ENHANCED PRIORITY-BASED ADAPTIVE ENERGY-AWARE MECHANISMS FOR WIRELESS SENSOR NETWORKS

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DEDICATION

This thesis is dedicated to Almighty God who gave me the strength, good health, and stable mental capacity to start and finish this programme. It is also dedicated to my beautiful and loving wife and to my Children who supported me with their love and prayers. I love you all from now to infinity Amen.

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ABSTRACT

Wireless Sensor Networks (WSN) continues to find its use in our lives. However, research has shown that it has barely attained an optimal performance, particularly in the aspects of data heterogeneity, data prioritization, data routing, and energy efficiency, all of which affects its operational lifetime. The IEEE 802.15.4 protocol standard, which manages data forwarding across the Data Link Layer (DLL) does not address the impact of heterogeneous data and node Battery-Level (BL) which is an indicator for node battery life. Likewise, mechanisms proposed in the literature – TCP-CSMA/CA, QWL-RPL and SSRA have not proffered optimal solution as they encourage excessive computational overhead which results in shortened operational lifetime. These problems are inherited on the Network Layer (NL) where data routing is implemented. Mitigating these challenges, this research presents an Enhanced Priority-based Adaptive Energy-Aware Mechanisms (EPAEAM) for Wireless Sensor Networks. The first mechanism is the Optimized Backoff Mechanism for Prioritized Data (OBMPD) in Wireless Sensor Networks. This mechanism proposed the Class of Service Traffic Priority-based Medium Access Control (CSTP-MAC). The CSTP-MAC is implemented on the DLL. In this mechanism, unique backoff period expressions compute backoff periods according to the class and priority of the heterogeneous data. This approach improved network performances which enhanced network lifetime. The second mechanism is the Shortest Path Priority-Based Objective Function (SPPB-OF) for Wireless Sensor Networks. SPPB-OF is implemented across the NL. SPPB-OF implements a unique shortest path computation algorithm to generate energy-efficient shortest path between the source and destination nodes. The third mechanism is the Cross-Layer Energy-Efficient Priority-based Data Path (CL-EEPDP) for Wireless Sensor Networks. CL-EEPDP is implemented across the DLL and NL with considerations for node battery-level. A unique mathematical expression, Node Battery-Level Estimator (NBLE) is used to estimate the BL of neighbouring nodes. The knowledge of the BL together with the priority of data are used to decide an energy-efficient next-hop node. Benchmarking the EPAEAM with related mechanisms - TCP-CSMA/CA, QWL-RPL and SSRA, results show that EPAEAM achieved improved network performance with a packet delivery ratio (PDR) of 95.4%, and power-saving of 90.4%. In conclusion, the EPAEAM mechanism proved to be a viable energy-efficient solution for a multi-hop heterogeneous data WSN deployment with support for extended operational lifetime. The limitations and scope of these mechanisms are that their application is restricted to the data-link and network layers, moreover, only two classes of data are considered, that is; High Priority Data (HPD) and Low Priority Data (LPD).

ABSTRAK

Rangkaian Sensor Tanpa Wayar (WSN) masih terus mendapat tempat dalam kehidupan kita. Namun begitu, kajian menunjukkan bahawa ia hampir tidak mencapai prestasi yang optimum, terutama dalam aspek heterogeniti data, keutamaan data, penghalaan data, dan kecekapan tenaga, dimana ia mempengaruhi tempoh masa operasi. Protocol standard IEEE 802.15.4 yang menguruskan pemajuan data melintasi lapisan pautan data (DLL), tidak mengambilkira kesan terhadap kepelbagaian data dan tahap bateri (BL) nod dalam menentukan penanda aras jangka hayat bateri nod. Demikian juga, mekanisme yang dicadangkan dalam tinjauan literatur - TCP-CSMA/CA, QWL-RPL dan SSRA belum memberikan penyelesaian yang optimum kerana ia mendorong kepada penggunaan komputasi yang berlebihan yang mengakibatkan jangka hayat operasi menjadi lebih pendek. Masalah-masalah ini diwarisi pada lapisan rangkaian (NL) di mana penghalaan data dilaksanakan. Untuk mengatasi isu ini, kajian terhadap Mekanisme Pengukuhan Tenaga Adaptif Berasaskan Keutamaan (EPAEAM) dilaksanakan. Mekanisme pertama ialah Mekanisme Undur yang Dioptimumkan untuk Data Keutamaan (OBMPD) dalam WSN. Mekanisme ini mencadangkan Pengendalian Akses Medium berasaskan Keutamaan Lalu Lintas Perkhidmatan (CSTP-MAC) dimana ia dilaksanakan pada DLL. Dalam mekanisme ini, ungkapan tempoh undur unik bagi menghitung jangka masa undur adalah berdasarkan kelas dan keutamaan kepelbagaian data. Pendekatan ini meningkatkan prestasi dan jangka hayat rangkaian. Mekanisme kedua untuk WSN ialah Fungsi Objektif Berasaskan Laluan Terpendek (SPPB-OF) dimana ia dilaksanakan di seluruh lapisan rangkaian (NL). SPPB-OF melaksanakan algoritma pengiraan jalur unik untuk menghasilkan laluan terpendek yang cekap tenaga antara nod sumber dan destinasi. Manakala mekanisme ketiga adalah Laluan Data Cekap Tenaga Berasaskan Keutamaan Lintas-Lapisan (CL-EEPDP) di mana CL-EEPDP dilaksanakan di seluruh DLL dan NL dengan mengambil kira tahap bateri nod. Ungkapan unik matematik, Node Battery-Level Estimator (NBLE) digunakan untuk mengira BL nod jiran. Pengetahuan berkaitan BL serta keutamaan data digunakan untuk menentukan hop nod seterusnya yang cekap tenaga. Penanda aras EPAEAM dengan mekanisme yang berkaitan - TCP-CSMA/CA, QWL- RPL dan SSRA, menunjukkan bahawa EPAEAM mencapai prestasi rangkaian yang lebih baik dengan nisbah penghantaran paket (PDR) 95.4%, dan penjimatan tenaga sebanyak 90.4%. Kesimpulannya, mekanisme EPAEAM terbukti menjadi solusi yang cekap tenaga untuk penggunaan kepelbagaian hop WSN dengan sokongan jangka hayat operasi yang panjang. Batasan dan ruang lingkup mekanisme ini ialah aplikasinya terbatas pada lapisan pautan data dan rangkaian, malah, hanya dua kelas data yang dipertimbangkan, iaitu; Data Keutamaan Tinggi (HPD) dan Data Keutamaan Rendah (LPD).

