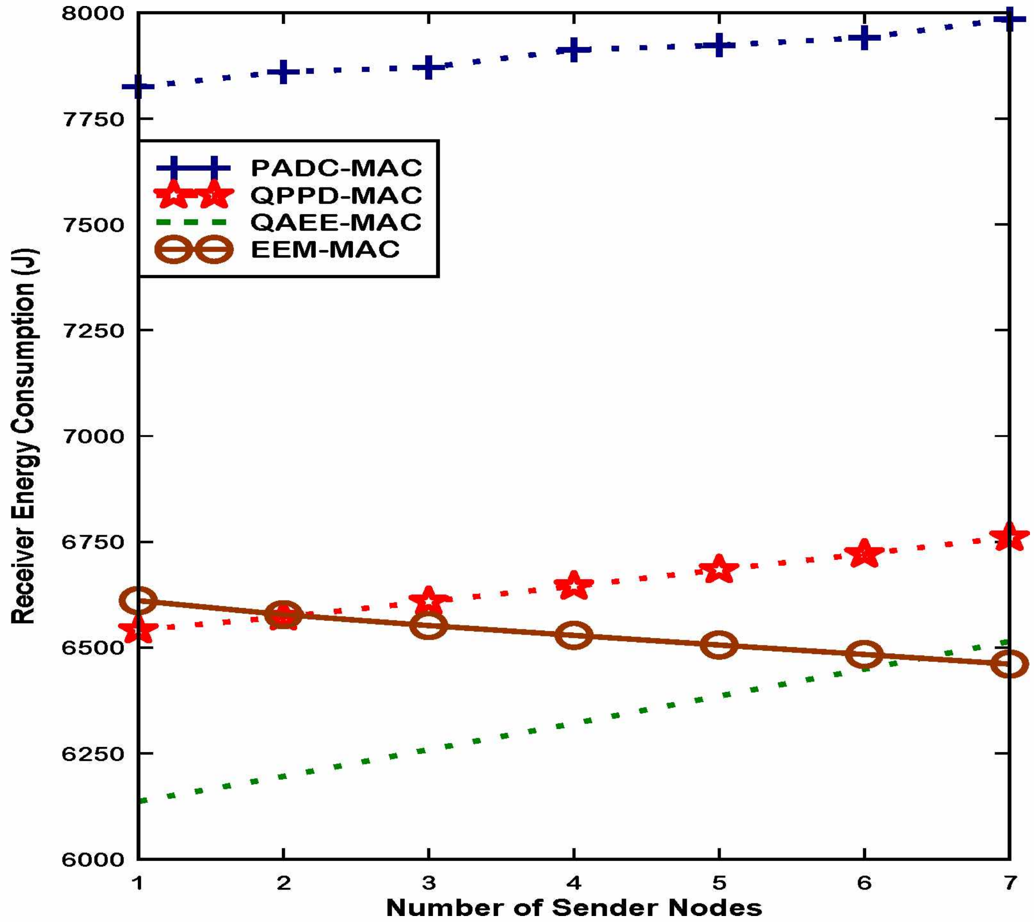

Figure 4.21: Receiver energy consumption

Figure 4.22 presents the total energy consumption in the network. The results show that the PADC-MAC reduces energy consumption by up to 77.7%,77.7%, and 78% compared to QPPD-MAC, QAEE-MAC, and EEM-MAC, respectively. This is mainly because of the self-adaptation technique, that allows the sender to conserve energy by reducing idle listening time, that reduces overall energy consumption in the network.

