ENERGY MANAGEMENT MODEL FOR RFID SENSOR NETWORKS IN INTERNET OF THINGS (IoT) CONTEXTS

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ENERGY MANAGEMENT MODEL FOR RFID SENSOR NETWORKS IN INTERNET OF THINGS (IoT) CONTEXTS

ABSTRACT

The Internet of Things (IoT) technology has the capability to encapsulate the identification potential, sensing technology, artificial intelligence, and interconnection of nano - things, ultimately striving towards the objective of developing seamlessly interoperable and securely integrated systems. These integrated communication networks comprise of many interconnected units such as processor, memory, energy storage unit, radio, microcontroller and so on. The energy consumed by these units is very high during communication. Therefore, optimization of this energy consumption is a primary necessity to increase the lifetime of integrated systems. A crucial conduct norm for a sensor network is to avoid network failures and packet drop. One of the other essential requirements is to effectively manage the energy levels of the nodes according to the states of the operation required for an application. This research aims to propose an energy management model with the aim of allowing energy optimization of Radio Frequency (RF)-enabled Sensor Networks (RSN) through Energy Harvesting (EH) and Energy Transfer (ET) techniques. The main aim of this research is twofold – Firstly, to integrate the Wireless Sensor Network (WSN) nodes with Radio Frequency Identification (RFID) technology to enable energy optimization. The focus of this integration is to minimize the burden for the sensor nodes to rely completely on primary energy storage devices such as batteries and capacitors. Currently, these energy storage devices face the drawback of limited lifetime, node failure, energy scarcity, packet loss and poor network performance on the pretext of heavy sensing operations. Therefore, energy harvesting of sensor networks through RF signals is proposed in this research to address the drawback of frequent replacement of batteries, persistent recharge request, dead state of nodes and periodical eradication of batteries. Secondly, this research focuses on mathematical modeling of the RF sensor nodes within the proposed Energy Harvesting RSN (EHRSN) and Energy Transfer RSN (ETRSN) framework where the nodes are characterized using Semi Markov Decision Process (SMDP) and optimal policies are computed for numerically evaluating and analyzing the issue of higher energy consumption. The proposed EH and ET techniques are implemented through simulations and its performance evaluation is carried out in terms of parameters such as throughput, end-to-end delay, latency, network lifetime and residual energy levels. Furthermore, the proposed RSN energy model is validated using real hardware prototype where the results show nearly 80 % of additional energy saving achieved through EH and ET mechanisms of RF-enabled sensors. These proposed mechanisms which are implemented through event trigged approach and enhanced backscattering techniques are further tested and evaluated by comparing it with existing RSN systems in terms of performance and network latency. The proposed system is thereafter applied in IoT context of monitoring air quality levels using temperature, humidity, gas and dust sensors that are energized by RF signals. The empirical values recorded by these sensors that are configured and programmed according to the proposed energy model and energy management techniques are quantified, statistically analyzed and compared with existing systems in use, to validate the efficiency of the proposed system.

Keywords: RFID, WSN, Energy Management, Energy harvesting, Energy transmission

MODEL PENGURUSAN TENAGA UNTUK RANGKAIAN SENSOR RFID DALAM KONTEKS OBJEK RANGKAIAN INTERNET (IOT)

ABSTRAK

Penyelidikan objek rangkaian internet (IoT) mempunyai keupayaan untuk merangkum keupayaan pengenalan, teknologi penderiaan, kecerdasan buatan dan penyambungan-antara nano – perkara, akhirnya berusaha untuk mencapai matlamat membangunkan kelancaran beroperasi dan sistem bersepadu yang selamat. Rangkaian komunikasi bersepadu ini terdiri daripada banyak unit yang saling berkaitan seperti pemproses, memori, unit penyimpanan tenaga, radio, mikropengawal dan sebagainya. Tenaga yang digunakan oleh unit-unit ini tinggi semasa berkomunikasi. Oleh kerana itu, pengoptimuman penggunaan tenaga ini adalah keperluan utama untuk meningkatkan hayat sistem bersepadu. Satu norma kelakuan penting untuk rangkaian sensor adalah untuk mengelakkan kegagalan rangkaian dan kehilangan paket. Salah satu keperluan penting lain adalah mengurus dengan berkesan tahap tenaga nod mengikut keadaan operasi yang diperlukan untuk aplikasi. Kajian ini bertujuan untuk mencadangkan satu model pengurusan tenaga dengan tujuan untuk membolehkan pengoptimuman tenaga Frekuensi Radio (RF) membolehkan Rangkaian Sensor (RSN) melalui teknik Penuaian Tenaga (EH) dan Pemindahan Tenaga (ET). Tujuan utama penyelidikan mempunyai dua bahagian – Pertama, untuk mengintegrasikan nod rangkaian sensor (WSN) dengan teknologi RFID untuk membolehkan pengoptimuman tenaga. Tumpuan integrasi ini adalah untuk meminimumkan beban bagi nod sensor yang bergantung sepenuhnya pada peranti penyimpan tenaga utama seperti bateri dan kapasitor. Pada masa ini, peranti penyimpan tenaga ini menghadapi kelemahan jangka hayat yang terhad, kegagalan nod, kekurangan tenaga, kehilangan paket dan prestasi rangkaian yang buruk disebabkan operasi penderiaan berat. Oleh itu, penuaian tenaga rangkaian sensor melalui isyarat RF dicadangkan dalam penyelidikan ini untuk menangani kelemahan penggantian bateri yang kerap, permintaan cas semula berterusan, keadaan nod yang mati dan penghapusan bateri secara berkala. Kedua, kajian ini memberi tumpuan kepada pemodelan matematik nod sensor RF dalam rangka kerja Penuaian Tenaga RSN (EHRSN) dan Pemindahan Tenaga RSN (ETRSN) di mana nod tersebut dicirikan mengguna Proses Keputusan Semi Markov (SMDP) dan dasar-dasar optimum yang dikira untuk menilai secara numerik dan menganalisis isu penggunaan tenaga yang lebih tinggi. Teknik EH dan ET yang dicadangkan dilaksanakan melalui simulasi dan penilaian prestasinya dilakukan dari segi parameter seperti pemprosesan, kelewatan hujung ke hujung, latensi, hayat rangkaian dan tahap tenaga sisa. Tambahan lagi, model tenaga RSN yang dicadangkan disahkan menggunakan prototaip perkakasan sebenar di mana hasil menunjukkan hampir 80% penjimatan tenaga tambahan yang dicapai melalui mekanisme EH dan ET sensor penderiaan RF. Mekanisme yang dicadangkan, dilaksanakan menerusi pendekatan tertutup dan teknik pesongan yang dipertingkatkan akan lebih diuji dan dinilai dengan membandingkannya dengan sistem RSN sedia ada dari segi prestasi dan latensi rangkaian. Sistem yang dicadangkan itu kemudiannya digunakan dalam konteks IoT untuk mengawasi tahap kualiti udara menggunakan suhu, kelembapan, gas dan sensor debu yang bertenagakan isyarat RF. Nilai-nilai empirikal yang dicatatkan oleh sensor-sensor ini, dikonfigurasikan dan diprogramkan mengikut model tenaga yang dicadangkan dan teknik pengurusan tenaga dikira, dianalisis secara statistik dan dibandingkan dengan sistem sedia ada, untuk mengesahkan kecekapan sistem yang dicadangkan.

Kata kunci: RFID, WSN, Pengurusan Tenaga (Energy Management), Penuaian tenaga (Energy harvesting), Penghantaran tenaga (Energy transmission).

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LIST OF ABBREVIATIONS

ACO	:	Ant Colony Optimization
AODV	:	Adhoc On-Demand Vector routing
AQI	:	Air Quality Index
BANNET	:	Body Area Nano-NETworks
BEO	:	Bellman Equation of Optimality
BFSA	:	Basic Frame Slot Aloha
BLE	:	Bluetooth Low Energy
BRL	:	Business Rules Layer
CBR	:	Constant Bit Rate
CEP	:	Complex Event Processing
CH	:	Cluster Heads
CoAP	:	Constrained Application Protocol
CR	:	Cluster Reader
CRFID	:	Computational RFID
CTMP	:	Continuous – Time Markov process
DP	:	Dynamic Programming
DSR	:	Dynamic Source Routing
DTMC	:	Discrete-Time Markov Chain
EAR	:	Efficient and Reliable routing
ECG	:	Electrocardiography
EEFSSP	:	Energy-efficient Evo-Fuzzy Sleep Scheduling Protocol
EEG	:	Electroencephalography
EH	:	Energy Harvesting
EHP	:	Energy Harvesting Phase

EHRSN	:	Energy Harvesting RSN
EM	:	Energy Management
EMCA	:	Energy efficient Multi-Sink Clustering Algorithm
ESN	:	EPC Sensor Network
ET	:	Energy Transfer
ETRSN	:	Energy Transfer RSN
FTP	:	File Transfer Protocol
GBR	:	Gradient based routing
GRAB	:	Gradient Broadcast
HCI	:	Human Computer Interaction
ICRDC	:	Improved Cross Redundant Data Cleansing
ILP	:	Integer Linear Programming
IoT	:	Internet of Things
IWRSN	:	Industrial Wireless Rechargeable Sensor Network
6LoWPAN	:	IPv6 over Low-power Wireless Personal Area Networks
LoC	:	Lines of Code
LPL	:	Low Power Listening
MAC	:	Medium Access Control
MDP	:	Markov Decision Process
MP	:	Markov Process
MEB	:	Minimum Energy Broadcast
MinMCP	:	Minimum Mobile Charger Problem
MOSFET	:	Metal Oxide Semiconductor Field Effect Transistor
MQTT	:	Message Queuing Telemetry Transport
MTE	:	Minimum Transmission Energy
NCS	:	Non-Cooperative Systems

O3DwLC	:	Optimized 3-D deployment with Lifetime Constraint
OOK	:	On–Off keying
OTCL	:	Object-Oriented Tool Command Language
P2P	:	Peer-to-Peer
PA	:	Power Amplifier
PASCCC	:	Priority based Application Specific Congestion Control Clustering
PDR	:	Packet Delivery Ratio
PI	:	Policy Iteration
PLEM	:	Product Life-cycle Energy Management policies
PRM	:	Probability Reward Matrix
PSO	:	Particle Swarm Optimization
PTM	:	Probability Transition Matrix
QoS	:	Quality of service
RF	:	Radio Frequency
RF-EHNs	:	Radio Frequency Energy Harvesting Networks
RFID	:	Radio Frequency Identification
RL	:	Reinforcement Learning
RTC	:	Request to Charge
RPL	:	Routing Protocol for Low power and Lossy networks
RSN	:	RF- enabled Sensor Networks/ RFID sensor Networks
SHIP	:	Supply Hub in Industrial Park
SHM	:	Structural Health Monitoring
SMDP	:	Semi Markov Decision Process
SMP	:	Semi Markov Process
SP	:	Sensing Phase
SPS	:	Smart Parking System

SPSE	:	Smart Personalized System for Energy Management
SWIPT	:	Simultaneous Wireless Information and Power Transfer
TBR	:	Tag Based Relay
TCS	:	Tag-based Cooperative Systems
TDC	:	Tag-based Data Channel
THF	:	Total Harvesting Factor
TP	:	Transmission Phase
TSP	:	Travelling Salesman Problem
TTF	:	Total Transfer Factor
TTM	:	Transition Time Matrix
UCB	:	Upper Confidence Bound
UHF	:	Ultra-High Frequency
UWB	:	Ultra-wideband
VI	:	Value Iteration
WISP	:	Wireless Identification and Sensing Platform
WNSNs	:	Wireless Nano Sensor Networks
WRSNs	:	Wireless Rechargeable Sensor Networks
WSN	:	Wireless Sensor Network

LIST OF SYMBOLS

λ : Wavelength of RF signal

α : Policy (Control Mechanism)

μ_α : General average reward of a policy

$\gamma_\alpha\ (j)$: Limiting probability distribution function

$\alpha(j)$: Action in state ‘j’

ρ : Discounted reward factor

α_{DC} : Conversion efficiency

β_{node} : Energy transmission efficiency

η_r^2 : Additional energy costs due to interferences and SNR

LIST OF APPENDICES

CHAPTER 1: INTRODUCTION

1.1 Overview

Internet of Things (IoT) can be defined as a paradigm where every day physical objects are connected to the internet. The successful evolution of IoT vision has paved way for computing portables and smart-phones as an extension of past traditional scenarios. The evidence of such evolution can be witnessed in the growing presence of 4G-LTE and Wi-Fi. Such a seamless integration of physical objects into information network provides intelligent and ubiquitous services leading to a promising future in fields of surveillance, healthcare, security, transport, food safety, object monitoring, and control. In an IoT environment, the connected web is a highly distributed network consisting of dynamic services, information providers and data consumers who share the information. When compared to the traditional desktop realm, IoT based services and systems faces major risks of handling the dynamic services and heterogeneity of devices. To meet this challenge, it is envisioned that sensing capabilities and identification technology will become increasingly integral to the human environment, where communication and information systems will be invisibly integrated. This need makes Wireless Sensor Networks (WSN) and Radio Frequency Identification (RFID) as two major aspects of IoT. RFID and WSN represent two most prominent technologies that have a wide range of applications. These two ubiquitous computing-based technologies have gained considerable attention in potential research and development fields. RFID applications include supply chain management, manufacturing, search and rescue and on the other hand, WSN technology is used for sensor mote deployment to monitor air pollution and for battlefield surveillance. The integration of RFID and WSN have paved way for the evolution of RF-enabled Sensors Networks or RFID Sensor Networks (RSNs), which means that Radio Frequency (RF) signals are the energy sources for the sensor nodes, either through an ambient RF energy source or through a dedicated RFID reader integrated to the sensors. RFID is used to track or to locate the identity of an object without providing any traces about the physical environment of the object. WSN on the other hand, are networks of small interconnected devices that are incorporated to collect information by sensing the environmental conditions of the surroundings like temperature, light, humidity, pressure, vibration, and sound. These two technologies provide extended capabilities, enhanced efficiency, cost-effectiveness and eventually bridge the gap between real and virtual world, from an integrated perspective. The requirements for the development of RSN includes accurate communication, reliability, energy efficiency, network maintenance survivability, tolerable latency and criticality of the application. Energy efficiency is considered to be one of the most attention-seeking limitations because both sensor nodes and RFID tags comprise of scarce resources. The Wireless Identification and Sensing Platform (WISP) conjugates the identification potential of the RFID technology and the sensing, computing capability of the wireless sensors. The practical issue lies in the fact of periodical recharging of these integrated devices which puts forth the challenge of effective deployment of large-scale RSNs consisting of RFID readers and WISP nodes. To make the integrated system efficient and reliable, the goal of minimum possible energy consumption should be focused upon. An auxiliary solution for the efficient integrated system is energy harvesting and recharging by Han, Qian, Jiang, Sun, & Liu (2015). Different sources of energy exist in different forms (e.g. light, vibration, RF, air, and electromagnetic waves). These sources can be harvested and used either to extend the battery life of a sensor node or power a sensor node directly without any storing techniques. Reducing or eliminating the problem of a limited lifetime will enable node designers to enhance the functionality of a node by adding extra features and components. A sensor node comprises of four basic components with additional units being added depending on application requirements by Shaikh &

Zeadally (2016). The basic components of sensor node consist of a sensing unit used for acquiring data from the environment and converting it to digital data, a processing unit for processing raw data to store the results, and a transceiver unit for sharing data with other nodes or the end-user, a power unit that consists of an energy sink (battery, capacitor or both) and power management that monitors and routes power to the entire node. Figure 1.1 illustrates the interconnection of these four units and the division of power unit into a battery module and a power management module. A lifetime of a sensor node depends on the capacity of the power resources it is equipped with. One way of prolonging the lifetime of sensor network would be to periodically replace the batteries of all or some of the deployed sensor nodes.

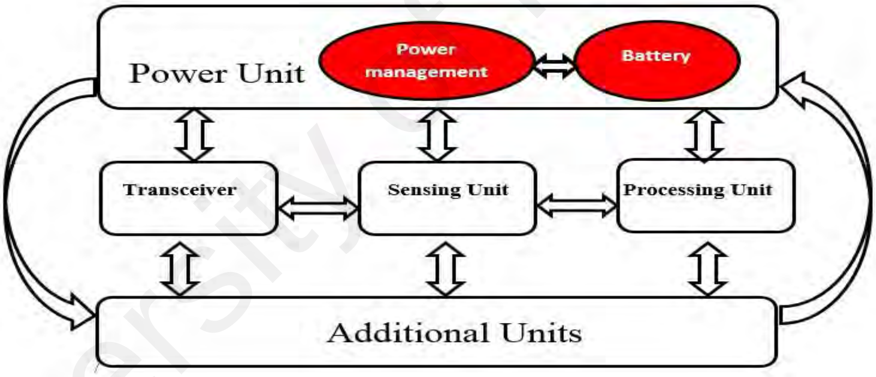

Figure 1.1: Interconnection of basic components and power unit sub-module in a wireless sensor node

The problem of optimization in large scale scenarios can belong to two categories- they are Parametric optimization and Controlled optimization. The optimization that is performed to find the values of a set of parameters that optimize some performance measure is Parametric optimization, for instance, minimize a cost or maximize a reward. This is done using mathematical programming such as linear, non-linear and integer. Conversely, Control optimization is defined as finding a set of actions to be taken in different states that a system can visit to optimize some performance measures of the system, which can be carried out using Dynamic Programming (DP). This research aims to address the issue of energy consumption of sensor nodes when they are energized through RF signals. An auxiliary solution for efficient integrated system (nodes with RF) is energy harvesting and recharging as suggested by Cheng et al (2013). Therefore, using Controlled optimization, these integrated networks are characterized using Markov Process (MP) and solved through DP. The purpose of employing MP here is to correlate the dynamic nature of sensor networks with state transition in a MP which is usually probabilistic that is a random affair. An important property of a MP is that it jumps regularly. What it means here is that after unit time, the system either transitions to a new state or else the system returns to the current state. This nature is modeled to the duty cycle switching of the sensor nodes and energy optimization is focused to be achieved through proposed research objectives and experimentations.

1.2 Background

The emergence of wireless charging techniques provides a more flexible and promising way to solve the energy constraint problem in Wireless Rechargeable Sensor Networks (WRSNs). Although considerable research has been conducted on wireless charging algorithms, the majority of them have focused either on passively replenishing energy for nodes with insufficient energy or providing event-driven duty cycles according to the energy needs as described by Han et al., (2015). When the energy of a sensor node is depleted, it will no longer fulfill its role in the network unless either the source of energy is replaced, or some harvesting mechanism is induced to bridge the energy gap. The existing solutions utilize energy source powered by batteries in sensor nodes of RSN's but are associated with many drawbacks, like chemical leakages, extreme weather conditions and limited energy density as stated by Shaikh & Zeadally (2016). The problem of finite node lifetime is addressed using energy harvesting. The drawbacks of relating expected energy levels of all nodes in a network, their routing paths, and traffic pattern, with duty-cycle and MAC parameters, are of potential interest for research suggested by Sudevakatam & Kulkarni (2011). The improvement of energy efficiency of discrete- manufacturing facilities through state of art and IoT solution has been addressed in Shrouf & Miragliotta (2015). This enables a high level of awareness, large data collection and flexible installation of energy-related data in real time. In presence of energy harvesting, the preamble length or wait duration can be increased or decreased based on the effective energy at a node, to allow energy- scare nodes to sleep for longer durations. The problem of energy sharing in sensors networks has been studied in Padakandla, Prabuchandran, & Bhatnagar (2015) the authors have proposed a new technique to manage energy available through harvesting, but still needs improvisations by tuning the partition thresholds for clustering the state space. Energy harvesting in wireless cooperative network is essential as it can enable information relaying as depicted in Figure 1.2. The existing solutions do not consider how to optimally allocate transmitted power and provide power splitting ratio to minimize energy efficiency by Padakandla et al., (2015). The most challenging aspect lies in the fact of estimating the periodicity and magnitude of the harvestable source and the deciding factor for the avoidance of energy depletion before the next recharge cycle. WSN occupy a different place in the vast categories of wireless networks. It plays a vivid role when compared to Adhoc Networks by being solely dependent upon limited energy storage capabilities, recharging abilities, and seamless integration provisioning. The sensor networks rely upon the basic working principle of running on a limited sized DC powered batteries or capacitors, which have constrained longevity. The deployment of these sensor networks in remote locations makes the replacement of these batteries and capacitors, very tedious and impossible. Comparatively, the protocols that are designed for WSN turn out to be unsuitable and unfavorable for any category of Adhoc Networks.

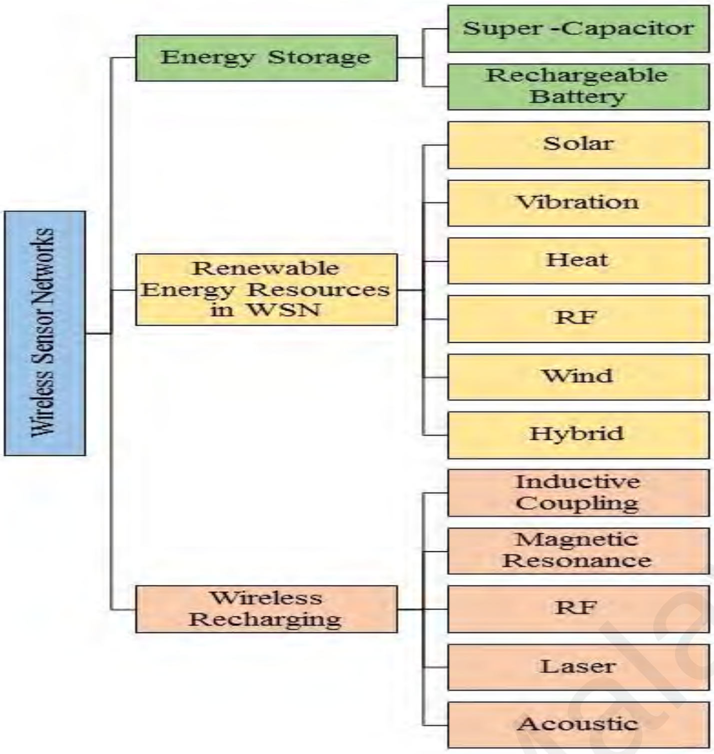

Figure 1.2: Energy management in WSN

1.3 Statement of the Problem

The most commonly used energy storing technique for RFID sensor networks is battery based. The applications that deploy such sensor nodes include habitat monitoring, vehicle tracking and structural monitoring as described by Akhtar & Rehmani (2015). A major drawback is finite operation duration of the battery incorporated in the sensor nodes. This limitation leads to finite node lifetime which implies limited lifespan of the applications, additional overhead due to increased cost and frequent battery replacements. Sensor nodes though composing on the usage of large batteries for longer lifetime, they will also have to deal with increased size, weight and cost factors. On the other hand, sensor nodes may also opt for low- power hardware at the cost of lesser computation capabilities and decreased transmission ranges. The existing techniques in literature have been proposed to prolong the application lifetime and the time interval between battery replacements but do not address the energy-related inhibitions. The finite energy source results in higher battery capacity, low duty cycle, higher transmission range and higher energy consumption. The problem of finite node lifetime is addressed by an alternative technique called energy harvesting. Energy harvesting refers to the process of preserving energy from the environment or other energy sources and converts it into electrical energy. This harnessed electrical energy is used to drive the sensor node according to the need of parameters of the employed application. The energy limited based source nodes can optimize the energy usage needs till the next recharge cycle hence increasing the performance, for example, a sensor node can increase its sampling frequency or duty-cycle to enhance its sensing reliability or increase the transmission power to minimize the length of routing paths. The major drawback in this mechanism turns out to be the quantitative scheduling of the harvested energy and effective synchronization of the nodes with lower energy levels. The energy recharging requests of sensor nodes need to be sent to the mobile charges or energy source through wireless communications, which may be lost due to the dynamic network conditions. On the other hand, network densities also play a major role in energy request. The more the number of nodes, the load of energy recharging workload increases, hence decreasing the throughput and performance of the network as proposed by He, Kong, Gu, Pan, & Zhu (2015). The parameters to be considered are time taken for delivery of request, recharging time and travel time of the requesting sensor node. The on-demand energy recharging problem for RSN's must be analytically evaluated on the pretext of overall network throughput and energy efficiency that has not been addressed in the literature. The drawback of efficient wireless energy transfer and request in RFID sensor networks still needs to be addressed between cooperative and clustered nodes. The major challenge in the network with wireless energy transfer is to determine the amount of energy to be transferred to the nodes as suggested by Angelopoulos, Nikoletseas, & Raptis (2016). The process of transferring wireless energy not only requires additional energy consumption by the access points but also creates strong interference to other networks sharing the same spectrum. To overcome this cost, the access point may charge the nodes based on their wireless energy demand.

The nodes must make the decision for wireless energy transfer according to the charged cost with achievable data transmission performance, from the access point. The existing solutions that are discussed by Niyato.D & Wang (2014) focuses on non- cooperative scenarios for wireless energy transfer and requests, where the nodes can comparatively bid for wireless power transfer for an access point and use that energy for packet transmission, but the interference management due to wireless energy transfer has not taken into consideration. The attention-seeking observation is that most of the research work in literature have seldom contributions towards energy optimization solutions in RSN.

Therefore, this research aims at solving four major problems. Firstly, there is no control on the energy level of sensor nodes and prompting of energy shortage levels, which is addressed through the first objective of energy modeling. Secondly, there is inadequate distribution of the harvested energy ultimately leading to energy loss and inefficiency, which is solved through the second objective of RF energy harvesting. Thirdly, the present scenarios face the issue of interferences from other nodes when there is energy shortage alert and dynamic alterations which is aimed at being solved and addressed through the third objective of stochastic backscattering-based energy transfer. Basically, how to prevent the interferences from other nodes and address the alert indicated by nodes with depleting energy levels is focussed during this stage. And finally, the theory stated in literature claims that there are no simulators available for possible integration of RFID and WSN. Therefore, the fourth objective of this research deals with integration of RFID and WSN through experimental evaluation on both macro and micro scale followed by applying the model in an IoT context of monitoring the quality of air. This can be employed at traffic signals and toll gates to record the air quality values during predefined time intervals and provide energy to these sensor devices through the RF signals emitted from nearby mobile phone, cell tower, Wi-Fi access points and so on. Hence this research aims at preventing energy losses due to idle listening and packet drop in order to maintain optimal network performance, adequate energy consumption and maximum energy efficiency.

1.4 Research Objectives

The following lists the objectives of the research:

1. To develop Energy Management (EM) model by controlling and handling the energy level of nodes through modeling and dynamic programming approach.
2. To develop an algorithm of RF energy harvesting using Event-triggered programming approach for the EM model.
3. To develop an enhanced stochastic backscattering mechanism for energy transmission to improve the throughput of network and avoid recurring interferences for the EM model.
4. To evaluate, appraise and apply the EM model in real-time IoT based application of air quality monitoring.

1.5 The scope of the Study

One of the most challenging aspects of sensor networks is its lifetime with regards to the energy and power provided through the storage devices. Therefore, focusing on energy management when two technologies are integrated with each other (RFID +WSN) is a strenuous goal to accomplish. The existing research contributions that focus on minimizing energy consumption have suggestions related to protocols, algorithms, and framework only for traditional WSNs. There are hardly any solutions for optimizing energy and mitigation of energy consumption when sensor networks are energized using resources such as RF signals and integrated on a shared platform. The current study has the limitations of shorter coverage distance between the RF source and the node. The energy harvesting and transmission, however, cannot take place when the reader or source is not in close proximity to the sensor nodes. Therefore, the proposed techniques are designed, modeled and developed in a such a way that the states of each node are fine-tuned with respect to EH and ET durations. The proposed model is aimed at enabling energy optimization of RSN at the Data Link, Medium Access Control (MAC) layer. The runtime of the sensor nodes during the active state is considered to be limited since the sole purpose is to optimize the energy levels via RF harvesting and reduce energy wastages due to idle listening. The validation and application of proposed EM techniques using the existing WISP device are out of the scope of this research due to higher costs of deployment. The aim of this work is to provide cost-effective solutions for EM in IoT contexts.

1.6 Motivation and Significance

Currently, most of the proposed and suggested research have dealt with the framework, protocols, algorithms, and mechanisms for energy consumption mitigation through data aggregation, the mobility of nodes, hierarchical/data-centric routing, single/multiple path modeling, clustering of nodes and energy balancing methods. The problem formulation and solving methods focus upon conventional based EM for general applications that deploy generic class of sensors. The statistical analysis of the existing solutions with regards to EM for sensor networks reveals that only 28% of the total wireless networks research contributions have dealt with RSN for integrative, energy-efficient and secure solutions. Furthermore, it is also observed that 57% of related articles deal with mitigation of power consumption rather than harvesting or wireless energy transmission. The need for energy harvesting through renewable energy sources like RF signals and wireless recharging through radio signals stems from the fact that the lifetime of energy storage devices such as batteries and capacitors is limited. Moreover, the deployment of such limited lifetime devices for sensors in remote locations make the replacement more tedious and can lead to dead nodes, packet loss or network failure. The existing solutions also focus on simulations and emulations with more predefined assumptions which put forth the drawback of not applying them to other class of sensors or on integrated systems with different routing protocol and network topology. Therefore, this research work has been motivated towards achieving an energy-efficient solution for RSN that is different from conventional WSN. The focus of this research is to develop and design an energy model for an RF-enabled sensor network that can efficiently conserve and control the energy levels. A system which incorporates RF technology and wireless sensing technology would allow the energy harnessing policies from renewable energy sources such as radio frequencies to replace the traditional battery- based and capacitor-based energy storage techniques hence aiming to provide quantitative scheduling of the harvested energy without considerable energy losses. The mechanism of controlling/handling the energy levels of the nodes and energy transmission in RSN is also one of the researcher’s focuses, eventually preventing node failure and improvising the overall network throughput different from the classical schemes in the literature. The issue of energy management in RSN stands out to be the most prominent one and urges to be addressed by the majority of the researchers in literature for promising research directions in IoT contexts.

1.7 Organization of the thesis

Following the general introductory sections of the research work stating the background, objectives, scope, motivation, and significance of the research, the remainder of the thesis has been organized as follows:

Chapter 2 discusses the research contributions from the literature related to IoT, energy consumption in IoT, energy efficient routing approaches in WSN followed by RFID system. In addition, energy management related concepts in RSN has also been presented with a focus on energy modeling, harvesting, and energy transmission.

Chapter 3 presents the challenges and analysis related to energy consumption of IoT based systems and RSN. It also briefs the various contributing factors for energy consumption in sensor networks along with a description of the nature of EM problem.

Chapter 4 provides the details about the development of proposed solutions through energy modeling using SMDP and dynamic programming. Mathematical modeling, problem formulation and numerical analysis of proposed EH and ET mechanisms for Tag based Cooperative Systems (TCS) is discussed to aid the implementation of the EM model.

Chapter 5 describes the implementation steps for the proposed EM techniques and also provides a brief description of the simulation tools used. It presents the description of the methods used to achieve the objectives.

Chapter 6 presents the experimental results obtained through simulations followed by validation results using hardware model deployment in IoT based application of air quality monitoring.

Chapter 7 outlines the conclusion, research findings, and summary of achieved objectives followed by future directions.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

This section gives a brief introduction to the emergence of IoT and the role of sensor networks in IoT contexts. The following sub-sections outline the issue of energy consumption in IoT and its relative applications respectively. WSN and RFID form the two major enabling technologies in the IoT realm, therefore it is necessary to understand the core functionalities, working issues and applications of each of these individual technologies in order to understand the working of IoT systems. Hence sections 2.3 and 2.4 outlines the concepts, energy management aspects and the relative applications of WSN and RFID. A detailed discussion about the integration of RFID and WSN has been presented in section 2.5 followed by the relevant research contributions while section 2.6 concludes and summarizes the chapter. The ultimate objective of this chapter is to provide a conceptual understanding of the evolution of IoT, WSN, RFID, and RSN followed by outlining the major challenges of EM in each of the core technologies.

2.2 Internet of Things

The emergence of wireless communication protocols, efficient application-based sensors, cheaper processors and ubiquitous computing had given rise to the evolution of the IoT mainstream. According to IoT research, the number of internet-connected devices has transcended the number of users in 2011 and by 2020, internet connected devices are expected to amount to nearly 50 billion. IoT is referred as a vast pervasive presence of a network of things that are capable of interacting with each other and predictable of providing huge amounts of data and information to the internet in the future. It is a pervasive computing-oriented platform that encompasses a wide variety of enabling technologies and key research areas to extend the internet capabilities and bridge the gap between the real world and virtual world of things. The IoT platform extends communications well beyond the traditional realm.

2.2.1 Emergence of IoT

The web provides an interaction model by allowing the users to assess the device-related information and control it though a ubiquitous web browser. The roadmap of IoT is depicted in Figure 2.1 which shows the technological emergence along the timeline. The authors as suggested by Roy Want, Bill N. Schilit (2011) urge that through direct interaction, gateway devices can query the state of an IoT device in its proximity range and enable a bridge between low-level Peer-to-Peer (P2P) protocols such as Wi-Fi or Bluetooth and Internet protocols such as HTTP and TCP. The researchers Jang et al. (2016) have found that the key challenge of IoT based systems is to achieve small size, low power consumption, sufficient communication distance and accurate duty cycling mechanisms for the connected networks. They have provided insights on challenges and mitigating techniques for mm-scale computing platforms targeting the next generation of IoT era.

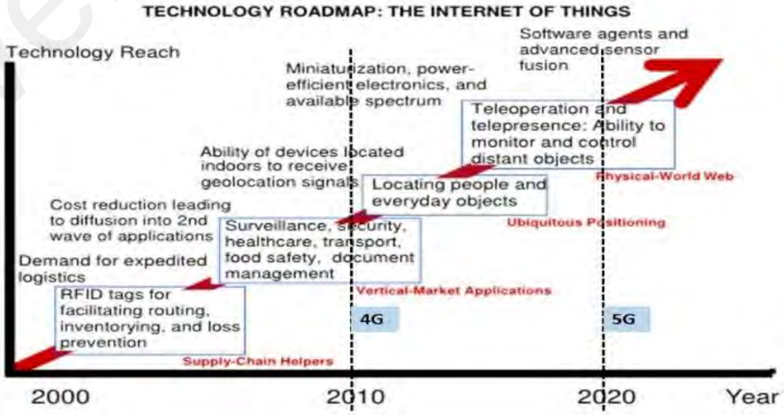

Figure 2.1: **Technology Roadmap of IoT**[1]

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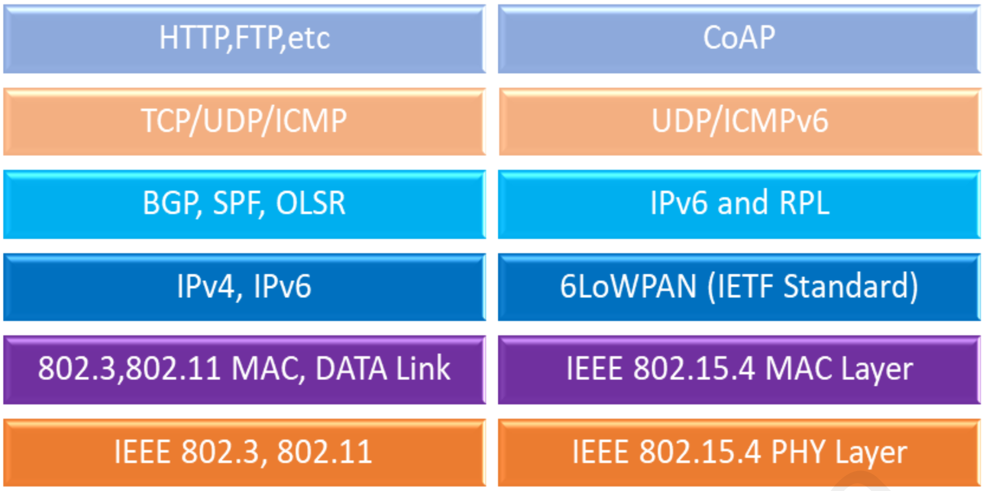
[1] Source: SRI Consulting Business Intelligence

The research article presented by Mital, Chang, Choudhary, Pani, & Sun (2015) has vast ranging effects on the future of IoT and can be applied to applications of elderly health support, energy efficient systems, and smart cities. The process of combining cloud computing with ubiquitous deployment of IoT services, more objects tend to get connected to the internet thereby allowing huge amounts of data to be processed and shared for keeping the users well-informed of the trending updates and sociable by Akhbar, Chang, Yao, & Méndez Muñoz (2016), Hodkari & Aghrebi (2016) along with Diaz, Martin, & Rubio (2016). The descriptive study presented by Alsaadi & Tubaishat, (2015) with that of Gubbi, Buyya, Marusic, & Palaniswami (2013) and Qin et al. (2016) provides explorations on the significant impact of IoT on everyday life, its vision, architectural elements and its relative vulnerabilities.

2.2.2 IoT and Sensor Networks

WSN comprises of varied applications such as medical, healthcare, military surveillance, habitat monitoring and industrial control. The functionality of these applications is to transmit the sensed information over dedicated communication channels and networks provided by IoT technology. This technology enables the respective sensors to record and reciprocate with the sensing information through a layered architecture as depicted in Figure 2.2. The data delivery process carried out in an efficient and reliable manner plays the key role in the performance of sensor networks for smarter IoT contexts.



HTTP,FTP,etc	CoAP
TCP/UDP/ICMP	UDP/ICMPv6
BGP, SPF, OLSR	IPv6 and RPL
IPv4, IPv6	6LoWPAN (IETF Standard)
802.3,802.11 MAC, DATA Link	IEEE 802.15.4 MAC Layer
IEEE 802.3, 802.11	IEEE 802.15.4 PHY Layer

Figure 2.2: **OSI and IoT Layered Stack**

An integrated IoT system comprises of sensor nodes that suffer drawbacks such as limited lifetime, area coverage, smaller size and limited processing power. Each sensor node is designed with sensing and data processing components for communicating with its neighbor nodes over dedicated channels. The node either transfer data directly or through relays to the sink node, which is forwarded to the end user or server via a gateway and the internet. Hence, these wireless class of networks poses the challenge of centralized data forwarding, management, and control of sink node's placement and area coverage of access points in an IoT domain. In contrary to the IoT networking devices, which have IP address-based approach, the sensor nodes work based upon node ID or index addressing. Moreover, the energy consumption in sensor networks is inversely proportional to the mesh formation of the nodes. The feature of mesh formation by the sensor nodes can hence play a vital role to improve the lifetime and sustainability of sensor networks. The energy optimization and management are handled by the MAC layer in sensor networks, whereas for IoT devices, the energy optimization is hardly possible since IP based access consume a huge amount of power across all the layers of the stack. Such humungous energy consumption is handled by IPv6 over Low-power Wireless Personal Area Networks (6LoWPAN) operating in the 2.4GHz range of frequency with 250Kbps of data transfer rate. The IPv6 that is responsible for the networking and communication of switched packets and datagram transmission aids in the mitigation of power consumption during compression of these packets over the data link layer. As illustrated in Figure 2.3, low-power WSN communications based on IEEE 802.15.4 and 6LoWPAN contribute and support actuating capabilities using low-power WSN devices and capillary communications for applications that need the sensing operations. Therefore, in a nutshell, it can be said that WSN forms to be a subset of a larger IoT domain. Since devices in both the technologies rely on energy storage devices for their functioning, it is necessary to focus on the aspect of energy optimization.

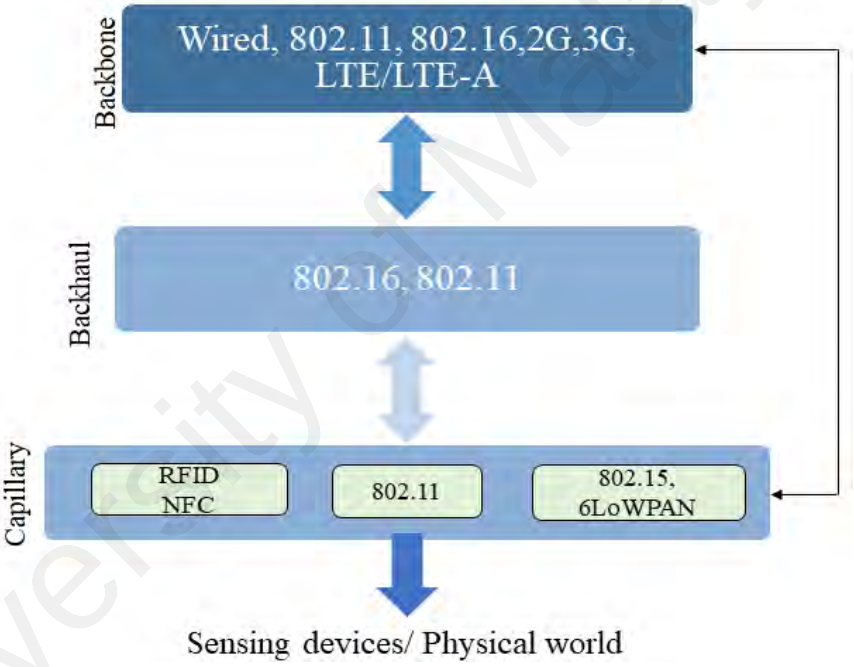


Figure 2.3: **IoT Communication technologies**

2.2.3 Energy Consumption in IoT

On one hand, there is an advantage of the seamless integration of sensors and actuators in an IoT system whereas on the other there is also a drawback of higher power consumption by the connected devices. IoT on a whole also provides an opportunity for user-based remote accessibility and centralized management control of all the connected devices through a cloud-based web interface. Many research contributions have suggested that since IoT devices are powered by energy sources that are easily depleted or run out faster, its necessary for energy optimization techniques. The primary drawback for cloud-based interfacing in an IoT context is network connectivity, Quality of Service (QoS) and operational capabilities of off-line services that are independent of applications and processes. Moreover, according to Parwekar (2011), Human Computer Interaction (HCI) resources, embedded objects such as RFID, sensors, and actuators cater to the requirement of sufficient energy balances, bandwidth, and efficient communication protocols. When such embedded devices are connected for internetworking communications, many low energy consumption protocols and wireless technologies can be employed namely. Bluetooth Low Energy (BLE), ZigBee, Ultra-Wideband (UWB), and RFID. The literature states that considering the Gaussian function for fuzzy logic can considerably increase the robustness and accuracy of time critical and complex IoT systems. The energy modeling of sensors is different when compared to energy modeling strategies of IoT devices as suggested by Jang et al (2016) and Martinez, Montón, Vilajosana, & Prades (2015). This basic difference is in terms of communication protocols such as Constrained Application Protocol (CoAP), Message queuing Telemetry Transport (MQTT), Routing Protocol for Low power and Lossy networks (RPL) and 6LoWPAN. The correlation of energy consumption oriented IoT architecture across the different IoT and OSI layers has been shown in Figure 2.4. The embedded devices connected through IoT puts forth many drawbacks such as relatively higher energy consumption for battery power, the design of self-managing devices under dynamic network conditions and deployment of smarter interconnected systems. Among these issues, the most prominent challenges according to current literature are- network lifetime, battery runtime and sensor network deployment.

Figure 2.4: IoT Layered architecture for energy consumptions[2]

2.2.4 Applications of IoT

IoT relies upon various enabling technologies that bridge the gap between virtual and physical world entities. These technologies include identification, tracking the location, sensing, embedded information processing, actuation, localization, graphical user interfacing, communication across multiple networks and nanocomputing. The research in IoT and the technological advances have given pace for evolution of various applications wherein everything is connected to the internet as depicted in Figure 2.5. The survival of human life has become impossible without the use of the internet these days. Moreover, in the absence of internet's existence and smarter technology, the exposure and progress towards human invention, discoveries, and technical advancements get out of the scope of one's knowledge and intellectual capabilities. The research contributions surveyed and reviewed by Roy Want, Bill N. Schilit (2011) and YIN, Zeng, Chen, & Fan, (2016) describes the IoT related healthcare innovations and also outlines the state-of-art network platforms/architectures, usage and automotive/industrial shift of IoT based medical care solutions.