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µIP	-	Micro IP
5G	-	Fifth Generation telecommunication standard
6LoWPAN	-	IPv6 over Low-power Wireless Personal Area Network
ACK	-	Acknowledgement
ADC	-	Analogue to Digital Converter
AODV	-	Ad-hoc On-demand Distance Vector
API	-	Application Programming Interface
APP	-	Application Layer
BAN	-	Body Area Network
BE	-	Backoff Exponential
BEB	-	Binary Exponential Backoff
BER	-	Bit Error Rate
BF	-	Bloom Filter
BI	-	Beacon Interval
BLE	-	Battery Life Extension
BL	-	Battery-Level
BMAC	-	Berkeley MAC
BO	-	Beacon Order
BP	-	Backoff Period
BPCM	-	Backoff Period Computation Mechanism
BSN	-	Body Sensor Network
CAP	-	Contention Access Period
CBR	-	Constant Bit Rate
CC	-	Coulomb Counting
CCA	-	Clear Channel Assessment
CFP	-	Contention Free Period
CL-EEPDP	-	Cross-layer Energy-efficient Priority-based Data Path
CMO	-	Control Messages Overhead
CoAP	-	Constrained Application Protocol

COOJA	-	Contiki Object Oriented JAva-based simulator
CP	-	Critical Packet
CPM	-	Closest-fit Pattern Matching
CPU	-	Central Processing Unit
CRQ	-	Collision Resolution Queueing
CS	-	Class of Service
CSMA/CA	-	Carrier Sense Multiple Access with Collision Avoidance
CSMA/CD	-	Carrier Sense Multiple Access with Collision Detection
CSTP-MAC	-	Class of Service Priority-based MAC
CTC	-	Critical Traffic Class
CTS	-	Clear to Send
CW	-	Contention Window
CXMAC	-	Compatibility XMAC
DAG	-	Directed Acyclic Graph
DAO	-	Destination Advertisement Object
DAO-ACK	-	Destination Advertisement Object with Acknowledgement
DARPA	-	Defence Advanced Research Projects Agency
DC	-	Duty Cycle
DGRM	-	Directed Graph Radio Model
DIO	-	DODAG Information Object
DIS	-	DODAG Information Solicitation
DLL	-	Data Link Layer
DODAG	-	Destination Oriented Directed Acyclic Graph
DTC	-	Delay Traffic Class
DTSN	-	Destination Advertisement Trigger Sequence Number
eMC-MAC	-	Energy-efficient Multi-constrained QoS aware MAC
EPAEAM	-	Enhanced Priority-based Energy Aware Mechanism for extended wireless sensor networks lifetime
ERPL	-	Enhanced Routing Protocol for Low-power and Lossy Network

ESB	-	Embedded Sensor Board
ETASA	-	Energy and Traffic-Aware Sleep Awake
ETX	-	Expected Transmission Cost or Expected Cost of Transmission
FFD	-	Full Function Device
FIFO	-	First In First Out
GPS	-	Global Positioning Satellites
GSN	-	Global Sensor Network
GTS	-	Guarantee Time Slot
GUI	-	Graphical User Interface
HC	-	Hop Count object
HPD	-	High Priority Data
IC	-	Integrated Circuit
ICMP	-	Internet Control Messaging Protocol
ICMPv6	-	Internet Control Messaging Protocol version 6
IEEE	-	Institute of Electrical and Electronics Engineering
IETF	-	Internet Engineering Task Force
IoT	-	Internet of Things
IP	-	Internet Protocol
ISM	-	Industrial, Scientific and Medical
ISR	-	Improved Secure Routing
JNI	-	Java Native Interface
LAN	-	Local Area Network
LA-RPL	-	Learning Automata bases RPL
LBR	-	Low-power and Lossy network Border Router
LEACH	-	Low Energy Adaptive Clustering Hierarchy
LLC	-	Logical Link Control Layer
LLN	-	Low-power and Lossy Networks
LPD	-	Low Priority Data
LPL	-	Low Power Listening
LPM	-	Low Power Mode
LPP	-	Low Power Probing
LQL	-	Link Quality Level

LQM	-	Link Quality Metric
MAC	-	Media/Medium Access Control
MC	-	Metric Container
MCS	-	Mobile Crowd Sensor
MCU	-	Microcontroller Unit
MDN	-	Multi-DODAG Node
MEM	-	Micro-Electro-Mechanical
MFR	-	MAC Footer
MHR	-	MAC Header
MOP	-	Mode of Operation
MP2P	-	Multipoint-to-Point
MPDU	-	MAC Protocol Data Unit
MRHOF	-	Minimum Rank with Hysteresis Objective Function
MSDU	-	MAC Service Data Unit
NB	-	Number of Backoff
ND	-	Neighbour Discovery
NDR	-	New DODAG Request
NE	-	Node Energy object
NL	-	Network Layer
NRT	-	Non-real-time
NS	-	Network Simulator
NSA	-	Node State Attribute
NTC	-	Non-constraint Traffic Class
OCP	-	Object Code Point
OF	-	Objective Function
OF0	-	Objective Function Zero
OP	-	On-demand Packet
OS	-	Operating System
OSI	-	Open System Interconnect
P2MP	-	Point-to-Multipoint
P2P	-	Peer to Peer
PAN	-	Personal Area Network
PDR	-	Packet Delivery Ratio