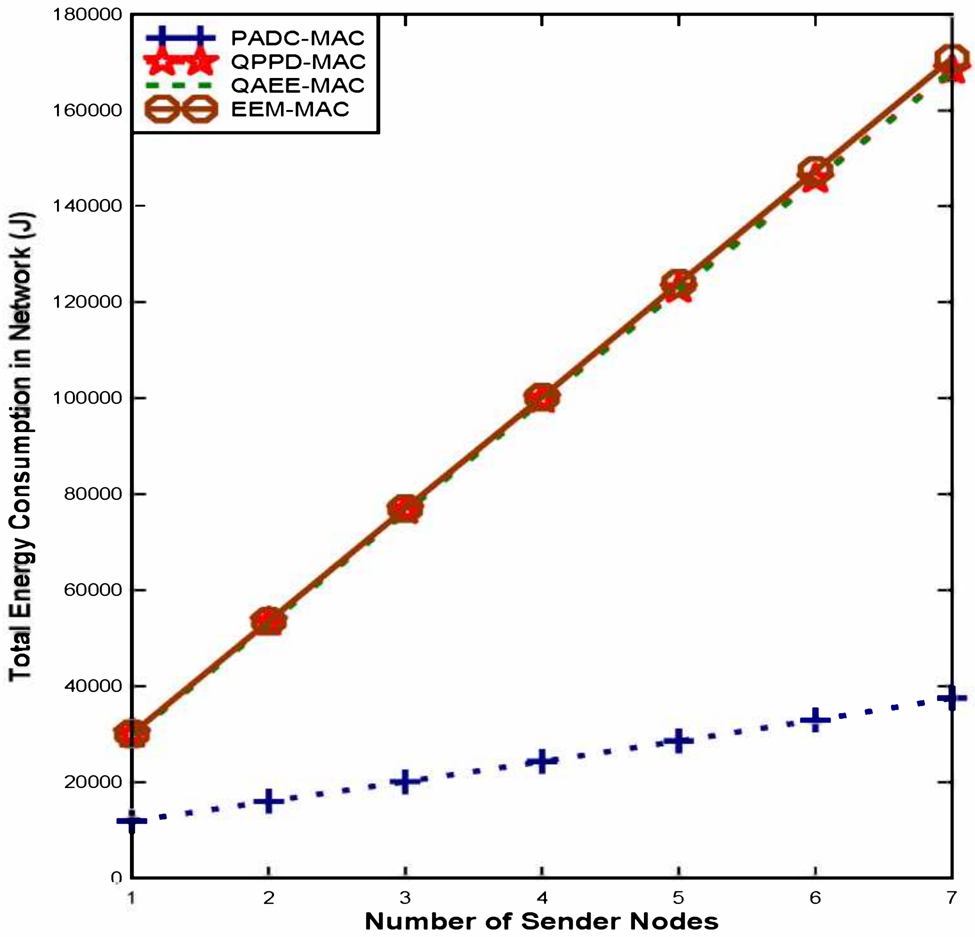

Figure 4.22: Total energy consumption

4.3 Summary

The performance of the proposed NARNET model in comparison with EWMA and actual energy is presented using high and low solar harvesting scenarios. The simulation results show that NARNET achieves good prediction with a correlation coefficient, R greater than 0.95, and provides an notable reduction in MAE of more than 28% in both solar irradiance conditions. Furthermore, the performance of PADC-MAC is evaluated under both scenarios using prediction results obtained from NARNET for four consecutive days, i.e., 96 hours. In both scenarios, the PADC-MAC demonstrated a significant reduction in average ETE delay of the highest priority packets and all packets, energy consumption per bit, and total energy consumption of more than 10.7%, 7.8%, 81%, and 76.4% when compared to other protocols. This is because PADC-MAC uses the duty cycle adjustment mechanism, which allows its receiver to operate more aggressively when sufficient energy resources are available.

The receiver increases its duty cycle corresponding to the battery capacity and predicted energy in the next hour. Thus, it stays operational most of the time, which helps to minimize the packet delay. Furthermore, PADC-MAC uses a self-adaptation technique in which the receiver shares its following wake-up schedule with senders, allowing them to sleep and wake up active slightly prior to the receiver to conserve energy.

Chapter 5

Conclusion and Future Work

5.1 Conclusion

Energy harvesting technology has become a promising solution to power up sensors using energy sources from the ambient environment. However, dynamic harvesting rate due to weather conditions leads the development of adaptive MAC protocols. In the literature, existing MAC protocols have limited consideration in incorporating the future energy intake in scheduling tasks, i.e., duty cycle, which may affect the ongoing node operation and degrade the network's performance. In certain circumstances, for instance, in a high irradiance scenario, nodes may not be able to fully harness the high harvested energy to perform aggressively despite sufficient energy resources.

In this thesis, a novel and more realistic prediction-based adaptive duty cycle MAC protocol has been developed for EH-WSNs, called PADC-MAC. PADC-MAC follows the receiver-initiated approach of asynchronous communication. The receiver establishes the communication by broadcasting a wake-up beacon that contains the receiver duty cycle, which is changed corresponding to energy harvesting conditions. Furthermore, it supports QoS through traffic differentiation by providing the lowest delay for the highest priority packet compared to less critical data packets.

The harvesting rate is known to vary significantly over time due to dynamic weather conditions. Therefore, an energy prediction model, NARNET, has been proposed to support the execution of ongoing tasks efficiently and use the knowledge of future energy intake to enhance the network performance. The developed model forecasts hourly energy intake with good prediction accuracy under dynamic harvesting conditions. Furthermore, PADC-MAC incorporates the predicted energy obtained from NARNET to plan the available energy using a duty cycle adjustment scheme. The proposed approach enables the receiver node to adjust its duty cycle based on current energy and incoming harvested energy to increase network performance. In addition, it allows the receiver node to perform more aggressively by increasing the duty cycle when it has a sufficient inflow of incoming harvested energy to minimize the packet delay. Furthermore, the self-adaptation technique has been introduced to mitigate the idle listening of contending senders and conserve energy in the network. This technique allows sender nodes to use the duty cycle information of the receiver, which is available in the wake-up beacon. In addition, it allows senders to adjust their sleep time accordingly and enables them to wake up slightly before the receiver in the next cycle. As a result, nodes conserve significant energy by reducing idle listening.