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[2] Kumar et al. (2017)

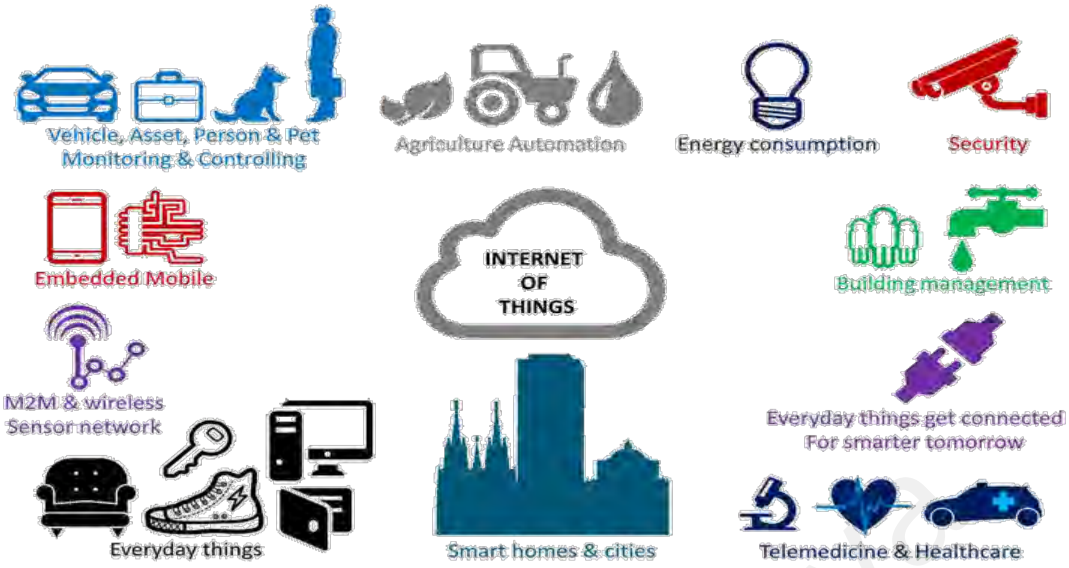


Figure 2.5: **Applications of IoT**

A methodological foundation for analysis of IoT-based medical contexts has also been studied by La (2016) and a novel IoT-based mobile gateway solution for mobile health (m-health) scenarios have been described by Santos et al. (2016). Apart from the medical field, research by Tao, Wang, Zuo, Yang, & Zhang (2016) provide insights into the existing applications and challenges of IoT in Product Life-cycle Energy Management policies (PLEM). Industrial innovations include an IoT-enabled Supply Hub in an Industrial Park (SHIP) for improving the effectiveness and efficiency of physical assets sharing and services for IoT context-aware public logistics as described by Qiu, Luo, Xu, Zhong, & Huang (2015). Relative IoT-based business ecosystem within a 6C framework by setting up a systematic benchmark along with the demonstration of basic working of the business ecosystem has been investigated by Rong, Hu, Lin, Shi, & Guo (2015).

2.3 Wireless Sensor Networks

2.3.1 Fundamentals

The IoT researchers have urged that all objects in the future will have unique features for identification that can be interconnected to create the IoT. Communication, as a result, will shift from being solely between humans to communication between humans and things, which will alter life. It has been effectively predicted that through the emergence of ubiquitous communications and computing era, RFID and other sensing technologies such as WSN used for relevant identification purposes will widely be held as cornerstones of the coming IoT era as suggested by Alsaadi & Tubaishat (2015). The success of IoT will depend on the improved performance, mainly in reliability and energy efficiency performance of WSNs. The reliable delivery of sensor data plays a crucial role in the WSNs of smart environments and IoT. The reliability requirements may vary depending on the application or the content of the data as developed by Gokturk, Gurbuz, & Erman (2016).

The field of WSN has been emerging as an interesting topic of research since few decades, which was originated from applications of military and surveillance as proposed by Gokturk et al. (2016). From traditional desktop realm to the most modern internet enabled personal devices, a large amount of data processing systems has focused on information exchange based on the input provided by the human beings rather than the surrounding environment on an automated basis. Conversely, another major class of systems such as embedded systems produces information of the surrounding environments or machines. These systems are usually integrated into the devices or machines and its major task is to control the state of machines or perform/repeat user enabled tasks for a certain period of time. The ubiquitous computing envisions a large number of tiny and intelligent devices that are interconnected in a network and enabled to interact with the environment and humans as stated by Akkaya & Younis (2005). In addition to computation and control, a vital requirement is an autonomous communication among these devices that should meet the user's need. Although wiring can possibly be a solution, this would entail a great number of wires, cost, and limitation to mobility. Therefore, a new class of network, a network of sensors has emerged namely WSNs. The generic architecture of WSN is depicted in Figure 2.6. In these types of networks, a large number of tiny sensor nodes are deployed. Each sensor node can collect, store, process and communicate information over wireless channels. Because of their small physical size, these nodes have a limited processing power which further confines the processor's capacity and battery size. Working conjointly, these sensor nodes collect and process the information about the physical environment and sends it to the base station or the sink as described by Kaur.R & Singh (2015). The sensors work in a collaborative manner to gather and provide information by sensing environmental conditions and surrounding such as temperature, humidity, pressure, light, sound, and vibration. They not only sense the environment but also process the collected information in a collaborative way. WSNs provide cost-effective monitoring of critical applications including border monitoring, industrial control, military, environmental monitoring and healthcare application as described by Nagpurkar & Jaiswal (2015). These class of networks also present several interesting engineering challenges as for example the power supply for the devices might be limited which makes the nodes to be operated either on batteries or to rely upon the environment for saving energy. Some other applications might require high data accuracy and reliability, for example, a higher activity duty cycle of nodes and higher computation power supply is beneficial for detecting moving objects. However, in order to become ubiquitous, each device in a WSN must be of low-cost and thus deterring the limitations in processing and storage capabilities as stated by Nagpurkar & Jaiswal (2015).

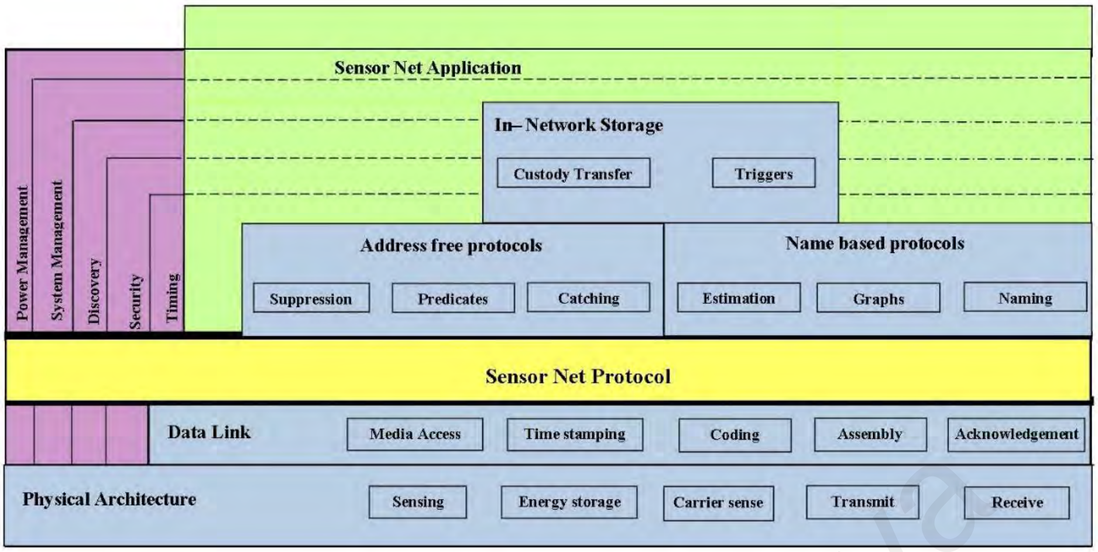


Figure 2.6: **Generic Architecture of WSN**

2.3.2 Energy Consumption in WSN

The varied applications in the field of WSN put forth common challenges whose accomplishment is a major challenge to be met. There are many research contributions aiming at altering the sensor node's energy efficiency and designing an efficient routing algorithm is one of the most important approaches. A sensor network comprises a few sink nodes and a considerable number of sensor nodes based upon the employed application. The energy for sink node is provided through cable and sensor node's energy is limited battery based. If the sensor node's energy is depleted, the data from the monitored area is eventually not obtained, thus increasing the transmission relay burden on other active sensor nodes in the network. This leads to node failure and hence degrades the network performance. Considering these drawbacks, energy consumption in WSNs is one of the major research areas and the goal to increase the energy efficiency of the sensor nodes plays a vital role in improving the overall performance of the network. There are three kinds of routing algorithms for energy efficiency in WSN namely data-centric routing algorithm, hierarchical routing algorithm and location-based routing algorithm as proposed by Du, Qu, Liu, & Wang (2015).

Fault tolerance is also one of the major challenges in WSN that needs to be addressed at various layers. The redundant nodes are enabled with self-healing and self-configuration abilities to improve fault tolerance. The working of networks in hostile environments might result in either temporary or permanent disconnection of nodes in the network thereby creating disturbed communication between the nodes. The architecture and communication protocol should be scalable since WSN involves a large number of nodes. The topology of a network affects many of its characteristics such as robustness, latency, and capacity. The process of dense deployment of thousands of sensor nodes in sensor field requires careful handling of network topology maintenance. Data aggregation represents a solution for data congestion in sensor networks. The other risks that are posed by the deployment of sensor networks include hardware constraints, coverage of the physical environment, connectivity of nodes and robustness as stated by Di Stefano, La Corte, Leotta, Lio, & Scata (2013).

Energy is utilized across all the layers of the sensor networks, predominantly at the transport, network and MAC layers. Nevertheless, assigning duty cycling mechanisms for the operational states of the sensor networks, there is relatively higher energy consumption by the active sensor nodes during sensing, communication and data processing. The inclusion of radio enables MAC at the data link layer to play a vital role in communication and connection establishment.

2.3.3 Application of WSN

The WSN are deployed in several applications and the researchers predict that these networks will pave way for a multitude of novel applications and also facilitate the existing ones. The sensors commonly sense the conditions such as light, pressure, humidity, acceleration, vibration, movement, weight, light, wind and acoustic implications. There are other sophisticated sensing devices too that include magnetometers, mechanical sensors, chemical sensors to check the water/air quality in the atmosphere and medical applications-based sensors. The literature till date provides a range of many applications for WSN that includes domains such as commercial, environmental, health, disaster management, face recognition, image processing and military surveillance as described by Elgamel & Dandoush (2015). In rescue operations, these sensor networks can assist in locating survivors and make the rescue team aware of the risky areas involved. In military applications, few of the advantages can be the remote handling of landmines, minimizing personal involvement in dangerous missions and intruder detection thus serving the whole purpose of security and safety.

The concept of a threshold is highly significant in a variety of WSN applications, such as fire alarm, temperature monitoring and so on. An innovative and proprietary WSN for steam sterilizers temperature probes, capable to overcome limitations of existing wired solutions has been developed and experimentally tested by Sisinni, Depari, & Flammini (2016). A novel 3-D deployment strategy called, Optimized 3-D deployment with Lifetime Constraint (O3DwLC), for relay nodes in environmental applications has extensively been introduced by Al-Turjman, Hassanein, & Ibnkahla (2013), wherein the strategy optimizes network connectivity while guarantying specific network lifetime and limited cost. The introduction of novel compression algorithms for real-time transmission of medical data and monitoring of epileptic patients have been validated and tested using Electroencephalography (EEG) and Electrocardiography (ECG) datasets comprising the two most demanding Epilepsy modalities, as a part of research contributions relative to health care applications of WSN as suggested by Antonopoulos & Voros (2016).

2.4 Radio Frequency Identification

2.4.1 Fundamentals

RFID stands for Radio Frequency Identification which is termed as a technology that is used for identification and tracking of objects through the embedded electronic circuitry in an RFID tag attached to an object and transmits a unique code to the RFID reader. Basically, RFID is the usage of radio frequency signals to transmit the tracking data of tags attached to objects. Research and development in the field of RFID have become advanced from the past few decades as depicted in Figure 2.7 due to its application in various fields such as transportation, security, supply-chain, health care utilities and industrial monitoring. The move from traditional systems towards pervasive computing and IoT demands a large number of tags for modern applications on a large scale.

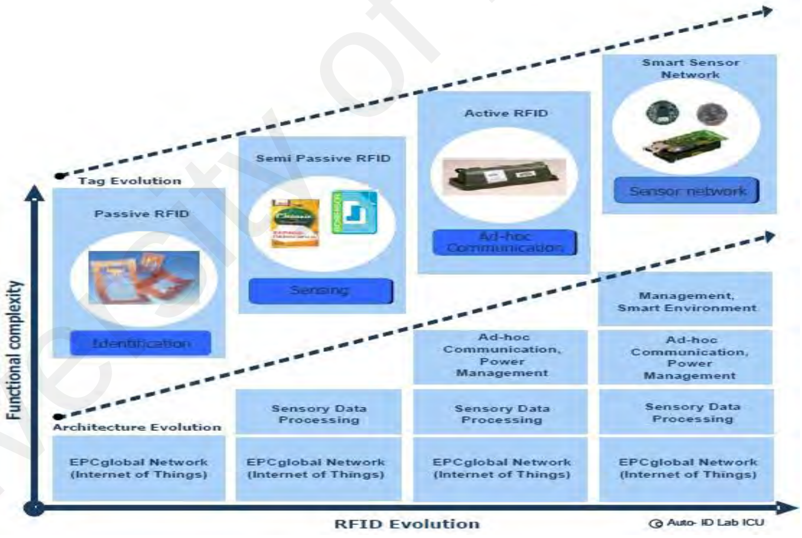
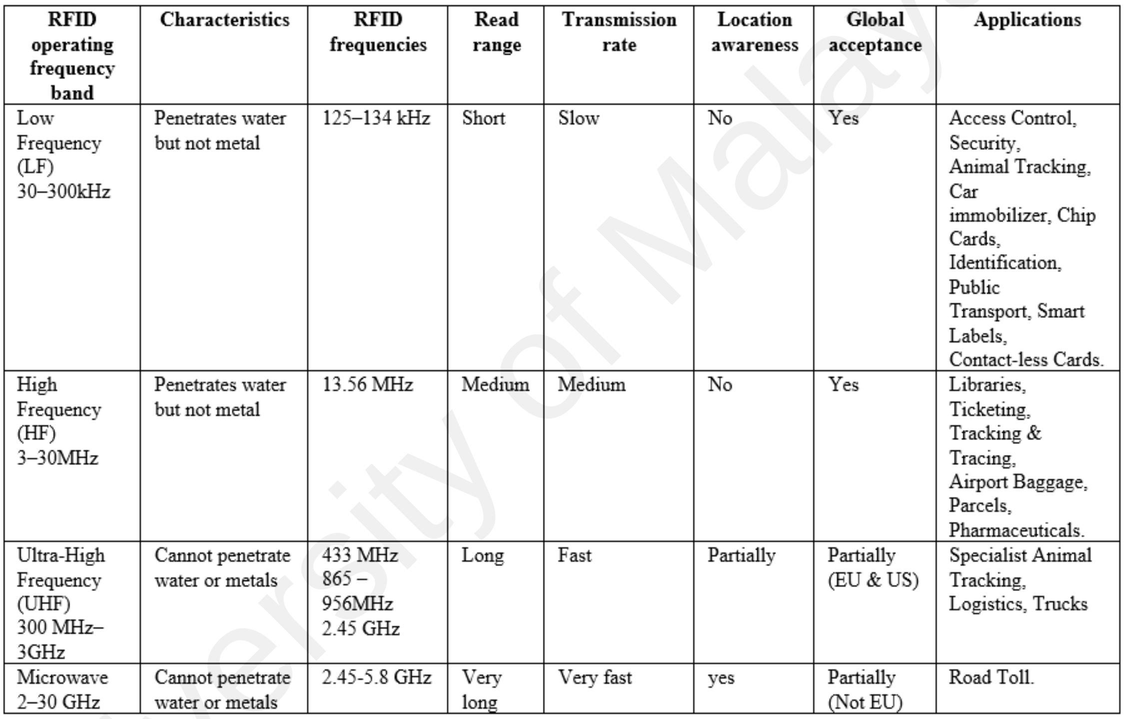


Figure 2.7: Evolution of Radio Frequency Identification

2.4.2 Types of RFID tags and Readers

There are two types of RFID: Active and Passive. The active tags use an external power source for charging its radio for communication purposes with the reader. The passive tags utilize energy provided by the reader when it comes in the read range of the reader by means of electromagnetic induction. The frequency range of active tags ranges at around 2.4 GHz and for passive tags at under 100MHz. The storage capacity for active tags is around 128Kbytes whereas for passive tags is considerably lesser as stated by Gulcharan, Daud, Nor, Ibrahim, & Nyamasvisva (2013). The RFID readers are majorly classified according to the frequency at which they operate as shown in Table 2.1. The categorization also depends upon the type of application in which the RFID readers and tags have been employed.

Table 2.1: **RFID characteristics, frequencies, and applications**[3]



RFID operating frequency band	Characteristics	RFID frequencies	Read range	Transmission rate	Location awareness	Global acceptance	Applications
Low Frequency (LF) 30–300kHz	Penetrates water but not metal	125–134 kHz	Short	Slow	No	Yes	Access Control, Security, Animal Tracking, Car immobilizer, Chip Cards, Identification, Public Transport, Smart Labels, Contact-less Cards.
High Frequency (HF) 3–30MHz	Penetrates water but not metal	13.56 MHz	Medium	Medium	No	Yes	Libraries, Ticketing, Tracking & Tracing, Airport Baggage, Parcels, Pharmaceuticals.
Ultra-High Frequency (UHF) 300 MHz–3GHz	Cannot penetrate water or metals	433 MHz 865 – 956MHz 2.45 GHz	Long	Fast	Partially	Partially (EU & US)	Specialist Animal Tracking, Logistics, Trucks
Microwave 2–30 GHz	Cannot penetrate water or metals	2.45-5.8 GHz	Very long	Very fast	yes	Partially (Not EU)	Road Toll.

Low-Frequency RFID which operates in the range of 30KHz to 300KHz with tag detection ranging up to 10cm. High-Frequency RFID operates in the range between 3MHz to 30MHz and is used for applications where tag detection needs to be tracked for a distance of more than 10cm, considerably higher than the previous type. The Ultra High-Frequency RFID readers are the most common and fast developing among all the types, because of its high operating frequency band of 300MHz to 3GHz and tag detection range

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[3] EU-Europe, US- United States

of about 12m. This type of RFID transponders are most receptive towards interference because of their high-frequency range as described by Leian, Dashun, Jiapei, & Hongjiang (2009).

2.4.3 Energy Management in RFID Systems

RFID technology faces many major challenges such as energy efficiency, privacy, security, collision and indoor location tracking as stated by Leian et al. (2009). The researchers Gulcharan et al. (2013) have made exploration on integrating the current active RFID transponder with other wireless technology available nowadays. The exploration is also made on solving the issues of continuously powering the transponder to avoid sudden power drainage that would lead to disruption of data transmission. Three main issues are holding back RFID's widespread adoption, the first of which is cost, followed by the complex design of the RFID system and reader collision problem as described by Want (2014). A possible ZigBee implementation in active RFID deployments, its involvement in the active system and the advantages of ZigBee integration in the active RFID tag has been described by Abdulla (2013) and conclusively found that energy efficiency is a central challenge in implementing RFID tags. The RFID systems are relatively believed to be one of the major cornerstones for wireless communication technologies due to its lower cost, higher data densities when compared to other auto ID systems such as OCR, voice recognition, fingerprinting and barcode. Hence, finding optimal solutions for minimizing the energy consumption can extend the functionalities and lifetime of integrated and cross-platform RFID systems.

2.4.4 Applications of RFID

A low power, high data rate passive RFID transceiver was presented by Abdo, Odeh, & Shahroury (2015) for usage in industrial and acoustic applications, designed and simulated using 28-nm CMOS process technology. The downlink works in the 900 MHz

ISM band at a data rate of 100 Kbps using a special modulation scheme that suits the passive systems. The uplink uses IR-UWB to achieve high data rate at low energy consumption. The author Want (2014) had urged in his intel research that radio frequency identification technology has moved from obscurity into mainstream applications that help speed the handling of manufactured goods and materials. RFID has also been used in various other domains such as to identify animals, label airline luggage, time marathon runners, make toys interactive, prevent theft, and locate lost items. The relative features of RFID such as small size, inexpensive, portable and wireless sensing are put to good use for many applications for monitoring and tracking items. Although the promise of RFID technology is thought to be great, its development has been slow because of anticipated implementation difficulties in areas such as signal quality and energy efficiency as described by Abdulla (2013). The other applications that are bound to exploit the capabilities of RFID technology are health care and automotive manufacturing industry stated by Want (2014).

2.5 RFID Sensor Networks

2.5.1 Requirements for RSN

The concept of integrating RFID and WSN has given way for the evolution of RFID sensor networks (RSN) hence bridging the gap between virtual and real-world entities. Both RFID and WSN are reckoned to be as the two most significant enabling technologies of IoT. This integration provides new perspectives to a wide variety of scalable, portable and cost-effective applications. The integration of both RFID and WSN can eventually maximize the functionality and provide means an effective scope for pervasive computing aspects. The architecture of RSN is shown in Figure 2.8. RFID utilizes the identification potential to trace the location of an object whereas WSN on the other hand, provides information about the physical condition of the object and the surrounding environment by enabling multihop communication. These two promising technologies when integrated together result in extended capabilities along with portability, scalability, and reduction of unnecessary costs as suggested by Douligeris (2009). There are four classes of integration that have been explored and experimented by the researchers till date. They are *i) Integrating tags with sensors ii) integrating tags with WSN nodes and wireless devices iii) integrating readers with WSN nodes and wireless devices and iv) a mix of RFID and WSNs.* The requirements for integrating RFID and WSN include factors adhering towards energy efficiency, reliable communication, accuracy and network survivability. There are numerous research contributions in the literature that provide insights into the various types of architectures for integrated RFID and WSN.

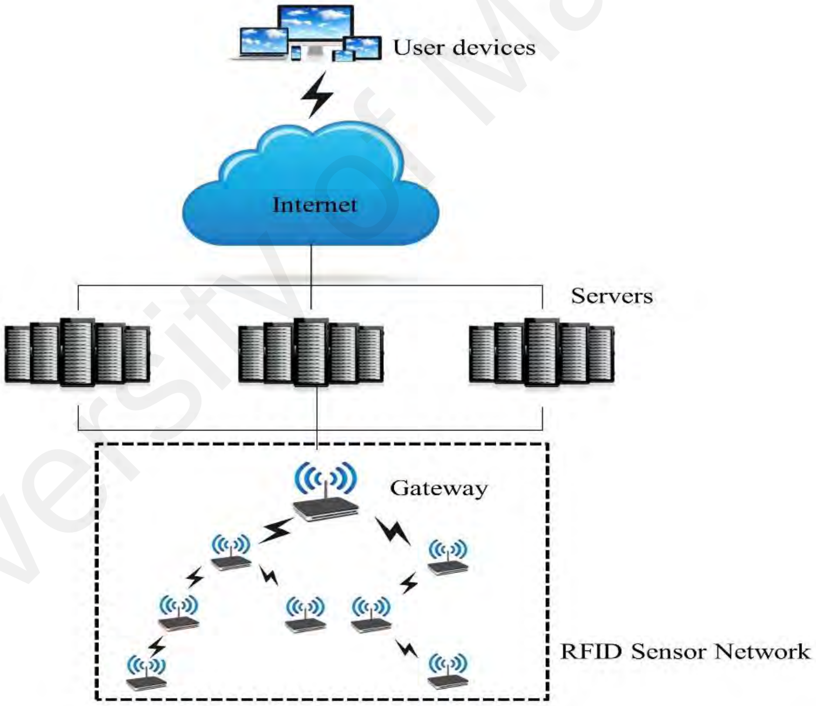
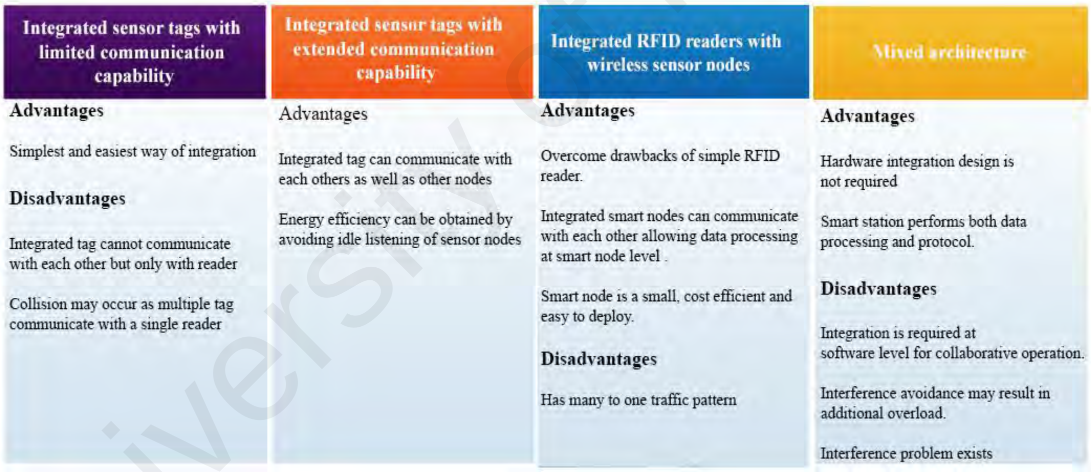


Figure 2.8: **Architecture of RFID Sensor Networks**

2.5.2 Types of RFID-WSN integration architectures

The RFID tags that can be embedded with sensors can be classified into two major classes: Integrated sensor tags that can communicate with RFID readers and integrated sensor tags that are able to communicate with each other to form a network. The authors Liu. H, Bolic, Nayak, Stojmenovic, & Stojmenović (2008) provide a survey on research work, new products, patents and applications that integrate RFID with WSNs where elaborated information can be referred on different types of integration, its applications, and technical challenges and also alike contributions by Asghari & Cheriet, 2018; Kaur . S& Mahajan (2018). When RFID tags are integrated with sensors, their communication capabilities are either limited or extended. There are active, semi-active and passive integrated RFID sensor tags which exhibit their own properties and have distinctive features from each other as explained in detail by author Douligeris (2009). The four major classes of integration architecture have their own advantages and disadvantages but the sensor tags with extended communication capabilities are said to be superior among all the four classifications as depicted in Figure 2.9, since it enables energy efficient operation and has no shortcomings as urged by Nagpurkar & Jaiswal (2015).



Integrated sensor tags with limited communication capability	Integrated sensor tags with extended communication capability	Integrated RFID readers with wireless sensor nodes	Mixed architecture
Advantages Simplest and easiest way of integration **Disadvantages** Integrated tag cannot communicate with each other but only with reader Collision may occur as multiple tag communicate with a single reader	Advantages Integrated tag can communicate with each others as well as other nodes Energy efficiency can be obtained by avoiding idle listening of sensor nodes	**Advantages** Overcome drawbacks of simple RFID reader. Integrated smart nodes can communicate with each other allowing data processing at smart node level . Smart node is a small, cost efficient and easy to deploy. **Disadvantages** Has many to one traffic pattern	**Advantages** Hardware integration design is not required Smart station performs both data processing and protocol. **Disadvantages** Integration is required at software level for collaborative operation. Interference avoidance may result in additional overload. Interference problem exists

Figure 2.9: **Types of RFID-WSN integration architecture**

The connected target coverage problem in RFID/Sensor networks has been presented by Jedda, Khair, & Mouftah (2012) wherein, the different approaches to solve the coverage and connectivity problem with the help of distributed algorithms have also been surveyed. Bluetooth and ZigBee technologies have been selected as communication protocols for WSN on integration with RFID, to meet the requirements of larger node density, area coverage and higher cost factors using Improved Cross Redundant Data

Cleansing (ICRDC) algorithm Wang. L et al. (2014). The purpose of this technique is to validate and eliminate the redundant data in integrated RSN systems. An EPC Sensor Network (ESN) architecture based on EPCGlobal standardization considered to be the defacto international standard for RFID and Complex Event Processing (CEP) technology has been proposed by Wang. W, Sung, & Kim (2008) to handle larger volumes of events from distributed RFID and sensor readers in real time. A significant research contribution towards integrated RSN systems is a novel data cleansing algorithm based on clustering mechanism, where the cluster head eliminates the duplicate data and thereby, forwards the filtered data towards the base station proposed by Dupare & Sambhe (2015). Similarly, according to Al-Turjman, Al-Fagih, & Hassanein (2012), an array of applications is accommodated based upon Integer Linear Programming (ILP). A novice reader can relatively find brief introduction to background research, patents filed, hardware construction framework, taxonomies, products developed and applications employed using integrated RFID Sensor Networks by the authors Liu. H et al. (2008), Hai Liu Harbin; Miodrag Bolic (2009);Jain & Vijaygopalan (2010);Shi, Su, & Xiong (2010) and Vishwakarma & Shukla (2013) respectively. The three distinctive forms of network architecture where the functional nodes act as either RFID tags or readers with sensor nodes have been described by Lei & Zhi (2006) and Huanjia Yang and Prof. Shuang-Hua Yang (2007). FlexRFID is a middleware solution that is developed to handle large amounts of RFID and scanned sensor data to execute an application's business rule in real time through its policy-based Business Rules Layer (BRL) described by Khaddar et al. (2014). Focusing upon sensor network system, that uses distributed smart node network architecture and employs Basic Frame Slot Aloha (BFSA) as the MAC protocol of smart node for reading tags, an energy model and energy consumption technique based on quantitative methodology are proposed and analyzed by Zhang. B, Hu, & Zhu (2010). The ontology and a reference model layout of roles with interfaces of sensor-integrated

EPCGlobal network have been described by Jin Mitsugi, Tatsuya Inaba (2007). There are significant research contributions towards RFID enabled wireless sensor network infrastructure using UHF and microwave frequencies as stated by Rida, Lakafosis, Vyas, Tentzeris, & Nikolaou (2011). Comparatively to FlexRFID, an on-demand wake-up capability namely RFID impulse achieved via off-the-shelf battery less RFID tag attached to each sensor node along with RFID reader capability has been developed and presented by Ruzzelli, Jurdak, & O'Hare (2007). Despite the numerous research contributions of integrated RSN systems, the current solutions fail to propose a global vision that is essential for pervasive computing stated by Sung, Lopez, & Kim (2007). This drawback has ultimately lead to the evolution of RSN based on EPCGlobal standard architecture framework.

2.5.3 Energy Management in RFID Sensor Networks

RFID Sensor Networks consist of miniature sensor nodes which are deployed to gather information on a particular object or area. The ability of these networks to monitor remote and hostile environments along with tracking capabilities has attained significant attention for research in past few years. They also have technical challenges to be met in order to maintain efficiency and reliability of the connected network and active nodes participating in the communication process. These challenges include resource constraints, transmission range, storage, battery power and energy consumption of the sensor nodes. Hence energy conservation is one of the key issues that need to be addressed. The existing solutions do not consider how to optimally allocate transmitted power and provide power splitting ratio to minimize energy efficiency. The most challenging aspect lies in the fact of estimating the periodicity and magnitude of the harvestable source and the deciding factor for the avoidance of energy depletion before the next recharge cycle. The taxonomy of energy management strategies in sensor networks is depicted in Figure 2.10.

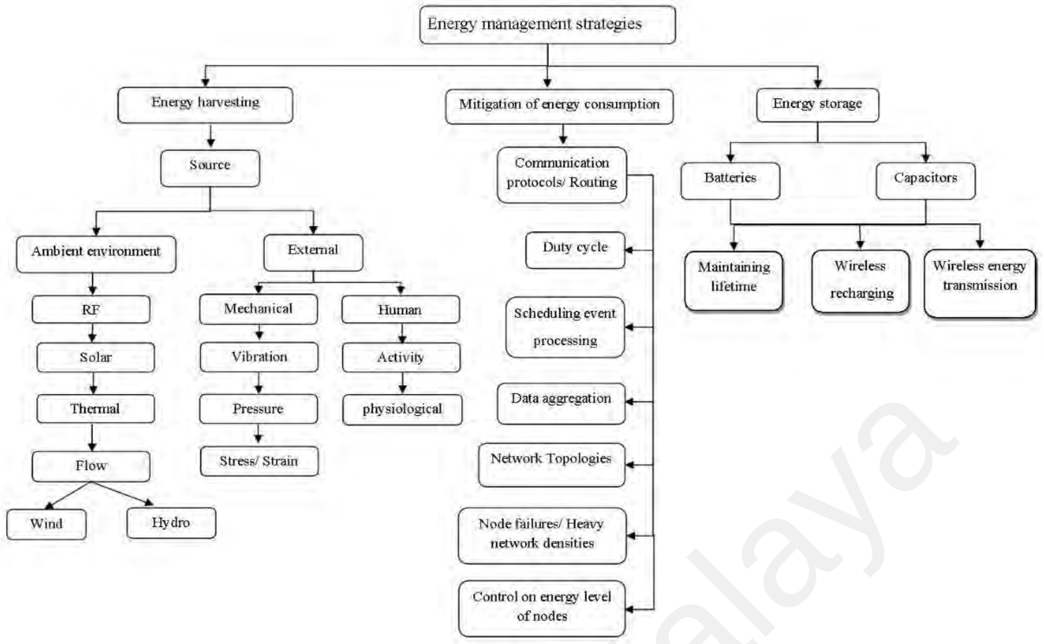


Figure 2.10: **Taxonomy of Energy management strategies in RSN**[4]

2.5.3.1 Energy Efficient Routing and Communication in Sensor Networks

The need for energy efficient routing protocols is a necessity for increasing the lifetime of the network and to prevent node failure. The operation and maintenance of sensor nodes in an intimidating environment and also the presence of error-prone communication links expose these networks to low energy levels thereby hindering the overall network performance and throughput. The networked infrastructure of heterogeneous devices in IoT contexts are equipped with sensors, controlling processors, wireless transceivers, and energy resources for data transmission and monitoring activities. One of the dominant hurdles for implementing such interoperable networks is supplying adequate energy for network operation without compromising on QoS as suggested by Kamalinejad et al. (2015). Hence it is important to improve the energy efficiency of the connected devices in the sensor network. The authors Abdul-Salaam,

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[4] This thematic taxonomy has been adopted from one of the research contributions by the author published in IEEE Internet of Things Journal, 2017

Abdullah, Anisi, Gani, & Alelaiwi (2016) have urged that though several energy efficient protocols have been designed to prolong the lifetime of the sensor nodes in traditional WSN, the integration of mobility-enabled technology with conventional static sensor networks, promises a new solution that balances energy consumption among the sensor nodes and eventually extends the lifetime of the network. The power management protocols can be implemented either as independent sleep/wake-up protocols running on top of a MAC protocol (typically at the network or application layer), or strictly integrated with the MAC protocol itself as stated by Anastasi, Conti, Di Francesco, & Passarella (2009). A standard protocol needs to be used for communication in sensor networks. Emerging communication standards such as IEEE802.15.4 is being used in wireless sensor networks as an underlying protocol for building other standardized communication protocols such as ZigBee and LowPAN as stated by Vullers, Schaijk, Visser, Penders, & Hoof (2010). A critical performance criterion in backscatter modulation-based RFID sensor networks is the distance at which an RFID reader can reliably communicate with passive RFID sensors (or tags). Researchers Iannello, Simeone, & Spagnolini (2010) have proposed a mechanism to introduce a Power amplifier (PA) and an energy storage device (such as a capacitor or a battery), in the hardware architecture of conventional passive RFID tags as illustrated in Figure 2.11, with the aim of allowing amplification of the backscatter signal to increase the read range of RSN during communication.

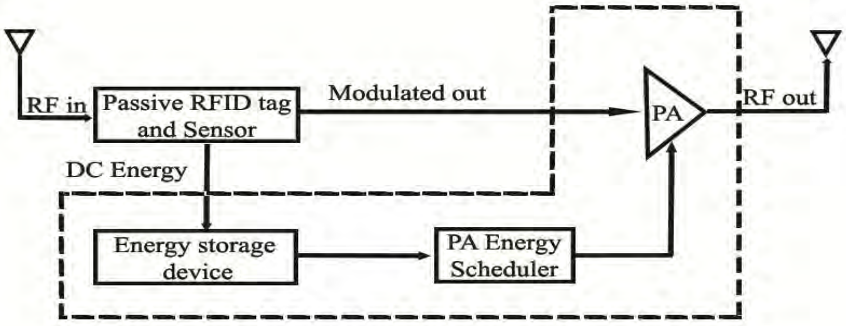

Figure 2.11: **Block diagram of RFID ABEH sensor node**

On the contrary to the traditional wireless class of networks, the criterion for RF-based EH network's routing protocol includes circuitry design of the nodes and propagation of RF energy factor. The reason for this difference is the distinctive amount of RF energy that can be harvested by the active nodes during each operational cycles of the network.

The EH parameters predominantly define the routing metric. These parameters include quality of network link, the sensitivity of RF energy harvester, the distance between the nodes and RF sources, number of available communication channels, hop count and also on the rate of conversion for harvested RF energy. There are research contributions which deal with the relationship and correlation between RF energy recharging and sensor network routing. The heterogeneity and movement of the nodes can be used to determine the congestion in a network using Priority based Application Specific Congestion Control Clustering (PASCCC) protocol as proposed by Jan, Nanda, He, & Liu (2014).

2.5.3.2 Energy Modeling

The sensor nodes in a network comprised of two components - energy dischargers (transceivers, radio, antenna, connectors, sensors, tags, readers) and energy suppliers (capacitors, batteries and so on). The nodes are energized by the use of batteries or capacitors. The real-time batteries tend to discharge energy even when they are idle as when compared to the simulators of linear characteristics. A considerable amount of energy is lost for every charging and recharging cycles, thereby leading to lesser voltage retention and a complete failure mode of the battery. The solutions for efficient optimization with the utilization of empirical, abstract, and physical models have been suggested by Chiasserini, C.F & Rao (2001). In physical prototyping, electrochemical batteries were employed whose reactions lead to either charging and discharging of energy storage devices. The behavior of these devices can well be predicted using stochastic and abstract models whereas empirical modeling employs mathematical equations for charging and recharging of batteries. The residual energy of the battery can be calculated according to the following Equation 2.1 as,

$$R_E = R - \int_{t_0}^{t_n} c(t)dt \tag{2.1}$$

Where, R_E is the residual energy, R is the rate of energy gain or loss, C(t) is the electricity that is drawn during the time interval of t_0 to t_n. Computational RFID (CRFID) runtime, namely dewdrop employs an exponentially adaptive polling interval for the purpose of gathering energy over longer ranges of input power and huge target voltages as suggested by Buettner, Greenstein, & Wetherall (2011). The system model as described by Carla Fabiana Chiasserini & Garetto (2006) studies the pattern of a single sensor node using Discrete-Time Markov Chain (DTMC) modeling technique. In DTMC, the transmission time for a data unit decides the time slotting technique which means that the duration needed to transmit one unit of data along with the MAC layer overhead. A heterogenous two-tier WSNs compromising of two distinctive and hierarchical set of nodes: sensor-tier nodes (M) and processing-tier nodes (N) is studied by Machado, Ansari, Wang, & Tekinay (2010) to explore and resolve the coverage processes of the deployed region using optimization theory, power control and clustering techniques. The efficiency of a harvester circuit is iterative and is affected through energy losses from switching process of Metal-Oxide-Semiconductor Field-Effect Transistor (MOSFET) and diode to inductive resistance and power consumption of the comparator as stated by Dondi, Bertacchini, Brunelli, Larcher, & Benini (2008).

2.5.3.3 Energy Harvesting

The energy harvesting process of a sensor node takes place at the energy storage device typically either the battery or the capacitor. During this process, the energy consumption by the transceivers and radio is minimized. The existing research solutions which focus on EH consider conserving the energy that is utilized during data transmission, but as suggested by Liu, W., Zhou, Durrani, Mehrpouyan, & Blostein (2016), EH process is carried out during both transmission and sensing processes. The duration between the start of a sensing operation and the time at which information is stored in the sink is used for the purpose of harvesting energy. It also uses the consecutive differences in the operational time period of each active duty cycles. The frequency of the updates is faster if the processing time and the information transmitted to the sink is smaller. The components of the harvesting node are depicted in Figure 2.12, which harvests energy through renewable energy resources such as solar, wind, RF and so on.

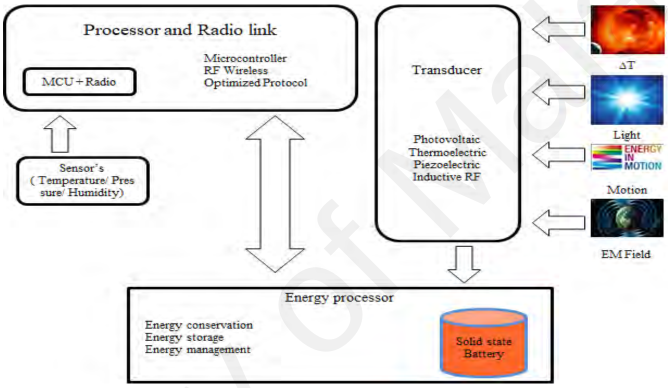

Figure 2.12: **Energy harvesting components of a sensor node**

The energy gets preserved in a battery. The different modes for the process of EH in sensor networks are - Sensing Phase (SP), Transmission Phase (TP) and Energy Harvesting Phase (EHP). According to the literature contribution of Han et al. (2015), the algorithm for EH is as depicted in Figure 2.13.

```
Input: harvest_energy;
Output: ESP, ETP
If sensor_phase = harvest_energy
Calculate ESP + ETP
If TP > 0, then
Calculate and Continue
Until ESP + ETP is more
Than battery storage
Else if TP== 0, then
Calculate ETP
Transfer data_packet if
EH < ESP + ETP
Repeat for all cycles
```

Figure 2.13: **Energy harvesting pseudocode**

The battery consists of the harvested energy. During data packet transmission, energy is not harvested and vice-versa. The comparison between deterministic, gamma and exponential distribution EH models shows that deterministic models have relatively higher transmission time between the packet delivery and data availability at the sink. Another observation is that higher cost of sensing energy leads to lower information update frequency Kamalinejad et al. (2015). A hybrid EH model has been studied by Yang et al. (2017) for the purpose of power stabilization to the load, using hybrid system combining magnetic, thermoelectric vibrational energies. The research contributions by Abdulhadi & Abhari (2015) describes the drawback of resource allocation in Radio Frequency Energy Harvesting Networks (RF-EHNs) through optimized operational policies and enhanced throughput of RFEH node. The architecture of RF-EHN has been depicted in Figure 2.14. The emergence of wireless charging techniques provides a more flexible and promising way to solve the energy constraint problem in WRSNs.