PG-MAC	-	Priority Guarantee MAC
PHY	-	Physical Layer
PPDU	-	Physical Protocol Data Unit
PRE	-	Packet Replication and Elimination
PriNergy	-	Priority-based and energy-efficient routing
PRR	-	Packet Reception Rate
PSDU	-	Physical Service Data Unit
QoS	-	Quality of Service
QWL-RPL	-	Queue and Workload-based condition RPL
RAM	-	Random Access Memory
RDC	-	Radio Duty Cycle
RE	-	Residual Energy
RF	-	Radio Frequency
RFC	-	Request for Comments
RFD	-	Reduced Function Device
ROLL	-	Routing Over Low-power and Lossy networks
RPL	-	Routing Protocol for Low-power and Lossy Network
RREQ	-	Route Request
RT	-	Real-time
RTC	-	Reliability Traffic Class
RTS	-	Request to Send
SD	-	Superframe Duration
SMAC	-	Sensor MAC
SO	-	Superframe Order
SOC	-	State of Charge
SOH	-	State of Health
SPPB-OF	-	Shortest Path Priority-based Objective Function
SSL/TLS	-	Secured Shell Layer/Transport Layer Security
SSRA	-	Smart and Self-organized Routing Protocol
TAP-MAC	-	Traffic Adaptive Priority-based MAC
TCP/IP	-	Transmission Control Protocol/ Internet Protocol
TCP-CSMA/CA	-	Transmission Control Protocol-Carrier Sense Multiple Access with Collision Avoidance

TDMA	-	Time Division Multiple Access
TMAC	-	Timeout MAC
TRQ	-	Transmission Queueing
TSCH	-	Time-Slotted Channel Hopping
UDGM	-	Unit Disk Graph Model
UDP	-	User Datagram Protocol
USB	-	Universal Serial Bus
WBAN	-	Wireless Body Area Network
WCETT	-	Weighed Cumulative Expected transmission Time
WT	-	Waiting Time
WSN	-	Wireless Sensor Networks

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CHAPTER 1

INTRODUCTION

1.1 Overview of Wireless Sensor Network Lifetime

The world as we know it is phenomenally evolving and everything in it is complying accordingly, bearing new names – *smart cities, smart world, Internet of Things (IoT), fifth-generation telecommunication (5G)* (Junior et al., 2020). This process generates huge volume of data that can be represented for gainful use using data analytics (Feng et al., 2020). This paradigm holds the promises of animating the world in such a way that it appears to have a *virtual brain* of its own, which is made up of living and non-living things, tagged with trackable wireless sensor devices/nodes forming the network termed as *Wireless Sensor Networks (WSN)* (Kalidoss et al., 2020). These wireless nodes function cooperatively and collectively, making decisions that may be partially dependent or completely independent of human intervention. These sensors or nodes are so autonomous that they can act on their own as they are powered by long-span battery or by energy harvesting means such as solar or mechanical vibrations. Been an autonomous self-powered device (node), with an expected long working life, one of its major challenges is power/energy. While routing data from one node to the other in a multi-hop pattern, it becomes imperative to utilize routing and power-efficient mechanisms that can sustain the nodes and the network for a long duration even amid unfavourable situations such as network threats (attacks) and natural disasters. A typical wireless sensor network is formed by a tree-like hierarchical virtual routing graph consisting of the *Sink* (network coordinator) also referred to as the Root node and some sets of *Relay nodes* and *Leaf nodes* (also known as Edge or Boundary nodes). Nodes closer to the sink are referred to as Hotspot nodes, as they are the busiest of nodes besides the Sink. Data is constantly routed through them to the Sink. A typical WSN topological architecture is depicted in Figure 1.1.