The performance of PADC-MAC has been evaluated for single-hop network scenario using GreenCastalia in terms of average ETE delay for the highest priority packet and all packets, throughput, PDR, energy consumption per bit, receiver energy consumption, and total network energy consumption under dynamic solar irradiance conditions. The simulations have been performed for 96 consecutive hours and compared with three state-of-the-art receiver-initiated MAC protocols. In both scenarios, the PADC-MAC demonstrates a significant reduction in average ETE delay of the highest priority packets and all packets, energy consumption per bit, and total energy consumption of more than 10.7%, 7.8%, 81%, and 76.4% when compared to QPPD-MAC, QAEE-MAC, and EEM-MAC protocols. This is because the duty cycle adjustment mechanism in PADC-MAC allows the receiver to adjust the node operation according to the available energy resources i.e., remaining battery energy efficiently, and utilizes the excess incoming harvested energy to enhance the network performance. It has been noticed that in both scenarios, the PADC-MAC has lower remaining energy values when compared to others. This is because the PADC-MAC uses its availabe energy to regulate its duty cycle more aggressive to enhance the network performance, while maintaining and ensuring a stable level of battery energy.

Furthermore, the self-adaptation technique enables sender nodes to manage their sleep time dynamically, which helps mitigate idle listening and saves energy in the network. It is concluded that PADC-MAC effectively contributes to the primary goals of EH-WSNs: long-term network sustainability and efficient utilization of harvested energy to enhance application performance under dynamic harvesting conditions.

5.2 Future Work

The future research works include:

- PADC-MAC can be extended on a large scale to support a multi-hop scenario in EH-WSNs.
- The extension can be made by mathematical modeling and validating the PADC-MAC protocol using testbeds for the specific application that generates different data packets in the network.
- Multi-source energy harvesters can be employed to ensure sustainable operation and increase the amount of harvested energy for adjusting the protocol functionalities such as power control to set the coverage range. In addition, it can limit the use of external energy storage devices, i.e., rechargeable batteries, which offer a limited capacity and are harmful to the environment.
- The enhancements can be made in the energy prediction model to improve the prediction accuracy under different short and medium prediction horizons.

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Овај Образац чини саставни део докторске дисертације, односно докторског уметничког пројекта који се брани на Универзитету у Новом Саду. Попуњен Образац укоричити иза текста докторске дисертације, односно докторског уметничког пројекта.

План третмана података

Назив пројекта/истраживања
MAC протокол адаптивног фактора испуне заснован на предвиђању у бежичним сензорским мрежама са прикупљањем соларне енергије / Prediction based Adaptive Duty Cycle MAC Protocol for Solar Energy Harvesting Wireless Sensor Networks
Назив институције/институција у оквиру којих се спроводи истраживање
а) Факултет техничких наука, Универзитет у Новом Саду
Назив програма у оквиру ког се реализује истраживање
Истраживање је реализовано за потребе израде докторске дисертације на Департману за енергетику, електронику и телекомуникације.
1. Опис података

1.1 Врста студије

Укратко описати тип студије у оквиру које се подаци прикупљају

Студија у оквиру докторске дисертације је спроведена симулацијом. Подаци који су коришћени у докторској дисератици су јавно доступни.

1.2 Врсте података

а) квантитативни

б) квалитативни

1.3. Начин прикупљања података

а) анкете, упитници, тестови

б) клиничке процене, медицински записи, електронски здравствени записи

в) генотипови: навести врсту ___________________________________

г) административни подаци: навести врсту _________________________

д) узорци ткива: навести врсту____________________________________

ђ) снимци, фотографије: навести врсту_______________________________ е) текст, навести врсту ____

ж) мапа, навести врсту _______________________________________

з) остало: нумерички подаци за предикцију соларне енергије

1.3 Формат података, употребљене скале, количина података

1.3.1 Употребљени софтвер и формат датотеке:

a) Excel фајл, датотека CSV

b) SPSS фајл, датотека __________________

c) PDF фајл, датотека ___________________

d) Текст фајл, датотека __________________

e) JPG фајл, датотека ___________________

f) Остало, датотека ____________________

1.3.2. Број записа (код квантитативних података)

а) број варијабли 2

б) број мерења (испитаника, процена, снимака и сл.): 13 862

1.3.3. Поновљена мерења

а) да

б) не

Уколико је одговор да, одговорити на следећа питања:

а) временски размак између поновљених мера је ______________________________

б) варијабле које се више пута мере односе се на ________________________________

в) нове верзије фајлова који садрже поновљена мерења су именоване као ____________

Напомене: ____

Да ли формати и софтвер омогућавају дељење и дугорочну валидност података?