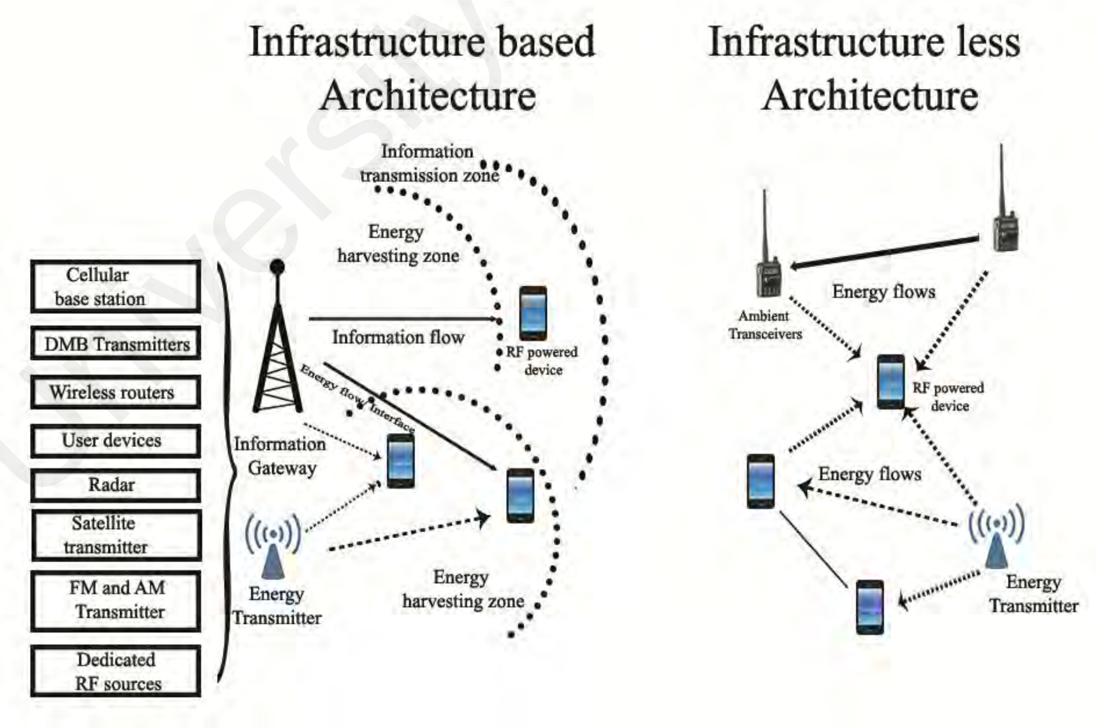

Figure 2.14: **Architecture of RF-EHNs**

Although considerable research has been conducted on wireless charging algorithms, the majority of them have focused either on passively replenishing energy for nodes with insufficient energy or providing event-driven duty cycles according to the energy needs. When the energy of a sensor node is depleted, it will no longer fulfill its role in the network unless either the source of energy is replaced, or some harvesting mechanism is induced to bridge the energy gap. The existing solutions utilize energy source powered by batteries in sensor nodes of RSN’s but are associated with many drawbacks, like chemical leakages, extreme weather conditions, and limited energy density. Energy harvesting in sensor networks has reached to contributions such as grid-based joint routing and clustering technique for Industrial Wireless Rechargeable Sensor Networks (IWRSNs) to overcome the drawback of proactive charging Han et al. (2015) and asset tracking architecture for traditional tracing facilities using smartphones developed by Bisio, Sciarrone, & Zappatore (2016). The target of minimizing the rate of energy usage in smart buildings has been aimed by Aryadevi Remanidevi Devidas, George, & Ramesh (2015) where a smart personalized system for EM guarantees optimization of energy and preserves energy for renewable energy resources. The target coverage issue hinders the lifetime of sensor networks in applications such as surveillance and habitat monitoring. These drawbacks have eventually lead to research contribution for improving the network lifetime and addressing the other drawbacks such as network fault tolerance, target coverage, and connectivity of the sensor circuit for energy efficiency Ganguly (2016). A Smart Personalized System for Energy Management (SPSE) which is a low-cost context-aware system integrated with personalized and collaborative learning capabilities to understand the real-time behavior of individuals in a building for optimizing the energy usage has been developed by Devidas, A.R, George, & Ramesh (2015). A novel Energy-efficient Evo-Fuzzy Sleep Scheduling Protocol (EEFSSP) for equitable distribution of nodes and to solve the target coverage problem pertaining to WSN has been studied by

Ganguly (2016). A detailed survey of the systematic and comprehensive taxonomy of the energy conservation schemes in Sensor networks can be referred to Zahid Kausar, Reza, Saleh, & Ramiah (2014). The contributions by Ferdous, Reza, & Siddiqui (2016) have discussed energizing WSN by energy harvesting systems. A model that is able to drive a wireless sensor with energy harvested from renewable sources has been proposed by Shaikh & Zeadally (2016) and a comprehensive classification scheme for energy harvesting techniques in WSNs has been presented by Sudevalayam & Kulkarni (2011). The research contribution by Shrouf & Miragliotta (2015) had developed a comprehensive classification scheme for energy harvesting techniques in WSNs. A framework to support the integration of gathered energy data into a company's information technology tools and platforms, for energy-efficient production management practices that are enhanced and enabled by the IoT technology, has been proposed by Akhtar & Rehmani (2015). A survey on typical renewable energy resources, their characteristics, battery recharging techniques and its potential applications with respect to WSN followed by the discussion about the feasibility of using IEEE 802.11 in energy harvesting low-power sensing applications has been investigated by Fafoutis, Sorensen, & Madsen (2014). Piro, Boggia, & Grieco (2015) have proposed a hierarchical network architecture, which integrates a Body Area Nano-NETworks (BANNET) and a macro-scale healthcare monitoring system with two different energy-harvesting protocol stacks that regulate the communication among nano-devices during the execution of advanced nano-medical applications. A Total harvesting efficiency parameter to achieve solar energy harvesting followed by a numerical investigation about the matching efficiency between a nano dipole and rectifier solar energy harvesting has been presented in Ma & Vandenbosch (2013) and Park, Lee, & Bond (2014) respectively.

2.5.3.4 Energy transmission

The process of transmitting energy either through a wired medium or wirelessly is termed as energy transmission. The consumption of energy during transmission is one of the attention-seeking issues for EH sensor networks. This issue urges for energy usage minimization and optimization of operational policies during packet transmission. Data transmission process here refers to either transfer of information between the active sensor nodes or between a node and the gateway node (Sink). The energy required for packet transmission is comparatively higher when compared to energy consumed by radio. The past research contribution has witnessed many modeling techniques for reduction of energy consumed by sensor nodes during transmission. Solar energy and many other sources have been extensively used as a replacement to overcome the higher energy consumption and to supplement the limited lifetime of energy storage devices such as batteries and capacitors. The operational power cycle process of a sensor node has been depicted in Figure 2.15.

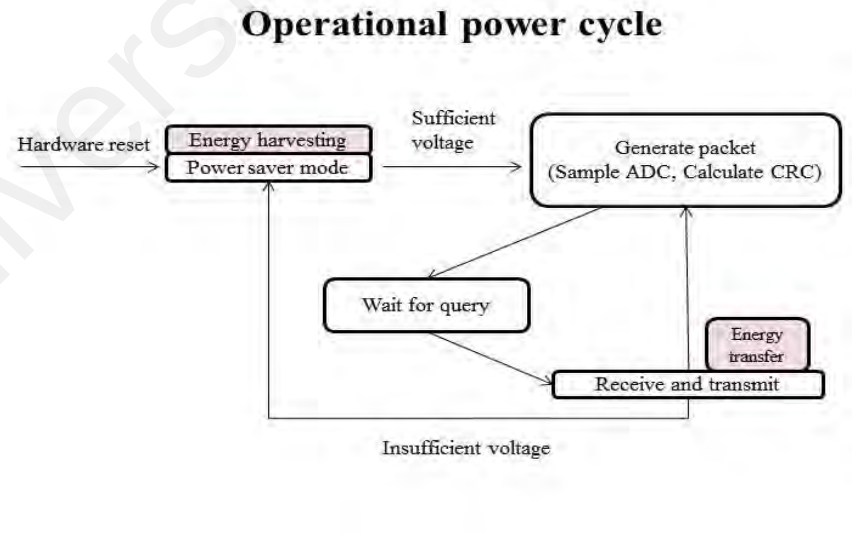

Figure 2.15: **Operational power cycle of energy harvesting sensor node**[5]

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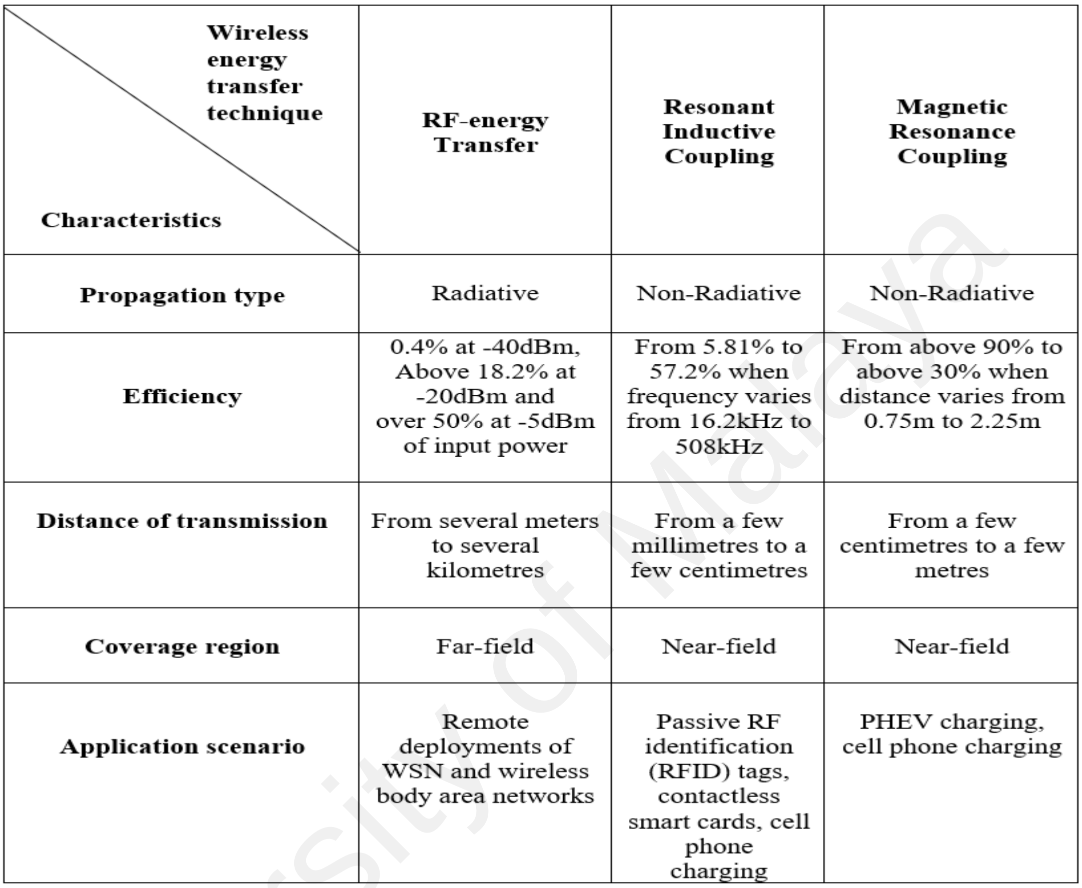
[5] ADC-Analog to digital convertor; CRC-Cyclic Redundancy Check

The other prominent drawbacks in sensor networks during transmission are connectivity, higher power consumption and coverage of target area as suggested by Sherazi, Grieco, & Boggia (2018). The comparison of various wireless energy transmission techniques has been tabulated in Table 2.2. The solution for sensor connectivity is to either increase the range of transmission or to increase the node density, both of which will eventually lead to a poor lifetime of the network and higher energy usage. Therefore, connectivity assurance and energy optimization can be achieved by assigning and scheduling appropriate duty cycling mechanisms and choosing the best optimal policies for the operation of sensor nodes as described by Sun, Zonouz, Xing, & Vokkarane (2016). The systematic review presented by Mitrokotsa & Douligeris (2010) provides a comprehensive discussion on the existing solution for energy transmission in RF-enabled sensor networks. It provides the novice readers an in-depth explanation about wireless ET protocols for heterogonous frequencies in RFEH, followed by existing solutions of RF powered cognitive radio networks, RF- MAC as proposed by Lu, Wang, et al. (2015), ALOHA-Q described by Chu, Kosunalp, Mitchell, Grace, & Clarke (2015), SWIPT presented by Lu, Flint, Niyato, Privault, & Wang (2015), Dewdrop by Buettner et al. (2011), Markov decision framework-based optimization solution presented by Hoang, Niyato, Wang, Kim, & Le (2017) and MinMCP by Haipeng Dai , Xiaobing Wu, Guihai Chen, Lijie Xu (2014) for 2D WRSNs respectively. The method of data aggregation is employed for avoiding redundancy and to alter the cost. Ant Colony Optimization (ACO) is explored for mitigating the energy consumption and to improve the sensor node’s lifetime. The concept of Minimum Energy Broadcast (MEB) is used when the communication channel is secured and also for the purpose of minimizing energy consumption. Routing protocols are designed and developed by employing encoding and multi-objective fitness function. The considerable mitigation of energy consumption is achieved through a clustering algorithm and network layer optimization to improve the lifespan of the network for packet transmission as developed by Jurdak, Ruzzelli, & O'Hare (2010). The wireless communication may get hindered due to the dynamic network conditions, where the sensor nodes are fixed to send energy recharging requests to either the mobile chargers or energy sources. The network densities also play a major role in energy request. The more the number of nodes, the burden of energy recharging workload increases eventually causing decreased throughput and performance of the network as stated by Dhondge, Shorey, & Tew (2016). The total time taken for delivery of request, recharge time and the time taken for the sensor node to travel to the gateway are the parameters to be considered for charging. The dynamic energy recharging problem for RSN has to be evaluated analytically in terms of energy efficiency and network throughput, that has not been addressed in the literature. The issue of wireless energy transfer and request in RSN still needs to be focussed in an efficient way between clustered and cooperative nodes. The major challenge in the network with wireless energy transfer is to determine the amount of energy to be transferred to the nodes as stated by Rafsanjani, Ahn, & Alahmad (2015). The process of transferring wireless energy not only requires additional energy consumption by the access points but also creates strong interference to other networks sharing the same spectrum.

To overcome this overhead, the access point may charge the nodes based on their wireless energy demand. The nodes have to make the decision for wireless energy transfer according to the charged cost with achievable data transmission performance, from the access point. The existing solutions that are discussed by Dhondge et al. (2016) focuses on non- cooperative scenarios for wireless energy transfer and requests, where the nodes can comparatively bid for wireless power transfer for an access point and use that energy for packet transmission, but the interference management due to wireless energy transfer has not taken into consideration. A distributed event-triggered communication for time synchronization in order to reduce the energy consumption in WSNs has been proposed by Chen, Li, Huang, & Tang (2016).

Table 2.2: **Comparison of different wireless energy transmission techniques**[6]



Wireless energy transfer technique Characteristics	RF-energy Transfer	Resonant Inductive Coupling	Magnetic Resonance Coupling
Propagation type	Radiative	Non-Radiative	Non-Radiative
Efficiency	0.4% at -40dBm, Above 18.2% at -20dBm and over 50% at -5dBm of input power	From 5.81% to 57.2% when frequency varies from 16.2kHz to 508kHz	From above 90% to above 30% when distance varies from 0.75m to 2.25m
Distance of transmission	From several meters to several kilometres	From a few millimetres to a few centimetres	From a few centimetres to a few metres
Coverage region	Far-field	Near-field	Near-field
Application scenario	Remote deployments of WSN and wireless body area networks	Passive RF identification (RFID) tags, contactless smart cards, cell phone charging	PHEV charging, cell phone charging

A co-operative solution to effectively handle energy replenishment and data collection in large scale RSNs has been presented by Farris, Militano, Iera, Molinaro, & Spinella, (2016). The researchers Angelopoulos, Nikoletseas, & Raptis (2016) have proposed three new, alternative protocols for efficient charging, addressing key issues of efficient wireless energy transfer in Wireless Rechargeable Sensor Networks. A framework for node deployment and delay tolerance in RSNs under the IoT paradigm has been introduced by Al-Turjman, Al-Fagih, Alsalih, & Hassanein (2013). Consequently, a

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[6] PHEV- Plug-in Hybrid Electric Vehicle

mathematical model (OPT-t) which is time-dependent for co-locating a wireless charger and a mobile base station on the same mobile platform has been developed by Xie et al. (2015). An optimization model to derive the optimal policy for each mobile node has been formulated and further a repeated coalition formation game model to capture the cooperation strategies of the mobile nodes has been introduced by Dusit Niyato, Wang, Hwee-Pink, Walid, & Dong In (2014). The researchers Madhja, Nikoletseas, & Raptis (2015) proposed four new protocols for efficient charging and wirelessly replenish the energy of sensor nodes. The design of energy and spectrum-aware MAC protocols for Wireless NanoSensor Networks (WNSNs) with the objective to achieve fair throughput and lifetime optimal channel access by jointly optimizing the energy harvesting and consumption processes in nanosensors is also one of the significant research contribution by Wang.P et al. (2013). An efficient energy sharing algorithms, a Q-learning algorithm with exploration mechanisms based on the €-greedy method as well as Upper Confidence Bound (UCB) has been presented by Padakandla et al. (2015). Ultimately, an energy consumption model based on energy expenditure analysis for WNSNs by jointly accounting for the energy consumption of both sender and receiver have been extensively developed by Huang, Wang, & Shen (2016). An approximation algorithm for Minimum Mobile Charger Problem (MinMCP) of two-dimensional (2D) WRSNs and investigation on the design of their recharging routes by Haipeng Dai , Xiaobing Wu, Guihai Chen, Lijie Xu (2014) followed by the invention of a novel scheme of integration paradigm for RFID and WSN technologies by Ding (2013) produce relatively vital contributions for ET in RSN. The authors Chi, Zhu, Jiang, & Tian (2013) have explored the transmission energy minimization issue in a WNSN with On-Off Keying (OOK) modulation, and also have developed the corresponding Minimum Transmission Energy (MTE) coding solutions with the considerations of code rate constraint and codeword length constraint.

2.5.4 Applications of RSN

The authors Baghaei-Nejad, Zou, Tenhunen, & Zheng (2007) have presented a radio-powered module with asymmetric wireless link utilizing ultra-wideband radio system for RFID and WSN applications. This research has revealed that impulse-based UWB is a promising technology for RSN applications. In the research work developed by Hussain, Schaffner, & Moseychuck (2009) an integrated RSN system for smart homes such as identifying a caregiver who enters home, lighting, personalized music and to identify motion within an environment under surveillance has been presented. The authors Jedermann, Behrens, Westphal, & Lang (2006) have proposed a sensor system that autonomously configures itself to a product-specific supervision task based on data scanned by an RFID reader during freight loading. Mobile software agents accompany the freight along the supply chain. They pre-process the vast sensor data and submit only substantial changes to the freight owner. A study on evaluation of the dynamic behavior of wireless sensors on integrated systems had been proposed by Badia-Melis et al. (2014). The researchers Nasir & Soong (2009) have proposed a novel technique called EnvironSense which is based on RFID magnetic induction to measure the air contamination through environmental sensors installed near the vehicle's exhaust and convey them back to the driver through feedback. The research contribution by Sharma, Singh, & Saini (2011) has presented an integrated RSN to build an intelligent and secured RFID credit card system. The authors Mirshahi, Akbari, & Uysal (2015) have presented a study that demonstrates the algorithm for Structural Health Monitoring (SHM), by applying the integration of RFID system with sensor-tags in order to indicate how communication takes place throughout the system. A prototype system for verifying the possibility of electrical industry application using RFID/WSN to manage the electric facility has been developed by Kim, Yi, Song, Shin, & Lee (2008). In the research by Li.Z, Shen, & Alsaify (2008) the employment of effective integration of RFID and WSN in applications such as precious animal and patient health monitoring where real-time updated information is of utmost importance has been discussed. The authors Rajesh et al. (2013) have proposed a low-cost approach to the development of a system that can monitor the real-time parameters of a patient using an active UHF RFID system along with the respective parameter monitoring sensor. An integrated RFID reader into a WSN has been developed to authorize and keep track of people carrying RFID tags described by Torres, Pang, Skelton, Bridges, & Meghanathan (2010). A software framework which makes the integration of RFID and WSN easier task for its usage in supply chain management systems has been proposed by Gomez, Laurent, & Moustaine (2011). The researchers Mainetti et al. (2014) have presented a Smart Parking System (SPS) based on the integration of Ultra High Frequency (UHF) RFID and IEEE 802.15.4 WSN. The contribution by Ahmed & Raja (2012) have proposed a hierarchical security management scheme that utilizes biometric data, e-health card or RFID tag for the patient or doctor authentication to access healthcare services. The research article by Pereira et al. (2008) presents an integrated RSN architecture to be applied on animal monitoring applications. An integrated model system in which RFID capabilities are combined with WSN technology to serve as reliable decision-making platform when products, materials, and information are moved across the supply and demand chains has been designed and developed by Mejjaouli & Babiceanu (2015). The other significant research contributions include development of seamlessly integrated information management framework that can provide logistics information to project stakeholders for the effective decision-making process as stated by Shin, Chin, Yoon, & Kwon (2011) and also innovation of a smart space named SmartExhibition which is defined as a scenario of RFID integrated with sensor networks enabling the whole architecture along with pervasive computing-based application mode as presented by Zhang.T, Ouyang, & Liu (2008). The various applications of RSN developed by the researchers in the literature have been depicted in Figure 2.16.

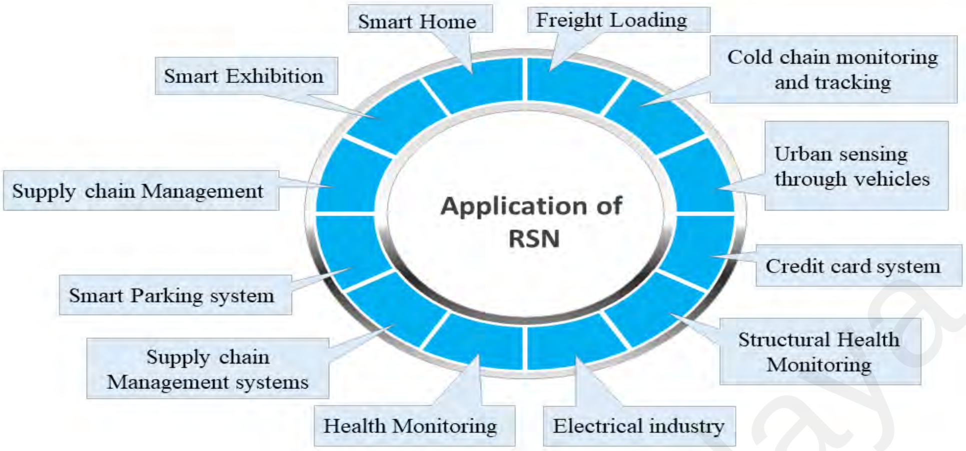

Figure 2.16: **Applications of RSN**

The focus of this research is firstly to integrate RFID and WSN through simulations and also to integrate the approaches of EH and ET together into an EM model which is solved for energy expenditure using DP approach. The reason here to use EH concept is because it is one of the EM strategies for sensor networks as stated by researchers in the literature and also harvesting through ambient energy sources, for instance, RF signals, provides energy to the nodes three times much higher than what is actually needed for a normal sensing operation. Moreover, the process of wireless energy transfer in this research is employed to overcome the barrier of loss of Request to Charge (RTC) packet due to packet collision or channel conditions. And also, to avoid destructive interferences caused due to recharge requests from multiple nodes. The EM model is characterized as SMDP to reduce the computational complexities since the time complexity of this approach is O(n) when compared to the highly time-consuming approaches stated in literature.

2.6 Summary and chapter conclusion

This chapter has given a detailed explanation and comprehensive background knowledge that is vital to understand the concept of IoT, WSN, RFID and RSN. The basic information about each of the enabling technologies is important to conceptualize the drawback of energy management in IoT contexts. Moreover, energy harvesting, and energy transmission are two important aspects of managing the energy levels in a sensor network. The chapter also outlines the mechanisms, algorithms, and models for energy efficient routing and communication in sensor networks. The energy consumed during transmission of packets is much higher when compared to the energy consumption by connecting components such as transceivers, radio, and antennas. Energy management in RF- Sensor networks is the main goal of this research and hence the subsequent chapters present a brief discussion about energy conception, its associated factors, drawbacks, and analysis in order to achieve the research gaps and to eventually address the EM issue.

CHAPTER 3: PROBLEM ANALYSIS

3.1 Introduction

In RSN, the most advantageous feature is that the sensors need not have to rely solely upon batteries for transmission of sensed data. The other sources of energy can be obtained from renewable energy sources like solar, wind, vibrational, RF and so on. Therefore, to maintain the energy levels for remaining at an active and operative state of sensing, transmitting and processing data, there is a need for the development of efficient EM techniques as suggested by Godoy, Cayssials, & García Garino (2018); Li.X et al. (2018); Shah, Chen, Yin, Khan, & Ahmad (2018); Singh, Singh, Hoang, & Aziz (2018). The recent literature in the field of wireless networks has found many significant research solutions for the mitigation of energy consumption for instance by the researchers Gasmi, Mosbahi, Khalgui, Gomes, & Member (2018); Peng et al. (2018); Thirukrishna, Karthik, & Arunachalam (2018); Wu & Yang (2018). The different methods by which energy levels can be managed are – 1) To assign duty cycling mechanism and scheduling tasks for mitigation of energy losses. 2) To harvest energy from non-exhaustible resources such as solar, RF, wind, vibration and so on. 3) To store enough energy in devices such as capacitors and batteries. 4) To recharge the batteries through RF, magnetic and inductive coupling. The researchers have given more priority to assigning and developing solutions for minimization of energy consumption rather than focusing on solutions for efficient EH and ET. Therefore, the following sections (3.2, 3.3 and 3.4) in this chapter deals with the factors relative to the energy consumption in sensor networks of IoT based system and their corresponding impact on the overall energy levels leading to consumption during an operational state. The aim of this chapter is to find the significant research gaps for EM in RSN of complex IoT systems and analyze the contributing factors for energy consumption.

3.2 Analysis of Energy Consumption in IoT Systems

The enabling technologies of IoT are sensor networks, RFID, nanotechnology and smart technology. The two prominent technologies like sensor networks and RFID have individual capabilities of sensing and computation for complex and time-critical IoT systems. The nodes in sensor networks are equipped with small-sized batteries which are executed using mesh formation. The main goal for a sustainable sensor node is to minimize the overall energy consumption of the system. The lifetime and deployment of batteries depend upon the type of application- wherein some require that the batteries and perhaps others follow ‘discard after usage’ policy. In such types of applications, the replacement and fixing of new energy storage devices become tedious for mission and time-critical systems.

3.2.1 Impact of routing mechanisms

The function of sensors in a wireless network is not only to sense the physical conditions of the surrounding environment but also to transmit and relay the sensed data to its neighboring nodes using wireless links. The sensor’s data is stored and collected by the centralized unit or the sink node which is responsible to provide the global procedure of the underlying physical phenomenon. When sensor networks are connected in an IoT system, the main objective lies in the fact of reassigning the underlying physical procedure accurately at the centralized unit. This aspect enables the optimization of network utility as well as the mitigation of estimation distortion of the overall system. The underlying issue is that each of the sensors in the network, seldom identify the nature of the physical phenomenon, the estimation of the overall system relies upon the individual data rates of the active sensors. The transmission rate trade-offs between each of the sensors can be handled using coupling function of the network utility and data rates (distributive source coding method). Furthermore, when sensors are deployed in a particular area forming a wireless network, they share the similar wireless medium, due to which the issue of interferences occurs across spatially closer transmissions. This issue discards the assumptions of link capacity, where adaptive power control can be employed. For the larger density of sensors, an ad-hoc network is formed, where a selection of a multihop path to the sink node becomes the issue for the routing of the nodes. This routing problem along with link capacity issue and transmission rates overhead, complicate the overall network design of an IoT system leading to the higher energy consumption of the nodes during packet transmission. Therefore, the overall network optimization problem is formulated and solved by individual solvation of source coding sub-issue at the application layer and the power control challenge at the physical layer as depicted in Figure 3.1, along with routing over updating of multiplier variable λ.

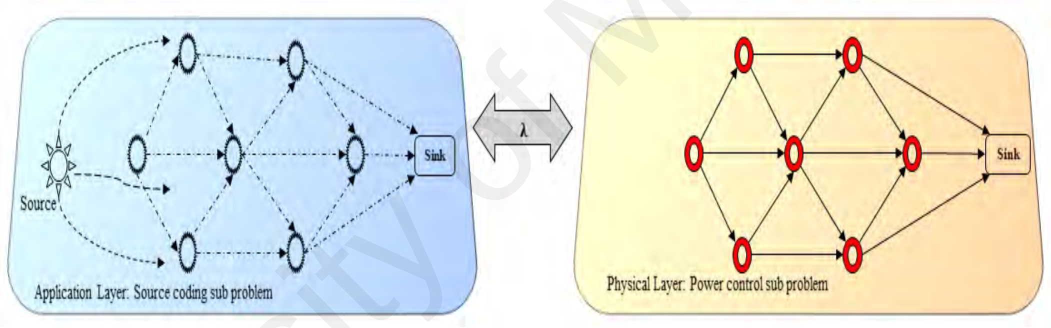

Figure 3.1: Sub-issues of network optimization problem

The energy level of a node and the hop count-based routing do not relate to randomized RF link of the dynamic network environment. The definition of an optimal route doesn't necessarily mean the shortest path to the destination, and moreover when compared to the RF link which is time-varying and dynamically changing, the one which is stable fetches efficient and reliable results. The success of packet delivery is enhanced by routing and transmitting duplicate copies of the data packets, which in turn causes increased energy consumption and network latency. The five routing protocols of multihop WSN for multiple to one routing pattern namely Adhoc On-Demand Vector routing (AODV), Efficient and Reliable routing (EAR), Gradient Broadcast (GRAB), Gradient based routing (GBR) and Dynamic Source Routing (DSR) are compared in terms of packet delivery, latency and energy consumed per packet with respect to the equally distributed active and inactive number of nodes has been depicted in Figure 3.2, 3.3 and 3.4 as per researchers Kok, Loh, Jing, & Pan (2009). Moreover, the task of tracing the routing information of the packet for the entire transmission period turns out to be an extortionate task, in an attention seeking unstable network environment according to Sherazi et al. (2018). The focus turns towards improving and increasing the lifetime of the sensor network and also handling frequency distortions and node failures. The network density also has a major role to play to match up with the operation of the routing protocol. The aim in such a scenario would be to focus on the overall energy consumption incurred by the routing protocol designed to meet the contradicting requirements. The tabulated information as in Table 3.1 describes the comparison between the different current routing protocols for RF-EHNs. It can be noted that the utilization of RF charger by all the protocols lead to the consideration of out-of-band charging frequency for interference avoidance.

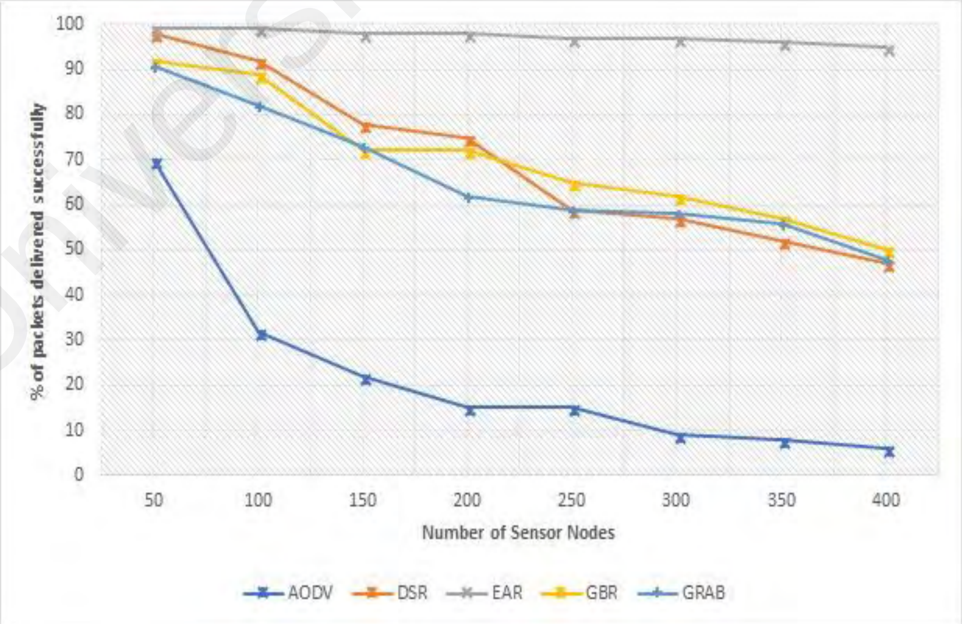

Figure 3.2: **Packet Delivery Ratio (PDR)**

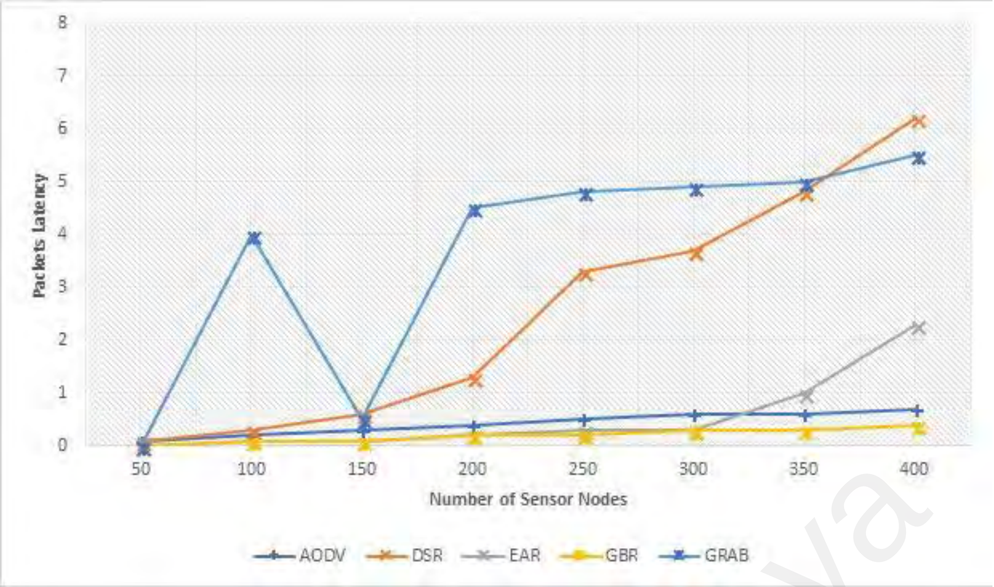

Figure 3.3: Data Packet Latency

Figure 3.4: Energy Consumption per data packet

Table 3. 1: Comparison between routing techniques/protocols for RF-based EHN's[7]

Routing protocol	Charging frequency	Charger	Route metric	Channel state information	Routing decision	Mobility
R. Doost et al	In- band	Mobile	Charging time	High	Distributed	Limited
Routing first heuristic algorithm	Out-of-band	Static	Minimum recharging cost	High	Centralized	low
Incremental deployment based heuristic algorithm	Out-of-band	Static	Minimum recharging cost	High	Centralized	Low
J-RoC	Out-of-band	Mobile	Charging-aware routing cost, factoring the estimated energy minimum routing cost and real time link quality	Medium	Distributed	Limited

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[7] J-RoC- Joint Routing and Charging

3.2.2 Impact of communication protocols

When the sensor nodes are deployed in an area, they transfer the data to the sink node via two methods- Primarily, it transmits data directly to the centralized base station through a direct communication protocol. This approach leads to higher energy consumption by the nodes if the distance of transmission between the sensor nodes and the base station is longer, eventually leading to quicker exhaustion of the nodes. Secondly, the nodes act as relays to route the data to neighboring nodes. This is effective for the smaller density of the network since node localization can be computed easily to achieve a faster rate of data collection and forwarding towards the mobile sink node. The requirements to aid the restrained battery power capability of the sensor nodes, for enhanced network lifetime, is indeed vital and imperative. A considerable research contribution which has made conclusive remarks that communication protocols in sensor networks adopt the clustering techniques for mitigation of energy consumed during data collection and aggregation methods. The clustering technique minimizes the higher energy consumption caused due to longer transmission ranges between the node and the sink. It also reduces the range of communications among the clusters in a network, thereby facilitating the duty-cycling mechanisms and assigning packet forwarding tasks to Cluster Heads (CH). The switching of different states in the radio of a sensor node also needs to be controlled for avoiding energy wastages and also for time synchronization between packet transmission and task scheduling. The communication protocols also adopt different transmission mode, based upon the application in which the sensors are deployed. For single-hop communication, there is more energy consumption per task particularly in larger area deployments. On the other hand, for multi-hop communications, data packet collection carried out over several hops by the sensor nodes have to do multiple communications and recalculate their routes towards the sink node. This, in turn, causes more energy consumption leading to ineffective communications. The process of topology control protocol is to find the nearest neighbor to the node which is in the process of active communication, to act as a data channel for packet transmission towards the mobile sink. Therefore, an effective communication protocol with the definitive transmission mode, sink mobility, node localization and application type (event-triggered or query-driven) can have a considerable and noteworthy impact on the energy conservation and mitigation approaches. The past decades have witnessed the evolution of many energy-efficient MAC protocols as tabulated in Table 3.2, that are asynchronous with sensor network communication. These protocols utilize the Low Power Listening (LPL) technique for the mismatch of synchronization between the transceivers and radio unit in a commercialized sensor network. The tabulation as described in Table 3.3 shows the feature-based comparison between the three prominent wireless communication protocols.

Table 3.2: **Comparative analytics between the MAC protocols of sensor network communications**[8]

	S-MAC/T-MAC/DSMAC	**Wise MAC**	**TRAMA**	**SIFT**	**DMAC**
Time sync needed	No	No	Yes	No	Yes
Comm. pattern support	All	All	All	All	Convergecast
Type	CSMA	Np-CSMA	TDMA/ CSMA	CSMA/ CA	TDMA/ Slotted aloha
Adaptive to changes	Good	Good	Good	Good	Weak

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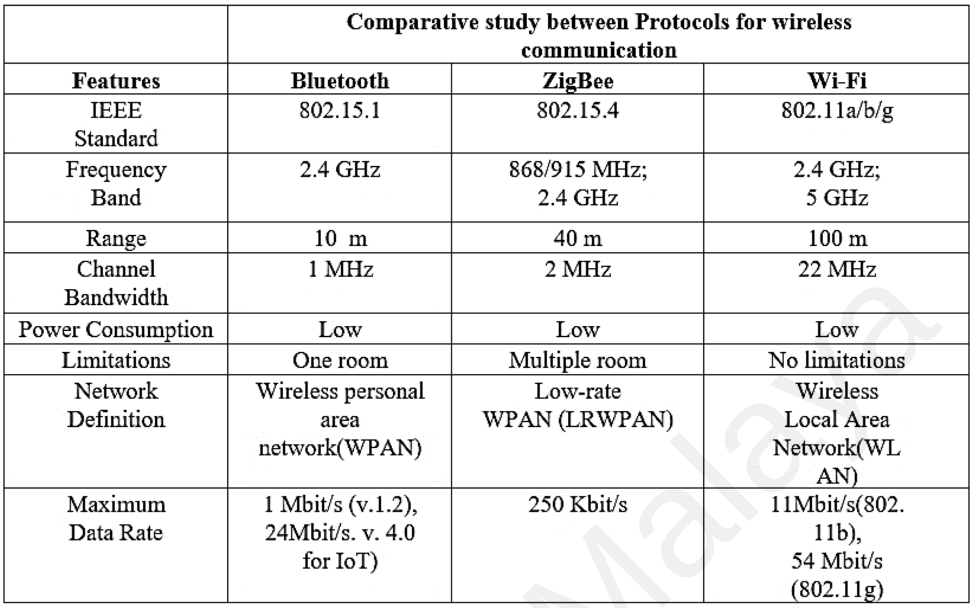
[8] S-MAC-Sensor-MAC; T-MAC-Timeout MAC; DSMAC- Dynamic Sensor MAC; TRAMA-Traffic Adaptive MAC protocol; SIFT- MAC protocol for event-driven WSN; DMAC- Data gathering MAC; CSMA- Carrier Multiple Access; Np-CSMA- Non-persistent CSMA; TDMA- Time Division Multiple Access; CA- Carrier Access

Table 3.3: **Feature comparison between the wireless communication protocols**



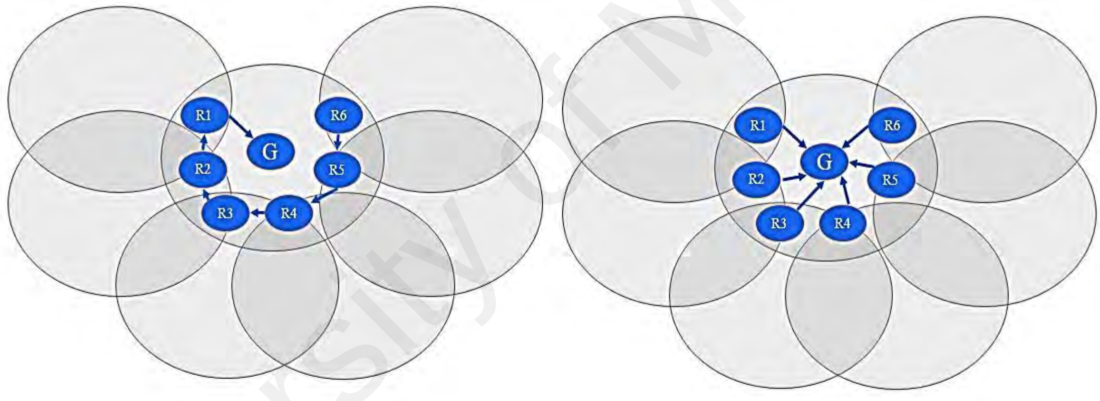
	Comparative study between Protocols for wireless communication		
Features	**Bluetooth**	**ZigBee**	**Wi-Fi**
IEEE Standard	802.15.1	802.15.4	802.11a/b/g
Frequency Band	2.4 GHz	868/915 MHz; 2.4 GHz	2.4 GHz; 5 GHz
Range	10 m	40 m	100 m
Channel Bandwidth	1 MHz	2 MHz	22 MHz
Power Consumption	Low	Low	Low
Limitations	One room	Multiple room	No limitations
Network Definition	Wireless personal area network(WPAN)	Low-rate WPAN (LRWPAN)	Wireless Local Area Network(WLAN)
Maximum Data Rate	1 Mbit/s (v.1.2), 24Mbit/s. v. 4.0 for IoT)	250 Kbit/s	11Mbit/s(802.11b), 54 Mbit/s (802.11g)

3.2.3 Impact of network topology

The energy of the nodes needs to be utilized efficiently in order to maintain the overall lifetime of the network. The sensed data need to be routed to the sink through energy-efficient methods. The network topology of the deployed sensors plays a major role in the effective packet transmission with appropriate consumption of energy. The research contribution in the field of sensor networks has focused on evenly flattened network region. In practical applications, such as indoor monitoring, the sensors are usually intervened with obstacles (such as furniture's, walls etc.,) due to which the network performance can eventually be degraded. Such obstacles can lead to energy losses and hinder the network throughput. Therefore, the design of network topology can give satisfactory results with regards to network lifetime improvement and overall energy consumption.

The different topologies of the sensor networks can be either uniformly distributed, centrally distributed or multi-centrally distributed. For randomly-distributed sensor node, if the probability density function of nodes spatial distribution is limited, then the maximum throughput achievable for both uniform and non- uniform topologies of the network remains a constant as stated by Li.C et al. (2014). The different topologies by which the sensors network can be deployed are- Bus, Tree, Star, Ring, Mesh, Circular and Grid based. The comparison between each of these topologies has been described in Table 3.4. In mesh- based topology, the nodes, and the gateway together form a mesh. The gateway handles the list of nodes in the form of a serial number that has been given authorization for network access. When the power unit of the sensor node gets activated, the gateway or the router is identified by the node and it sends a request to get connected. If the gateway finds the match with the list of nodes that it already contains, then the connection is made successful for the node to join the network.

The existing network route is changed when the node newly joins the network rather than connecting to the gateway or router. The mesh-based topology in this way acts as the self-configuring and self-building network. This action may eventually lead to decreased network throughput, due to the lack of provisions for configuring manually a router or an end node to connect to the user-defined device in the network. Therefore, each time a node gets connected to the router, the overall throughput is decreased to half the value leading to higher energy consumption because the node must hop through the other node to send its information back to the gateway. The depiction of inefficient and efficient ways of network mesh topologies has been depicted in Figure 3.5 (a) and (b) respectively. This is the issue for any kind of topology for all the category for sensor networks. Therefore, it can be conclusively defined that the network topology and configuration of nodes, has a considerable impact on the overall energy consumption of the network. At the MAC layer, there is energy expenditure during transmission and reception of data packets and also due to multiple packets being delivered to the destination causing packets collision and idle listening. The data packets also cause communication overhead ultimately leading to more energy consumption per delivery of the packet. The issue of higher energy consumption is also present at the network layer and transportation layer. The reasons such as neighbor discovery, computation, and communication for efficient packet delivery are contributive factors towards energy consumption during transmission. Computation process also leads to higher energy expenditure. Data aggregation and prompting of duplicate data packets should be enabled for mitigation of energy consumption since the reliability of the network is dependent on the type of appropriate transport layer protocol. The higher energy consumption leading to node failure issues is caused due to error and congestion control at the transport layer. The scalability of the network can be increased after each packet transmission and by balancing the energy level of nodes in the active state.