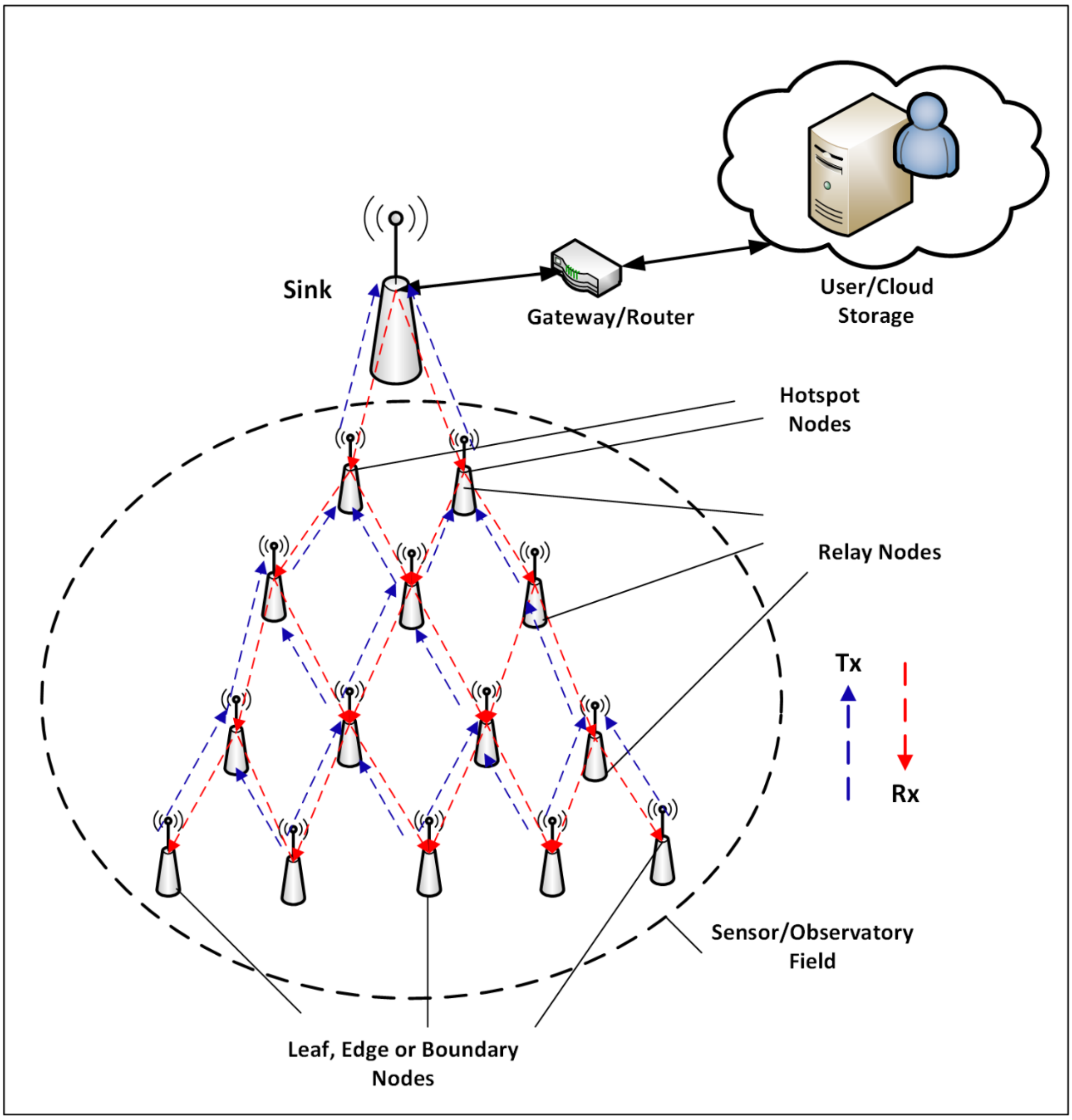

Figure 1.1 A typical wireless sensor network topological architecture

Network lifetime is a critical issue in WSN as sensor nodes are mostly autonomously powered by battery that are limited in capacity. It is defined as the time for which the first node completely runs out of battery energy (Tekin & Gungor, 2020). This leads to the creation of a hole in the network which encourages the shortening of the network operational lifetime. While the primary goal of the WSN is to monitor and transmit sensed data of its target environment, the network lifetime determines how long the network will remain operational to execute this primary function.

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1.2 Energy Efficiency Issues of Wireless Sensor Network

The energy efficiency and network lifetime of WSN has become a major cause of concern as this is a factor that determines the extended operational network lifetime for large-scale WSN, particularly as it generates huge volume of data, which can which can be best represented by the concept of data analytics (Hossein Motlagh et al., 2020). This has attracted attention both from the academia and the industry. This is attributed to the autonomous battery powered nature of the sensor nodes/devices, which is mostly limited as this impact negatively on the network lifetime of the sensor network.

An efficient and optimized operational mechanism is needed to efficiently manage the routing of data across the nodes while ensuring that energy is conserved. While the demanding request is for a node to remain operational for as long as possible, this leaves an open area of research on finding effective ways to optimizing the constrained/limited power of the observatory nodes in such a way as to extend the overall operational lifetime of the WSN (Balamurugan & Arulkumaran, 2019; Ghaleb et al., 2019; Muzakkari et al., 2020).

The most important aspect of a sensor node in a sensor network is, keeping the nodes operational for as long as possible, as they operate in mostly harsh environments that are sometimes not easily accessible. The goal of a sensor network is defeated if the sensor node cannot operate for a long period in the harshest of conditions. However, sensor nodes are faced with lots of challenges, which adds pressure on them leading to early power drainage as they are mostly battery powered. The primary operation that drains the most power of a node is when it is under active operations (that is, sensing, processing, and transmitting). Keeping the node alive as long as possible is paramount and finding the best way of doing so will continue to be a lucrative open research area.

Whether powered by energy harvesting means or by a battery, WSN faces power depletion challenges, especially under extended computation and data routing which may be under legitimate (normal operations) or illegitimate (under attack) operations. Over the years, researchers have been proposing various means to optimize the network lifetime of WSN. However, to achieve this feat, it becomes important to practically understand the operations and components of the sensor node that drains its battery as well as the layers of the WSN protocol stack concerned with data forwarding, data routing and power consumption.

Because the energy consumed by sensor nodes is very low, they can operate unattended for several months or even years, especially if working in ideal conditions. With little or no management cost, WSN supports large deployment of sensor nodes. Its advantageous small size has made it easy to be used for various applications, like in the military, health, logistics, farming, home automation, and education.

1.3 Problem Background

The heterogeneous nature of data generated by WSN has often been overlooked, as much attention has not been paid to it in the literature. Heterogeneous data are generated from various user-specific applications of WSN (Gupta & Biswas, 2020; Masud et al., 2019). These data can be classified into real-time and non-real-time, which defines the degree of timeliness and importance attached to the information been conveyed, where real-time data convey time-sensitive information and non-real-time data conveys delay-tolerant information. This overlooked yet significant aspect of WSN contributes largely to how the sensor node constrained energy is utilized. To achieve optimal WSN performance while improving power management, heterogeneous data need to be classified and prioritized into an order of importance, as non-prioritized or poorly prioritized data stream may lead to excessive power consumption, as the data routing mechanism will unintentionally handle all classes of data as the same without treating a particular class different from the other. This practice results in suboptimal network performances and eventual shortening of the network lifetime, bearing in mind that effective energy conservation is the key to extended operational lifetime.