а) Да

б) Не

Ако је одговор не, образложити ____

____

2. Прикупљање података

2.1 Методологија за прикупљање/генерисање података

2.1.1. У оквиру ког истраживачког нацрта су подаци прикупљени?

а) експеримент, навести тип симулација

б) корелационо истраживање, навести тип ____

ц) анализа текста, навести тип ____

д) остало, навести шта ____

2.1.2 Навести врсте мерних инструмената или стандарде података специфичних за одређену научну дисциплину (ако постоје).

Сензори

2.2 Квалитет података и стандарди

2.2.1. Третман недостајућих података

а) Да ли матрица садржи недостајуће податке? Да **Не**

Ако је одговор да, одговорити на следећа питања:

а) Колики је број недостајућих података? __________________________

б) Да ли се кориснику матрице препоручује замена недостајућих података? Да Не

в) Ако је одговор да, навести сугестије за третман замене недостајућих података

____

2.2.2. На који начин је контролисан квалитет података? Описати

Подаци су припремљени и обрађени у складу са предложеном медологогијом у докторској дисертацији.

2.2.3. На који начин је извршена контрола уноса података у матрицу?

Унос података није контролисан с обзиром на то да су коришћени подаци који су доступни онлине.

3. Третман података и пратећа документација

3.1. Третман и чување података

3.1.1. Подаци ће бити депоновани у ___________________________________ репозиторијум.

3.1.2. URL адреса https://midcdmz.nrel.gov/oahu_archive/

3.1.3. DOI ____

3.1.4. Да ли ће подаци бити у отвореном приступу?

а) Да

б) Да, али после ембарга који ће трајати до ___________________________________

в) Не

Ако је одговор не, навести разлог ____

3.1.5. Подаци неће бити депоновани у репозиторијум, али ће бити чувани.

Подаци неће бити депоновани у репозиторијум, јер се налазе онлине. Поред тога, на самом сајту одакле су коришћени подаци налази се образложење да подаци не смеју даље да се дистрибуирају.

3.2 Метаподаци и документација података

3.2.1. Који стандард за метаподатке ће бити примењен? ___________________________________

3.2.1. Навести метаподатке на основу којих су подаци депоновани у репозиторијум.

____

____

Ако је потребно, навести методе које се користе за преузимање података, аналитичке и процедуралне информације, њихово кодирање, детаљне описе варијабли, записа итд.

____

____

3.3 Стратегија и стандарди за чување података

3.3.1. До ког периода ће подаци бити чувани у репозиторијуму? ________________________

3.3.2. Да ли ће подаци бити депоновани под шифром? Да Не

3.3.3. Да ли ће шифра бити доступна одређеном кругу истраживача? Да Не

3.3.4. Да ли се подаци морају уклонити из отвореног приступа после извесног времена?

Да Не

Образложити

___

___

4. Безбедност података и заштита поверљивих информација

Овај одељак МОРА бити попуњен ако ваши подаци укључују личне податке који се односе на учеснике у истраживању. За друга истраживања треба такође размотрити заштиту и сигурност података.

4.1 Формални стандарди за сигурност информација/података

Истраживачи који спроводе испитивања с људима морају да се придржавају Закона о заштити података о личности *(https://www.paragraf.rs/propisi/zakon_o_zastiti_podataka_o_licnosti.html)* и одговарајућег институционалног кодекса о академском интегритету.

4.1.2. Да ли је истраживање одобрено од стране етичке комисије? Да **Не**

Ако је одговор Да, навести датум и назив етичке комисије која је одобрила истраживање

___

4.1.2. Да ли подаци укључују личне податке учесника у истраживању? Да **Не**

Ако је одговор да, наведите на који начин сте осигурали поверљивост и сигурност информација везаних за испитанике:

а) Подаци нису у отвореном приступу

б) Подаци су анонимизирани

ц) Остало, навести шта

___

___

5. Доступност података

5.1. Подаци ће бити

а) јавно доступни

б) доступни само уском кругу истраживача у одређеној научној области *ц) затворени*

Ако су подаци доступни само уском кругу истраживача, навести под којим условима могу да их користе:

____

____

Ако су подаци доступни само уском кругу истраживача, навести на који начин могу приступити подацима:

____

____

5.4. Навести лиценцу под којом ће прикупљени подаци бити архивирани.

____

6. Улоге и одговорност

6.1. Навести име и презиме и мејл адресу власника (аутора) података

Сохаил, sohail@uns.ac.rs

6.2. Навести име и презиме и мејл адресу особе која одржава матрицу с подацима

Сохаил, sohail@uns.ac.rs

6.3. Навести име и презиме и мејл адресу особе која омогућује приступ подацима другим истраживачима

Сохаил, sohail@uns.ac.rs