(a) Inefficient mesh topology

(b) Efficient mesh topology

Figure 3.5: **Impact of network topology on energy expenditure**

Table 3.4: **Performance Comparison between WSN network topologies**

Performance Topology	Path	Node failure	Load balance	Congestion in path of packets	Packet reception ratio	Energy consumption	Network lifetime	Reliability
Bus	Single	More	Less	More	Less	More	Less	Less
Tree	Single	More	More than bus	More	Less	More	Less	Less
Star	Single	More	Less than tree	More	Less	More	Less	Less
Ring	Double in same direction	More	Less	More	Less	More	Less	Less
Mesh	Multiple irregular	Less	More	Less	More	Less	More	More
Circular	Multiple	Less	More	Less	More	Less	More	More
Grid	Multiple	Least	Most	Least	Most	Least	Most	Most
Hybrid	Multiple	Most	Less	Most	More	Most	Least	Least

3.2.4 Sensor networks in IoT systems

The sensor nodes deployed for any kind of application are equipped with minuscule batteries which functions based upon the mesh formed by the incoming nodes joining the network. If the mesh formed has low power adoption then there are chances for higher survival rate for the node, conversely, if there is high power utilization, the node will deplete at the much faster rate. In many practical situations, the energy storage device could not be removed, thereby making the sensor network susceptible to dead state. The sensor node when deployed in complex IoT systems, need to be adapted to dynamic energy management mechanism (either random or user-defined) for efficient optimization. As stated by researchers Parwekar et al. (2011) the inherent drawback for IoT systems is that the end user has less access or impact on the connected devices. Therefore, to ensure reliable operations and QoS, IoT systems should be checked for connectivity issues. This is due to the fact that, interconnected computing modules such as sensors, embedded identification resources, and HCI periodically having insufficient bandwidth channel with limited network access. Nevertheless, the mechanism has been designed to meet the requirement of the application in which the sensor is deployed and moreover must ensure delivery of flexible QoS and process-oriented offline operational capabilities. Through IoT having been made its potential mark using RFID, the cloud service server acts as the backbone for efficient deployment of sensors and actuators in everyday activities. Therefore, it is a vital requirement to ensure that the sensor networks provide energy efficient solution for IoT systems. The communication technology such as 6LowPAN, RPL, and CoAP provides end-to-end communication between sensing devices and the internet as shown in Figure 3.6. The cross-layer security aspects need to be addressed to ensure secure communication when a sensor network is integrated with IoT at an architectural level as proposed by Granjal, Monteiro, & Silva (2015).

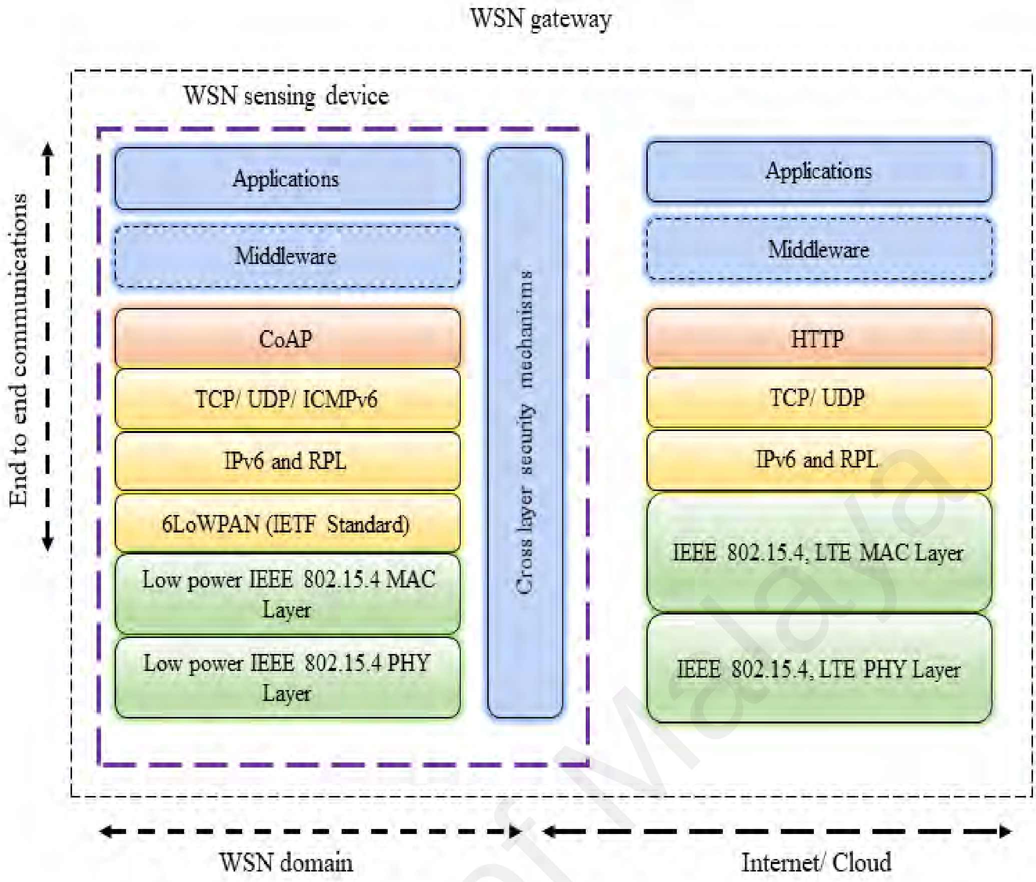


Figure 3.6: A Basic architecture for the integration of WSN with the internet stack via 6LoWPAN based communication

3.3 Analysis of EM techniques in RSN

The primary advantage of RSN is that it does not need to rely upon batteries for transmission of sensed information. To maintain the energy level in the operational state, for sensing and transmission of packets, effective EM techniques is essential. The RF-enabled sensor network has the node which has different characteristics of getting energized through sources emitting RF signals such as RFID reader or RF coil, whenever they are in close proximity range with each other. But when they are out of range, these nodes act as storage devices. The concept of integrating RFID and WSN can be found in WISP device. The working principle of this device is that the WISP hardware utilizes the concept of ambient backscattering between the node and the reader (passive RFID tag and sensor). The other RFID tags such as active and semi-active cater to the energy supplied via a storage device such as batteries and capacitors, that are set up at the time of initial installation of the sensor nodes. Therefore, these tags tend to have constrained lifetime with a higher cost as presented by Lu, Wang, et al. (2015). The essential feature that characterizes the performance and throughput of RSN is the capability of the reader to read the data from the RSN nodes. This feature depends upon two aspects - the energy level at which the node can be configured to stay in active mode (Tags reaction) and the energy required by the reader to identify the backscattered RF signal emitted by the node in an efficient manner (readers response). EM deals with addressing these two aspects to improve the performance and lifetime of RSN. The two main techniques for managing the energy levels are EH for tags reactivity and ET for adhering to readers responsiveness.

Table 3.5: **Summary of existing Energy Management strategies**[9]

Techniques/ Network Type	Application type	Network topology/ Use Case	RSN enabled	EM technique	Issues focused	Real time/ Simulation
Production management, optimization techniques	Application specific	Deterministic	Yes	EH	Energy efficiency of production management	Real time
Nano antenna technology	Periodic	Nano-rectennas	No	EH	Total harvesting efficiency	Simulation
Nano-rectenna systems	Event driven	Nano-rectennas	No	EH	Optimization	Simulation
HOLA, IIoT	Event based	Random	Yes	ES	Residual battery power and radio links	Simulation
TDMA protocol	Event based	Dynamic	No	ECM	Time synchronization	Simulation
TBR, TDC	Query based	Cluster	Yes	ER	Scalability	Simulation
WRSN, LRP, RTP, GKP	Distributive and adaptive	Random	No	ECM	Energy transfer	Simulation
RFID, WSN, RSN, IoT, SIWR, DIRSN	Event driven	Dynamic	Yes	ECM	Minimizing delay, cost factors, packet loss and traffic congestion	Simulation
WET, WCV, OPT	Periodic	Fixed	No	ECM	Energy transfer efficiency	Simulation
DTN	Event driven	Static and dynamic	Yes	ECM	Delivery rate of data packets	Simulation
DC, DCLK, CC,CCGK	Event based	Random	No	ECM	Efficient wireless power transfer	Simulation
WNSN, MAC, CTR	Query based	Cluster	No	EH	Optimization of energy harvesting and consumption process	Simulation
MinMCP	Periodic	Random	Yes	ECM	Quantification of MCs	Simulation
RSN	Application specific	Star and tree	Yes	ECM	Cost factors	Real time
WNSN	Event based	Random	No	ECM	Optimization of energy transfer	Simulation

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[9] This table has been adopted from one of the research contributions by the author published in IEEE Internet of Things Journal, 2017

There are relatively attention seeking challenges for routing and communication strategies when RFID and WSN are integrated such as reliability, scalability, node localization, security, energy scarcity and interoperability as shown in Table 3.5, the techniques adopted in sensor networks are tabulated with regards to types of application, EM technique, issues focused, nature of experimentation and type of network topology. The research effort carried upon till date in the literature have predominantly focused upon mitigation of energy consumption as the EM techniques such as energy harvesting/ storing and energy recharging and transmission over wireless medium or dedicated communication channels. These techniques are aimed to ensure increased network performance and lifetime of nodes.

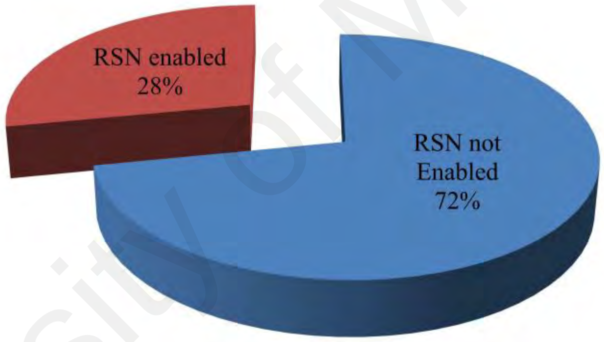

Figure 3.7: **The percentage of RSN employment among research contributions**

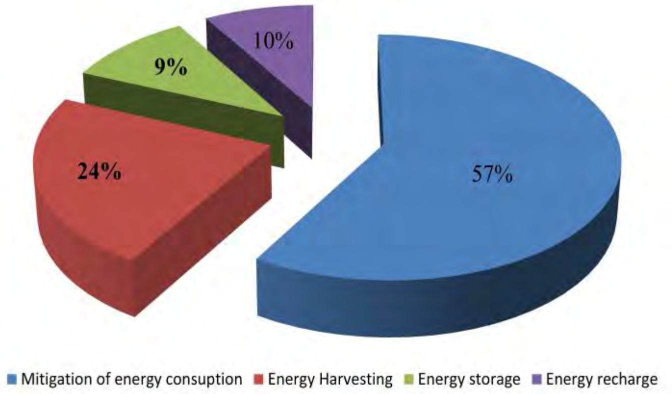

Figure 3.8: **EM techniques and strategies**

It can be noted from the table that the researchers Shrouf & Miragliotta (2015) , Dhondge et al. (2016) , Farris et al. (2016) , Al-Turjman et al. (2013), Dusit Niyato et al. (2014), Haipeng Dai et al. (2014) and Ding (2013) focus on energy management by integrating both RFID and WSN, whereas other articles have addressed mitigation of energy consumption for conventional WSN. Figure 3.7 and 3.8 depicts the statistical analysis by comparing the metrics such as RSN deployment and EM adoption strategies of each of the reviewed article from the previous chapter. The graphical representation shows that a total of 68 articles from the references of this thesis are not RSN enabled and 27 are RSN enabled. The following pie chart depicts that 53 articles have focused on mitigation of energy consumption, followed by 10 articles on energy recharging, 23 on energy harvesting and 9 on energy storage respectively. The research findings that can be observed is that energy consumption plays a vital role in routing, communication and there have been seldom research contributions which focus on EM of RSN Systems.

3.3.1 Energy harvesting techniques

The EH techniques proposed in the literature focus on providing energy in a wireless medium which converts radio signals to DC that is eventually fed to the connecting devices. The stochastic approach for EH utilizes deterministic modeling for the basis of the assumption that the value of EH is known prior to the packet transmissions. The EH process through renewable energy resources attempts to convert the harvested energy to electric form. The EH module is embedded into the sensor node, for energizing them through sources such as heat, light, RF signals, Vibrations, Electromagnetic energy or wind as tabulated in Table 3.6. Such harvesting methods rule out the dependency on energy storage devices such as batteries and capacitors. This could eventually result in self-configuring and self-performing sensor networks based on the application scenario. The RSN outperforms the conventional WSN because it gets charged from the RF signals emitted by the RFID reader. In RF-based EH, the amount of RF energy that can be harnessed relies upon the transmitted power, RF signals wavelength and the internetwork distance between the RF energy source and the harvesting node during the active state. The RF energy propagation models can be either- Free space, Two Ray ground or shadowing model. At the transmitter side, the harvested power can be calculated using Friis equation as denoted in equation 3.1,

$$P_R = P_T \; \frac{G_R \, G_T \lambda^2}{(4\pi d)^2 \, L} \tag{3.1}$$

Where P_T is the transmitted power, P_R is the received powder, G_T is transmitting antenna gain, G_R is the receiving antenna gain, λ is the wavelength of the RF signal emitted and d is the distance between the receiver antenna and transmitter antenna.

Table 3.6: **Comparison of characteristics features of energy harvesting methods and sources**

EH Source Characteristic	Passive tag (RFID Signal)	Solar panel (solar radiation)	Piezo electric materials (Vibration)	Antenna (AM signal)	Thermal generator (Heat/ temperature difference)
Requirement of energy storage device	Not compulsory	Compulsory	Compulsory	Compulsory	Compulsory
Wireless	Yes	Requires extra components	Requires extra components	Yes	Requires extra components
Form	Compact, Versatile	Fixed, requires large area	Compact	Fixed, requires large area	Compact
Requirement of antenna	Compulsory	Not compulsory	Not compulsory	Compulsory	Not compulsory
Availability of full system	Industrially available	Industrially available	Industrially available	Not available (For research only)	Not available (For research only)
Portable	Yes	No	Yes	No	Yes
Availability of energy source	Always available (If within range)	During the day only	During motion/ vibration	Always available	Availability depends on application

For Two ray ground model, the harvested RF power from a transmission is derived by equation 3.2,

$$P_R = P_T \; \frac{G_T \, G_R {h_t}^2 \, {h_r}^2}{d^4 \, L} \tag{3.2}$$

Where h_t and h_r are the heights of the transmitter and receiving antennas respectively. The RF sources can broadly be classified into ambient RF sources and dedicated RF sources. Comparatively to other renewable resources such as solar wind and vibrations based EH, the process of RFEH is distinctive by following characteristics.

- The RF energy sources can produce constant, controllable and fixed energy transmitted over a particular distance for the harvesting node.
- Due to the fact that the rate of harvested energy entirely depends upon the internetworking distance between the RF source and the nodes, there is a probability for notable differences in the levels of harvested RF energy for nodes placed at different locations.

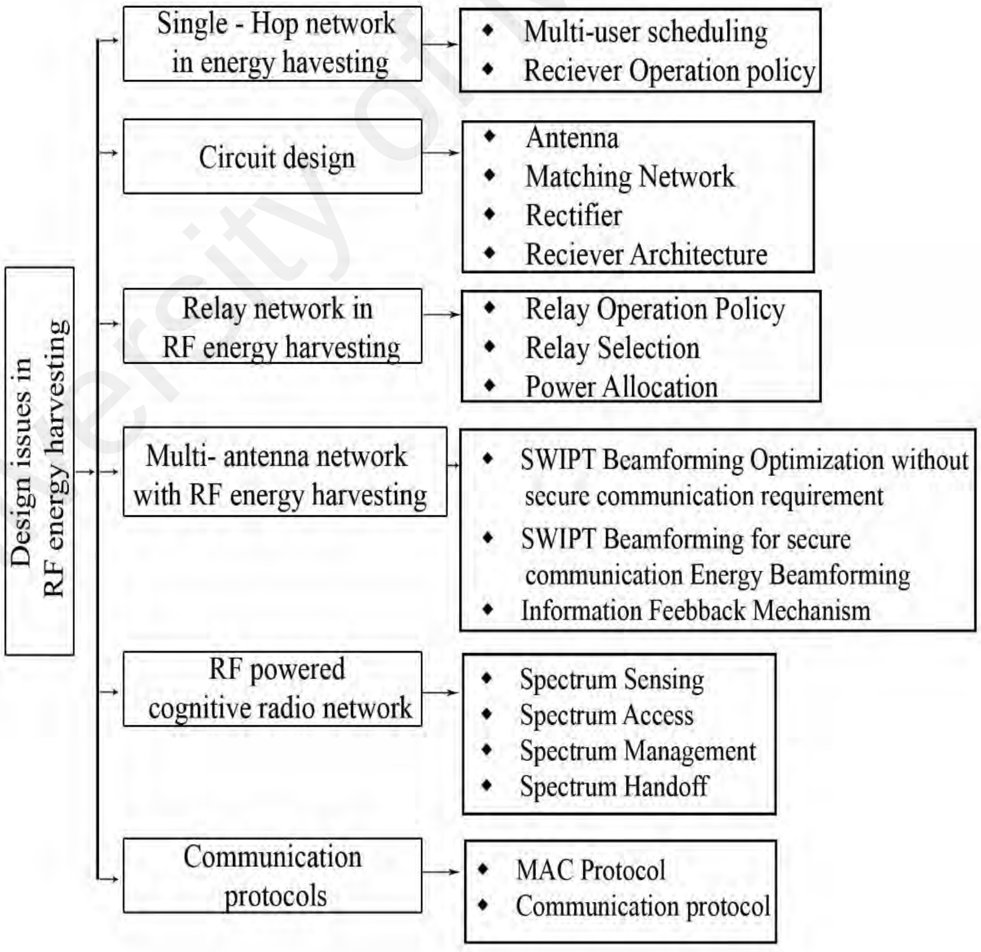

Figure 3.9: **Taxonomy of RF Energy Harvesting Networks design challenges**

The past research contributions have witnessed mechanisms by increasing the network lifetime and maintaining the energy efficiency by addressing issues such as Network fault tolerance, target coverage, and connectivity concerns stated by Sheng et al. (2015). The existing surveys of the literature have focused on network lifetime improvement and energy efficiency for conventional WSN, but still, lack EM strategies when sensor networks are embedded with RF technology. The need for harvesting energy from sources such as RF signals stems due to the fact that both sensing capabilities and identification techniques when combined together eventually consume a lot of energy to provide the predefined results during operational states as described by Ferdous et al. (2016). There are many aspects that stem out during the design of RF-based EH such as- nature of communication protocol, circuitry design, single hop/ multi-antenna/ relay network, and spectrum sensing when integrated with cognitive radio. Figure 3.9 shows the taxonomy RFEHN design issues.

3.3.2 Energy modeling tools

The remaining energy in the nodes and the distance of transmission has been suggested by Xiang, Wang, & Zhou (2016) for energy optimization of WSN with user-defined software notifications. These sensor nodes provide NP-hardness since it has optimal energy consumption. Moreover, when such control nodes are designed to perform multiple monitoring operations at the same time, it consumes more energy. This issue is overcome using Particle Swarm Optimization (PSO) technique. The modeling method is utilized for selection of either free space or multiple modes. This is the method for energy modeling using the distance of transmission. The type of propagation model is selected based upon the transmission distance and the threshold. The PSO technique models the distance between the control nodes and its neighbor to be shorter, so that the overall energy consumption of the network is smaller.

In Energy-efficient Multi-sink Clustering Algorithm (EMCA) proposed by Abdul Salaam, Abdullah, Anisi, Gani, & Alelaiwi (2016) the CH transmits the forwarded data through shortest distance towards the gateway sink and it is modeled as in equation 3.3,

$$E_T(CH, B_K) = \begin{Bmatrix} m * E_{elec} + k * E_{fs} * \ d^2 \\ m * E_{elec} + k * E_{mp} * \ d^4 \end{Bmatrix} \begin{matrix} d < d_0 \\ d \geq d_0 \end{matrix} \tag{3.3}$$

The energy expenditure that is caused because of longer transmissions can be mitigated through multiple hopping strategy. The energy modeling for node S_j, to transmit information to CH is provided by equation 3.4,

$$E(Sj, CH_{sj}) = \begin{Bmatrix} k * E_{elec} \ + k * E_{fs} * \ d\left(Sj, CH_{sj}\right)^2 \\ k * E_{elec} \ + k * E_{fs} * \ d\left(Sj, CH_{sj}\right)^2 \end{Bmatrix} \begin{matrix} d < d_0 \\ d \geq d_0 \end{matrix} \tag{3.4}$$

Another aspect to be considered for energy modeling is the network topology across the network. Clustering method has been utilized, suggested and explored by many researchers in the wireless networks research domain. It is utilized for addressing the energy limitations across larger density of application-specific nodes. The working of remotely deployed sensor networks is designed to be self- configured, therefore, clustering techniques adapt to the automatic grouping of sensors to monitor the rate of energy consumption. The concept behind clustering technique is that a CH is elected by the nodes to transmit the data packets. The CH acts as a relay node and performs data aggregation and forwarding to the gateway sink. The characteristic parameters for a CH are usually modeled based upon its distance to the sink node, the range of transmission and residual energy levels. Since all the reception and transmission operations are handled by the CH there is more energy consumption and communication overhead which may ultimately lead to packet drop, CH elimination and network performance degradation. The other energy modeling methods can be adopted using Markov Decision Process (MDP) where the problems are formulated and solved using Dynamic Programming (DP) and Reinforcement Learning (RL). These tools are utilized for solving stochastic and control optimization issues. A detailed explanation of the energy modeling concepts adopted from MDP and DP for proposed scenario has been discussed in the subsequent chapter of this thesis. Basically, the performance evaluation of any algorithm/techniques is done via three methods- analysis model, simulations and testbed implementation. The existing research efforts done so far for EM of any class of sensor networks focus only upon simulations with application-based assumptions. The research finding observed from the qualitative literature review carried out for this research was that communication hardware also plays a vital role in overall energy consumption in the network. The amount of energy consumed during an active state of a node not only depends upon the metrics of radio but also on the drain efficiency of circuitries such as an inverter, Power Amplifier (PA) and so on. Therefore, energy modeling should be done based on all the parameters which directly or indirectly cause higher energy consumption.

3.3.3 Energy transmission methods

Wireless energy transmission can be either through sources such as light, vibration, wind or through magnetic coupling, RF signals and so on as shown in Table 2.2. The usage of these sources poses challenges for conventional WSNs. As the transmission distance increases, the network performs with lower efficiency and higher energy consumption. The deployment of a mobile entity can overcome this solution as suggested by authors Li.F & Xiong (2013) but the additional energy consumed by such mobile nodes due to the random movement and multi-hops for transferring data to sink, may lead to further network performance degradation. Nevertheless, making these nodes as ‘leader’ nodes or ‘helping’ nodes may produce better solutions and serves to be a reliable option for energy recharging. Conclusively, it can be inferred from the research efforts done so far that despite the fact of rechargeable batteries and mobile entity recharge technique providing the best solution for ET, mitigation of energy consumption still remains an attention seeking aspect rendering to decreased lifetime of the network. Therefore, for ET and wireless energy charging, longer distance and non-line of sight recharging by the node is a more challenging issue that needs research efforts as suggested by Abdul Salaam et al. (2016).

The dual usage of RF signals for both providing energy as well as for transferring information has been developed using the Simultaneous Wireless Information and Power Transfer (SWIPT) technique on demand and controllable wireless energy and data simultaneously. Therefore, it offers a cost-effective and reliable solution for sensor networks without tailoring to the need of any modification at the hardware transmission section Phung et al. (2015). However, handling both information optimization as well as ET together can cause design trade-off issues of the entire wireless system. The contribution factor for this issue can firstly be the entropy rate which is the quantity of RF signal variation that signifies the information quantity. Secondly, the squared values of RF signal efficiency on an average determines the overall power for a particular transformation. Therefore, the quantified information as well the level of transferred energy can be improvised or maximized concurrently. This research finding urges for redesign and revaluation of existing wireless sensor network. The aim of improvised network lifetime can be achieved through – multihop transmission, policies, varying and dynamic transmission ranges, balanced duty cycle based on energy levels and regularity with regards to interference avoidance, pattern mismatching, and asynchronous scheduling.

3.4 Analysis of energy consumption of RSN in IoT contexts

Despite the fact that energy storage devices such as batteries and capacitors serve as the primary energy sources for WSN, its constrained lifetime and unpredictable nature for both event-based and query- based operations by the nodes, makes it susceptible to drawbacks such as energy depletion, packet drop, information loss, node failure and performance degradation of the network. Therefore, to resolve these issues, EH from renewable energy sources serves to be the best forward solution in comparison with the current solutions for RSN communication. RF-EH complies with the application specific requirements and ensures more scope for energy efficient solutions. The problem analysis for the taxonomy of RSN problem challenges as shown in Figure 3.10 which depicts the causes and the effects of energy consumption drawback for RSN in IoT context. The previously mentioned data analysis and systematic review described in this thesis states that EM has direct impact on several performance metrics of the network - like throughput, latency, network lifetime, end-to-end delay and QoS, with advent of enormous current as well as future research directives in the field of IoT and pervasive computing, there is a constant urge for promising solutions for EM when WSN and RFID are integrated on a single platform. The issue of poor transmission range, readers and passive tags potential to read the data and store the energy followed by reader - tag collisions and packet drop are bound to be solved using IoT. The read range of the passive tags can be improvised using concept such as backscattering as proposed by Kellogg, Parks, Gollakota, Smith, & Wetherall (2015). In complex IoT systems, there is a drawback of cross-platform routing protocol for wireless energy transmission and increased EH rate. This is due to the fact that when multiple devices are connected within the IoT framework sharing the same spectrum, there is interference caused by the communication channels.

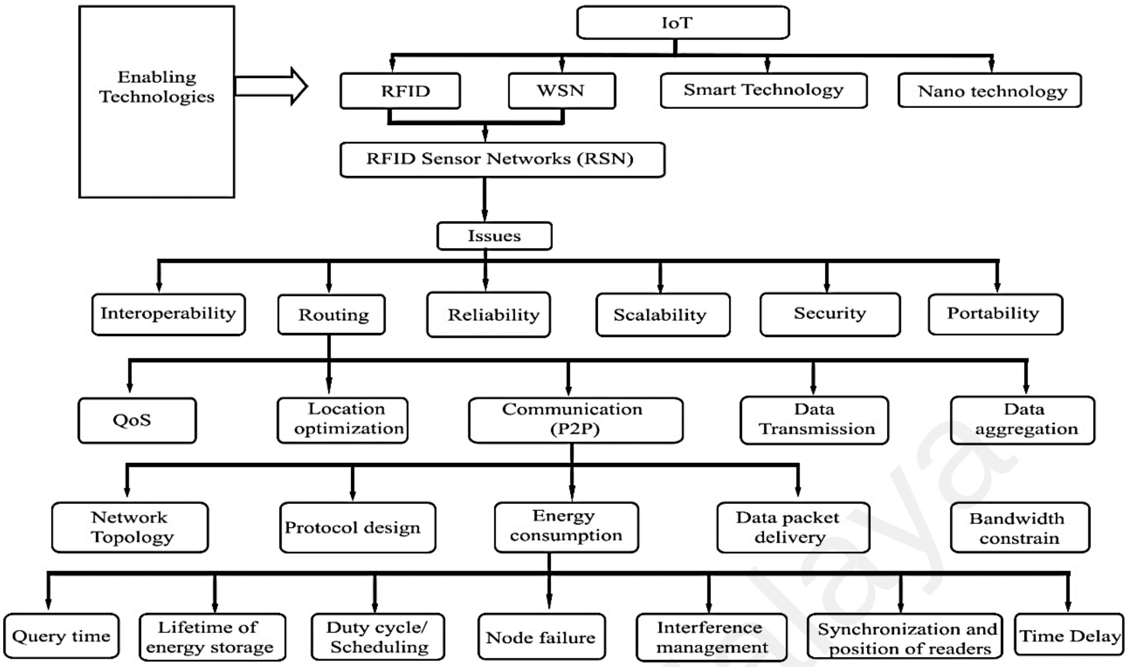

Figure 3.10: **Taxonomy of RFID Sensor Network Challenges in IoT context**[10]

Therefore, IoT can be explored for the design of novel communication protocols by modeling the sensors for efficient EM solution, interference avoidance, and synchronous ET policies. This power modeling of IoT sensor can be carried out using RL approaches. The problem of data delivery due to time critical application specific data frames for EH also needs to be addressed. This is because of the unpredictability in the availability of the node during the active state for sending the data according to the time synchronization of its duty cycles. Despite IoT being the most sought after and significant solution for overcoming the current problems of multi-hop sensor networks, there is a need for the design of energy efficient MAC protocols, with the IoT based communication technologies as stated by Sunny & Kuri (2016). The gap between the lower level of energy utilization and optimal performance level needs to be addressed during the design

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[10] This thematic taxonomy has been adopted from one of the research contributions by the author published in IEEE Internet of Things Journal, 2017

of MAC protocols for EM in RSN for complex IoT systems as described by Sherazi et al. (2018).

3.5 Summary and chapter conclusion

In this chapter, an in-depth analysis of all the problems encountered when WSN is integrated with any other technology was discussed. The core problem of energy consumption leading to degradation of network performance was mapped into further subproblems. The taxonomy, tabulations, and statistics with regards to the relevant research efforts were also presented and discussed. The contributing factors for energy consumption in IoT systems were comprehensively discussed in section 3.2. To identify and relate the correlation between the problem and the factors, analysis of EM technique was presented in section 3.3 along with the discussion of research efforts done previously. The drawback of the contribution made by the researchers was identified to understand the nature of the problem and to identify the gap between the research findings. The focus of this research was motivated by the quantitative and systematic review of existing techniques discussed in Chapter 2 followed by the problem analysis done on EM issues of RSN in this chapter. Therefore, few of the issues that have been discussed in this chapter are solved using proposed techniques and are further described in the following chapters.

CHAPTER 4: DEVELOPMENT OF ENERGY MANAGEMENT MODEL FOR RSN

4.1 Introduction

The RSN nodes during communication with other neighboring nodes, both during transmission and reception, consumes more energy. Therefore, energy management is employed for the long lifetime of the nodes, where the energy level of nodes is controlled and handled with optimization. This chapter describes the development and methodology of the proposed energy model for IoT context. It also presents the steps that are carried out to address some of the issues outlined in Chapter 3 and achieve the research objectives stated in Chapter 1. Section 4.2 presents the nature of Non-Cooperative Systems (NCS) and TCS for getting an idea behind the working of existing RSN scenario. The following section 4.3 describes the concept of energy modeling of RSN nodes using SMDP and dynamic programming followed by steps to solve the problem and its numerical analysis in the subsequent chapters. Finally, section 4.7 briefs the summary of the chapter.

4.2 Non-cooperative and tag-based cooperative systems for RSN

The system in which tags, readers, and sensor nodes are integrated is referred to as the RSN in this research. The NCS do not allow any cooperation between the readers and consider only a single tour to the sink, which implies that all the nodes will be visited once by the reader along that tour to collect saved information from each of the RSN nodes. This tour executed by the mobile reader to visit each of the nodes to collect information and recharge them as well causes more energy consumption is modeled using Travelling Salesman Problem (TSP). The TSP being NP-hard and having longer tour length at the expense of more energy is solved using a genetic algorithm. The tag-based co-operative system, on the other hand, depends upon the interactions between the readers, tags and sensor nodes. The mobile readers and RSN node are designed based upon Tag Based Relay (TBR) mechanism or Tag-based Data Channel (TDC) techniques. The NCS are the systems where the tags do not cooperate with the readers in communication and data transmission to the sink node. On the other cooperative solutions, such TBR and TDC have the nodes and readers to communicate with each other by forming clusters and cooperatively perform the data delivery to the sink or gateway node. The major drawback of an NCS scheme is that all the nodes are to be visited at least once by the mobile reader for transmitting of packets to the sink. Hence, there is more energy consumption in these types of systems followed by drawbacks such as poor synchronization between the nodes and readers as well as difficulty to be employed in wide area networks. In TBR, the data exchange takes place between the Cluster Reader (CR) (of each cluster), [huge memory passive tags] and a master bus reader (mobile). Each of the cluster reader CR collects information from the node when it comes in close proximity communication range with the nodes. These CRs then act as relays for transmitting the information in delay tolerant mode. The drawback of this approach is that there are relatively higher energy and time constraints in delay tolerant mode. In TDC approach, the nodes in each of the cluster serve as a virtual communication channel for data exchange between the master reader and the cluster reader. The drawbacks of TDC is that a number of devices such as cluster reader when communicating with the bus reader through RSN node increases the overhead that lead to consumption of more energy and performance degradation of the network. The other prominent drawbacks of the scenarios depicted in Figure 4.1, 4.2 and 4.3 are – there is no communication between RSN nodes, absence of notification of energy shortage levels of clustered RSN, energy/time constraints in delay tolerant mode, energy loss resulting from packet collision, improper reader synchronization leading to buffer overflow and data loss at the relay tag and more pre-defined assumptions on the path for movement of readers. All these mentioned drawbacks are aimed to be addressed using the proposed EHRSN and ETRSN techniques throughout the course of this chapter and the subsequent chapters as well. The quantified and empirical results of the proposed techniques are then compared with these existing systems of NCS, TBR, and TDC for performance analysis.

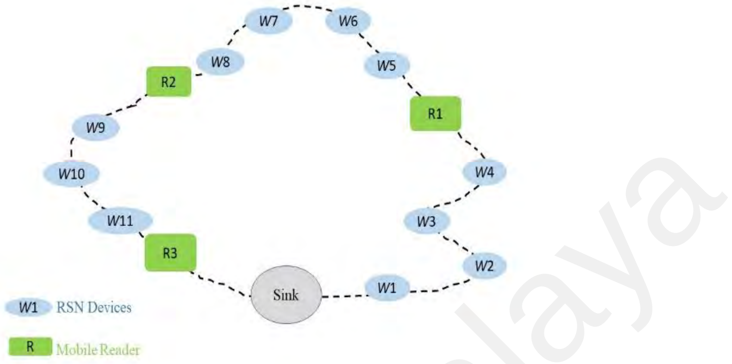


Figure 4.1: The scenario of an NCS

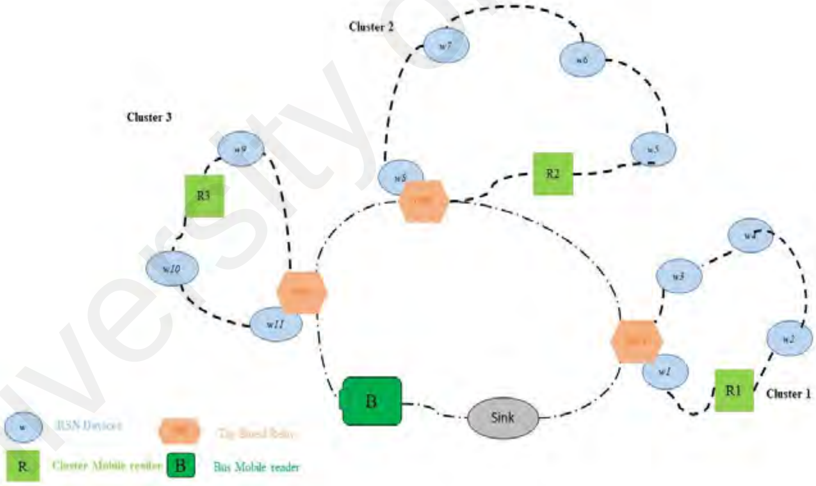


Figure 4.2: The scenario of a TBR scheme

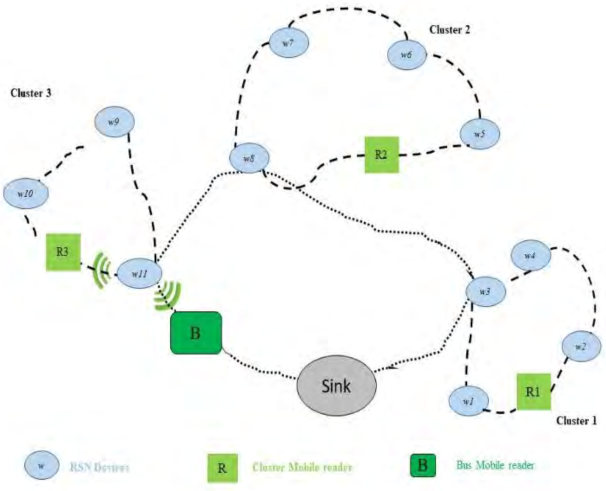


Figure 4.3: **The scenario of a TDC scheme**

The proposed energy model is aimed at modeling EH and ET mechanism for TCS. This research handles the energy management strategies by adopting TBR scenario for EH and TDC for ET respectively. The performance of EH and ET mechanism are compared with existing TBR and TDC solutions comprising of WISP devices and also with NCS for performance comparison.

4.3 Research methodology

The methodology of this thesis comprises of three main phases namely

(i) Literature review and problem analysis.
(ii) Design and development of energy management model for RF-enabled sensor networks. Followed by
(iii) Validation and statistical analysis of the proposed model

Literature review and problem analysis: This phase is based on understanding the basic knowledge and emergence of each of the key technologies such as IoT, WSN, RFID, and RSN followed by state-of-the-art energy management techniques. The problem analysis covers all the causes and effects of higher energy consumption of RSN in IoT contexts

(Chapter 2 & 3). The research output of this phase has been published by the author as per the list of publications mentioned, following the reference section of this thesis.

Design and development of EM model: this phase describes and focuses on 3 aspects- Energy modeling, numerical analysis/ problem formulation and implementation using network simulators. The energy modeling is based on solving the SMDP using dynamic programming approach. The optimal policy solvation and numerical analysis are carried out for both EH and ET processes. The issues such as harvesting energy through backscattered RF signals of an RF coil has been addressed in this phase, which has not been discussed in the literature. The other issues such as energy losses due to idle listening, energy leakages and packet duplication that had not been addressed by the researchers in the literature are also solved using proposed EM model. RF – energy harvesting technique using event-triggered programming as well as enhanced stochastic backscattering method is implemented using NS2 and Python. The interference management issue is also solved using the proposed EM techniques. This phase corresponds to the first, second and third objective of this research where firstly the EM model is characterized as SMDP and solved using controlled optimization technique of DP. The steps such as calculation of energy expenditure, computation of optimal policy, calculation of average reward and numerically analyzing it through problem formulations and graphical representations is carried out. Secondly, the EH technique is developed based upon checking the levels of residual energy and harvested energy in a loop before proceeding to the process of packet transmission. The scheduling here is based upon the events triggered as well as the individual weights that are assigned to the nodes. Thirdly, the technique of ET based upon stochastic backscattering concept is developed where amount of energy needed for transmission, for backscattering is calculated in a loop followed by checking the residual energy levels.

Verification and validation: This phase is mainly focused on evaluating the proposed techniques using parameters such as- throughput/End to end delay, residual energy levels, network latency and lifetime on macro scale through simulations. Since the methodology involves the integration of two technologies, the validation process is carried out at micro scale as well, through real testbed hardware system implementation, where a temperature, dust, gas and humidity sensor is run based upon energy obtained through RF signals of an RF coil. Furthermore, to apply and appraise the proposed techniques (that is the outcome of the previous phase - research objective 1, 2 and 3) in an IoT application, the Air Quality Index (AQI) values are monitored and recorded using the proposed integrated RSN system followed by analyzing it statistically.

The performance of each of the techniques (EH and ET) has been evaluated in terms of residual energy levels before and after EH, network density, state of the nodes and also based upon the different network traffic. The ET mechanism is also evaluated in the performance for the amount of energy transferred with and without applying the stochastic backscattering technique.

Both of these techniques are applied to the EM model which is the outcome of the first objective to compare the overall throughput of the network followed by network latency and energy efficiency. The two technologies of RFID and WSN are integrated together through simulations. Here the theory stated by the researchers in the literature that there are no simulators available for the integration is contradicted. Moreover, the levels of residual energy are compared for the integrated sensor networks with the sensor networks without the integration to evaluate the efficacy of the integrated approach. And also, the effect of how RFID behaves in a different manner with various MAC is also analyzed through graphical representation. This type of evaluation is basically carried out to identify the energy profile of the sensor nodes.

The methodology of this research work has been summarized in Figure 4.4. In the subsequent sections, we describe the details about the proposed EM model, to address some of the issues stated in the previous chapter and account for the stated research objectives. The practical application of the model to real world sensor platform has been described elaborately in Chapter 6 and the pictures have also been presented in the Appendix I section, where the sensor motes are modeled according to the EM model and integrated with EH and ET approaches to monitor the quality of the air in the atmosphere. The system is deployed near traffic signals and toll gates for small distance communication between the RF source and sensor motes. The system proposed by the researcher behaves well when the nodes are minimal in size with a range of 100*100 mts. The limitation of this research is that it may not function well in larger scenarios like environmental monitoring, habitat maintenance and smart environments due to the fact that both EH and ET can take place only when the RF source and motes are in closer proximity ranges. This drawback is aimed by the author to be addressed as one of the future directives using techniques such as Cognitive Radio and RL.

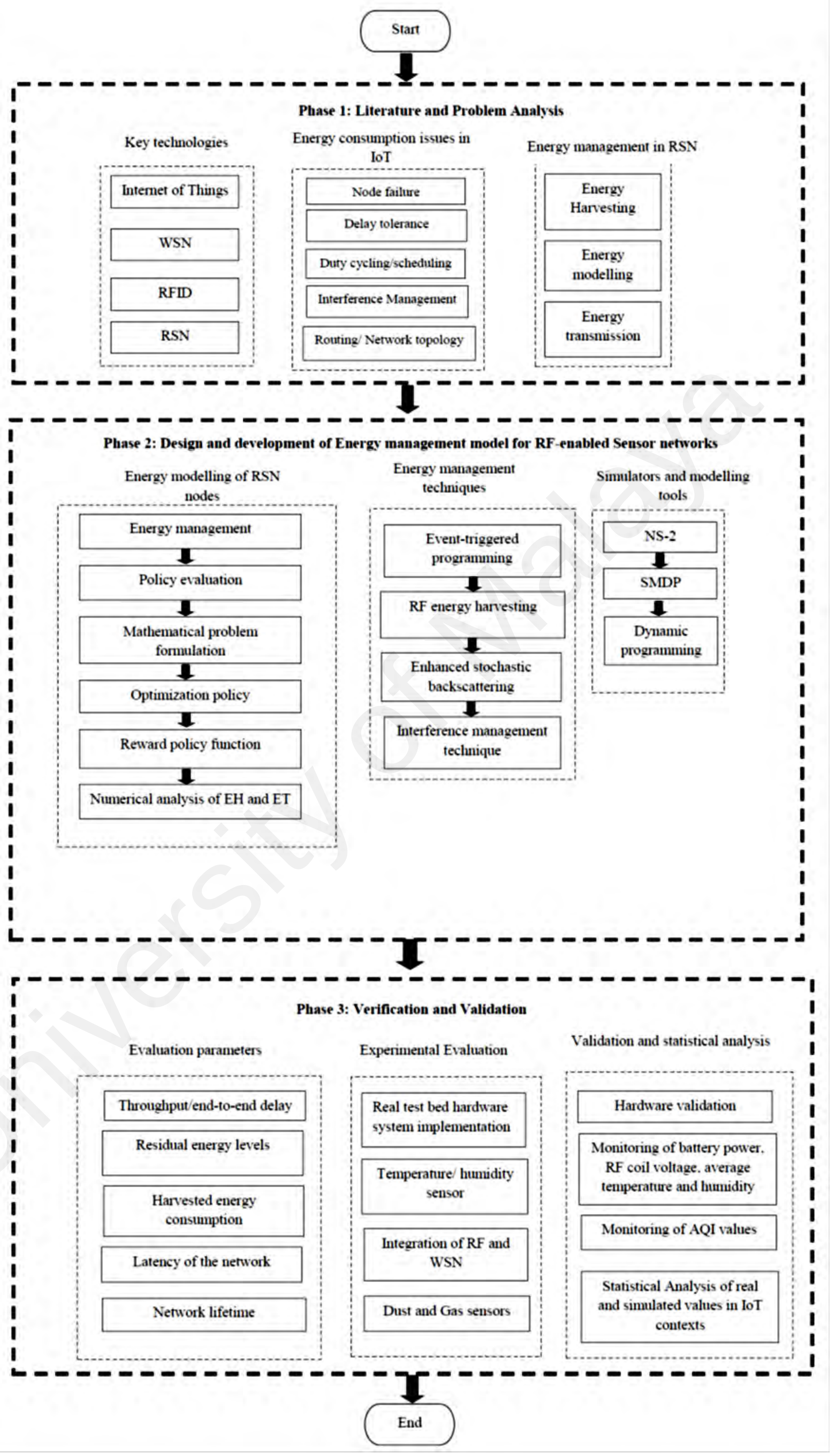


Figure 4.4: **Research methodology flowchart**

4.4 Energy modeling of sensor nodes

The energy management of the RSN nodes is modeled and solved using SMDP and dynamic programming approach. The further sub-sections describe a fundamental explanation of these modeling methods to solve the issue of EM.

4.4.1 Markov Decision process

MDP is defined as a controlled optimization process that results in providing a solution for the actions between node's state transitions. When an event/ action is triggered, the current state is transitioned to another state and a reward is presented to the state. This immediate reward presentation for each change in the states of the node ultimately leads to average reward being calculated for the entire model to solve the issue of energy consumption and arrive at favorable results. The MDP constitutes of the following elements –

i. Policy sets
ii. An agent which decides and selects the action-based set of policies.
iii. Policy-based matrix for transition- which saves the probability of a particular transition.
iv. An award/ reward function- is the resultant function that provides a reward when the probability of a state's transition is successful. On the contrary, a transaction failure will result in either a discount function or penalty.
v. Objective function- this is the function which is vital for the performance comparison between the policy sets to solve the optimization issue.