The longevity of the network lifetime of a sensor node is dependent on how busy or active it executes operations (that is, data forwarding, data routing, data prioritization methods/mechanisms, and route rerouting/recovery mechanism). The amount of data transmitted and received, the time it takes to transmit and receive data, and the processing durations also affect the sensor node lifetime. In order words, *the network lifetime of an entire sensor network is directly proportional to the lifetime of a single sensor node*. The exhaustion of a single node in the network creates a hole as its responsibilities are shared among other active constrained nodes, leading to processing and communication overhead on the fewer available nodes, this results in excessive power consumption of available nodes, leading to a possible failure of the entire network. The major issues affecting optimal energy utilization of WSN are; inefficient classification and prioritization of IEEE 802.15.4 heterogeneous data across the data link layer, suboptimal prioritization and route estimation of heterogeneous data across the network layer, and unreliable and inefficient node battery-level estimation and forwarding paths for heterogeneous data. The following sections further provide details that describes the problem background for this research.

1.3.1 Inefficient Classification and Prioritization of IEEE 802.15.4 Heterogeneous Data

The prioritization of heterogeneous data in WSN gives meaning to mission-critical data that are time-sensitive as they may be conveying information that may be a matter of life and death, hence such data needs to be processed timely and with the highest available priority. However, the IEEE 802.15.4 standard which operates on the data link layer of the WSN protocol stack, does not consider the heterogeneous nature of WSN data, nor does it implement data prioritization (Masud et al., 2019; Society, 2020). Subsequently, prioritization mechanisms proffered in the literature have not adequately addressed this issue as the proposed mechanisms either uses a single or complex backoff algorithm to estimate backoff time-slots for prioritized data. Also, the carrier sense multiple access with collision avoidance mechanism exhibits an exponentially increasing range of backoff times. These approaches are not only inefficient but result in high latency and increased power consumption, which impacts negatively on the network lifetime of the WSN.

The IEEE 802.15.4 nodes use the mechanism of carrier sense multiple access with collision avoidance (CSMA/CA) (Punia & Ziya, 2019) to gain access to the shared medium of transmission. According to application or user requirements, most WSN data conveys data of varying priorities which can be majorly grouped into *real-time (RT)* and *non-real-time (NRT)* data. Without prioritizing these data, data with less importance can clog the shared medium of transmission, thereby denying data that needs urgent attention which may be conveying mission-critical information. This inadequacy in the standard IEEE 802.15.4 has prompted active research for improvement. In the CSMA/CA mechanism, nodes need to sense the medium of transmission to ascertain that it is free of any ongoing transmission before attempting to engage in data transmission. If the medium is perceived to be busy, the node backoff by a predetermined period before reattempting to transmit the data. The *Binary Exponential Backoff (BEB)* algorithm (Sahoo et al., 2019) is used to compute the backoff period. *However, this computation is done without regard to the heterogeneous nature of the data*. This practice results in depriving data of critical importance the timely access they need to access the shared transmission medium, and subsequently degrades the entire network performance. This leads to an open area of research that calls for improvements.

Masud et al. (2019) proposed the TCP-CSMA/CA mechanism which handles heterogeneous data. Data are classified into four categories namely the Critical Traffic Class (CTC), Reliability Traffic Class (RTC), Delay Traffic Class (DTC), and the Non-constraint Traffic Class (NTC). These classes are assigned priority levels and backoff periods unique to the class of data; however, the proposed backoff estimation algorithm appears rather complex which adds an extra layer of computational overhead on the already constrained nodes.

While Wireless Body Area Network (WBAN) handles the heterogeneous data generated by the patient under observation, the data latency and energy consumption call for concern as this impact negatively on the performance of the heterogeneous data. Based on data prioritization, Markov's method was adopted to propose a mechanism that improves network delays and energy consumption (Rismanian Yazdi et al., 2019). The proposed mechanism classifies data into three categories; emergency, periodic, and normal. However, the prioritization and classification approaches were not clearly stated, and the unique backoff expression that estimates the backoff period for the categories of data was not provided in detail, leaving the reader with an unclear approach.

The Energy-efficient Multi-constrained QoS aware MAC (eMC-MAC) was proposed by Pandit et al. (2015), to improve the handling of heterogeneous data in WBAN with regards to energy consumption, latency, and packet delivery rate. Data packets were categorized into four different categories with assigned priority status. subsequently, the superframe was enhanced to accommodate all these categories of data types. In this mechanism, the superframe structure was modified to entertain the immediate transmission of critical data whenever available. Furthermore, mini-slots was introduced into the standard Contention Free Period (CFP), which collects the requests of data that needs urgent attention and send them to the coordinator node as required in an energy-efficient manner. An energy-efficient algorithm was also developed to assist in the preemption of higher priority data to facilitate timely transmission to the coordinator node. While the mechanism claims to be optimal, the detailed implementation of preemption was not explained, as there is no proactive mechanism that interrupts lower priority data once they gain access to the shared medium of transmission.

Rasheed et al. (2017) proposed the priority guaranteed MAC (PG-MAC) protocol with a modified superframe structure of the IEEE 802.15.4 standard. This mechanism claims to address the network lifetime challenge, which is a common problem of WSN. Subsequently, it addresses the issue of network delays and other related QoS requirements. To achieve this result, the mechanism modifies the standard superframe to accommodate heterogeneous data with varying priority tags. To save energy, a wake-up mechanism was also implemented. Also, the discrete-time finite-state Markov's model was used to find the state of the node, while analytical expressions were derived to estimate the average energy consumption, throughput, packet loss rate, and latency. Though the results of this mechanism look promising, however, the complexity of the mechanism adds excessive computational overhead on the network leading to untimely power degradation.

Finally, it is observed that most of the existing mechanisms generate suboptimal performances due to non or poorly implemented data prioritization and channel sensing mechanisms resulting in inefficient performances or excessive computational overhead which degrades the WSN scarce power. To achieve an improved performance for various types of IEEE 802.15.4 applications, an improved mechanism should be designed that considers all noted shortcomings in the literature while considering the heterogeneous nature of the WSN data with overall optimized network performances, which encourages extended network lifetime.

1.3.2 Inefficient and Suboptimal Prioritization and Route Estimation of Heterogeneous Data Across the WSN Protocol Stack Network Layer

The Routing Protocol for Low-power and Lossy Networks (RPL), is the de facto routing protocol for the IoT which manages and administers the smooth transportation of data packets across the WSN. However, the mechanism fails to address the heterogeneous nature of data packets traversing the network layer, as these packets may carry different classes of data with different priority status, some real-time (time-sensitive) while others non-real-time (delay-tolerant). The standard Objective Functions (OFs) (Solapure & Kenchannavar, 2020), which is used by RPL to create routing path, treats all classes of data as the same, this practice is not only inefficient but results in poor network performance. This inadequacy leaves an open area of research that has attracted attention from both academia and the industry.

The Priority-based and Energy Efficient Routing was proposed by Safara et al. (2020). This mechanism focuses on improving the challenges of energy consumption, load balancing, and related QoS constraints associated with data aggregation towards the coordinator node and to the outside network. Improving upon the RPL mechanism, PriNergy uses timing patterns to send data to the coordinator node while considering network traffic. Audio and image data are the two types of data considered. Using the Time Division with Multiple Access (TDMA) mechanism, in each time slot, the time and distance information of the sender node is sent to the destination node which synchronizes with each order before the data is sent. The result shows that the mechanism performs better than related mechanisms, however, the mechanism does not show in detail how the algorithm is established as there exist lots of assumptions in their approach. Subsequently, the heterogeneous nature of data is not adequately considered.

The Queue and Workload-based condition RPL (QWL-RPL) was proposed by Musaddiq et al. (2020). This mechanism considers the bottleneck experienced by an already exhausted parent node that receives a stream of heterogeneous data due to the poor decisions of the RPL Objective Functions; Objective Function Zero (OF0) and Minimum Rank with Hysteresis Objective Function (MRHOF) which leads to excessive power consumption, hole in the network and shortening of the network lifetime. QWL-RPL targets to achieve a reliable routing path with improved network performance. Using packet queuing techniques with the knowledge of the link workload, QWL-RPL maps the child node to a less congested parent node, by this way the mechanism enforces optimized load balancing and reduces unnecessary power consumption which eventually leads to extended operational lifetime. Compared to the related mechanism, the result of the QWL-RPL mechanism shows better network performance. However, the heterogeneous nature of the WSN data was not adequately described, and the implementation of prioritization for the data packets was unclear.

For concerns about the vulnerabilities and security of the WSN, Shi et al. proposed the am Improved Secure Routing (ISR) to secure the RPL protocol from malicious attacks (Shi et al., 2019). In this mechanism, the concept of trust value is used to define the integrity and status of the node. The trust value defines the attack probability upon the behaviors of the previously forwarded packets, the details of the node residual energy, and its distance to the sink. This helps to increase route integrity while securing the routing paths. The mechanism adopts the improved variant of the Dijkstra algorithm to generate a secured route while ensuring an optimized network. While results look promising, however, the mechanism does not consider the heterogeneous nature of WSN data in its implementations. Subsequently, the complexity of the mechanism is likely to cause increased routing overhead which leads to increased power consumption.

Learning Automata bases RPL (LA-RPL) was proposed by Homaei et al. (2019) to address the problems of energy consumption, communication constraints, data aggregation, resource, and routing challenges for WSN node deployment on the RPL protocol. The height of the routing graph is increased by restricting the degree, this results in reduced network congestions. Additionally, a dynamic data aggregation that is based on Learning Automata is implemented. This mechanism improved how nodes learn about the information of its neighboring nodes, which helped improved data aggregation and packet transmission. Results show that the LA-RPL mechanism performed better than related mechanisms. However, the mechanism does not consider the heterogeneous nature of WSN data, subsequently, the performance of the mechanism with a scaling network is not known.

AlSawafi et al. (2020) proposed the Hybrid RPL-based Sensing and Routing Protocol (HRSRP). Their work describes both WSN and Mobile Crowd Sensor (MCS) technologies to face network and performance challenges such as poor packet delivery, lossy network, high latency, and limited lifetime which is a result of the constrained nature of sensor nodes. Their HRSRP mechanism mitigates these challenges by integrating the WSN and MCS technologies and allowing them to work as a hybrid routing protocol, whereby MCS is used in an opportunistic way to support static WSN node to enhance performance. To achieve their objective, the standard RPL control messages were modified resulting in a unique DODAG construction mechanism. In comparison with related mechanisms, results show improved performance. However, the application of the mechanism in the realistic scenario is not known, subsequently, the mechanism does not consider the heterogeneous nature of the MCS and WSN data.

The outcome of the literature shows inadequate support for data heterogeneity, while those with proposed mechanisms are either poorly implemented or results in compromising the network performances which leads to unnecessary power consumption, resulting in a shortened operational lifetime. These inadequacies open the door for improvements that will be addressed in this research.