These MDP's can be applied to smaller systems and can be solved either using enumeration, DP or RL. The proposed EM model is characterized on the basis of SMDP. Semi Markov Process (SMP) is defined as the stochastic process that dedicates a random amount of time (not unity) at each transition. Except for this functionality, SMP and MDP are almost the same. In other words, it can be said that the time taken for each of the transitions marks the difference between SMP and MDP. If this time factor is expressed as an exponentially distributed random variable, then the stochastic process is termed as Continuous – Time Markov process (CTMP). The notable difference between SMP and SMDP is that in SMP the system does not return or jump back to the same state, whereas for SMDP jumping back to the same state is possible. MDP, as described earlier, comprises of policies sets, reward function in the form of matrices, the objective function, policy-based matrix for state transition and the prime decision policy maker. All these together constitute the basic framework for solving the MDP. Accordingly, let us assume that α(i) refers to the policy α which determines the action chosen during i^{th} state and all such policies are deterministic in nature. The Probability Transition Matrix (PTM) is distinctive based upon each of the state's policy chosen and for each transition node, an immediate award in the form of reward function is assigned. After the completion of the transition, an average of all the reward function is assigned an average reward function, which utilizes the Probability Reward Matrix (PRM). Conclusively, the prime decision maker is either a network agent or processor. The transition time between the states is determined using Transition Time Matrix (TTM).

4.4.2 Dynamic Programming

Many research contributions have explored and utilized DP as one of the most helpful tools in solving the MDPs. DP figures out a complicated problem into many simple subproblems that can be determined and stored in a finite memory. The previous versions of the solution that was figured out for a particular problem can be utilized from this memory to determine the results of near future rather than starting it from the scratch. Many inter-related sub-issues can cause clarification on the major problem, which makes DP advantageous than its counterparts. It employs either a top-down or bottom-up approach where top-down solves the problem first followed by checking for the solution in the existing tabulated list if a solution exists it updates, utilizes and stores back the value in the list, otherwise it solves the problem and stores it in the table. Bottom-up approach focuses on solving the multiple sub-issues and integrating each of the solutions to solve the major complex issue. The energy modeling based on MDP is solved using DP for this research in IoT context. For optimization control, DP employs the computation of a value function for each of the states. The feature of handling the problem complexities is played out better by DP than enumeration technique.

4.5 Model description

The proposed energy model has two different aspects for modeling the energy consumed by the modes. First one is the modeling during EH phase followed by ET state. Basically, any sensor node will have or operate in any one of its different operative states such as active, semi-active, idle, sleep, process or transmit/ receive. This research deals with modeling the RSN node in an energy efficient manner by switching between different states and by scheduling the duty cycling mechanisms for TBCS. The prerogative nature of the sensor nodes is that during transmission and reception of data packets or during active state there is a lot of energy consumed. Whereas during idle or sleep state the relative energy expenditure is lesser. The semi-active state, on the other hand, works after a particular threshold level of the node's remaining energy is reached. The idle state is also more similar to the receiving state of the node, due to the fact that all the devices keep waiting to get the input. The fundamental system model of RSN during EH and ET is depicted in Figure 4.5 and 4.6 respectively. The two phases of the RSN node during and after deployment are – EH and ET.

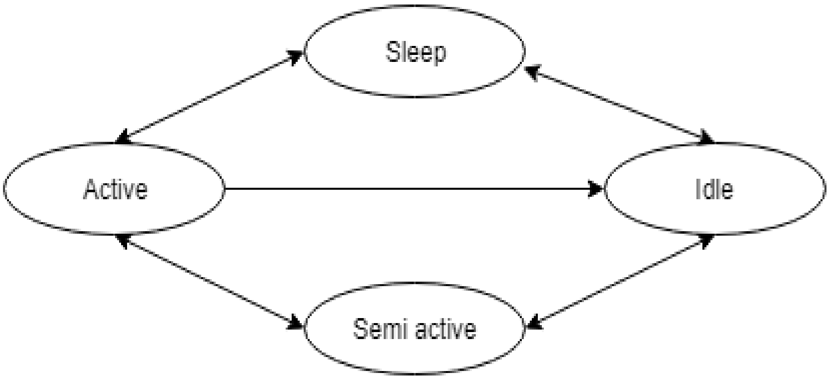


Figure 4.5: **State transition diagram for EHRSN**

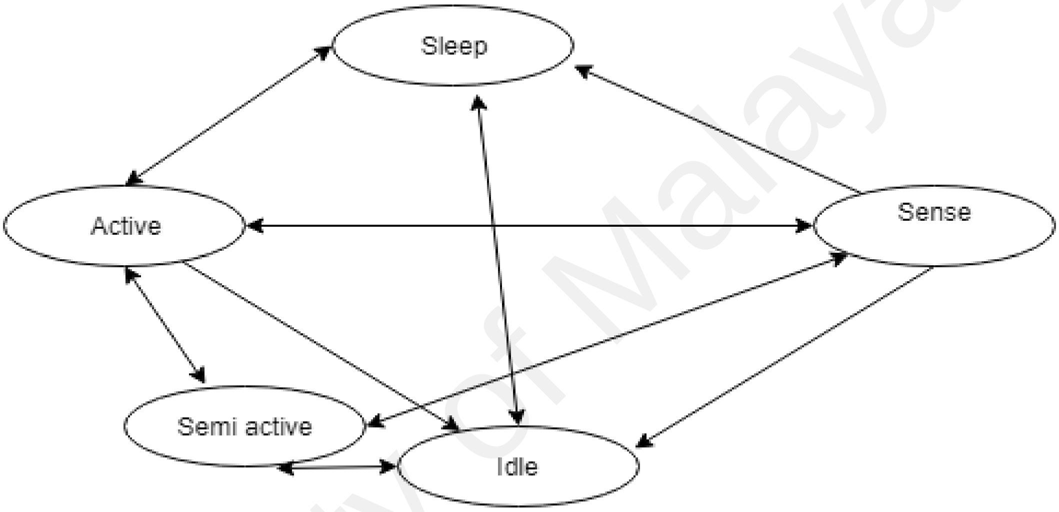


Figure 4.6: **State transition diagram for ETRSN**

- For energy harvesting systems, the harvesting happens at a low power rate during sleep mode and at a medium rate during idle mode. The transmission of packets is carried out during active state and the power saving / EH module is activated during semi-active state. The node's sense state is not made to function during EH, rather the process of sensing information is activated only during predefined time intervals followed by making the nodes to operate at lower power rate during harvesting, will also eventually improve the network lifetime.
- For energy transfer systems there are totally 5 states in which energy modeling is done. The transmission and reception activities are done in the active state. In the semi-active mode, the node adapts to half of the energy ratings of the active mode. In sense state, the reader/ RF energy source is away from the node and therefore the

sensed information is stored in the data buffer, by suspending the node from integrating with the RF source. In idle mode and sleep mode, the ET requests are queued up and in active mode, stochastic backscattering mechanism is carried out for ET, at high power rate.

4.5.1 Elucidation of EM in RSN nodes

Fundamentally sensor nodes comprise of components such as a processor, sensing unit, radio unit, microcontroller, RFID unit, and storage unit. Therefore, all of these components need the energy to power up their circuitries. This section further describes and determines the Total Harvesting Factor (THF) and Total Transfer Factor (TTF) for making each state of the node to run in an energy efficient manner. The term THF here is defined as the total amount of energy expended or spent during the process of harvesting and TTF here refers to the total amount of energy that is spent during the process of energy transmission. The Table 4.1 and 4.2 determines the energy modeling based upon the energy utilization factor for each corresponding state during EH and ET phases respectively. The concept that has been tabulated has been adopted from the research contribution by Wang. Q & Yang (2007).

Table 4.1: **Energy expenditure modes for EH**

States	Processor unit	Radio	T_x	R_x	Sensor unit	RFID unit	Total Harvesting Factor (THF)
Active (S0)	H_p	H_{Rad}	H_{T_x}	H_{R_x}	H_s	0	$H_p + H_{Rad} + H_{T_x} + H_{R_x} + H_s$
Semi active (S1)	$\frac{H_p}{2}$	H_{Rad}	H_{T_x}	H_{R_x}	$\frac{H_s}{2}$	0	$\frac{H_p}{2} + H_{Rad} + H_{T_x} + H_{R_x} + \frac{H_s}{2}$
Idle (S2)	0	H_{Rad}	H_{T_x}	H_{R_x}	0	$\frac{H_R}{2}$	$H_{Rad} + H_{T_x} + H_{R_x} + \frac{H_R}{2}$
Sleep (S3)	0	0	0	0	0	H_R	H_R

Table 4.2: Energy expenditure modes for ET

States	Processor unit	Radio	T_x	R_x	Sensor unit	RFID unit	Total Transfer Factor (TTF)
Active (S0)	T_P	T_{Rad}	T_{T_x}	T_{R_x}	T_s	T_R	$T_P + T_{Rad} + T_{T_x} + T_{R_x} + T_s + T_R$
Semi active (S1)	$\frac{T_P}{2}$	T_{Rad}	T_{T_x}	T_{R_x}	$\frac{T_s}{2}$	$\frac{T_R}{2}$	$\frac{T_P}{2} + T_{Rad} + T_{T_x} + T_{R_x} + \frac{T_s}{2} + \frac{T_R}{2}$
Sense (S2)	$\frac{T_P}{2}$	T_{Rad}	T_{T_x}	0	T_s	0	$\frac{T_P}{2} + T_{Rad} + T_{T_x} + T_s$
Idle(S3)	0	T_{Rad}	0	0	0	$\frac{T_R}{2}$	$T_{Rad} + \frac{T_R}{2}$
Sleep (S4)	0	0	0	0	0	0	0

In tables 4.1 and 4.2, THF and TTF are the total harvesting factor and total transfer factor respectively. The amount of energy expended by the sensor nodes during both EH and ET processes is recorded. This energy utilization factor is basically due to the fact that energy consumption also depends upon the communication hardware. When the node is in active state, the amount of energy consumed not only depends the metrics of the radio but also on the drain efficiency of the circuitries such as inverter, power amplifier, microcontroller, processor, RFID, sensing, Tx and Rx units. These factors determine the cumulative energy utilization factor during harvesting and energy transmission. The tabulation indeed depicts the various states of each process (EH & ET) along with the status of the circuits involved such as the status of the processor, radio, RFID, and sensing unit. Depending upon the type of process being carried upon, the utilization factor changes. For example, during active and semi-active states the nodes do not opt for harvesting process. The nodes get completely charged during sleep state and half charges during the idle state. We indefinitely assume that energy will be generated for sensors during the sleep state. For ET, on the other hand, there is no energy transmission during idle or sleep state. There is another state called ‘sense’ state where RFID unit is completely disconnected, and the operation of the sensor is to only sense the data and store it in its data buffer.

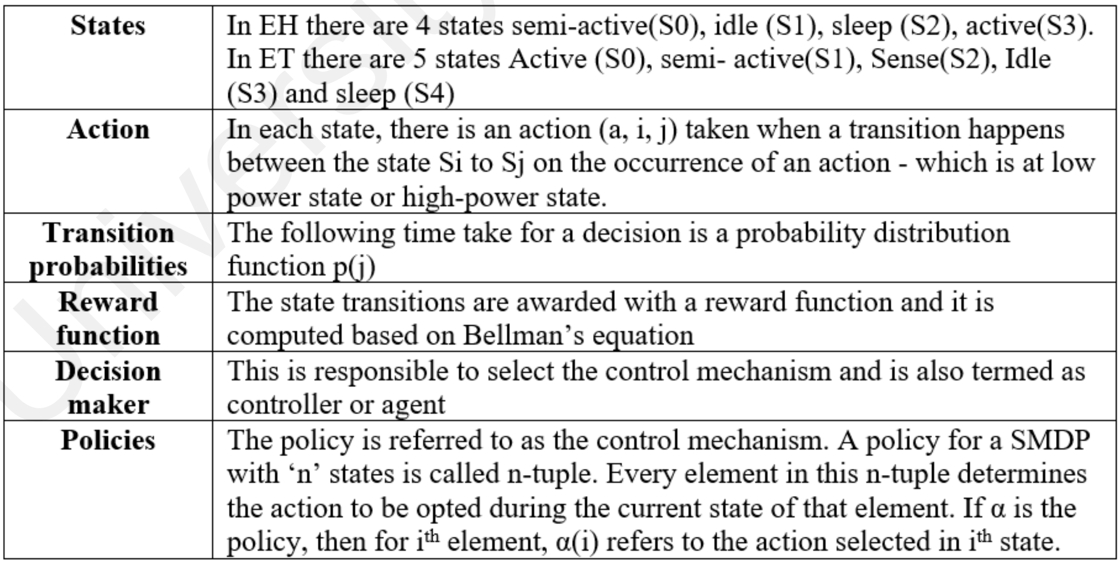
4.5.2 Policy Evaluation using Mathematical modeling

The process that involves SMDP modeling for various states during EH and ET, is to evaluate the optimization policy. The SMDP framework is designed to solve the Markov decision problem. The seven basic elements of this framework are

a) States of the node
b) Policies
c) Actions
d) Transition probability functions
e) Transition reward functions
f) A decision maker
g) An objective function

The characteristics of each of the elements have been tabulated in Table 4.3.

Table 4.3: **Characteristics of Nodes**



States	In EH there are 4 states semi-active(S0), idle (S1), sleep (S2), active(S3). In ET there are 5 states Active (S0), semi- active(S1), Sense(S2), Idle (S3) and sleep (S4)
Action	In each state, there is an action (a, i, j) taken when a transition happens between the state Si to Sj on the occurrence of an action - which is at low power state or high-power state.
Transition probabilities	The following time take for a decision is a probability distribution function p(j)
Reward function	The state transitions are awarded with a reward function and it is computed based on Bellman's equation
Decision maker	This is responsible to select the control mechanism and is also termed as controller or agent
Policies	The policy is referred to as the control mechanism. A policy for a SMDP with 'n' states is called n-tuple. Every element in this n-tuple determines the action to be opted during the current state of that element. If α is the policy, then for i^{th} element, α(i) refers to the action selected in i^{th} state.

The decision-making component usually executes the action to be processed in each state of an SMDP. Each action taken for the transition from the state i to j is associated with TPM. The transition in a Markov chain is associated with a reward function, which corresponds to the immediate cost implied for change in the state of the nodes. The control optimization problem consists of a performance metric called an objective function to compare the policies in terms of cost and reward factors. Average reward is termed as the expected reward function over an infinitely longer Markov processes calculated per unit time. The general average reward of a policy α can be determined by,

$$\mu_{\alpha=} \sum_{j \in s} \gamma_\alpha \ (j\ ) \overline{p}\ (j, \alpha(j)) \tag{4.1}$$

Where, $\gamma_\alpha\ (j\ )$ states the limiting probability distribution function when markov process is run using policy α. The notation S refers to the entire set of states in the markov chain. The term $\bar{p}(j, \alpha(j))$ relates to the immediate reward expected and earned during state j. This research utilizes the dynamic programming concept to solve the SMDP using controlled optimization technique. As stated earlier, the average reward policy is associated as a scalar quantity with every policy of a Markov process. Correspondingly, value function is utilized in the form of associative vector for each policy. This vector comprising of numerical values of the components can be solved by means of a linear set of equations, which is termed as Bellman equation. Therefore, in the context of average reward it is determined as,

$$k_\alpha\,(j) = \bar{p}\big(j, \alpha(j)\big) - \mu_\alpha + \sum_{i=1}^{|s|} r(j, \alpha(j), i) k_\alpha(i), \text{ for every } \ j \in s \tag{4.2}$$

$$k(j) = p(j, a, i) + \int \sum_{j \in s} \left[\int_0^x e^{-pt}\, \beta(j, a, i) r(j, a, i)\right] T dv \tag{4.3}$$

The above set of linear equations is equalized to the total number of elements in the set S, as |S|. Clearly, the two different DP- based methods for solving SMDP are either through Policy Iteration (PI) using Bellman equation for a policy or Value Iteration (VI) by utilizing the Bellman optimality equation. In equation 4.2 and 4.3, T is the total time distribution and the average reward is calculated using exponential distribution. $\alpha(j)$ refers to the action corresponding in state j for policy α and $r(j, \alpha(j), i)$ determines the probability of one state transition for jumping from state j to i, using α policy which can be obtained from TPM. For the advantage of reducing the computational complexities, the Bellman Equation of Optimality (BEO) based upon VI algorithm using DP is employed in this research. This is also due to the fact that PI has many unknowns, leading to needless solving of many equations. The following equation presents the BEO,

$$k^*(j) = \max_{a \in A(j)} \left[\mathrm{p}(j, a, i) - \mu^* \mathrm{t(j, a, i)} + \sum_{i=1}^{|s|} r(j, a, i) k^*(i) \right] \quad \text{where } j \in s \qquad (4.4)$$

In the above equation 4.4, A(j) determines the entire set of actions permissible in state j. k* denotes the components of value function vector $\vec{K}$* which equalizes to the number of states in the SMDP. $\mathrm{p}(j, a, i)$ refers to the immediate reward expected for selection of action ‘a’ in state j to transition towards the next state i. The notation $r(j, a, i)$ determines the PMT values for transitioning from state j to i on selection of action a and μ* denotes the average reward as stated in equation 4.1. According to SMDP the transition time between the state is non-exponential and deterministic. The reward function is calculated over T time distribution belonging to S, which specifies the instant of time when a transition should occur. t (j, a, i) represents the time taken to make a transition from state j to i when action a is taken. β (j, a, i) denotes the rate of reward. The values of p (j, a, i), r (j, a, i) and t (j, a, i) are computed and stored in matrix form which are PTM, PRM and TTM.

$$k^*(j) = \max_{a \in A(j)} \left[\mathrm{p}(j, a, i) - \mu^* \mathrm{t(j, a, i)} + \rho \sum_{i=1}^{|s|} r(j, a, i) k(i) \right] \quad \text{where } j \in s \qquad (4.5)$$

Where the notation ρ stands for discounted reward factor for negative awarding.

4.5.3 Optimal policy computation

The optimized policy is calculated and computed to improve the node’s lifetime following the identification of the energy expenditure details of a node in various states. DP is utilized for solving the SMDP for the computation of optimized policy. Random topologies of RSN have been extensively tested for time-based cooperative systems using temperature and humidity sensors, about which detailed explanation will be provided in the forthcoming chapters. The immediate reward for an RSN node is calculated using the following formula,

$$\mathrm{p}(j, a, i) = \frac{THF/TTF \ \ (utilization\, factor)}{[(Energy * transition\ time)] + \epsilon}\ for\ all\ i, j\ \in S \tag{4.6}$$

And where ϵ is the buffer for receiving/transmitting. The above equation is assigned to the transition of states by the node, based upon the energy utilization factor during EH and ET, explained in previous sub-sections.

4.5.4 Reward policy function for state transition

In this research, incentives in the form of rewards are awarded for favorable transitioned states. The term favorable here means that the state in which there is more energy optimization and packet generation for both the process of EH and ET. On the contrary, if the particular state transition does not provide energy optimization, negative reward or penalty will be imposed which is termed as a discounted reward. Therefore, efficient energy resource utilization will sum up for positive reward and vice-versa. On the transition from state j to i, immediate rewards are awarded under action a. For example, r (S0, a) denotes immediate reward r in current state S0, under action a, where action means availability of nodes either in low power or higher power levels. The following Table 4.4 and 4.5 shows the rewards awarded for each of the states in EH and ET processes.

Table 4.4: Reward factor for EHRSN model

States	Rewards (R)
Active (S0)	$2 \leq R \leq 4$
Semi active (S1)	$2 \leq R \leq 8$
Idle (S2)	$2 \leq R \leq 8$
Sleep (S3)	$4 \leq R \leq 16$

Table 4.5: Reward factor for ETRSN model

States	Rewards (R)
Active (S0)	$2 \leq R \leq 16$
Semi active (S1)	$2 \leq R \leq 8$
Sense (S2)	$2 \leq R \leq 8$
Idle(S3)	$2 \leq R \leq 4$
Sleep (S4)	$2 \leq R \leq 2$

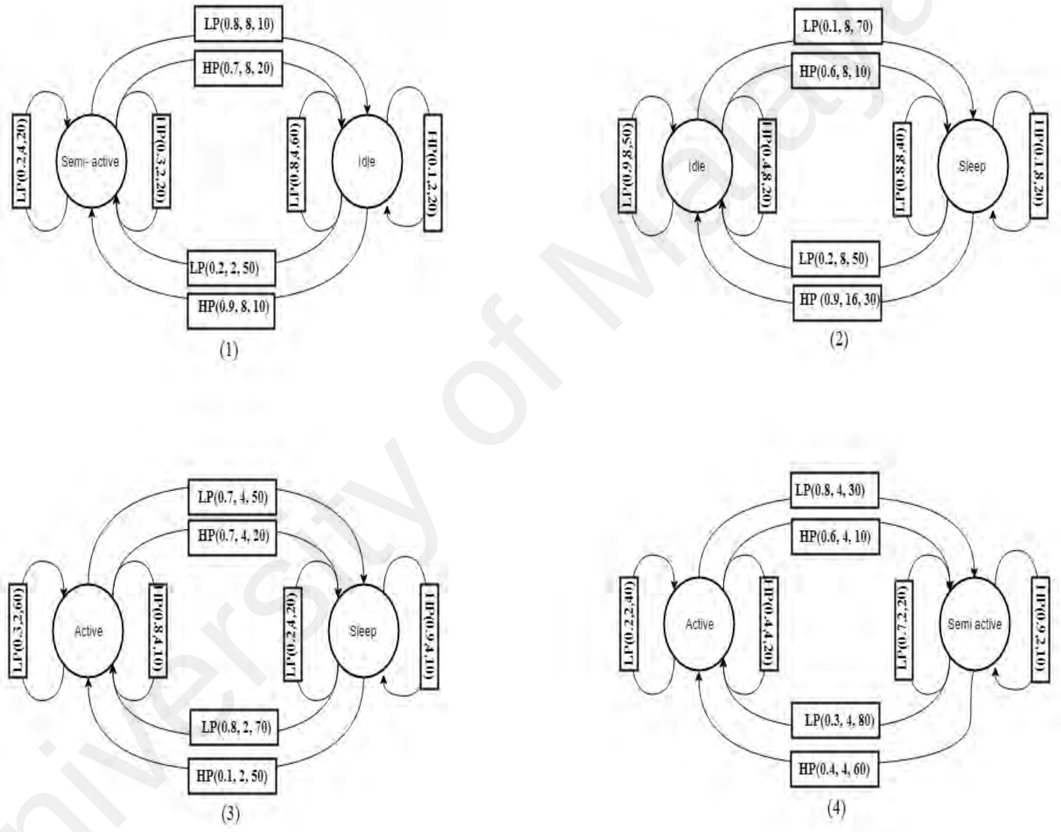
The illustration of assigning reward function for state transitions has been depicted in the form of the tuple in the following sub-section of this chapter using DP and Bellman's equation for optimality. Energy modeling based upon discounted reward factor is out of the scope of this research. The normalization of reward function is done on a scale of 0 to 1.0 by selecting 0.9 as the maximum value for the active state in both EH and ET. On the other hand, for more utilization of energy resources due to failed or uninitiated transaction, a higher penalty is imposed.

4.6 Problem formulation and solution

In this sub-section, the bellman's equation is solved based on DP, that has been adopted from research contribution by Gosavi (2003). The author in this context describes the concepts behind simulation-based control using approaches such as reinforcement learning and parametric optimization. Therefore, equation 4.4 is solved by computing PTM, PRM and TTM as depicted in Figure 4.7 and 4.8. For all the states of EH and ET processes, the corresponding matrices are derived and solved using DP based controlled optimization approach. The four scenarios for solving the stated SMDP are tabulated in Table 4.6,

Table 4.6: **Four scenarios for solving SMDP**

Process	Energy/ Power Levels	Notation
EHRSN	Highly powered/ highly available	HP
EHRSN	Low powered/ low availability	LP
ETRSN	Highly powered/ highly available	HP
ETRSN	Low powered/ low availability	LP



(1) (2) (3) (4)

Figure 4.7: **Illustrations of state transitions for EHRSN modeling**

The table 4.6 is utilized for stating the energy levels and fixing the rewards. The said scenarios are solved based upon the state transitions favorable for energy optimization and as specified in the SMDP tuple. The basic assumption in this context is that energy will be generated and harvested for sensor during the sleep state.

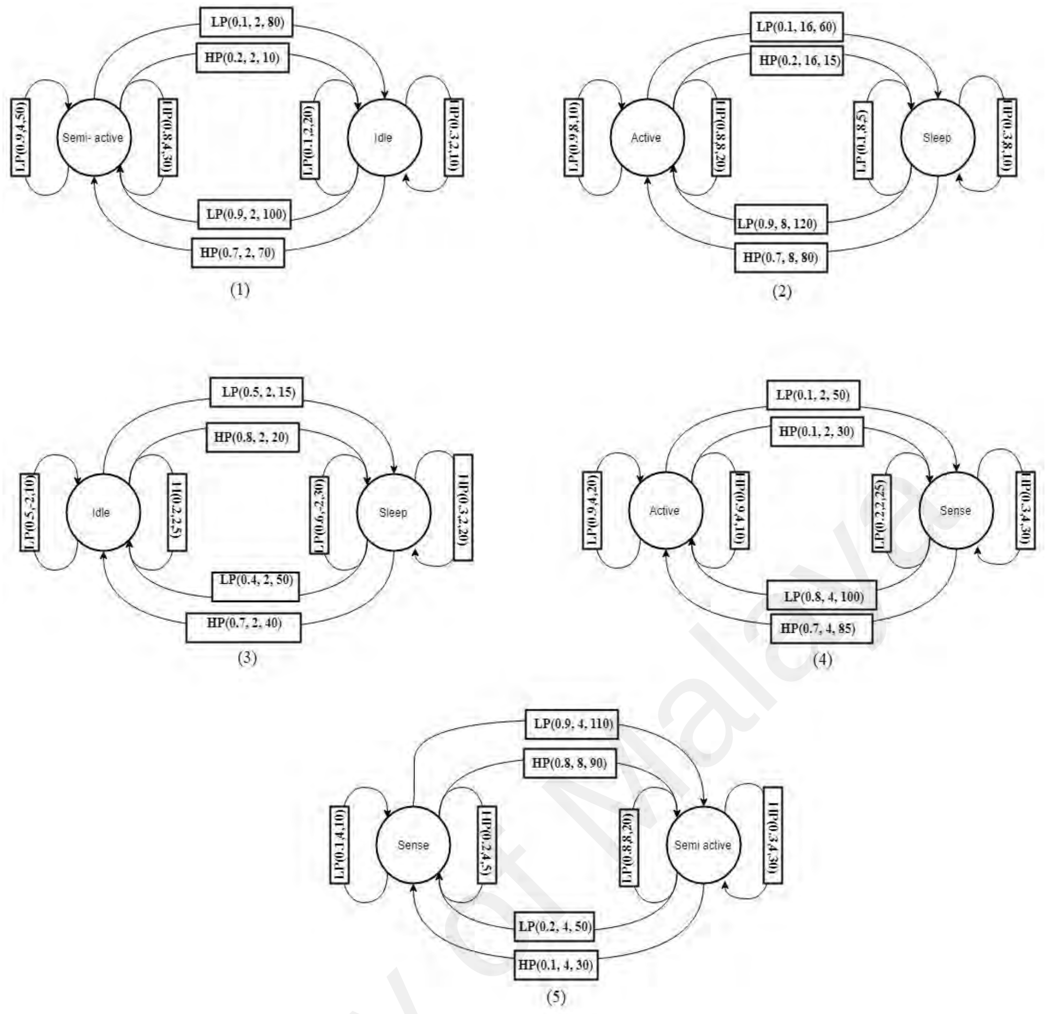


Figure 4.8: **Illustrations of state transitions for ETRSN modeling**

From Table 4.1 and 4.2, it can be evidently stated that all the state's operation and configurations are different for EH and ET. Since the aim of this research is to manage the energy levels, the process of EH is carried out during sleep state and idle state to maintain the balance between mitigation of higher energy consumption rate for T_xR_x operations and to prevent node failure/dead state of nodes. The nodes switch from idle to sleep state dynamically, when the network does not handle any tasks, or when there is no energy demand from the neighboring nodes. This dynamic state switching is done based upon the time synchronization of nodes and the residual energy levels. The notation tabulated in Table 4.6 describes the energy levels high/low for EH and ET processes respectively. The illustrations depicted in Figures 4.7 and 4.8, shows the various state transitions between two states based on the energy levels (highly powered/low powered). These illustrations are further used to mathematically solve the SMDP process. HP refers to highly available node, highly energized/highly powered mode stating that the node is highly active and does not opt for sleep state ultimately consuming more energy. LP refers to the mode of having low energy levels/low powered indicating that the node's availability is also low that is at predefined intervals leading to the node being in a sleep state for harvesting energy. The other states active, sense and semi-active make the node to jump to the idle state when there is a need for lesser resource utilization. Therefore, each of the states opts for transitioning to an idle state for a considerably lesser number of times in order to avoid energy wastage during idle listening. Figure 4.7 and 4.8 depicts the state transition diagram of EH and ET processes for tag-based systems where the transition is represented by a notation of HP and LP to indicate the energy levels/availability followed by a tuple notation indicating the transition probability, immediate reward and time taken for the transition respectively as in the following equation 4.7,

$$HP/LP < P_{mt}, R_{mt}, T_{mt} > \qquad (4.7)$$

The state transitions are depicted on two actions that is on low power levels or high-power levels in the form of tuple where P_{mt} denotes the probability of the state preference, R_{mt} signifies the immediate reward which is given for the state that is preferred and T_{mt} denotes the time that is taken to jump from one state to another or be in the same state either on low power or high-power levels. The option of SMDP makes the state transition possible along with the jumping back to its own state when compared to MDP. The transition between the different states of both EH and ET processes are computed mathematically using Bellman's equation and solved numerically based on DP. In this research, the optimal solution that can be achieved using consideration of the state's favorable transition is employed for effective resource allocation over a specific period of time. Hence, the policy evaluation algorithm is utilized to optimize the energy level and consumption during EH and ET processes of cooperative tag-based systems. For the purpose of policy improvement, the number of iterations is set to be, k and the number of states as S. The policy selection is made arbitrarily and for assumption basis, $O_{p(k)}$ is considered as the optimal policy achieved after computations. In the following equation 4.8, the variables t^k and μ^k are unknown, due to which either of the two should be replaced by 0. Since μ^k corresponds to the reward, it cannot be equivalized to 0, therefore, the equation is solved by replacing t^k to 0. The transition time t (j, a, i) is also considered during policy computation and evaluation. $O_{P(k)}$ is the selected policy with 'k' number of iterations as suggested by Gosavi (2003), and the new improved policy is chosen such that,

$$O_{P(K+1)}(J) \in arg \max_{a \in A(j)} \left[p(j,a,i) - \mu^k + \sum_{j=1}^{|s|} r(j,a,i) t^k(j) \right] \quad (4.8)$$

If $O_{P(K+1)} = O_{P(k)}$, then the chosen policy is said to be optimal and conclusive which stops the computation/evaluation of optimal policy. On the contrary, when there are no further improvisations with regards to the values of the policy's iteration, the computation furthermore, continues until the optimal policy is achieved. All the state transitions are considered for iterative policy evaluations for both the EH and ET processes, to compute the optimal policy and thereby achieve the most energy efficient solution.

4.7 Numerical analysis for tag-based integrated systems

The numerical analysis is carried out for both EH and ET process of TBCS by solving the SMDP process. The DP is employed for tabulating the values of transition probabilities ranging from 0.5 to 0.9 along with reward function of each of the transitions made from one state to another in the favor of harvesting and transferring energy followed by the time taken for each transition.

4.7.1 Numerical analysis of EH systems

The equation 4.7, shows the notation assigned for preference of energy levels and numerical data analysis for the probability of successful transition, reward and time taken for the transition from current state to the next. For instance, in Figure 4.7 (1), the notation LP (0.8,8,10) indicates that on the preference of low energy level mode, the transition probability for semi-active state to move to idle state is 0.8 for which higher rewards are given and since the transition happens from operational state to being idle, the time taken is much faster, 10 secs. Therefore, in low power mode, the preferable state for harvesting more efficiently is to transition to the idle state rather than staying in the semi-active state itself, for which LP (0.2,4,20) holds true. In this method, the numerical analysis is done for all the states during EH and ET processes. The factors contributing to energy efficiency are given more focus to, during the analysis. The last element which is the transition time considered to be a unique case of SMDP is based upon the probability and frequency of switching between the states. The tabulations are shown in Table 4.7 and 4.8 depict the metrics related to the rewards and the corresponding probability values (P). The value of P varies from 0.5 to 0.9 followed by the actual probability for the system. The evaluation and computation include two states where reward metric indicates incentives to be awarded for transitioning between the states. ‘0’ corresponds to initial/current state and ‘1’ indicates the second state.

Table 4.7: Optimal values and average reward for EHRSN

	A		B		C		D	
Low power	**Semi active to Idle**	**Reward**	**Idle to sleep**	**Reward**	**Active to sleep**	**Reward**	**Active to semi active**	**Reward**
$P_m = \infty$	-1.510	0.330	-2.610	0.200	-2.341	0.021	-1.710	0.431
$P_m=0.5$	6.441 0→0;1→1	0.129	6.576	0.242 0→1;1→1	9.717	0.210 0→1;1→1	2.761	0.079 0→1;1→0
$P_m=0.6$	1.815 0→1;1→1	0.169	4.00	0.400 0→1;1→1	1.205	0.222 0→1;1→1	3.964	0.072 0→1;1→1
$P_m=0.7$	3.852	0.380	0.112	0.340 0→0;1→1	4.240	0.234 0→1;1→0	4.632	0.207 0→1;1→0
$P_m=0.8$	0.489	0.479	3.640	0.632	3.000	0.280	2.972	0.318
$P_m=0.9$	1.886	0.434 0→1;1→1	4.597	0.524 0→0;1→1	6.1711	0.171 0→0;1→0	0.750	0.270 0→1;1→0
P_m=*Actual probability*	0.489	0.442	3.640	0.581 0→1;1→1	3.124	0.259 0→1;1→1	2.975	0.231 0→1;1→1
High power	**Semi active to Idle**	**Reward**	**Idle to sleep**	**Reward**	**Active to sleep**	**Reward**	**Active to semi active**	**Reward**
$P_m = \infty$	-1.2	0.16	-1.32	0.23	-1.28	0.291	-1.21	0.151
$P_m=0.5$	3.136	0.184 0→1;1→0	0.500	0.450 0→1;1→0	0.043	0.300 0→0;1→0	3.529	0.188 0→1;1→0
$P_m=0.6$	2.393 0→0;1→1	0.244	2.108	0.483 0→0;1→0	2.819	0.274 0→1;1→0	0.279	0.094 0→0;1→0
$P_m=0.7$	0.944	0.249	9.013	0.375 0→1;1→0	0.503	0.213 0→1;1→0	5.058	0.167 0→1;1→1
$P_m=0.8$	0.705	0.235 0→1;1→1	6.233	0.574 0→1;1→1	2.400	0.272 0→1;1→1	3.483	0.217 0→1;1→1
$P_m=0.9$	2.116	0.237 0→1;1→1	8.888	0.266 0→1;1→0	9.584	0.203 0→1;1→1	14.297	0.294 0→0;1→1

4.7.2 Numerical analysis for ET

The SMDP energy modeling provides the means for preferring the state and energy level that could favor the most for the efficient handling of EH and ET processes. The Bellman's equation is solved where 0 → 0 and 1→0 result denotes that irrespective of any probability chosen the state '0' is highly favorable. Accordingly, Figure 4.9 and 4.10 denote that, for EH, 'Idle' and 'Sleep' state are the most favorable states followed by 'Active' state being the most favorable for ET process. The EHRSN and ETRSN framework are set in compliance with the total amount of energy that is harvested (THF) and the total amount of energy transferred (TTF). The basic assumption is that energy will be generated for sensors during the sleep state. All the corresponding units should be powered up completely according to the utilization factors THF and TTF. The 'Sleep' state for ET process is negligible since all the units go to complete sleeping mode without any functioning or sensing operations. The Table 4.7 and 4.8 show the combination of different rewards for various probabilities of state transitions, indicating that these configurations should be considered for real-time deployment of RSN devices. The average reward calculation is done for the values of Table 4.7 and 4.8 based on equation 4.7.

Table 4.8: **Optimal values and average reward for ETRSN**

	A		**B**		**C**		**D**		**E**	
Low power	**Semi active to Idle**	**Reward**	**Idle to sleep**	**Reward**	**Active to sleep**	**Reward**	**Active to sense**	**Reward**	**Sense to semi-active**	**Reward**
$P_m = \infty$	-1.23	0.010	1.34	0.002	-1.114	0.014	1.76	0.128	-1.10	0.017
$P_m=0.5$	0.789	0.131 0→0;1→0	5.958	0.018 0→1;1→1	37.104	0.453 0→0;1→0	13.333	0.272 0→0;1→0	1.259	0.118 0→0;1→1
$P_m=0.6$	0.911	0.162 0→0;1→0	1.392	0.050 0→1;1→0	10.880	0.202 0→0;1→1	7.166	0.233 0→1;1→1	3.538	0.147 0→1;1→0
$P_m=0.7$	4.136	0.130 0→1;1→0	0.103	0.015 0→0;1→0	13.592	0.269 0→1;1→0	1.152	0.272 0→0;1→1	4.778	0.143 0→0;1→0
$P_m=0.8$	5.770	0.105 0→1;1→0	5.927	0.043 0→1;1→1	22.199	0.490 0→0;1→0	6.895	0.285 0→0;1→0	3.965	0.166 0→0;1→1
$P_m=0.9$	6.019	0.181	1.989	0.084 0→0;1→0	22.379	0.498 0→0;1→1	3.835	0.294 0→0;1→0	3.943	0.106 0→0;1→0
High power	**Semi active to Idle**	**Reward**	**Idle to sleep**	**Reward**	**Active to sleep**	**Reward**	**Active to sense**	**Reward**	**Sense to semi-active**	**Reward**
$P_m = \infty$	-1.12	0.021	-1.487	0.029	-1.298	0.126	-1.783	0.034	-1.875	0.110
$P_m=0.5$	2.480	0.131 0→0;1→0	2.857	0.114 0→0;1→0	23.320	0.294 0→0;1→0	16.437	0.338 0→0;1→0	1.394	0.017 0→0;1→1
$P_m=0.6$	6.809	0.218 0→0;1→0	4.370	0.059 0→0;1→0	15.891	0.277 0→0;1→0	39.024	0.199 0→0;1→0	2.574	0.067 0→1;1→1
$P_m=0.7$	4.147	0.147 0→0;1→0	0.262	0.041 0→1;1→0	9.060	0.199 0→1;1→0	17.749	0.246 0→0;1→1	3.509	0.103 0→0;1→0
$P_m=0.8$	8.636	0.233 0→1;1→0	1.129	0.159 0→0;1→0	37.263	0.526 0→0;1→1	10.066	0.397 0→1;1→0	2.000	0.428 0→0;1→0
$P_m=0.9$	6.727	0.219 0→0;1→0	7.870	0.149	20.951	0.353 0→0;1→0	15.190	0.366	4.078	0.370 0→1;1→1
P_m=*Actual probability*	6.727	0.228	2.019	0.153	20.951	0.383	23.481	0.420	27.136	0.413

All the probability for state transition is considered from 0.5 to 0.9 and the reward function values are plotted for graphical analysis as depicted in Figure 4.9 and 4.10. It can be evidently concluded that when the probability of staying in a particular state is higher, the corresponding reward function is also more. The energy modeling is done based upon SMDP and is solved using dynamic programming approach. The state with probability P (∞) with probability (1,0) is also tested for an unreal case, where the optimal value tends to be in negative and the average reward comparatively smaller when compared to other limiting probabilities. In the P(actual) mode, the optimal state for idle, active and semi-active is ‘sleep’ state due to the reason of energy harvesting being carried out during sleep and idle states. For ET, in the P (actual) mode, the most optimal state for idle, sleep and sense state are active and semi-active states respectively, due to the very obvious reason, that ET using backscattering is carried out during the node’s active state. For TBCS, ‘Sleep’ state is the optimal one during EH since there are no any transmission/ reception activities leading to energy wastage or expenditure. For ET, in the actual mode the node is seldom modeled to go to sleep or idle state, rather it is kept in the active state for efficient transmission of energy through backscattering. It can also be seen from the numerical analysis that the sensor nodes work best, and the average reward is higher when the transition probabilities are greater than 0.8 for both the processes as tabulated in Table 4.9. The limiting probabilities determine the average reward for a particular state and also optimality to stay in a state or to make a transition towards next state. The tabulations and numerical analysis clearly state that for EH process, the probability of 0.8 or more works best at the lower power level. And for ET, the sensors tend to work more when the probability is either 0.8 or more at higher power levels. For example, if we assume that the probability of being in the active or semi-active consumes more energy and the probability to move to idle or sleep state is 0.9, then the sensors are made to harvest energy for a longer time in sleep mode or idle mode since there are no transmission or reception of data packets. But during this period, there is a possibility of losing some information and queueing of data packets may again lead to overhead and energy consumption. This can amount to unfavorable modeling. Hence the process of numerical analysis has been carried out in this section by considering such factors for TBCS and the actual normalized values are considered for calculation of average reward. In order to validate the said EM model, the RSN nodes are programmed as per the THF and TTF designed and formulated throughout the course of this chapter. The real values of the temperature, humidity, gas and dust sensors adapted from their data sheets are approximated according to their respective utilization factors for suitable experimentation and validation.

The DHT11 and other motes are modeled for both the process of EH and ET through SMDP and thereby solved using DP. Based upon the energy utilization factor during each of the process, immediate rewards were given. Thereafter, the average reward was computed using the DP approach and the energy utilized areas of both the process are analyzed numerically. An optimal policy that maximizes the operation time of these motes during both EH and ET before going to complete dead state and getting depleted in their energy levels is computed. The author in this research had tested the EM model using DHT11, MQ-2 and dust sensor motes and computed the THF and TTF values for various cases. Three different timings of the day were employed in order to test the operating and sensing capability of the mote for light sensing activity (non-peak hours) and for heavy sensing (peak hours). The difference in these two here is that for peak hours, the motes are made to update the values for every 5 mins, whereas for non-peak, the frequency of updating ranges from 30-50 mins (depending upon the changes in sensor readings). For ET process, the active state needs more energy to perform the activities of packet transmission and data processing, based upon the application. During EH process, the policy states that in sleep mode more energy can be harvested during non-sensing activities. However, the system prefers sleep state rather than idle state based upon the energy demands and utilization factors. Also, the DHT11 along with other motes are applied along with system parameters described in the Chapter 6 to compute the total number of messages received, as well as throughput of generating and sending packets w.r.t. simulation time which have been presented graphically in the Results chapter. The packets generated by the sensor motes is depicted in Figure 4.11. Since node 2 and 4 (MQ2 and dust sensor) are set in high power mode (smaller mesh formation), therefore they generate more packets whereas nodes 1 and 3 (DHT11) are set in lower energy levels (larger mesh formation), ultimately generating lesser number of packets compared to other motes. However, the process of packet generation also depends upon the process of sensing. This result shows that when mote 1 and 3 which are set in low power mode generate lesser number of packets are made to carry out the process of EH during sleep or idle state, it would lead to minimum packet loss and hence lesser energy consumption. On the other hand, ET process during active state on high power levels would result in more packet generation, leading to no packet loss and maximum energy optimization. Moreover, the numerical analysis when applied to the sensor motes gave exponential distribution of throughput of the system that has been described in Chapter 6. This justifies the output that has been represented graphically through numerical analysis.