1.3.3 Unreliable and Inefficient Node Battery-level Estimation and Forwarding Paths for Heterogeneous Data

As power is key for WSN, the question is, are the current data forwarding and routing mechanisms optimal enough for an extended operational lifetime? Are the priorities of data packets adequately addressed across the data link and network layers? Is the battery-level (BL) of node adequately monitored and managed to help make a good decision of data forwarding for an optimal extended operational lifetime? Answers to these questions have prompted researchers into further improvements of the WSN operations to support an extended operational lifetime.

Queue and Workload condition RPL (QWL-RPL) was proposed by Musaddiq et al. (2020). The authors discussed the need for an improved objective function, as the standard RPL objective functions; OF0 and MRHOF do not adequately address the needs of heterogeneous data traffic. To achieve the improvements, the node to node-link workload and mapping a child node to a parent node with the knowledge of its congestion state which is revealed in the node buffer memory and packet queue status. With the knowledge of the Weighed Cumulative Expected transmission Time (WCETT), which depends on the link in the network, the mechanism can determine the congestion state of the network while ensuring effective bandwidth utilization, flow control, and power control constraints. Simulation results show that the mechanism performed better than related mechanisms. Even though the mechanism shows considerations for heterogeneous data, it does not show support for battery-level monitoring which is an important parameter that helps in the decisions of child-parent node mapping and relationship for optimized routing.

Hamrioui et al. (2018) argues that the complexity and heterogeneity of WSN make the existing routing protocols incapable of handling the growing needs and applications of WSN particularly in the area of smart cities. The authors proposed the

Smart and Self-organized Routing Protocol (SSRA) to address the performance degradation issues of the existing mechanism with regard to WSN applications in smart cities. The mechanism operates at the network layer of the WSN protocol stack by improving upon the route selection of nodes to improve packet forwarding. The mechanism shows support for node mobility, over time as packet routing takes place all neighboring nodes dynamically learn of each other's parameters and with this knowledge can decide and select paths that are power efficient and optimized for a extended operational lifetime. Results show improvement over related mechanisms; however, the mode of implementations may pose a possible computational overhead for the already constrained node leading to a shortened operational lifetime. Additionally, the mechanism does not show adequate support for heterogeneous data of WSN, subsequently, the support for node BL monitoring is not implemented which limits the versatility of the mechanism.

Nguyen et al. (2020) proposed the Balanced and constant Stretch protocol for bypassing Multiple Holes (BSMH) in their work. Network holes resulting from the power exhaustion of nodes due to suboptimal routing mechanisms result in shortening the network lifetime of the sensor network. Furthermore, routing path length, control packet overheads, and uneven load balancing pose major challenges for resource-constrained nodes. Mitigating these shortcomings, the BSMH mechanism improves upon the operational longevity of the sensor network by the use of a dynamic base path that varies from packet to packet. The base paths are probabilistically selected such that a path close to the destination node is likely to be chosen. Subsequently, the base path ensures that the routing path upper bound is optimal to path generation. Additionally, a node is assigned a priority index indicates how far it is from a power exhausted node. This mechanism helps nodes to avoid power exhaustion which leads to holes in the network. Results show improved performance as compared to related mechanisms, however, the complexity of the mechanism add extra computational overhead to the already power-constrained nodes. Moreover, the node prioritization implementation is not clear, subsequently, the mechanism does not show adequate support for heterogeneous data as well as support for node BL monitoring.

As power is key for WSN, the gradual increase and advancement of WSN applications are putting increasing demand on sensor nodes, leading to a huge generation of heterogeneous data that are resource-intensive which demands improved routing and forwarding mechanism as current standard and proffered mechanism in the literature are not optimal enough to cope with the robustness. The literatures have revealed that there is work to be done in improving upon node BL monitor and estimation which is a critical parameter in deciding data forwarding paths/ route computation, load balancing, and estimating expected network lifetime. To this end, this research aimed to proffer improved and optimized mechanisms for data forwarding/routing and power management, leading to improved operational lifetime.

1.4 Problem Statement

This research addresses the problems faced by heterogeneous data of WSN with regards to energy consumption while forwarding and routing data across the data link and network layers respectively, as it relates to performance requirements such as latency, packet delivery ratio, throughput, control messages overhead, and convergence time, all of which combine to determine the network operational lifetime. However, existing mechanisms as mentioned in Section 1.3 has limitations and had not sufficiently provided lasting solution to improve network lifetime. In this study, three critical problems are identified; the first is inefficient prioritization and classification of IEEE 802.15.4 heterogeneous data across the data link layer, the second is the suboptimal data prioritization and route estimation of heterogeneous data across the network layer, while the third is the unreliable and inefficient node battery-level estimation and forwarding paths for heterogeneous data across the DLL and NL. These issues led to the formulation of the three research questions with each addressing the aforementioned problem statements respectively.

1.5 Research Questions

Based on the discussions in Section 1.2, the following research questions are formulated:

i. How to optimize the forwarding of heterogeneous data with support for data priority across the data link layer of IEEE 802.15.4, for extended network lifetime?

ii. How to improve the routing of heterogenous data with support for data priority across the network layer for extended network lifetime?

iii. How to optimize the monitoring and management of the instantaneous node battery-level for optimal forwarding and routing of heterogeneous and prioritized data with support for extended network lifetime?

1.6 Research Aim

The aim of this research is to develop an energy-efficient data forwarding and routing mechanisms across the data link and network layers respectively with support for heterogeneous data as well as node battery-level monitoring and management which enhances extended network lifetime.

1.7 Research Objectives

From the perspective of the problem statement, research questions, and research aim, the following are the objectives of this research. Each objective addresses each research question respectively.

i. To develop an energy-efficient data forwarding mechanism for IEEE 802.15.4 heterogeneous data across the data link layer with support for extended network lifetime.

ii. To develop an energy-efficient data routing mechanism for heterogeneous data across the network layer with support for extended network lifetime.

iii. To design and develop a mechanism that monitors and manages the instantaneous node battery-level for an optimal forwarding and routing of heterogeneous data with support for extended network lifetime.