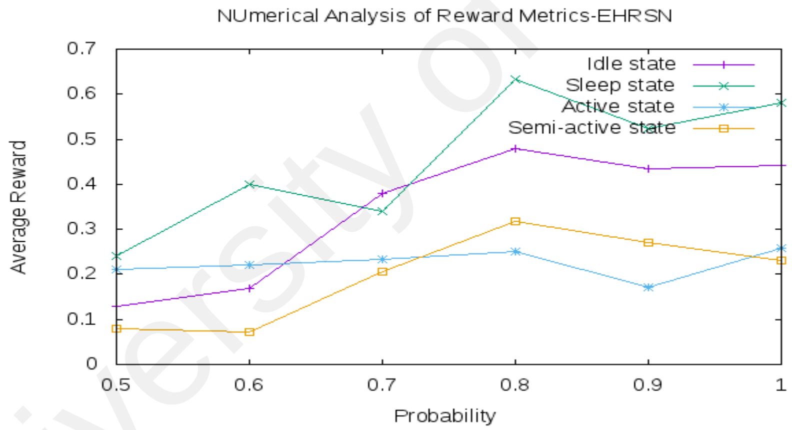


Figure 4.9: Average reward for EHRSN

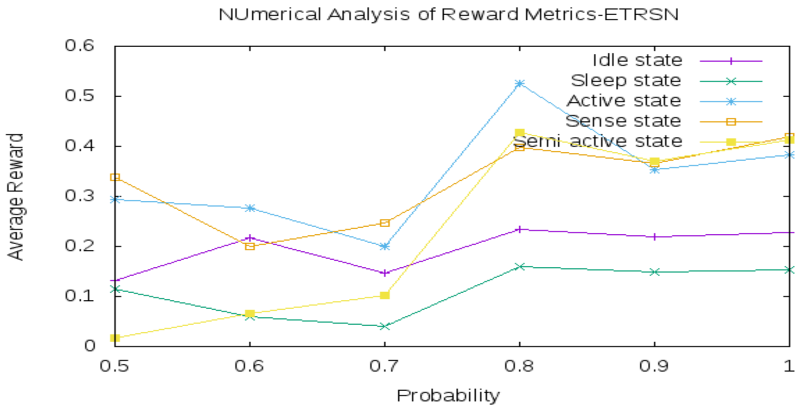


Figure 4.10: Average reward for ETRSN

Table 4. 9: Average reward for probabilities greater than 0.8

EHRSN	**Idle**	**0.479** for low power 0.249 for high power with $P_m = 0.8$
	Sleep	**0.632** for low power 0.574 for high power with $P_m = 0.8$
	Active	**0.280** for low power 0.272 for high power with $P_m = 0.8$
	Semi-active	**0.318** for low power 0.294 for high power with $P_m >= 0.8$
ETRSN	**Idle**	0.181 for low power **0.233** for high power with $P_m >= 0.8$
	Sleep	0.084 for low power **0.159** for high power with $P_m >= 0.8$
	Active	0.498 for low power **0.526** for high power with $P_m >= 0.8$
	Sense	0.294 for low power **0.397** for high power with $P_m >= 0.8$
	Semi-active	0.166 for low power **0.428** for high power with $P_m = 0.8$

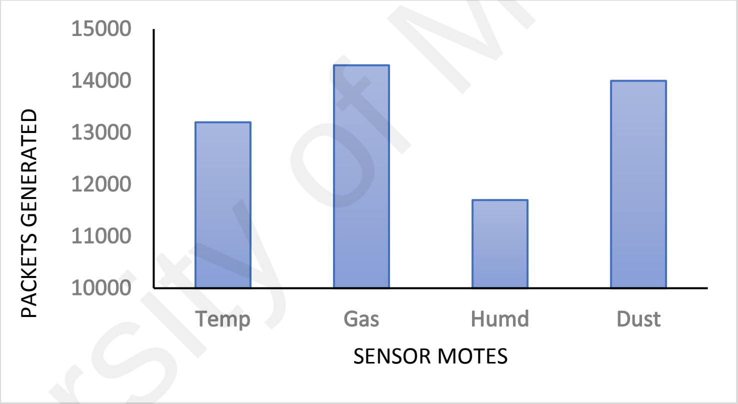


Figure 4.11: Number of packets generated by sensor motes

4.8 Summary

In this chapter the development of proposed EM model for RSN has been presented, to solve and answer few of the identified challenges from the previous chapter. The comprehensive methodology of the research along with a description of NCS, TBCS and energy modeling of sensors has been briefed in subsequent sections of this chapter. Thereafter a detailed description of the EM model, it's mathematical evaluation, and modeling to identify the optimized state transition during EH and ET process has been provided in section 4.5. the research gaps identified from Chapter 3 such as node failure, network lifetime and higher energy consumption during transmitting/ receiving of data packets are focused to be mitigated through the proposed EHRSN and ETRSN framework of EM model. Firstly, the model is described for both EH and ET process, followed by evaluation of optimal policy using mathematical modeling and solving the Bellman’s equation based on DP. The reward functions are calculated based upon the probability of a state’s transition and the time taken for the transition. The average reward is further calculated based on problem formulation and numerical analysis of SMDP for TBCS. The sensors are then programmed accordingly to achieve maximum throughput, network lifetime and energy efficiency. In the next chapter, a detailed and comprehensive explanation of the implementation procedure using network simulations will be presented, followed by a description of results and validation in Chapter 6.

CHAPTER 5: IMPLEMENTATION OF THE MODEL

5.1 Introduction

This chapter describes the implementation details of EM model which comprises of EHRSN and ETRSN framework. Particularly, it presents insights about the simulation tools employed for the implementation of the proposed methodology. Section 5.3 presents the implementation of EH mechanism based upon event-triggered programming approach, followed by implementation of ET technique and interference management mechanism in sections 5.4 and 5.5 respectively. Finally, the chapter is concluded in sections 5.6.

5.2 A simulation tool for RSN

The network simulator 2 (NS2) used in this research constitutes a relatively larger number of agents, protocols, scenarios, and applications which are termed as ‘simulative objects in C++ or OTCL languages. It also provides TCP simulation support, routing, protocols for various wireless to wired networks and also enables the addition of entities such as packet, application, agent, queue, and nodes. NS2 is basically defined as an event-driven simulator which comprises of C++ as backend language and Object-Oriented TCL (OTCL) as the front-end user interface. The structure of NS2 comprises of the following components –

C++

- The execution process is predominantly faster when compared to the slow compilation process.
- Nature of hierarchical compilation.
- Used to handle routing path, topology, application, packet, agent and communication protocol.

OTCL

- It stands for Object-oriented tool command language.
- Nature of interpreted hierarchical compilation.
- The execution process is slower when compared to faster interpretation.

TclCL

- It bridges and connects the OTCL and C++ through interfacing packages.
- Comprises of interface classes with TCL members and methods to enable cordial mapping between the two languages.

Figure 5.1 and 5.2 depict the structural architecture and hierarchical taxonomy of NS2. It shows that the input to the NS2 shell executable command is TCL script (.tcl) and the output is a simulation trace file (.tr) which can be utilized for animation (.nam) of resultant values and for plotting Xgraph of result analysis. The steps to be followed for working in NS2 are:

- Write the. tcl file.
- Execute and compile the file using *ns filename.tcl.*
- The execution and compilation produce two output files - (.nam) and (.tr).
- The trace file (.tr) is utilized for plotting graphs and also to monitor/identify the performance characteristics.
- The graphs can be plotted either using gnuplot, tracegraph or Xgraph.
- The trace file can also be processed through awk script for performance prediction of the network and also for textual information analysis.

As depicted in Figure 5.2, NS2 has a hierarchical structure with ns-allinone-2.35 at the 1st level followed by other packages at the subsequent levels. It comes either in the all-in-one package or as a component package, where each of the packages would require separate execution and compilation. The folder ns-2.35 at the second level of the hierarchical structure comprises of all the modules simulated and in pre-compiled form (such as packets, queue, routing, protocols, trace, applications and so on).

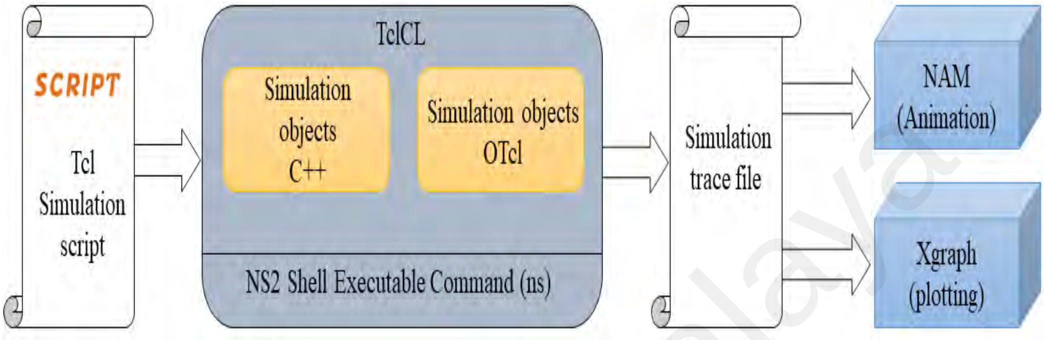


Figure 5.1: Architecture of Ns2

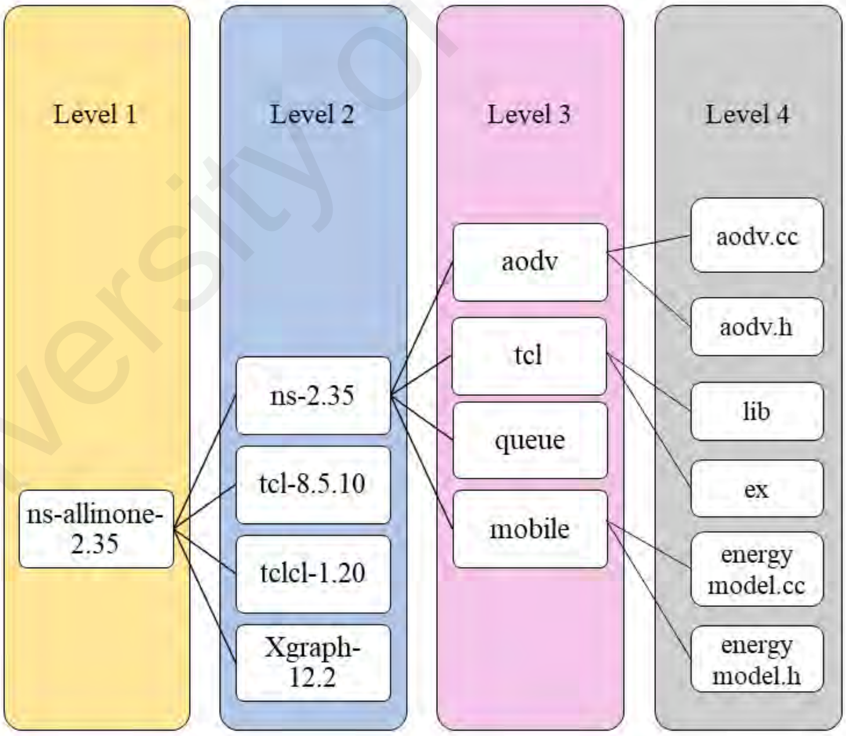


Figure 5.2: Hierarchical directory structure of Ns2

The energy consumption model can be enabled through the default support of NS2. Since energy is the primary factor for a node in a real scenario, NS2 supports the modeling of energy consumption by providing changeable/editable options such as – Fixing the initial energy, setting the transmission/reception power, energy levels of idle state and sleep state of the nodes. The various states of the nodes are depicted through color codes. During the process of transmitting/receiving the data packets, energy level falls and gets deduced from the initial energy of the node. The transmission of packets is halted once there is no longer energy left in the node and the node goes to the dead state. Therefore, this research utilizes this enabling feature of NS2 for integrating it with RFID and making the integrated network more energy efficient in terms of mitigating the node failure, increasing the network lifetime and controlling/handling the energy levels of the RSN nodes.

5.3 EMRSN Modeling Approach

The proposed system model comprises of randomly distributed static RSN nodes (N1 to N9) and mobile readers (R1, R2, and R3) grouped together in clusters as depicted in Figure 5.3 (a), by combining the Wireless Personal Area Networks (WPAN) and RFID modules through simulations. The term WPAN here corresponds to WSN because both have the same MAC. The RSN nodes perform the sensing task and communicate it to the mobile reader. The reader that is mobile in nature collects the sensed data from these nodes and recharges it through the concept of ambient RF energy harvesting. The RF energy that is harvested every time when the reader comes into the proximity range of the nodes is stored in the capacitor. The data collected from each cluster is delivered to the sink through the readers. The sink can be considered as an RFID tag, equipped with larger memory space. As mentioned earlier, the total time required by R, to read sensed data from N is directly proportional to the memory size of N. Hence, the size being in ‘B’ bits, the time required to recharge the sensor node is also comparatively smaller. Therefore, for larger complex operations of wide area RSN, the nodes would need more energy requiring the mobile readers to make frequent tours for recharging cycles. This can consume more energy and can also cause node failures or packet loss in the network if the mobile reader does not reach the recharging distance (R_d) from the energy depleted RSN node. To overcome this kind of energy constraint, multiple mobile readers can be deployed in large and wide area RSNs, so that all the ‘N’ nodes are visited and recharged without time delays. In such a scenario, the multiple mobile readers will move along the unique tour, but with different timings. Hence, the proposed methodology is designed and implemented for the proper time synchronization of RSN nodes during each path movement and recharging cycles of energy harvesting.

The main novelty of this research is the integration of RFID and WSN using network simulations for harvesting the energy of sensor nodes using RF energy. The proposed algorithm focuses on managing the energy levels of the nodes in RSN. The existing solutions of EH networks do not integrate RFID technology along with sensing capabilities. This research focuses on integrating both identification and sensing technologies at the data link layer as depicted in Figure 5.3 (b). The network density of proposed algorithm is tested by increasing the number of readers and sensor tag nodes that has been presented in the next chapter. The complexity lies in the fact of preventing node failure and avoiding inadequate distribution of harvested energy when WSN and RF are integrated because RFID used high frequency whereas radio model of other networks like AODV routing use medium frequency for communication. The proposed scenario is implemented and experimented for different network traffic such as Constant Bit Rate (CBR), Poisson, and File Transfer Protocol (FTP).

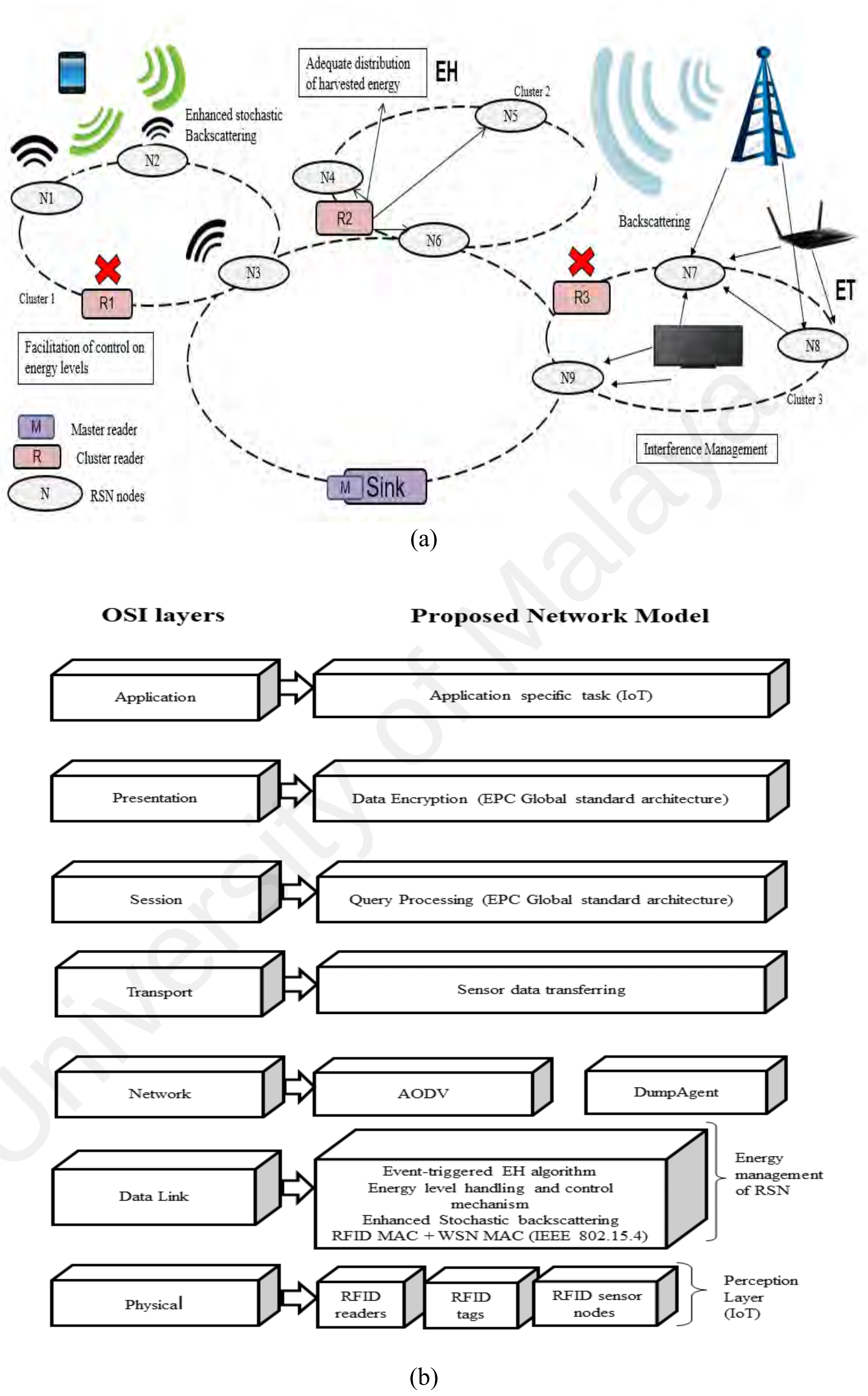
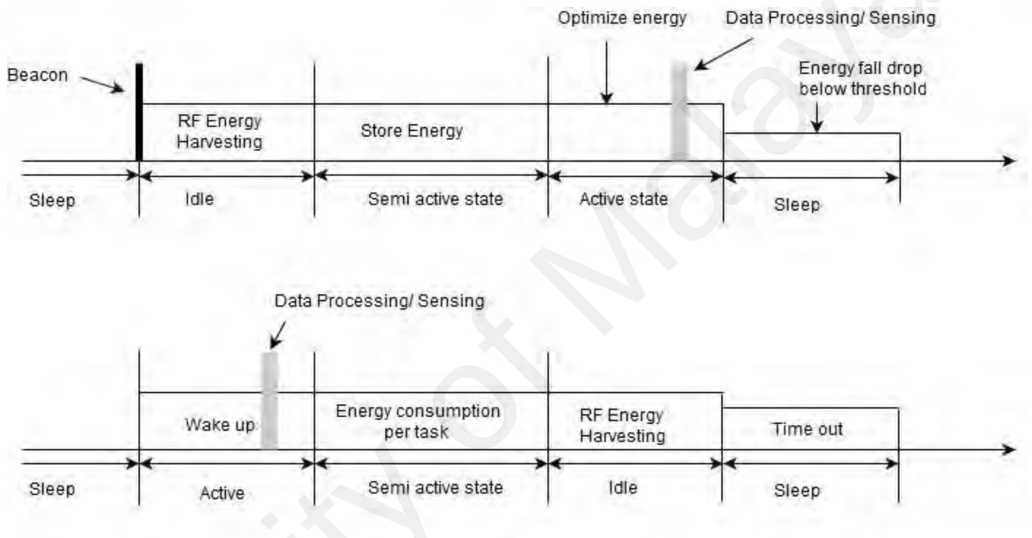
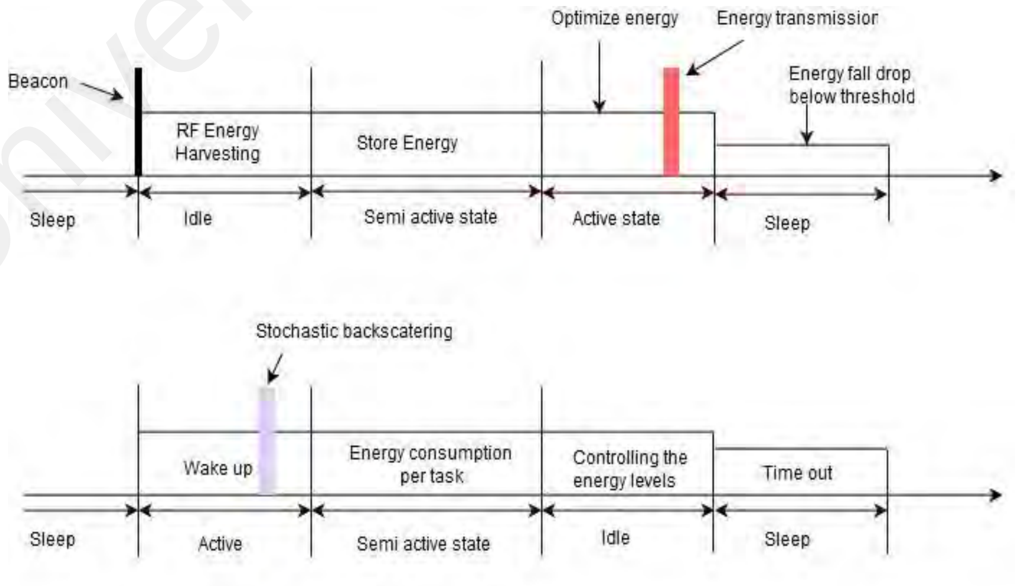


Figure 5.3: **(a) Proposed EMRSN system model (b) EMRSN network model**

The proposed EMRSN techniques focuses on enabling energy optimization by combining RFID and WPAN (IEEE 802.15.4) through NS-2. The focus here is to avoid entire dependence and frequent replacement of energy storage devices such as battery and capacitor. Instead, the energy supplied from sources of RF signals tend to guarantee more affirmation towards improved network lifetime and higher performance. The RF signal either from the RF coil or RFID reader can serve as the energy source to drive the sensor node to an active state and harvest energy during the sleep/idle state. Differently, from the classic duty cycling schemes in the literature which have been discussed in Chapter 2, the proposed EH mechanism has the ‘idle’ and ‘semi-active’ states of RSN node. The classic duty scheme here refers to the Always on model with OOK modulation and balance of duty cycles in accordance to regularity with pattern mismatching and asynchronous scheduling. After a particular period long enough for the nodes to activate the circuitries by grasping energy from the emitted RF signals in sleep state, the node goes into ‘idle’ state where there is RF-energy harvesting and then upon reaching a particular threshold changes its operating state to semi-active state for storing the energy harvested into devices such as batteries and capacitors, which can ultimately serve as secondary energy resources, when the reader or coil is not in the communicating proximity range of the RSN node. The timeline process of transition states modeled based on SMDP and discussed in the previous chapter is depicted in Figure 5.4. The first timeline shows the forward duty cycling phases of the nodes followed by reverse duty cycling of the node’s operational state transitions. The timeline depicts EH and ET as independent processes. The EH takes place whenever the node is in the sleep or idle state followed by ET being carried out during active state when the energy level reaches the threshold levels during the node’s semi-active state. The sensing and data processing process takes place during the node’s active state and eventually goes to sleep mode when the energy falls below the threshold value. The novelty of the proposed mechanisms is that during the idle time period, the process of energy harvesting takes place and this harvested energy is stored and utilized during the semi-active state to handle, monitor and control the energy levels. In the process of ET, the harvested energy is utilized for controlling the energy levels during the idle state. The energy storage and monitoring the energy values of each node is carried upon during semi-active state whereas, in the active state, the process of energy transmission via stochastic backscattering is focused upon for enabling energy optimization and thereby to prevent energy losses.



Timeline for energy harvesting mechanism



Timeline for energy transfer mechanism

Figure 5.4: **Timeline of EMRSN modeling**

The query initiated by the reader for a sensed information during a given instance of time is scheduled based upon the remaining energy of all the nodes in each cluster. For the cooperative tag-based RSN systems, the cluster heads either act as relays for delivering the data to the sink or as a virtual communication channel between the cluster reader and the master reader. Another drawback for the integrated RSN systems is the interference management caused due to RF-based transmissions along the same channel and bandwidth. The rate of EH (E_r) and the probability of success of packet transmission (P_t) depend upon the rate at which the reader needs to collect the information from the sensor nodes. The time required to process (Q) queries (T_q) and the duration of an active state for data transmission (T_a) together constitute the duration for the query to be processed $T = T_q + T_a$. The probability P_t also considers the node's interferences and demodulation inaccuracies. The model is characterized as an SMDP and the EH and ET processes are modeled and solved using dynamic programming approach as discussed in Chapter 4. Considering that the time duration (T_q) is much shorter than (T_a), the signal strength propagated towards the tag is calculated as,

$$s(t;m) = \sqrt{P}\mathrm{Cdl}\ (m)\ x(t) + k\ (t;\ m) \tag{5.1}$$

Where, the time for communication $mT \leq t < (m+1)\ T$ spreads over m^{th} time slot of duration T. The energy needed to transmit the data is (E_0), the two-ray ground propagation model produces a loss factor of 'P' units over a distance of 'd' meters from the ground and the function

$$x(t) = \int \sum i\ \in |st| \left[\int_0^j E_0\, p\right] T_{st}\ dv \tag{5.2}$$

During active state (i) of the node followed by k (t; m) being the additional energy of the system and other SNR factors. C_{dl} (m) is the downlink channel cost during time slot modeled as random variables. Equation 5.2 is stated as according to SMDP for cooperative tag-based systems with definitive recharging deadlines to be the frequency of the signal transmitted during closer proximity with the node, by the RF energy source (Reader or RF coil). Here, 'T' is the entire time duration of the node in the state 'st'. T_{st} is the time instant at which the state transition (from the state 'i' to next state 'j') should take place with 'p' being the transition probability. The process for EH is to check the levels of residual energy and harvested energy in a loop before proceeding to packet transmission as depicted in Figure 5.5.

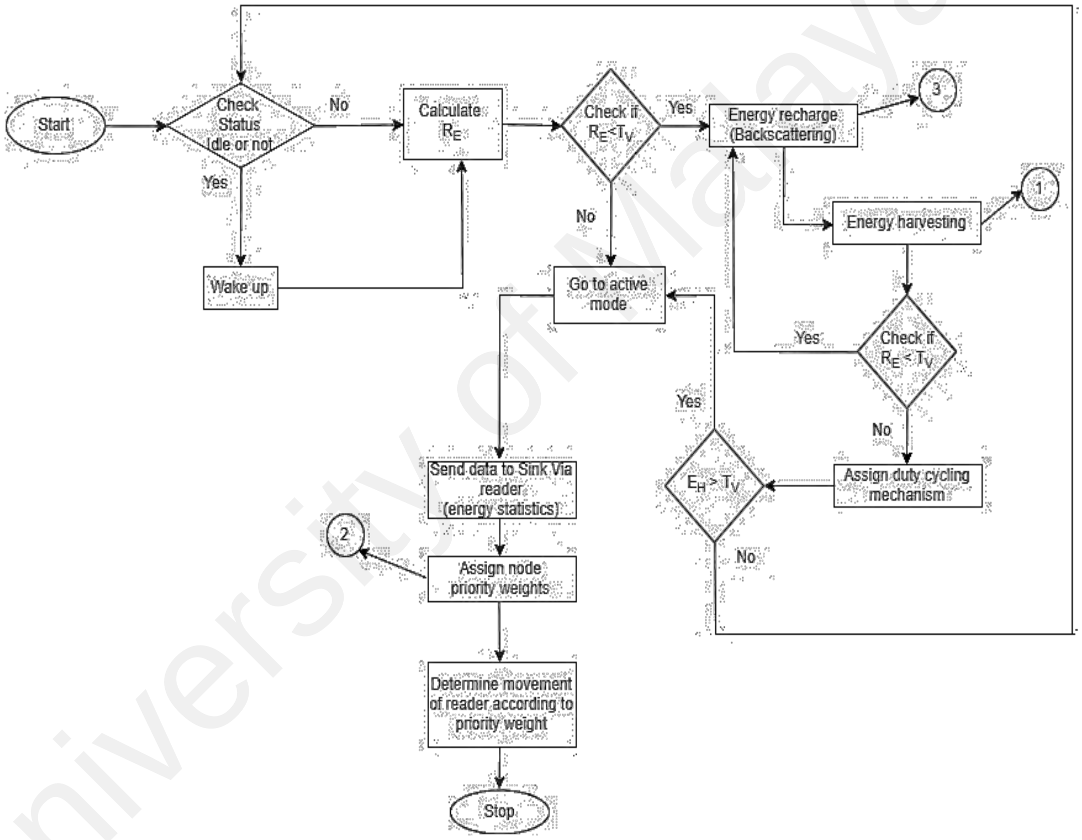


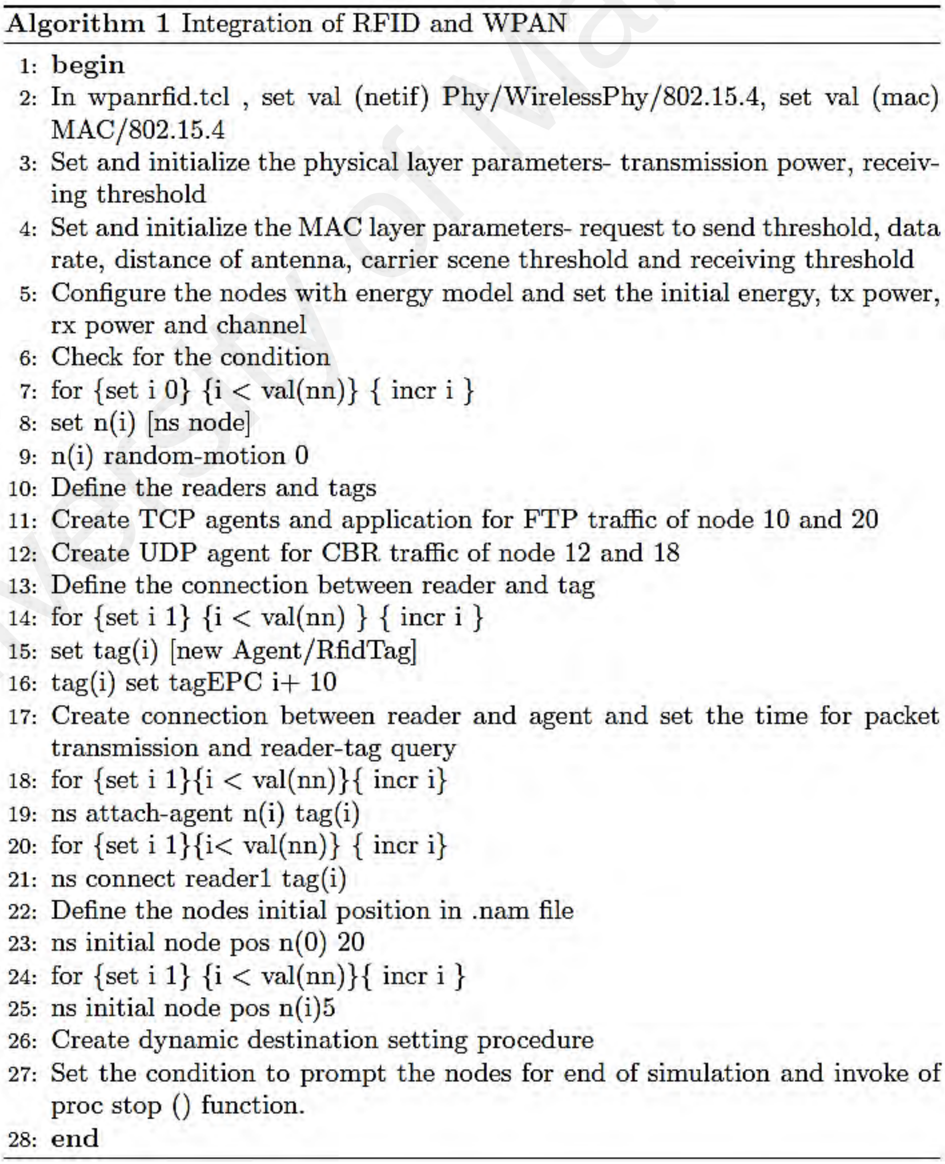
Figure 5.5: **Flowchart of EMRSN modeling approach**

5.4 EH mechanism implementation via simulation

The proposed EH method is focused on enabling energy optimization for RFID with WPAN. As stated earlier, there is a possibility that the energy model handled by NS2 can be integrated with few of the third-party tools which support the battery level of WSN.

Therefore, an RFID patch module is integrated with the NS2 modules. The implementation of proposed mechanism has mainly three aspects –

1. Integration of RF energy source (readers and tags) with WPAN (Zigbee) and write coding as depicted in Algorithm 1 to modify the parameters in order to identify how RFID behaves distinctively with different MAC. This is due to the reason that readers and tags are distributed in the network based upon MAC and query tags are also programmed based on MAC. Therefore, the performance characteristic of how RFID behaves when it is combined with other networks is observed for efficient energy modeling.



Algorithm 1 Integration of RFID and WPAN

```
begin
In wpanrfid.tcl , set val (netif) Phy/WirelessPhy/802.15.4, set val (mac) MAC/802.15.4
Set and initialize the physical layer parameters- transmission power, receiving threshold
Set and initialize the MAC layer parameters- request to send threshold, data rate, distance of antenna, carrier scene threshold and receiving threshold
Configure the nodes with energy model and set the initial energy, tx power, rx power and channel
Check for the condition
for {set i 0} {i < val(nn)} { incr i }
set n(i) [ns node]
n(i) random-motion 0
Define the readers and tags
Create TCP agents and application for FTP traffic of node 10 and 20
Create UDP agent for CBR traffic of node 12 and 18
Define the connection between reader and tag
for {set i 1} {i < val(nn) } { incr i }
set tag(i) [new Agent/RfidTag]
tag(i) set tagEPC i+ 10
Create connection between reader and agent and set the time for packet transmission and reader-tag query
for {set i 1}{i < val(nn)}{ incr i}
ns attach-agent n(i) tag(i)
for {set i 1}{i< val(nn)} { incr i}
ns connect reader1 tag(i)
Define the nodes initial position in .nam file
ns initial node pos n(0) 20
for {set i 1} {i < val(nn)}{ incr i }
ns initial node pos n(i)5
Create dynamic destination setting procedure
Set the condition to prompt the nodes for end of simulation and invoke of proc stop () function.
end
```

2. The number of readers is increased to check the working of RFID and the cluster formation with tags. On the other hand, WPAN coding is also configured to study the energy model. The residual energy levels are checked by increasing the number of nodes in RFID, WPAN (Zigbee) and WPAN+RFID thereafter compared for performance analysis.
3. For different traffic pattern such as CBR/Poisson/FTP, the WSN+RFID coding is modified for enabling the energy model and embedding the EH mechanism during sleep state of the node. The number of nodes is increased to compare the performance characteristics and the levels of average residual energy. The coding is written to create agents and applications. The total number of nodes is set to 25, out of which node 0 is the reader, 1 and 2 are tag nodes. The nodes 10, 20 are assumed as the source and destination for FTP traffic and 12,18 are the source and destination for CBR traffic. The AODV protocol along with 802.15.4 MAC is employed here. The RSN nodes are configured with energy model. The parameters for this evaluation have been tabulated in Table 5.1 and the illustration of the scenario can be referred from wpanrfid.tcl of Appendix B.

The residual energy (R_E) in RSN node is computed as,

$$R_E = 1/2\, C\, (V^2_x - V^2_d) = P_x T_x \tag{5.3}$$

where 'C' is the capacitance of the RSN capacitor, V_x is the maximum voltage of the embedded capacitor, V_d is the minimum operational voltage of RSN node, T_x is the time for completion of the fully charged capacitor, P_x is the received power of RF signal from the reader. The value of P_x is calculated from Friis equation as,

$$P_x = P_T G_T G_R\, \lambda^2 / (4\pi d)^2\, L \tag{5.4}$$

where d is the distance between the transmitting antenna and receiving antenna, P_x is the power received, P_T is the power that is transmitted, λ is the wavelength of the RF signal, L is the path loss factor, G_T is the antenna gain of the transmitter and G_R is the antenna gain of the receiver. The mobile reader should ensure the continuous operation of the RSN node and provide a guarantee about the fact that the energy stored in the capacitor does not run out. The amount of time spent by the mobile reader between two consecutive tours to recharge the RSN is referred to as the period of visit (T_{PV}). This is computed by summing up the total recharging time (T_x) and a lifetime of RSN (T_L). T_x can be calculated using equation (1), whereas T_L is dependent upon the operational cycles (D) of the RSN node. These operational cycles can be calculated as,

$$D= A_T/ (A_T+ S_T) \tag{5.5}$$

where A_T is active mode time interval and S_T is sleep mode time. The total lifetime (T_L) of RSN can be calculated as,

$$T_L= R_E/ A_P (D) +S_P (1-D) \tag{5.6}$$

where A_P & S_p are power consumed by RSN node in active and sleep modes respectively. According to EPC C1G2 standardization, the total time spent for read/write operations of RSN node is directly proportional to the memory size of the RSN node (B bits). The authors in this paper aim to provide an event triggered scheduling mechanism to prevent node failure and packet loss in wide area RSNs. In this way, the proposed solution is compared with existing mechanisms such as non-cooperative solution and co-operative tag-based solutions.

Set val (netif) Phy/WirelessPhy

Phy/Wireless Phy set P_idle 0.2

Phy/Wireless Phy set P_harvest 0.3

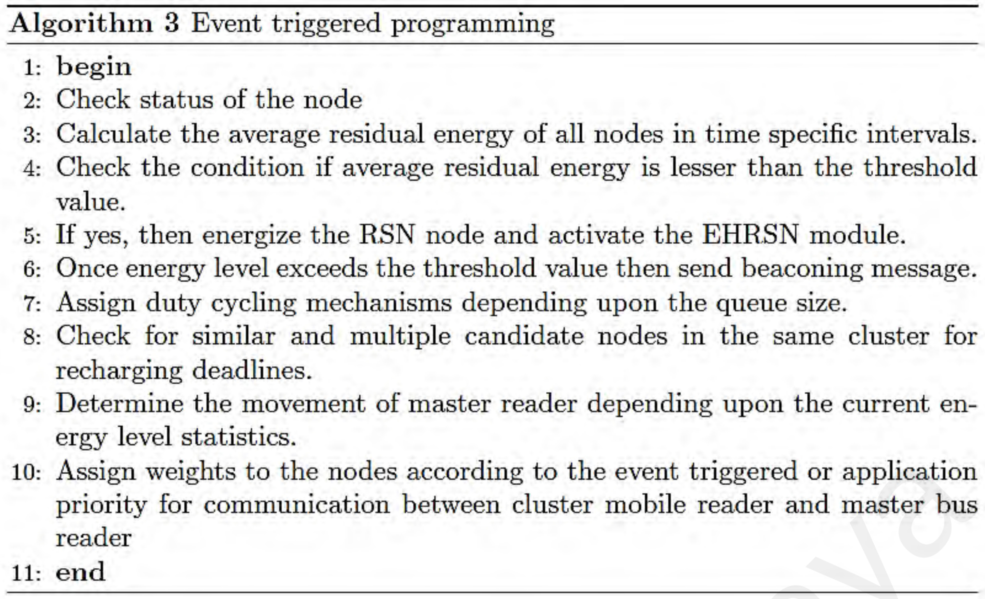
The above Lines of Code (LoC) are written for the generation of harvesting power in the RF layer. The EH technique presented in this chapter is invoked through the event-triggered algorithm as shown in Algorithm 2 and 3 respectively. The input for EHRSN is the residual energy of RSN node and the output is the harvested energy.

Table 5. 1: Parameters for performance evaluation of EH mechanism wr.t network traffic

Parameter	Value
Number of nodes	25
Reader node	0
Topology Used	cluster
Tag nodes	1, 2
Source and destination nodes	10,20 (for FTP) and 12,18 (for CBR)
Routing protocol	AODV and DumpAgent
MAC	RFID MAC+ 802.15.4 MAC

Algorithm 2 EHRSN technique

```
begin
Initialize the Energy model class.
Set the sleep_time; idle_time;harvest_time;active_time and semi-active_time;
Create variables for energy modelling (nid) and for event occurrence (intr);
Declare the Tcl object "Mobile node" for the public class of Energy Model.
Create a function for incrementing the harvesting energy.
virtual void Incr Harvest Energy (double harvest time, double P_harvest);
Return 'eh' variable to the calling function
Initialize the constructor with default values
float total_ harvesttime_;
inline virtual double Max Harvest time harvest (double P_harvest)
return (energy_/P_harvest)
Create another function for harvesting
void Energy Model :: Incr Harvest Energy(double harvest time, double P_harvest)
double dEng = P_harvest * harvest time
if $energy\_ \leq dEng$ then
    energy = 0.0
else
    energy_= energy_− dEng
if $energy\_ \leq 0.0$ then
    God :: instance () $\Longrightarrow$ Compute Route ()
else
    Initialize and calculate the variable that is utilized for keeping track of harvested energy in sleep and idle mode
eh_= eh_+ dEng
Create an instance procedure for harvesting power, in ns-lib.tcl
Simulator instproc harvest power val
Set harvest Power_Val
Check the condition to add harvest power in the RF
if $info=harvestPower\_$ then
    Set the node P_harvest as the harvest Power_
Include eh as harvesting energy in cmu-trace.cc
this node → energy_model() → eh()
Add energy model in wireless-mitf.tcl and change the protocol to AODV
Set energy model "EnergyModel"/
Set initial energy 5.6/
Set T_xPower 0.5/
Set R_xPower 0.4/
Set Sleep Power 0.05/
Set Idle Power 0.2/
Set harvest Power 0.4/
Get the trace files with eh values and RFID tracing
Obtain the values for harvested energy to plot the graphs for performance characteristics
end
```



```
Algorithm 3 Event triggered programming
begin
Check status of the node
Calculate the average residual energy of all nodes in time specific intervals.
Check the condition if average residual energy is lesser than the threshold value.
If yes, then energize the RSN node and activate the EHRSN module.
Once energy level exceeds the threshold value then send beaconing message.
Assign duty cycling mechanisms depending upon the queue size.
Check for similar and multiple candidate nodes in the same cluster for recharging deadlines.
Determine the movement of master reader depending upon the current energy level statistics.
Assign weights to the nodes according to the event triggered or application priority for communication between cluster mobile reader and master bus reader
end
```

The energy obtained by the RSN node during RF harvesting can be calculated as,

$$E_h\,(m) = \int_{mT}^{(m+1)T} |s(t;m)|^2\,dt \tag{5.7}$$

The rest of the energy losses consumed due to connecting circuits and indirect discharges can be derived as

$$PE_o\,|C_{dl}(m)|^2 \tag{5.8}$$

When the RF signal passes through the inverter circuitry, the conversion efficiency can be summed up to α_{DC}, which is assumed to be constant for all the RF power conversions. The energy after RF harvesting is stored during semi-active process of the node and can be available during the time slot ‘m’ as

$$E_s\,(m) = \alpha_{DC}E(m) = \alpha_{DC}PE_o|C_{dl}(m)|2 \tag{5.9}$$

The randomized energy stored depends upon the downlink channel fluctuations relative to the path loss factor ‘P’.

5.5 Implementation of Energy Transmission technique

The nodes during active state, replies to the query commands and transmits the data packets through the backscattering of the RF signal emitted in the closer proximity range. During this process, the energy of all the active nodes is checked and the one with the lowest available remaining energy gains energy through backscattering mechanism. This mechanism follows a stochastic technique to feed the nodes with operative levels of energy. The energy for transmission and for performing backscattering can be calculated as,

$$E_t(m) = \frac{P^2 E_o\, |C_{ul}(m)|^2 |C_{dl}(m)|^2}{\eta_r^2\, T}\, \beta_{node} \tag{5.10}$$

$$E_b(m) = \frac{P |C_{ul}(m)|^2 E_t\,(m)}{\eta_r^2\, T}\, \beta_{add} \tag{5.11}$$

Where, η_r^2 is the additional energy costs due to system and SNR circuitries. C_{dl}(m) and C_{ul}(m) are the downlink and uplink channel fluctuations randomized as integers. β_{node} is the energy transmission efficiency of the node and is denoted within the interval (0,1) and β_{add} is the efficiency of the backscattering node belonging to (0,1). $E_t(m)$ is the energy required basically for transmission of energy to drive the sensors to active state, whereas $E_b(m)$ is the additional energy required for performing the stochastic backscattering process and depends only upon the uplink channel. Therefore, the total energy required for transmission based upon backscattering is obtained by,

$$E_{tb}(m) = E_t(m) + E_b(m) \tag{5.12}$$

The process of energy transmission for the proposed scenario is during the period when the RF-energy source is away from the nodes. For instance, when only the ‘sense’ state is active, and the nodes are getting depleted in their energy levels, there cannot be any harvesting done by the RF reader or RF coil. Therefore, the energized even numbered node which is nearest to the node with minimum energy, carries out the process of ET based upon the enhanced stochastic backscattering technique. This concept can be related to the real-time scenario as energy getting transferred through an RF energy source (which is emitting RF signals) within the proximity range of the RSN node, apart from the RF reader (primary source). The backscattering here literally refers to reflecting back of the scattered RF signals to the node during ambient harvesting. Since the working of this process that takes place in the physical layer cannot be shown through simulations, the process is simulated as to energy transmitted to the node with lowest residual energy from the even-numbered node which has highest energy levels. Therefore, the changes to be done in NS2 simulations are in energy-model.cc, energy-model.h, aodv.cc, and aodv.h as described in Algorithm 4.