1.8 Research Scope and Limitations

The scope of this research focuses on the following:

i. The research addresses data forwarding and routing issues across the data link and network layers of the WSN protocol stack.

ii. The research focuses on performance optimization of the IEEE 802.15.4, and the Internet Engineering Task Force (IETF) Routing Protocol for Low-power and Lossy Network (RPL) standards

iii. All data generated by the WSN are considered heterogeneous and of two classes; High Priority Data (HPD) and Low Priority Data (LPD)

iv. The research focuses on data prioritization for optimized channel access and packet routing.

v. The research also focuses on optimized energy utilization to extend the network operational lifetime

vi. Homogenous nodes (that is, all nodes are of the same make and model) are considered under common energy and resource constraints

vii. Node deployment is on the open and flat network with a clear line of sight between neighbouring nodes (that is, there are no obstacles in-between nodes)

viii. Sensor nodes sense and acquire data periodically (proactive sensing), thus event-based sensing is not considered.

ix. The routing protocol is restricted to a proactive routing protocol

x. Deployment of nodes can be in a structured and unstructured manner, as long as the nodes are within communication range with each other.

1.9 Significance of Research

The significance of this research is improving upon the operational mechanisms of the WSN across the data link layer and the network layer particularly as it applies to its real-life applications. One of the most paramount challenges of the sensor node is energy, bearing in mind that most sensor nodes are autonomously powered by a battery and are expected to work unattended for a long duration. However, to achieve this aim, the operational mechanisms must be optimal enough to guarantee extended network lifetime. The proposed EPAEAM mechanism addresses all of the existing shortcomings of the state-of-the-art mechanism and those proposed in related literature. The EPAEAM is suitable for a wide range of applications that requires energy-efficient, reliable multi-hop communications that generate heterogeneous data, such as smart home, smart logistics, smart campus, smart industry, smart medicine, and a host of WSN applications. The major advantage of the EPAEAM mechanism is its high tolerance to link instability and network workloads as its dynamic node battery-level monitoring mechanism guarantee effective load balancing by ensuring that data packets are not forwarded to a node whose instantaneous battery-level is below a predefined battery-level status. Overall, the EPAEAM mechanism provides an excellent enhance energy-aware mechanism that meets the everyday need of modern WSN applications.

1.10 Organization of Thesis

This thesis comprises of seven (7) chapters. The rest of the chapters is organized as follow:

Chapter 2 presents a comprehensive literature review of the standard operational mechanism and those provided by related and existing literature in the study area and elaborating on the problem background and existing solutions. In particular, the available solutions in the context of effective channel sensing for heterogeneous IEEE 802.15.4 data over multi-hop communication were thoroughly examined to highlight the contributions of the research.

Chapter 3 describes the research methodological framework and experimental environment used to achieve and verify this research objective in line with standard performance requirements. In addition, the chapter presents the design, implementation, and validation process of the proposed EPAEAM mechanism.

Chapter 4 presents the design and evaluation of the *optimized backoff mechanism for prioritized data (OBMPD) in wireless sensor networks* mechanism, which is developed to support optimal channel sensing and forwarding of heterogeneous data with consideration for data priority, across the data link layer, while reducing network overhead and extending operational lifetime.

Chapter 5 presents the design and performance evaluation of the *shortest path priority-based objective function (SPPB-OF) for wireless sensor networks* mechanism, which provides optimal routing paths for heterogeneous data across the network layer with regard the priority of the data packet while ensuring improved performances which supports extended operational lifetime.

Chapter 6 presents the design and evaluation of the *cross-layer Energy-efficient priority-based data path (CL-EEPDP) mechanism for wireless sensor networks*, which provides optimized data forwarding and routing mechanism across the data link and network layers by monitoring the BL of the intended next-hop node. The mechanism ensures that data are not forwarded or routed to nodes whose BL is below a predetermined value. In this way, the mechanism ensures effective load balancing while guaranteeing an extended operational lifetime.

Chapter 7 summarizes this study by presenting the achievements, challenges and future directions.

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1. **Onwuegbuzie, I. U**., Razak, S. A., & Isnin, I. F., Darwish, T. S. J., & Al-dhaqm, A. (2020). Optimized backoff mechanism for prioritized data in wireless sensor networks: A class of service approach. *PLOS ONE*, *15*(8), e0237154. **(Q2, IF: 2.740)**

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1. **Onwuegbuzie, I. U.**, Razak, S. A, Isnin, I. F., & Badrul. A. N. (2020). Shortest Path Priority-based RPL (SPPB-RPL): The Case of a Smart Campus. *2020 IEEE Conference on Application, Information and Network Security (AINS)* (pp. 1–6). IEEE. https://doi.org/10.1109/ains50155.2020.9315041. **(Indexed by SCOPUS)**

2. **Onwuegbuzie, I. U**., Razak, S. A., & Isnin, I. F. (2019). Performance Evaluation for ContikiMAC, XMAC, CXMAC and NullMAC Protocols for Energy Efficient Wireless Sensor Networks. *2019 IEEE Conference on Wireless Sensors (ICWiSe)* (pp. 12-17). IEEE. https://doi: 10.1109/icwise47561.2019.8971832. **(Indexed by SCOPUS)**

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Non-indexed Journal

1. **Onwuegbuzie, I. U**., Razak, S. A., & Isnin, I. F. (2020). Control Messages Overhead Impact on Destination Oriented Directed Acyclic Graph—A Wireless Sensor Networks Objective Functions Performance Comparison. Journal of Computational and Theoretical Nanoscience, 17(2), 1227–1235. https://doi:10.1166/jctn.2020.8794.