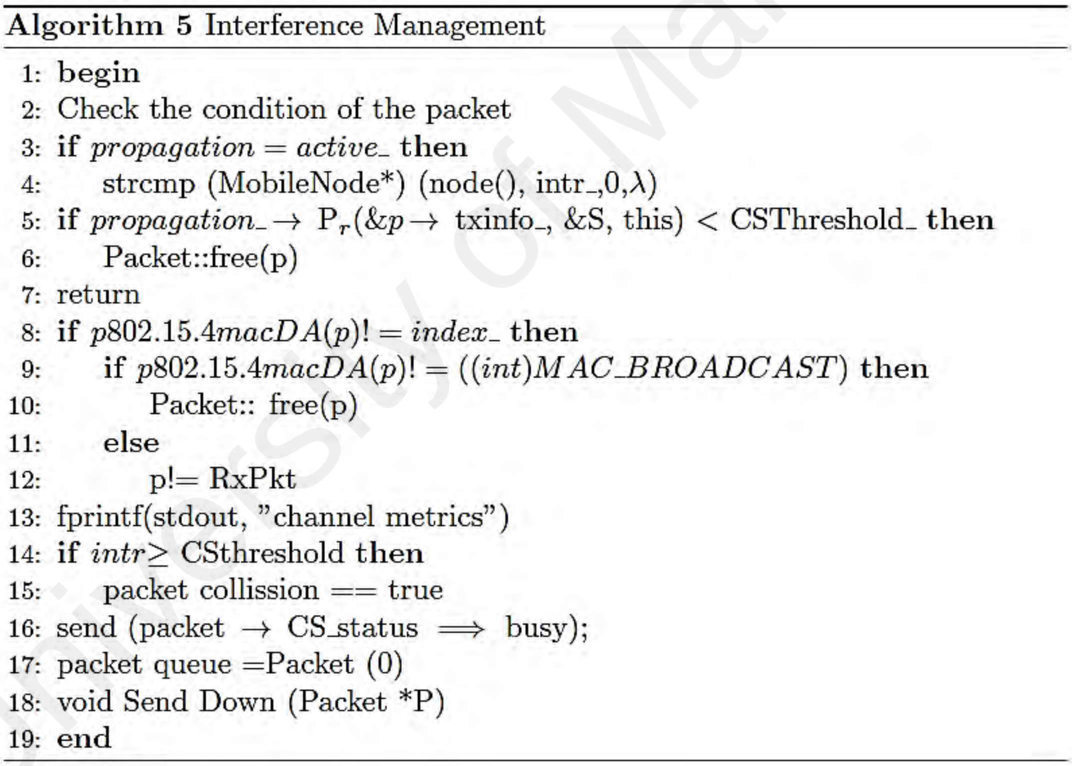
In the above algorithm, for step 13, if the backscatter is true, then it has to be enabled in some function of routing. Therefore, the forward function of AODV is employed here. During packet forwarding, if energy is less, it will increase its energy from the other nodes. The LOC in the following step reads the node by its address. The iNode is the variable to refer to a given node. The steps described in the algorithm are followed and the stochastic backscattering technique of a different number of nodes for ETRSN framework is implemented. The simulated values for scenarios before and after backscattering is generated and the relevant graphs are plotted that have been described in the next chapter for performance analysis of the proposed technique.

Algorithm 4 Enhanced stochastic backscattering

```
1: begin
2: Create a class for backscattering
3: EnergyModel class () :: TclClass ("BackScattering")
4: In aodv.h, include the header file for movement of the nodes.
5: #include "mobilenode.h"
6: Create a a file pointer
7: FILE *fp
8: Initialize a variable to increment or decrement energy for backscattering
9: double energy_
10: Create a boolean variable for backscatter
11: bool backscatter
12: Create an object for mobile node
13: MobileNode *iNode
14: Initialize and create an energy model object
15: Energy model *em
16: Repeat the steps 7 to 15 for creating constructor in aodv.cc
17: Create a file named energy.txt when running aodv protocol
18: fp = fopen ("energy.txt","w")
19: Initialize energy to zero
20: energy_= 0.0
21: Assign the backscatter boolean variable to false
22: bool backscatter $\Longrightarrow$ false
23: Check the condition of argument count and argument vector for backscattering to enable it in tcl file
24: if $argc == 2$ then
25:     if $strcmp(agrv[1], "backscatter") == 0$ then
26:         backscatter=true
27: return TCL_OK
28: Tcl & tcl ::instance();
29: if $strncasecmp(argv[1], "id", 2) == 0$ then
30:     tcl.resultf("%d",index)
31: return TCL_OK
32: Set boolean variable = true
33: aodv:: forward (aodv_rt_entry *rt, Packet *p, double delay)
34: struct hdr_cmn *ch= HDR_CMN(p)
35: struct hdr_ip *ih=HDR_IP(p)
36: if $backscatter == true$ then
37:     iNode = (MobileNode *) (Node :: get_node_by_address(index))
38: Read the energy of the node in the variable energy_
39: energy_=iNode $\rightarrow$ energy _model() $\rightarrow$ energy()
40: Create a random function to increment/decrement energy of a node based upon its address from step 33
41: Print the data to a text file along with node number and energy values
42: fprintf(fp,"%d %f",index, energy_)
43: In wpanrfid.tcl file, change the Energymodel to BackScattering
44: Create and set an agent for backscatter
45: for(set i 0) (i < val(nn))
46: incr i
47: ns at 1.0 [n(i) set ragent_] backscatter
48: Compile and run wpanrfid.tcl and energy.txt file
49: end
```

5.6 Interference Management mechanism

When two enabling technologies are combined together, there is an issue of interferences due to many data packets trying to communicate through the same communication channel and frequency range ultimately leading to packet collision and energy wastages. Therefore, using simulations, after including the RFID patch module in NS2, the proposed interference management technique is implemented for Two Ray ground propagation model as shown in Algorithm 5. The focus here would be to manage the recurring interferences during the process of EH and ET so that the energy loss due to packet collisions and communication overhead is mitigated in a timely manner.



Algorithm 5 Interference Management

```
 1: begin
 2: Check the condition of the packet
 3: if $propagation = active\_$ then
 4:     strcmp (MobileNode*) (node(), intr_,0,$\lambda$)
 5: if $propagation\_ \rightarrow$ $P_r$(&$p \rightarrow$ txinfo_, &S, this) < CSThreshold_ then
 6:     Packet::free(p)
 7: return
 8: if $p802.15.4macDA(p)! = index\_$ then
 9:     if $p802.15.4macDA(p)! = ((int)MAC\_BROADCAST)$ then
10:         Packet:: free(p)
11:     else
12:         p!= RxPkt
13: fprintf(stdout, "channel metrics")
14: if $intr \geq$ CSthreshold then
15:     packet collission == true
16: send (packet $\rightarrow$ CS_status $\Longrightarrow$ busy);
17: packet queue =Packet (0)
18: void Send Down (Packet *P)
19: end
```

The function in step 1 of the above algorithm returns 0 if the node is in a sleep state or if the R_x power is less than the CS threshold. For further CSMA operations, the total receiving power and receiving antenna gain are needed. Therefore, the function frees the data packet, when it finds that it is not destined for the current node. The $R_x$totPower has also been decremented w.r.t the state of the physical current channel. The following step enables an energy monitor module to keep track of all the noise and interferences experienced by an individual node for their respective durations. When the condition of cumulative interferences and noise level getting increased above the carrier sense threshold becomes true, then the MAC of physical carrier sense is prompted for a status change. The node's ET process is considered as "carrier sense busy" through the signaling interface. In this way, the status of the carrier sense is checked, and the packets are queued according to the time stamp and energy levels of the nodes.

5.7 Summary and chapter conclusion

This chapter has described the implementation of proposed EH and ET of EMRSN modeling approach that had been presented in Chapter 4. Particularly, the description of the simulation tool that has been utilized for the implementation is presented in Section 5.2 followed by the elaborate discussion about how the EMRSN techniques have been implemented for RF-based energy model. The chapter further discusses the steps involved to implement the EH and ET processes. The issue of how interference management is dealt and focused during both harvesting and transmission processes has been presented in section 5.6. In addition, this chapter gives the readers an overall understanding of how RFID and WPAN (Zigbee) has been integrated to manage the energy levels for integrated network and also to enable energy optimization of sensor networks through RF signals. In the subsequent chapter, experimental results followed by performance evaluation and validation using real hardware system of IoT context has been presented.

CHAPTER 6: RESULTS AND DISCUSSION

6.1 Introduction

The purpose of this chapter is to provide discussion about the experimental results through simulation, following the implementation in the previous chapter to achieve the research objectives. Firstly, the chapter presents the experimental settings and the parameters employed for simulations to implement the proposed techniques, following the modeling metrics obtained in Chapter 4. Secondly, the chapter presents the simulation results obtained for the comparative performance analysis of the proposed model. This chapter also elaborates on the experimental validation and evaluation carried out using real hardware system implementation of the proposed concept, followed by the application of proposed EM model in IoT context. Finally, in section 6.6, the results are analyzed and compared with other schemes proposed in the literature. Section 6.7 concludes the chapter.

6.2 Experimental Settings

The experimental analysis and validation of the proposed energy model as depicted in Figure 6.1, is based on the following assumptions:

- All nodes are not mobile
- All RF energy sources at the primary section are homogenous and have higher energy levels compared to sensor nodes, at the secondary side.
- The distance between RF readers and sources is d_{RFID}.
- The distance between sensor nodes is d_{sensor}. The distance between d_{RFID} and d_{sensor} is d_{RSN}.
- The backscattering distance between the primary and secondary circuits is d_{BS}.
- If $0 \leq d_{BS} \leq 15$, then there is harvesting, else if $d_{BS} > 15$, then there is no RF harvesting.

- If $0 \leq d_{RSN} \leq 15$, then there is stochastic backscattering, else if $d_{RSN.} > 15$, then there is no backscattering.

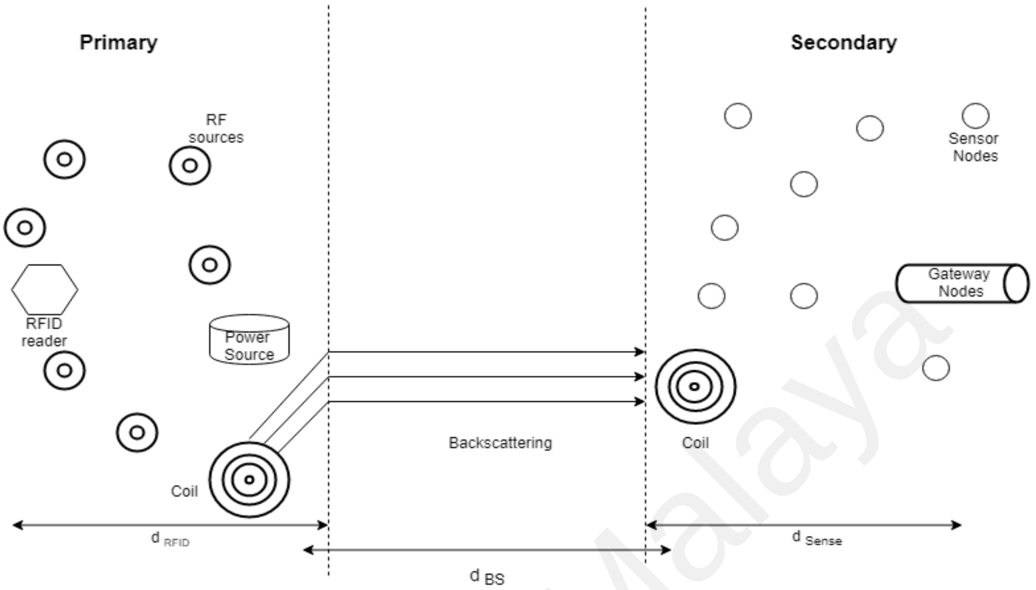


Figure 6.1: **Proposed system model**

The total energy consumed by the RSN nodes for a generic energy model in a given network comprises the cumulative energy consumption of all the circuits, sources and nodes employed during T_xR_x operations. The energy consumed by the system model is derived as follows

$$E_{RFID} = E_{READER} + E_{NODES} + E_{RSN} \quad (6.1)$$

$$E_{BS} = E_{Tx} + E_{Rx} + E_{PACK} \quad (6.2)$$

$$E_{SENSE} = E_{PROCESSOR} + E_{Tx} + E_{Rx} + E_{RADIO} \quad (6.3)$$

$$E_{OTHERS} = E_{SYSTEM} + E_{INTERFERENCES/NOISES} \quad (6.4)$$

The total energy consumed by the integrated RSN system comprises of energy occupied by RF sources (reader/coil) (E_{READER}), energy occupied by sensor motes while integrating with RF (E_{NODES}), energy consumed after interfacing both RFID and WSN due to connected circuitries (E_{RSN}). The total energy consumed during the process of backscattering involves, energy occupied during transmission, reception and packet transfer (E_{Tx}, E_{Rx}, and E_{PACK}). The energy consumed at the secondary circuit involves that of the processor unit, transmitter, receiver, and radio unit. The other contributing energy expenditure components are E_{SYSTEM} and the energy occupied due to incurring interferences. E_{SENSE} is usually during the sensing operation of the nodes, which includes the energy consumed at the data link layer or the MAC layer. The actual sensing takes place through radio unit, transceiver and system circuitries due to switching of states and semiconductor components within the RSN nodes. The depiction in Figure 6.2 shows the components of RF energy harvesting for easier understanding. E_{OTHERS} is the energy at the expense of noises, interferences, switching of electrical components or any other factors which are considered negligible when compared to other instances of energy consumption.

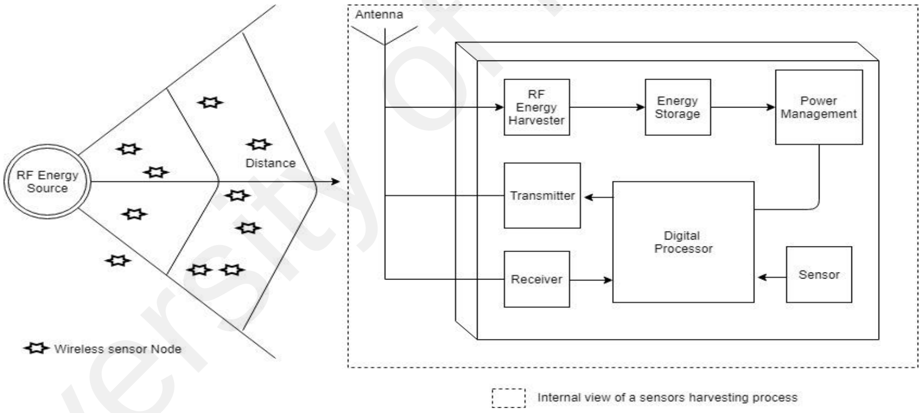


Figure 6.2: **The components of RF energy harvesting of a sensor node**

The experimental set up is based on considering all the above-mentioned energy consumption calculation. The E_{BS} and E_{SENSE} are calibrated to the sensors of the system according to the THF and TTF discussed earlier in Chapter 4. The other energy consuming factors are based on the working conditions of the circuitries which have been described in the following sections of this chapter. While the above-mentioned system model is validated using real hardware implementation, the EMRSN techniques that have been implemented using NS2 are tested through further simulations. The simulated EHRSN technique, event-triggered algorithm and enhanced stochastic backscattering mechanism that was implemented in NS2 in the previous chapter are further tested with regards to parameters such as throughput, delay, residual energy, latency and lifetime of the network. The simulation parameters are fixed and set according to the simulated technique and variables declared in .cc and .h files of energy model, the mobile node, and ns-library classes to analyze the effectiveness of the said mechanisms under dynamic conditions such as larger network density and higher energy consumption of the circuitries. Furthermore, the system model which integrates both RF and WSN technology is validated using real deployment of RF sources and sensors with regards to the metrics and assumptions discussed earlier. The energy model described in Chapter 4 is validated using a hardware prototype system and the sensors are programmed as per the total energy utilization factor with respect to the equations 6.1, 6.2, 6.3 and 6.4. The primary circuit corresponds to the RFID reader with equipped battery, RF transmitter to transmit the RF signals through electromagnetic induction. The secondary circuit consists of the sensor motes equipped with RF receiver and RF coil with matching impedance and frequency for receiving the RF energy to activate the sensors. The deployment of readily available RFID reader and tags for experimental validation is out of the scope of this research due to cost factors. Therefore, the RF coil embedded on both primary and secondary circuitries of the hardware model is replicated to the RFID reader and tag respectively, according to the concept depicted in Figure 6.3.

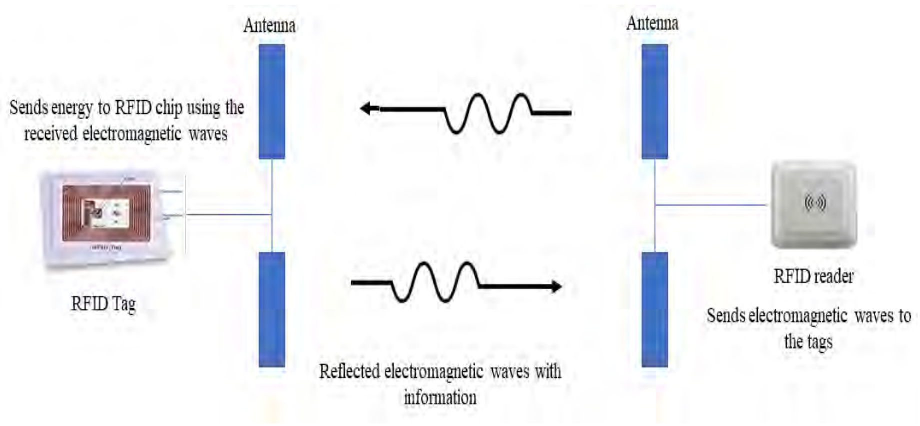


Figure 6.3: **Working concept of RFID technology**

6.3 Experimental results based on simulations

All the implemented techniques through simulations that were described in the previous chapter are tested experimentally to evaluate the performance metrics.

6.3.1 Experimental evaluation of EMRSN technique

The integrated RSN (WSN+RFID) after implementation via simulation is tested for its performance and to monitor how RFID behaves when it is combined with another wireless network. For this purpose, the integrated WSN + RFID, WSN, and RFID are compared in terms of energy consumption and residual energy to analyze the energy consumption factor of the integrated network. Here, the term ZigBee is used during some instances, instead of WSN since the MAC for both is the same (802.15.4 MAC) and the term tag here refers to the RSN nodes because tags are embedded together with the ZigBee sensor nodes in network simulations. It can be evidently seen from Figure 6.4 that RFID shows better residual energy than RSN (RFID+ Zigbee) because RFID consumes very less energy to read the tags, but no processing of sensor data.

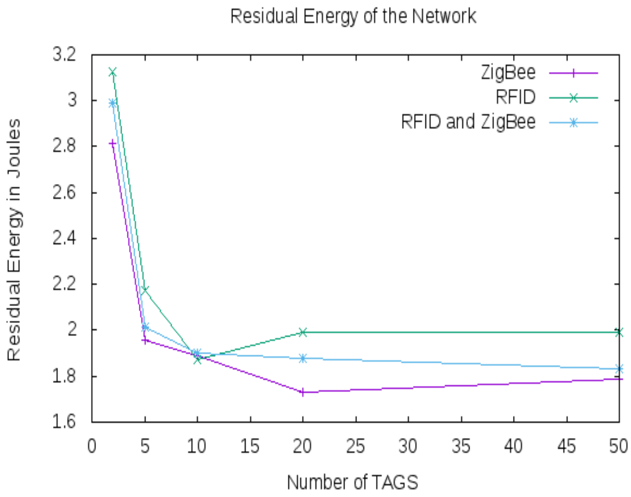


Figure 6.4: **Comparison of three technologies for a scenario of 50 nodes**

On the other hand, it is obvious that when both are combined they consume more energy due to sensing, processing, and reading capabilities. The proposed model is focused and implemented to manage this energy expenditure when both RFID + Zigbee are combined. The graphical representation show that the residual energy is increased on combining WSN with RFID when compared with WSN alone which means that WSN being entirely dependent on energy storage devices like batteries and capacitors are bound to have decreased residual energy levels rather than WSN with ambient energy harvesting of RF signals. The levels of remaining energy of integrated RFID+Zigbee is seldom altered on increasing the number of nodes as depicted in depicted in Figure 6.5. This clearly signifies the fact that integration of WSN with other prominent technologies such as RFID is advantageous in terms of improved residual energy levels through the EM strategies ultimately leading to increased network lifetime even on the pretext on higher network densities.

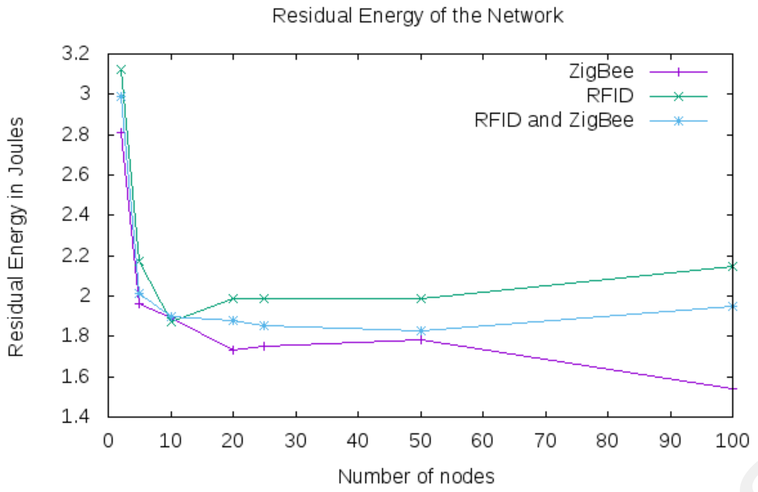


Figure 6.5: **Comparison of three technologies for a scenario of 100 nodes**

RFID behaves differently for different MAC. The readers and RSN nodes that are distributed in the network are based on MAC and the node's queries are also programmed based on MAC. Therefore, Figure 6.6 depicts how RFID behaves distinctively with each of the MACs based upon the residual energy levels of each of the networks. It shows that RFID+802.15.4 MAC consumes more energy when compared with other networks. Whenever a characteristic is plotted, RFID behaves differently with each of the MACs because of fact that readers and nodes that are distributed in the network obeys and are based on the MAC. Moreover, the wireless energy transmission from the receiver to the transmitter side is also based upon the induction principle and RFID MAC. The MAC performance is monitored here and compared because most of the network characteristics such as power ratings, energy and beacons depend upon the MAC layer. The average residual energy levels were found to be more with other wireless networks because they were no activities of packet transmission and data processing, whereas, for RFID+802.15.4, both harvesting, and transmission takes place which considerably consumes more energy per task. This evaluation was basically to show that RFID and WSN integration is possible through simulations which has effect on the overall energy consumption of the network to refute the theory stated in literature.

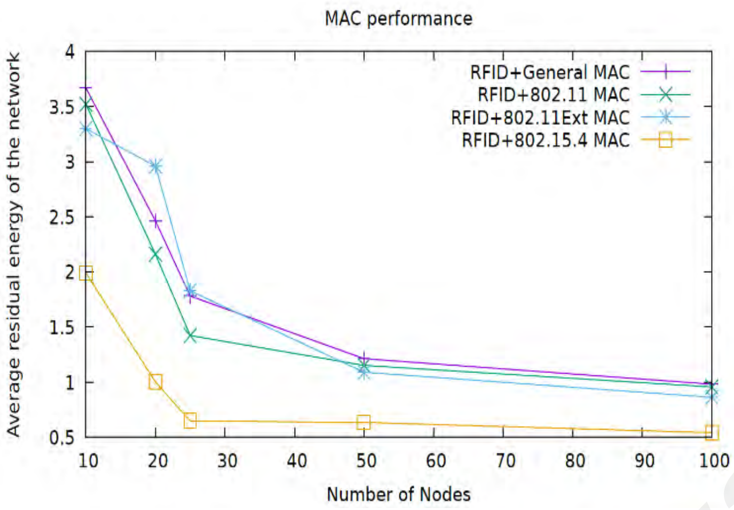


Figure 6.6: **MAC performance of RFID integration**

6.3.2 Evaluation of EHRSN mechanism

After integrating both RF and WSN through simulations, the performance of EHRSN technique using event-triggered algorithm implemented in the previous chapter is tested and its performance is analyzed comparatively in terms of average residual energy before and after EH of the entire network as shown in Figure 6.7 and also the residual energy when the number of nodes is increased as depicted in Figure 6.8. The comparison depicted in Figure 6.8 also shows that EHRSN provides better energy efficiency and increased harvested power inspite of increasing number of nodes. The reason for checking the residual energy levels with and without EH mechanism is to check the overall energy efficiency of the network. Moreover, the average residual energy of the nodes increases exponentially with the increase in the amount of power that has been harvested by the sensor nodes. The reason of increasing the number of nodes is to check the correlation between the harvested energy and residual energy of the nodes when the network density increases and also to address the tradeoff between network density and lifetime of the nodes.

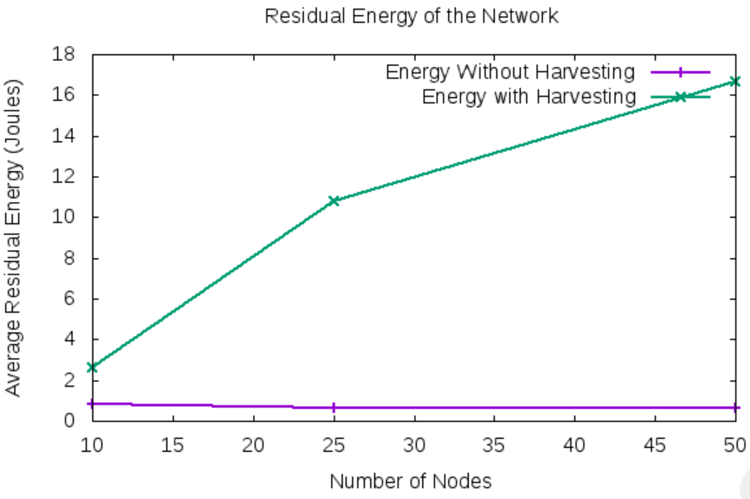


Figure 6.7: **Average residual energy levels before and after RF harvesting**

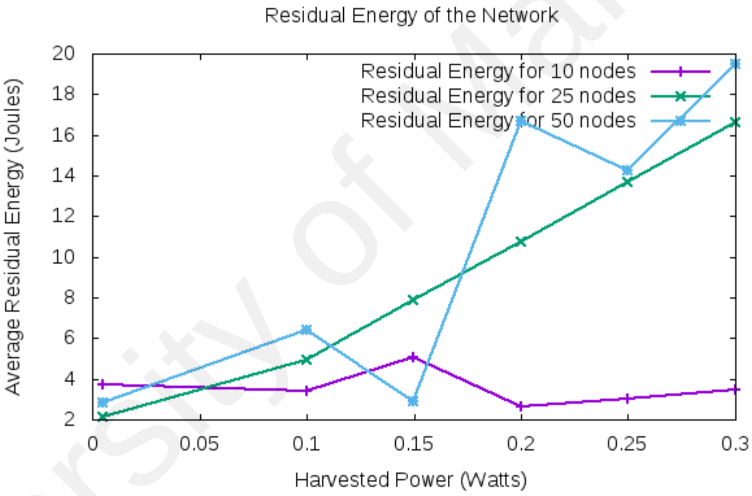


Figure 6.8: **Average residual energy levels Vs harvested power for 10,25,50 nodes**

The nodes which act as the source and destination for transmitting and receiving the data packets are non-idle and do not harvest energy which means that the nodes that are in active state and participate in communication or packet transmission are bound to lose more energy per task and have lesser remaining energy levels, whereas the other idle nodes which do not perform any operation, during sleep state harvest more energy. The comparison of residual energy after applying EHRSN mechanism between the nodes (23,10) for a scenario of 50 nodes, (19,9) for a network of 25 nodes and (3,8) for a scenario of 10 nodes has been depicted in Figure 6.9, 6.10 and 6.11 respectively. This evaluation is basically for analyzing the residual energy of nodes which harvest energy and the nodes which do not harvest any energy on the pretext of consuming more energy per task.

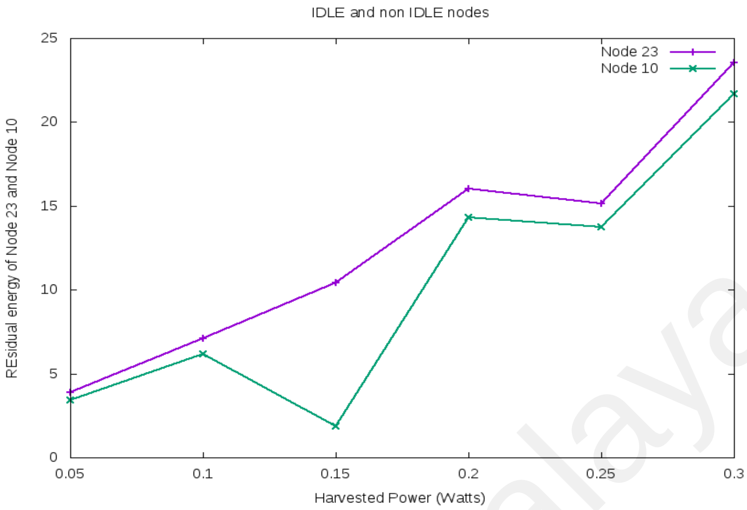


Figure 6.9: **Residual energy levels for Idle (node 23) and non-idle (node 10) for a scenario of 50 nodes**

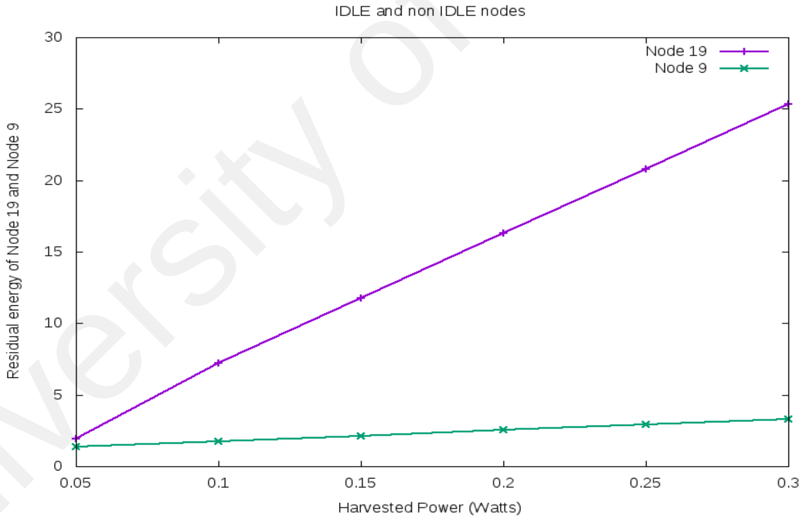


Figure 6.10: **Residual energy levels for Idle (node 19) and non-idle (node 9) for a scenario of 25 nodes**

This shows the lifetime of the nodes with respect to energy modeling applied on the node's state transitions, irrespective of the network density on the pretext of the proposed EHRSN technique. The same process is done for a network of 25 and 10 nodes, where the average residual energy of the node that participate in the harvesting process and the ones that are busy with operations such as packet transmission and data processing are compared w.r.t the amount of energy harvested. The network traffic pattern of the

WPAN+RFID is also tested and analyzed as shown in Figure 6.12, which shows that FTP has better performance and energy levels for the overall network when compared with CBR or Poisson after energy harvesting. The reason for comparing the network traffic parameters is to check the correlation between agent objects, traffic sources and network connection with the amount of energy consumed. The simulation parameters have been tabulated in Table 6.1.

Figure 6.11: **Residual energy levels for Idle (node 3) and non-idle (node 8) for a scenario of 10 nodes**

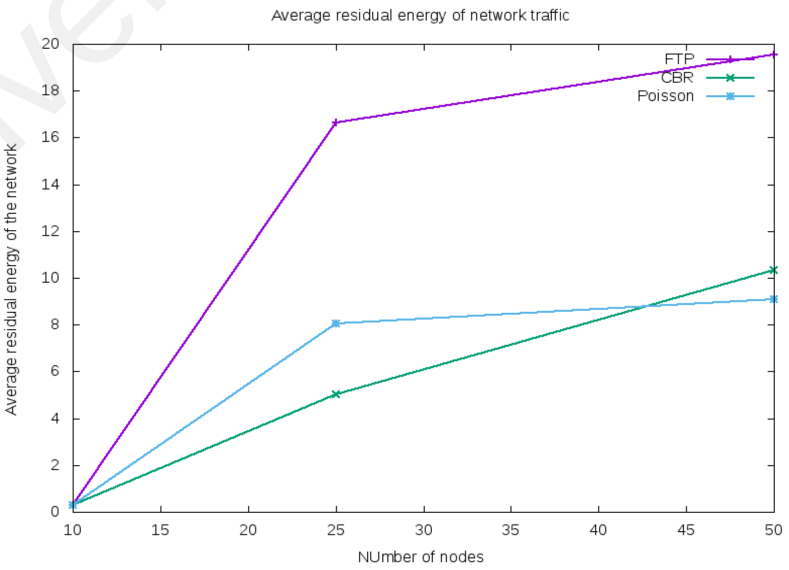


Figure 6.12: **Average residual energy levels for different network traffic**

Table 6.1: **Network parameters and values for EHRSN simulation**

Parameter	Value
Networks Used	WPAN and RFID (RSN)
Channel type	Wireless
Topology Used	Random and cluster
Number of nodes	10,25 and 50
Traffic	Poisson/FTP/CBR
Energy Level	0.5 for Transmission, 0.3 W for receiving
Harvesting energy	0.05W to 0.3W
Radio propagation model	Two-ray ground
Channel type and Antenna model	Wireless/Omni Antenna
Routing protocol	AODV and DumpAgent
Period of Simulation	50 seconds
Sensing type	On-demand/ programmed

6.3.3 Performance evaluation of ETRSN technique

The enhanced stochastic backscattering algorithm after implementing through network simulations is evaluated in terms of overall residual energy of a different number of nodes. The graphical representation depicted in Figure 6.13, 6.14 and 6.15 shows that the amount of energy transferred increases the remaining energy of the nodes with increasing number of nodes after applying the enhanced backscattering technique.

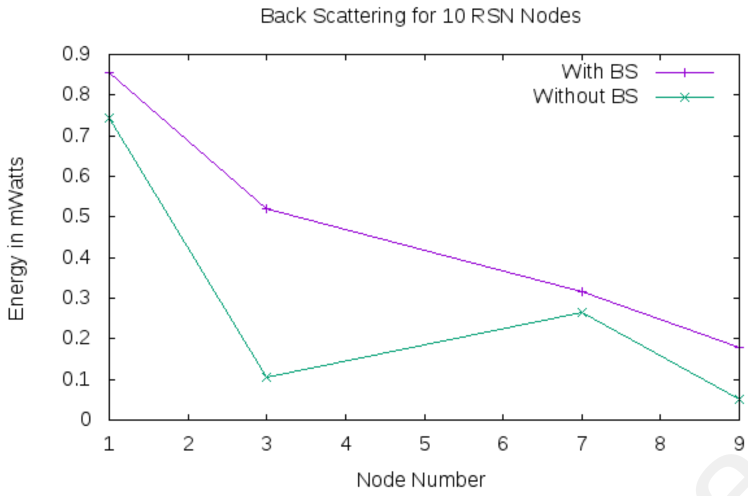


Figure 6.13: Average residual energy levels with and without backscattering for a scenario of 10 nodes

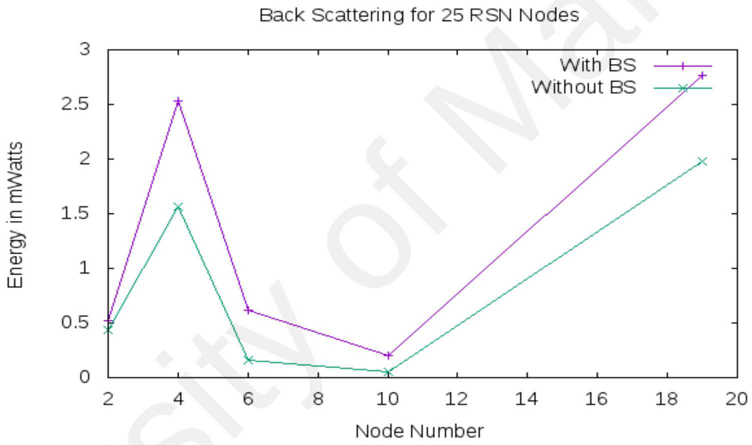


Figure 6.14: Average residual energy levels with and without backscattering for a scenario of 25 nodes

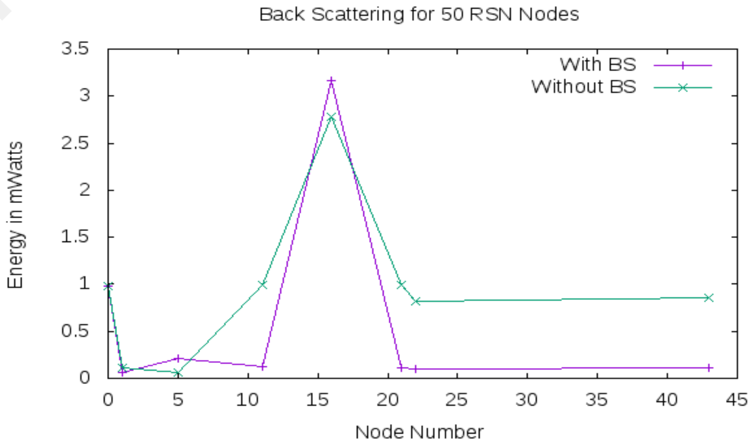


Figure 6.15: Average residual energy levels with and without backscattering for a scenario of 50 nodes

The reason for checking the remaining energy of the nodes in this context is to address the trade-off between the amount of energy needed for power transmission during a node's active state and the energy consumed per task. Since the transferred energy is the total power transferred, the units are depicted in watts, whereas for energy the unit of measurement used is joules. The power that is transferred is measured in the units of watts but when the remaining energy of the nodes is calculated then the unit of measurement is joules since energy is the product of power and time. The proposed technique provides energy efficiency of the entire network thereby improving the network lifetime. The average residual energy of 10, 25 and 50 nodes are also plotted as in Figure 6.16 for analyzing the cumulative residual energy levels of the whole network before and after the process of backscattering. The parameters and values used for simulation are tabulated in Table 6.2.

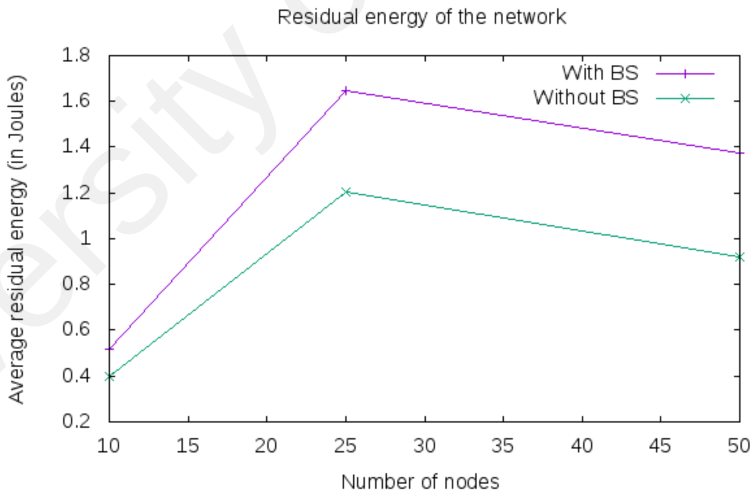


Figure 6.16: **Average residual energy levels of the whole network of 50 nodes before and after backscattering**

The data packets generated and the selection of the nodes to backscatter the RF energy are selected based upon even-odd numbering of the nearest nodes to recharge the node with lowest residual energy. This simulated technique is tested for a lifetime of the network as well as for various network densities. The results show that the proposed enhanced backscattering technique has better performance when compared with traditional WSNs without the process of backscattering.

Table 6.2: **Network parameters and values for ETRSN simulation**

Parameter	**Value**
Networks Used	WPAN and RFID (RSN)
Channel type	Wireless
Topology Used	Random with X= 50 and Y= 50
Number of nodes	10,25 and 50
Traffic	FTP
Energy Level	0.3 for Transmission, 0.2 W for receiving
Initial energy	1.6 W
Harvesting energy	0.05W to 0.3W
Radio propagation model	Two-ray ground
Channel type and Antenna model	Wireless/Omni Antenna
Routing protocol	AODV and DumpAgent
Period of Simulation	25 secs for 10, 25 and 50 for 50 nodes.

6.3.4 Evaluation of EMRSN model

The other parameters of the EMRSN model which are directly related to the performance of the network such as throughput, end-to-end delay, data packet generation is also tested, and the graphs are plotted accordingly. The proposed model has faster rate of wirelessly recharging capability when the distance between the source and node is relatively smaller and vice-versa. The depiction in Figure 6.17 shows the instantaneous throughput of the network after the 25 RSN nodes being programmed according to proposed EMRSN techniques. It states that the throughput of the system increases as the simulation time is increased. Figure 6.18 shows the throughput of 50 nodes with respect to the simulation time. The simulation is started for packet generation and data transmission only after 1 sec, that is the reason why throughput occurs after 1.0 secs.

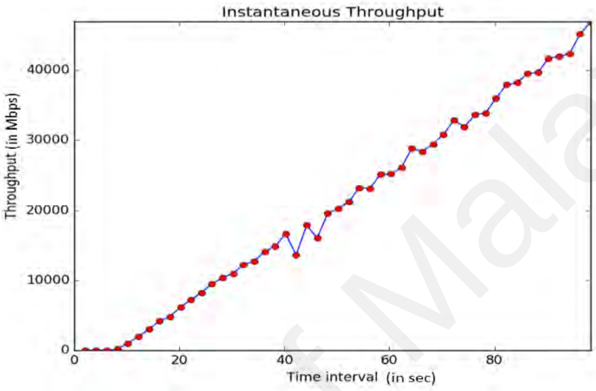


Figure 6.17: **Instantaneous throughput for a network of 25 nodes**

The instantaneous delay of the network is depicted in Figure 6.19, which states that when there is packet transmission taking place, the end-to-end delay is considerably lower and guarantees faster transfer of data packets from the source to destination. The throughput of generating packets by the RSN network with respect to simulation time has been depicted in Figure 6.20.

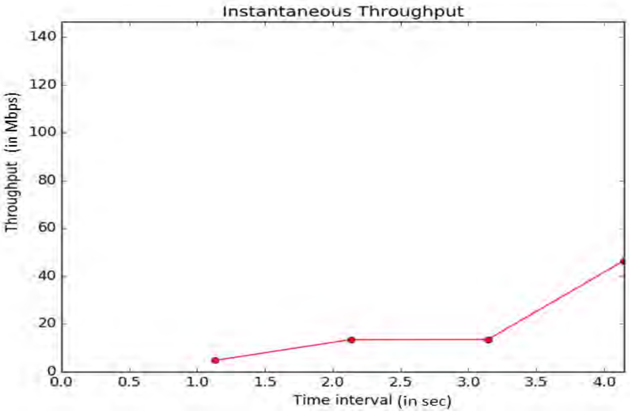


Figure 6.18: **Instantaneous throughput for a network of 50 nodes**

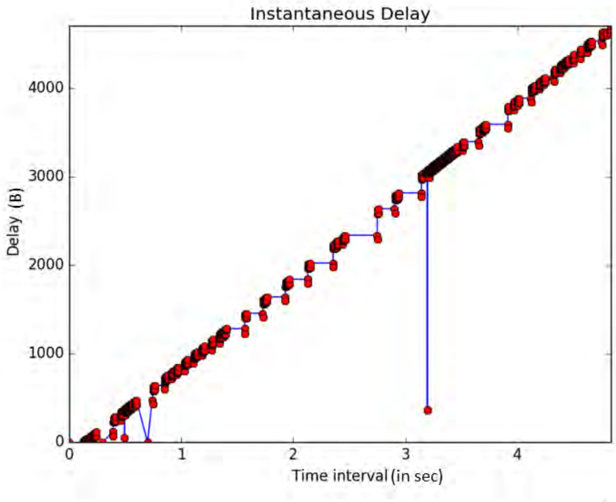


Figure 6.19: **Instantaneous delay of the network with respect to the time interval**

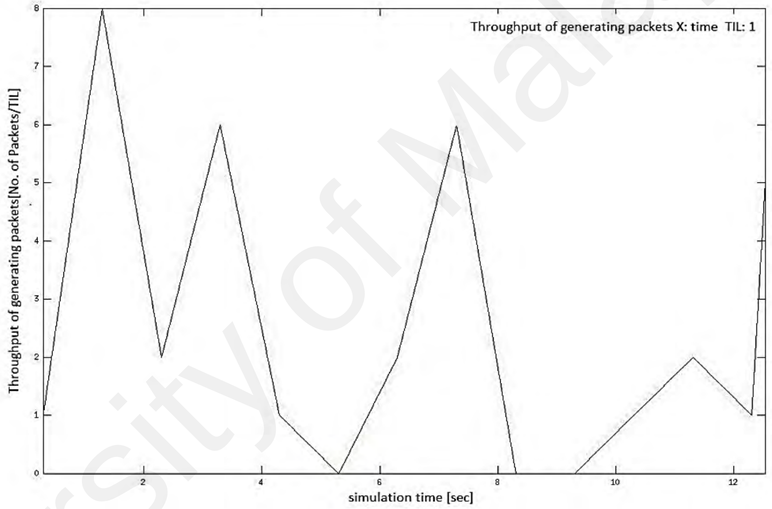


Figure 6.20: **Throughput of generating packets with respect to time**

The throughput increases whenever there are packet generation and transmission, which implies that the network latency is lower indicating towards higher network efficiency. On the other hand, Figure 6.21 shows the relationship between packet size and throughput of sending packets which clearly implies that the total time required to read the data from the RSN nodes (node 3 in the depiction) is directly proportional to the memory size of the node. Therefore, the size ‘B’ bits of the data and energy buffer of a particular node implies comparatively smaller time to recharge the node through harvesting or backscattering process.

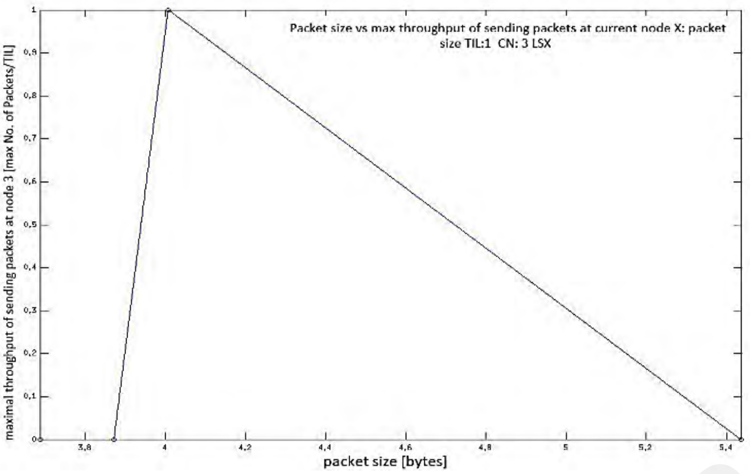


Figure 6.21: **Packet size Vs throughput at the current node**

The node 2, which is ‘idle’ for a network of 50 nodes, has more harvested power due to the fact that energy is harvested during a node’s sleep/idle state according to the proposed energy model. Therefore, node 2 shows a number of the cumulative sum of packets generated with respect to the time whenever an event is triggered as shown in Figure 6.22. The latency of the network is referred here as the average time taken for routing of a data packet from the source node to the gateway node. It is expressed as stated in the equation 6.5.

$$L_N = \frac{\sum L_p}{p}\ , for\ all\ p \in N \tag{6.5}$$

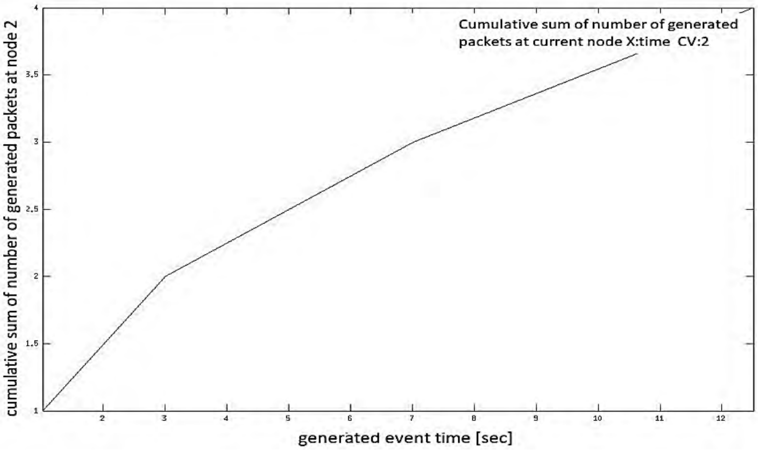


Figure 6.22: **Total number of packets generated on triggered event w.r.t time**

The network latency is L_N and is defined as the cumulative sum of individual data packet latency divided by the total number of 'p' data packets delivered to the sink of the gateway node. The proposed EH and ET technique measure lower packet latencies with exponentially increasing network throughput as shown in Figure 6.23.

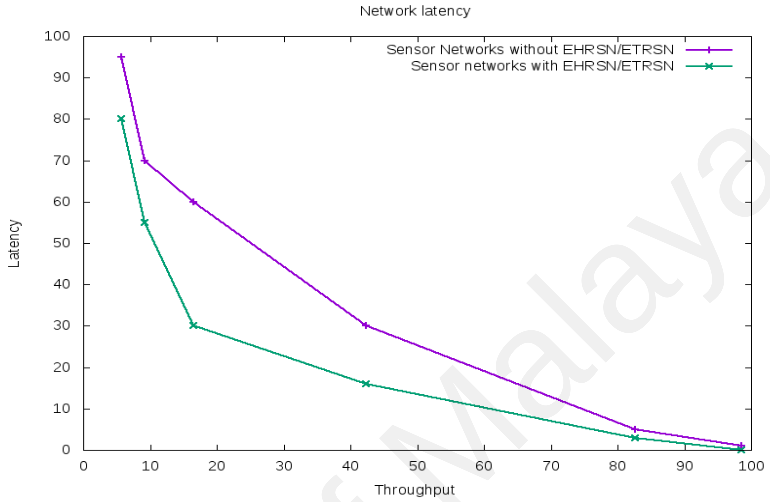


Figure 6.23: **Network latency w.r.t throughput for sensor networks with and without EMRSN techniques**

The network lifetime is defined as the total operational time taken by the network to remain in the active state to perform the dedicated task. It is also defined as the time until the first sensor node or group of sensor nodes of the network go to dead state or run out of energy. The depiction is shown in Figures 6.7 and 6.16 state that both EH and ET techniques provide improved network lifetime by nearly 80% when compared to networks without EH and ET. The network lifetime (T_N) is directly proportional to energy consumption (E_p) by the data packets p, which is expressed as equation 6.6.

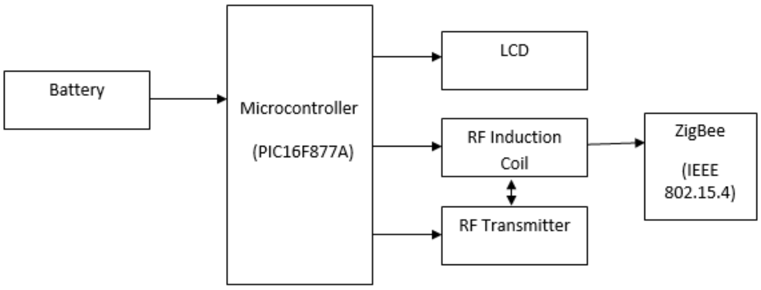
$$T_{N=} = \frac{E_P}{P}, for\ all\ p\ \in N \tag{6.6}$$

The calculated energy expenditure during transmission and reception operations by RF nodes/transceivers also indirectly monitor and record the overhead caused by control packets of a routing protocol.

6.4 Experimental validation using real hardware system

The proposed system model discussed in section 6.2 (Figure 6.1) and the energy model described in Chapter 4, are validated using the hardware model, where the sensors (temperature, humidity, dust, gas) are programmed accordingly by considering the THF, TTF, and the assumptions. The energy values of the said sensors are adopted from their respective data sheets, after which the idle, sleep and active states are approximated for further experimentation and validation. This research utilizes DHT11 temperature sensor, a humidity sensor, dust sensor and MQ-2 gas sensor along with PIC16F877A microcontroller boards. At the transmitter side, there is a 12V battery to power the RF source. Since the battery is DC supply and the energy transmission's input is AC, an inverter section is used to convert DC to AC and energize the coil at the transmitter side. The RF signals through the RF transmitter is transferred to the receiver section. At the receiver side, there are sensors whose energy source is RF signals through the RF receiver. The values of sensor readings, battery consumption, and energy levels (in %) are displayed in the LCD and viewed in the system through serial communication ports and codes (RS-232). The block diagram and circuit design are depicted in Figures 6.24 and 6.25 respectively. As discussed earlier, for the ease of deployment and low-cost solution, the RF induction coil at the primary (transmitter) side is assumed to be as the RFID reader which generates RF signals to the (receiver side). At the receiver circuit, RFID tags are assumed to be relative to the RF coil which is connected to the sensor motes, and the values are read/displayed on the LCD. This hardware deployment is basically to validate the concept of integrating and interfacing the RFID MAC with WSN MAC, to energize and to identify the energy profile of the sensors.

Transmitter (Primary) section



Receiver (Secondary) section

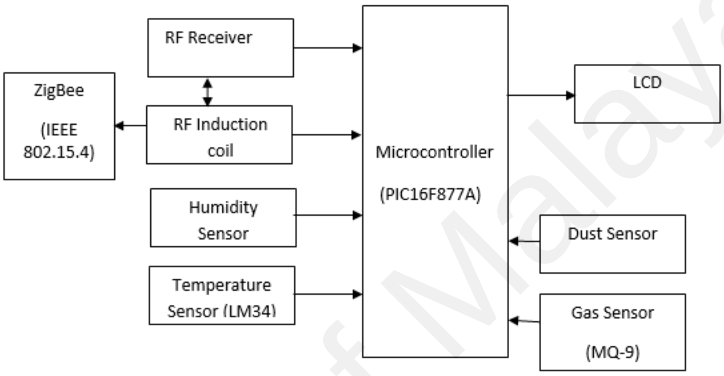


Figure 6.24: Block diagram of the hardware model

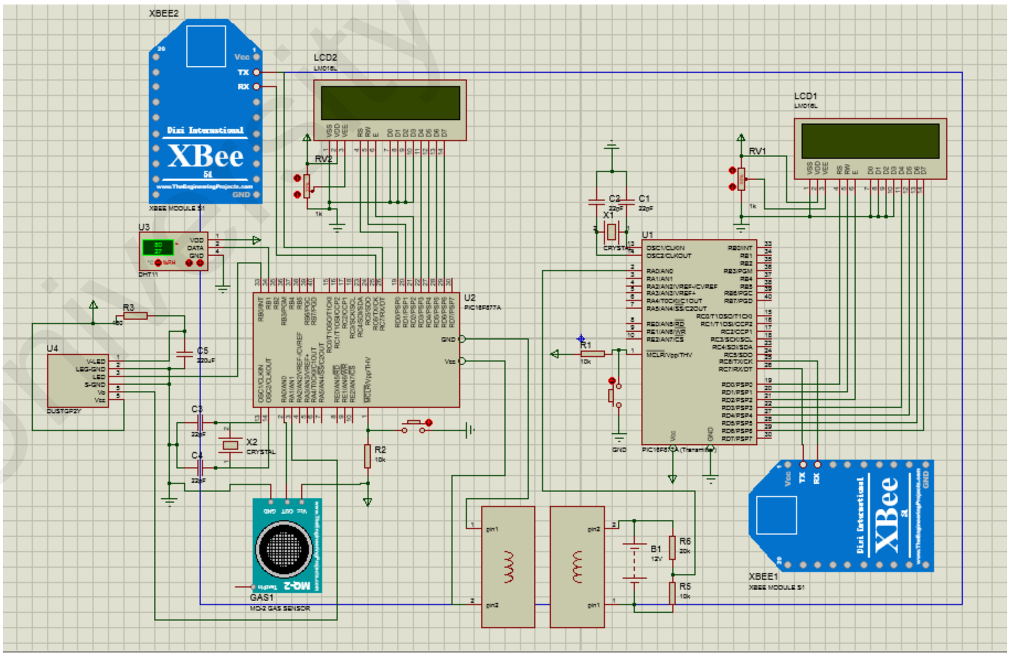


Figure 6.25: Circuit design of the hardware model deployed for validation

The experimentation is done to analyze and evaluate the energy consumption of the sensors during light sensing operations for both EH and ET mechanisms. The EHRSN mechanism is applied to temperature and humidity sensors inside a room to monitor the values of temperature and humidity during three different timings of the day. The sensors are also programmed according to the THF described in Chapter 4 to avoid energy wastages of idle listening. The discharging rate of the harvested/transferred energy and the operation time of the sensor motes are monitored for performance evaluation and lifetime of the model. The dust sensor and gas sensor, on the other hand, are programmed according to the TTF for validating the enhanced backscattering mechanism. These heavy sensing operations are calibrated and programmed to sense the air quality index values in the atmosphere. These values are also recorded and monitored during three different timings of the day. The recorded data is sent through the gateway node to the base station as well as displayed on the LCD through Zigbee (IEEE 802.15.4). The sensor nodes are programmed accordingly to enable energy optimization and save energy whenever there are no network operations taking place. The packets are transmitted/ received based upon Poisson distribution. The states here are based upon the states that were employed to characterize the nodes discussed earlier in Chapter 4 and the action here is low power level and high-power level.

$$E_r\ (n) = \frac{e^{-\beta_r T}\ (T\beta_r)^n}{n!} \tag{6.7}$$

$$E_t\ (n) = \frac{e^{-\beta_t T}\ (T\beta_t)^n}{n!} \tag{6.8}$$

According to Table 6.3, the circuitries and electronic components are disabled/enabled according to the event-triggered for data collection/dissemination. The temperature and humidity sensors are set in low power, whereas dust and gas sensors are set and fixed in high power mode, according to the proposed energy modeling discussed in Chapter 4. During high power state, the packets generated will be more which depends upon the sensing rate and the amount of energy transferred through backscattering. The arrival rate of the data packets is dependent on β and T according to equations 6.7 and 6.8. The depicted Figures 6.26 and 6.27 show the hardware model where the sensors are deployed for the validation of proposed energy model and implemented EH and ET techniques. The illustrations and few more instances of the working of the hardware model can be referred from the Appendix I.

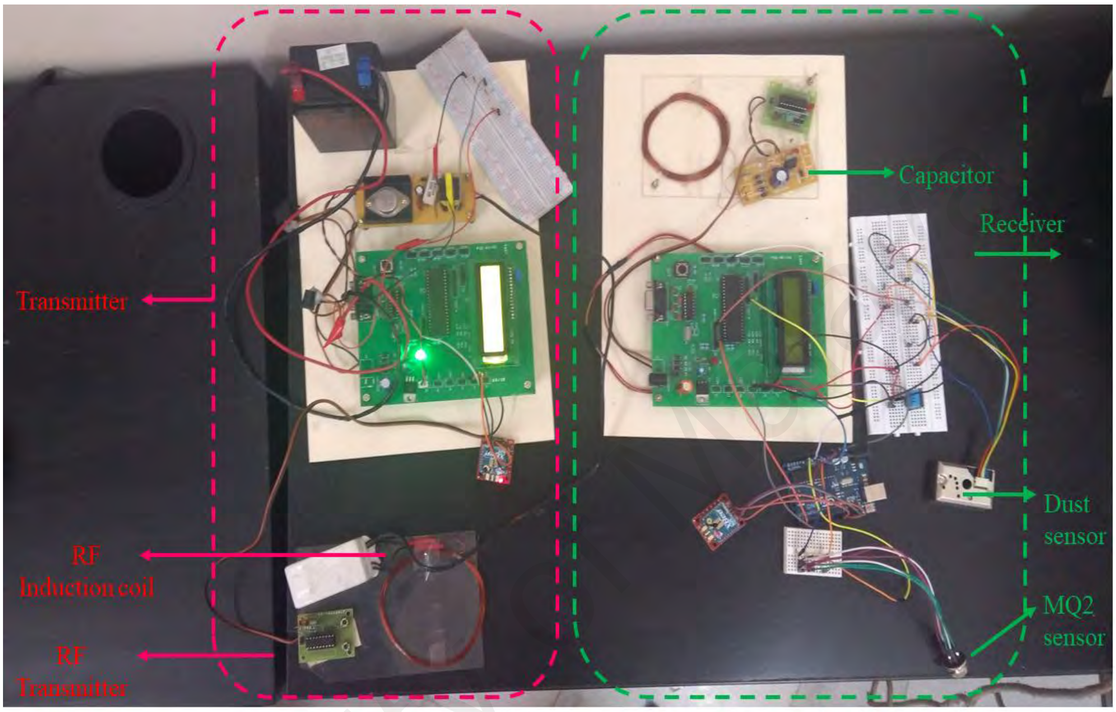


Figure 6.26: **Hardware model (without energy getting supplied to sensors)**

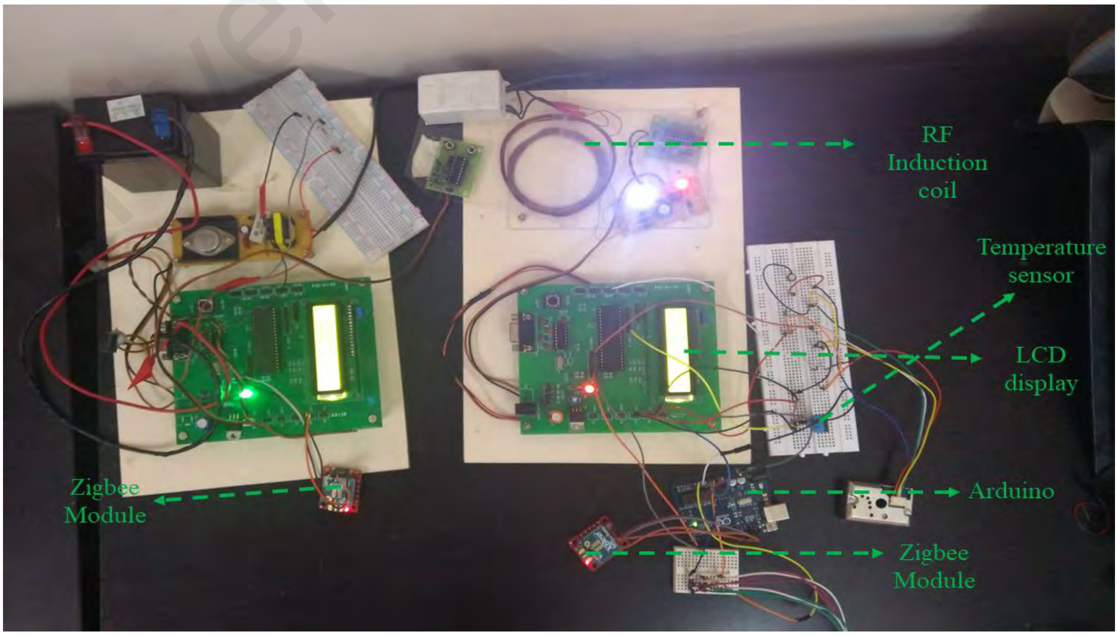


Figure 6.27: **The proposed EMRSN Hardware model (displaying values in LCD at receiver side after RF energy getting transferred)**

The following Table 6.3 shows the parameters used for experimentation and validation of proposed model using the hardware system and sensors.

Table 6.3: **Parameters used for validation**

Parameter	Value
OS Used	Windows 10, Linux
Framework Used	Proposed EMRSN
Number of sensors	4 (temperature, humidity, gas, and dust)
Duration of testing	1 month (3 timings in 24 hrs day)
Energy profile (according to data sheet, THF and TTF)	0.5 for Transmission, 0.3 W for receiving, Idle state energy- 10mW, Sleep – 25mW, Active/process- 1000mW, Semi-active- 475mW, Sense- 150mW
Battery power	12V, 2.3Ah
Circuit design software	Proteus
IoT application/context scenario	AQI value
Code dumping software	PICFLSH, MPLAB X IDE (PICIT 3)
RS-232 Serial communication	Terminal v1.9b, PuTTY

6.5 Validation results and analysis

Following the deployment of the hardware model, the EHRSN and ETRSN techniques are set and programmed for the sensor nodes which are energized by the RF signals. The results depicted in Figure 6.28 shows the energy discharging rate of the system. Furthermore, the energy is dissipated at a considerably slower rate for all the three scenarios rather than sudden fall in the energy levels due to sensing operations. The messages for packet delivery or data transmission are fixed and set for specific time intervals according to the events triggered.

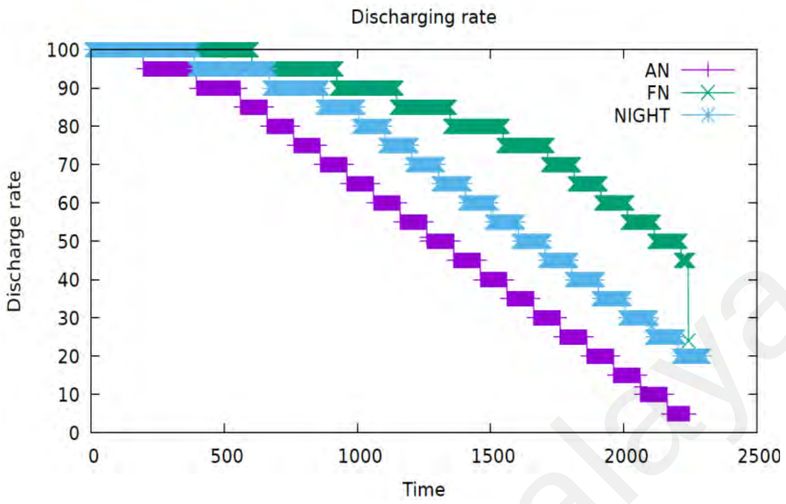


Figure 6.28: **Energy discharging rate of the hardware model**

For the rest of the time, the nodes are made to harvest RF energy (that is during idle and sleep state). The other results obtained during validation are described and discussed in the following section. The temperature and humidity values are monitored and recorded using the deployed sensors which are modeled according to proposed energy model for EH and discharge energy for every bit of data transferred over fixed time intervals. The results shown in Figure 6.29 depict the average temperature recorded during different timings (morning peak hours, non-peak hours and evening peak hours) until the entire energy stored in the battery at the transmitter side is drained out. The classification of timings during the day is basically to differentiate light and heavy sensing operations. This process is carried out at a low power rate of the sensors to avoid energy consumption during packet transmission and to avoid the dead state of the sensor due to sensing operation. The humidity values are also sensed and recorded by the sensor mote for three different timings as shown in Figure 6.30. The average concentration values of the harmful gases released during vehicular emissions at peak or non-peak hours is also sensed by the MQ2 gas sensor and recorded accordingly, as depicted in Figure 6.31. The dust sensor is also programmed on high power levels according to the states and utilization factors specified in the previous chapters. The dust density in the form of particulate matter level in the air is measured and recorded for peak and non-peak hours as depicted in Figure 6.32.

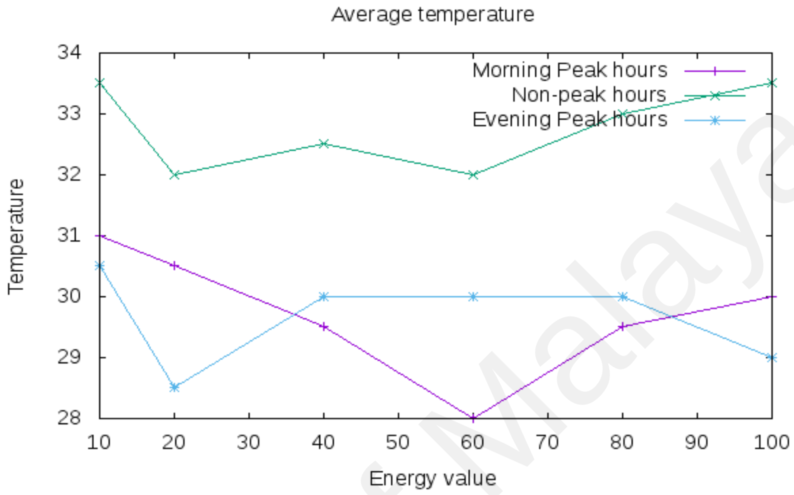


Figure 6.29: **Average temperature recorded by the hardware model**

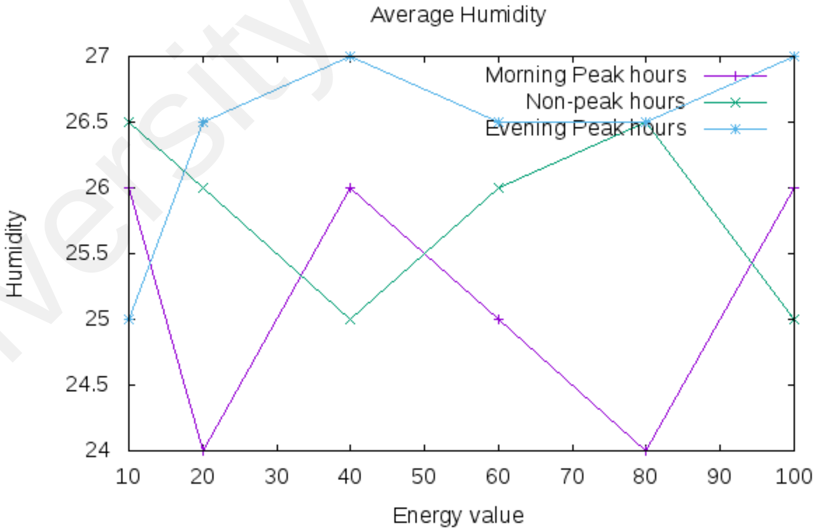


Figure 6.30: **Average humidity recorded by the hardware model**

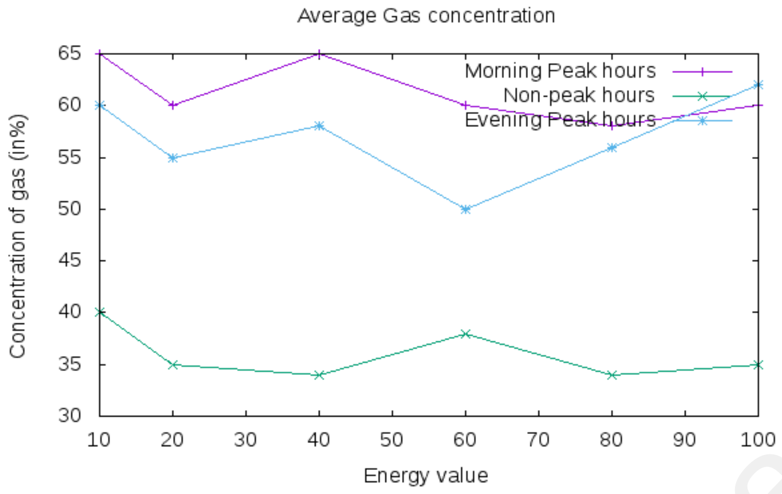


Figure 6.31: **Average concentration of gas from MQ2 sensor**

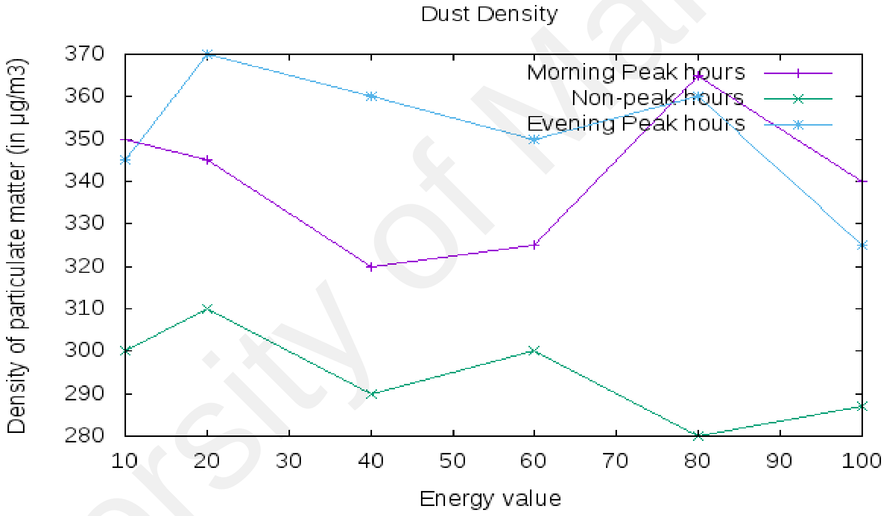


Figure 6.32: Dust density recorded by the sensor of hardware model

The performance evaluation of the validated set up was carried out by making the same sensor work for the same conditions but without EH and ET and also by using the traditional battery as the power source. It was found that the proposed validated system provided better results when compared to traditional systems as depicted in Figure 6.33 with respect to energy expenditure and discharging rate of the battery power.

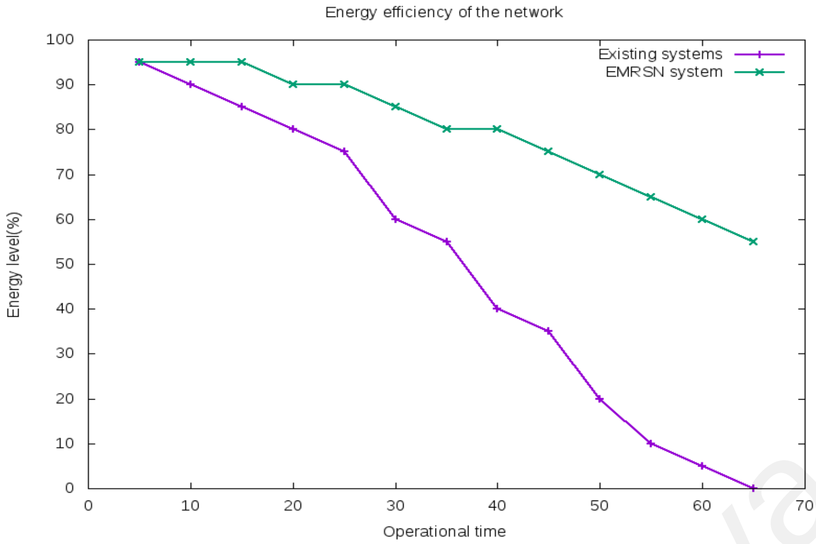


Figure 6.33: **Energy efficiency of existing and proposed systems**

On the other hand, the dust sensor and gas sensor are configured on high power levels to sense and monitor the air quality levels of the outdoor environment. The sensors are programmed and modeled according to proposed energy model of ET and discharge energy for data transmission during backscattering. The values obtained from the dust sensor ($PM_{2.5}$) which records the concentration of particulate matter and the gas sensor to record CO, CO_2 are utilized to calculate the AQI values. These values are monitored during three different timings of the day corresponding to peak and non-peak traffic hours.

6.6 Application of energy model in IoT based context

The combined values of temperature, humidity, $PM_{2.5}$, CO, and CO_2 utilized to check the overall air quality of the atmosphere. The deployed hardware model can be used in applications such as toll gates, highways, traffic signals and construction sites. This is due to the fact that the proposed model is designed and developed for harvesting and transfer to take place for shorter ranges. The same methodology for cases involving longer distances between readers (RF energy source) and nodes is out of the scope of this research and needs further research aspects to be dealt with. The hardware model was tested to record the AQI values for four different areas of Greater KL- Petaling Jaya, Jalan Tun Razak, Mount Kiara and Shah Alam. The results of the AQI values recorded using the proposed methodology have been depicted in Figure 6.34 for peak and non-peak hours. The operation time of the sensor motes is recorded upon power drain for all the sensing operations during both peak and non-peak hours. This operational time is compared with the existing pollution monitoring system and the results are represented graphically as depicted in Figure 6.35. Similarly, the AQI values for the whole month of October 2017 was recorded and monitored by applying the proposed energy modeling, EHRSN technique and enhanced backscattering method to the deployed hardware model. The statistical analysis was carried out to evaluate and validate the proposed system. The values of the analysis are tabulated in Table 6.4, 6.5 and 6.6 respectively.

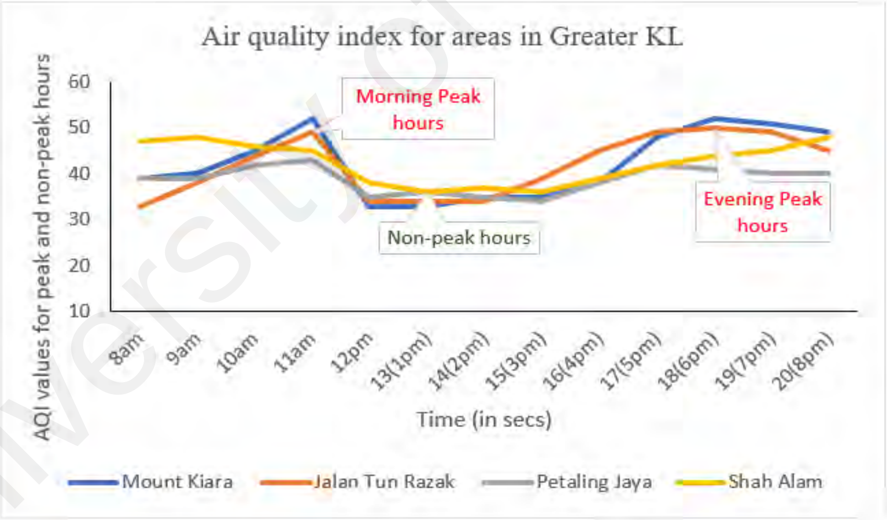


Figure 6.34: **Air quality index recorded by the hardware model**

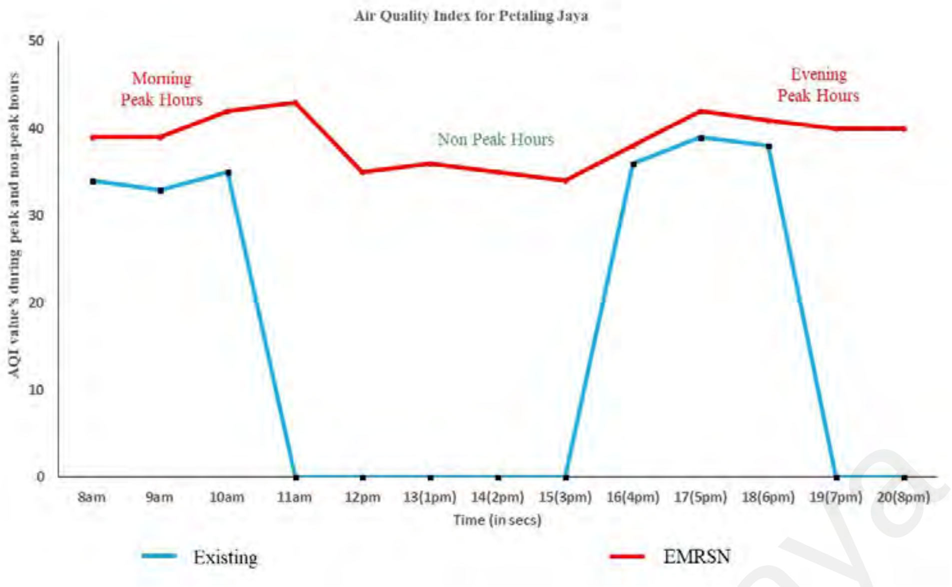


Figure 6.35: **Comparison of operation time of AQI monitoring by existing and EMRSN approaches at Petaling Jaya**

The mean Air Quality Index (AQI) values which were observed and recorded by "Proposed EMRSN system" and "Existing system" methods were compared in relation to state, location traffic hours, timing (every 1 hour for 24 hours) and days (each day of October 2017). The comparison of mean values of AQI shows highly statistically significant difference between proposed hardware system and existing methods for the two states (W.P. KUALA LUMPUR and SELANGOR). Out of these two mean values the proposed system's AQI mean values are statistically significantly higher than the existing methods that measure AQI mean values for both the states ($p=0.001$ & $p<0.0001$).

In relation to the 4 locations (Batu Muda-Mount Kiara (11 kms), Cheras-Jalan Tun Razak (8 Kms), Petaling Jaya & Shah Alam) there is statistically significant difference in the mean values of AQI between EMRSN and existing methods for the 3 locations (Batu Muda-Mount Kiara (11 kms), Petaling Jaya & Shah Alam) whereas no statistically significant difference was observed between the EMRSN and existing methods for the location of, Cheras-Jalan Tun Razak (8 Kms($p=0.98$).

Table 6.4: Comparison of mean values of Air Quality Index (AQI), Obtained from two sources (Proposed EMRSN system and Existing system) in relation to the State, Location and Traffic hours

Study variables	AQI Values (mean & sd.,)		t-value	p-value	95% confidence interval for difference of mean
	EMRSN	Existing			
State					
W.P. KUALA LUMPUR	32.6(5.3)	31.5(11.1)	3.29	0.001	(0.43, 1,68)
SELANGOR	36.5(6.0)	33.2(13.4)	8.73	<0.0001	(2.58,4.07)
Location					
Batu Muda-Mount Kiara (11 kms)	31.7(5.4)	30.5(12.8)	2.36	0.018	(0.21,2.22)
Cheras-Jalan Tun Razak (8 Kms)	33.5(5.1)	32.6(8.9)	2.37	0.98	(0.15,1.63)
Petaling Jaya	35.3(5.9)	30.3(12.8)	9.47	<0.0001	(3.90,5.94)
Shah Alam	37.7(5.8)	35.9(13.3)	3.24	0.001	(0.68,2.77)
Traffic hours					
Peak	36.2(6.0)	34.2(14.5)	4.25	<0.0001	(1.08,2.93)
Non-Peak	33.5(5.8)	31.2(10.6)	8.19	<0.0001	(1.75,2.85)

Table 6.5: Comparison of mean values of Air Quality Index, Obtained by two sources (Proposed EMRSN system and Existing system) in relation to different timings in a day

Time points	AQI Values (mean & sd.,)		t-value	p-value	95% confidence interval for difference of mean
	EMRSN	Existing			
1 am	32.8(6.0)	26.7(14.7)	4.27	<0.0001	(3.29,8.91)
2 am	32.3(5.7)	32.5(7.3)	-0.26	0.795	(-1.86,1.43)
3 am	31.6(5.6)	32.3(7.3)	-0.84	0.398	(-2.33,0.93)
4 am	31.3(5.5)	32.2(7.9)	-1.04	0.297	(-2.61,0.80)
5 am	31.1(5.3)	20.4(15.4)	7.33	<0.0001	(7.83,13.59)
6 am	32.2(5.2)	31.3(8.6)	1.01	0.312	(-0.86,2.68)
7 am	32.5(5.0)	31.3(8.6)	1.36	0.176	(-0.55,2.98)
8 am	33.8(5.2)	31.1(9.1)	2.93	0.004	(0.91,4.61)
9 am	34.3(5.4)	31.1(9.1)	3.50	0.001	(1.45,5.26)
10 am	35.1(5.5)	31.2(9.1)	4.11	<0.0001	(2.06,5.84)
11 am	35.5(5.6)	31.1(9.2)	4.47	<0.0001	(2.43,6.26)
12 pm	34.9(5.3)	31.4(8.7)	3.86	<0.0001	(1.76,5.37)
13 (1 pm)	34.7(4.8)	31.5(8.6)	3.65	<0.0001	(1.49,4.98)
14(2 pm)	34.4(4.9)	32.1(8.3)	2.64	0.009	(0.58,3.99)
15 (3 pm)	34.7(4.9)	32.1(8.7)	2.88	0.004	(0.82,4.36)
16 (4 pm)	35.6(5.5)	33.3(9.3)	2.37	0.019	(0.39,4.22)
17 (5 pm)	36.9(5.7)	36.1(13.9)	0.63	0.53	(-1.81,3.50)
18 (6 pm)	37.8(6.1)	38.3(19.4)	-0.26	0.799	(-4.07,3.14)
19 (7 pm)	38.3(6.4)	38.4(21.3)	-0.07	0.939	(-4.09,3.78)
20 (8 pm)	38.4(6.7)	37.3(19.4)	0.60	0.550	(-2.53,4.74)
21 (9 pm)	36.7(6.2)	35.7(15.1)	0.66	0.507	(-1.92,3.87)
22 (10 pm)	35.4(6.2)	33.6(10.1)	1.66	0.099	(-0.33,3.88)
23 (11 pm)	34.3(6.3)	32.8(8.3)	1.58	0.115	(-0.36,3.33)
24 (12 am)	33.6(6.0)	32.2(8.2)	1.60	0.111	(-0.34,3.26)

Table 6.6: Comparison of mean values of Air Quality Index, Obtained by two sources (Proposed EMRSN system and Existing system) in relation to 31 days of October 2017

Days of October, 2017	AQI Values (mean & sd.,)		t-value	p-value	95% confidence interval for difference of mean
	EMRSN	Existing			
1st	31.9 (4.8)	31.1 (2.4)	1.41	.158	(-.30,1.86)
2nd	33.8 (5.6)	33.4 (5.5)	.55	.580	(-1.14,2.04)
3rd	35.1 (6.4)	28.2 (6.9)	7.10	<0.0001	(4.96,8.78)
4th	35.7 (6.8)	35.1(5.8)	.66	.504	(-1.19,2.42)
5th	36.4 (6.7)	31.2 (2.4)	7.18	<0.0001	(3.80,6.69)
6th	35.6(6.4)	27.2 (13.5)	5.52	<0.0001	(5.43,11.46)
7th	32.5(5.5)	29.7 (6.6)	3.14	.002	(1.03,4.51)
8th	34.9(6.2)	43.5(11.9)	-6.27	<0.0001	(-11.33, -5.91)
9th	32.3(3.9)	50.1(23.5)	-7.26	<0.0001	(-22.55,12.92)
10th	35.7(6.8)	35.1(8.8)	.52	.598	(-1.65,2.86)
11th	39.7(6.3)	25.9(2.9)	19.39	<0.0001	(12.38,15.19)
12th	35.2 (6.4)	31.2(2.4)	5.71	<0.0001	(2.63,5.40)
13th	33.8(5.5)	24.8(5.9)	10.84	<0.0001	(7.39,10.68)
14th	35.3(6.5)	35.14(5.8)	.18	.853	(-1.60,1.93)
15th	32.2(4.9)	25.9(2.9)	10.75	<0.0001	(5.17,7.49)
16th	36.0(3.9)	32.1(8.6)	4.01	<0.0001	(1.98,5.82)
17th	38.8(3.4)	33.1(8.6)	5.94	<0.0001	(3.75,7.49)
18th	38.5(3.0)	41.9(14.7)	-2.18	.030	(-6.40, -.32)
19th	37.7(1.8)	50.1(23.5)	-5.12	<0.0001	(-17.14, -7.61)
20th	38.0(2.4)	45.7(12.2)	-6.07	<0.0001	(-10.28, -5.24)
21st	29.1(2.1)	33.3(8.5)	-4.62	<0.000	(-5.97, -2.40)
22nd	39.2(3.5)	26.3(5.9)	18.23	<0.0001	(11.48,14.26)
23rd	41.3(4.3)	24.8(5.9)	21.89	<0.0001	(15.02,17.99)
24th	29.8(5.0)	28.2(6.9)	1.84	.066	(-.11,3.34)
25th	28.9(2.4)	35.1(5.8)	-9.49	<0.0001	(-7.47, -4.90)
26th	29.6(2.9)	31.2(2.4)	-4.00	<0.0001	(-2.34, -.79)
27th	33.9(4.1)	31.6(9.1)	2.32	.021	(.35,4.39)
28th	35.3(4.9)	27.2(13.5)	5.56	<0.0001	(5.27,11.06)
29th	33.9(2.6)	20.2(14.7)	8.96	<0.0001	(10.66,16.68)
30th	32.8(6.6)	29.8(6.6)	3.17	.002	(1.15,4.93)
31st	26.3(2.4)	23.6(7.7)	3.24	.001	(1.05,4.32)

For the 3 locations, the mean AQI values of EMRSN method are statistically significantly higher than the real method ($p=0.018$, $p<0.0001$ & $p=0.001$). The comparison of mean AQI values between EMRSN and current methods for both ‘peak’ and ‘non-peak’ hours also shows the statistically significant difference, in which the mean AQI values which are observed by EMRSN method are statistically significantly higher than the mean AQI values observed by the existing method adopted by Department of Environment Malaysia, Ministry of Natural Resources and Environment ($p<0.0001$, $p<0.0001$), which means that if $p<0.05$, then it can be concluded as statistically significant. That is the difference between the two observed values if its real or due to chance. If this difference is small, then the p-value is higher and hence statistically not significant. Whereas if difference is large, then p-value is low and hence statistically significant. If its >0.05, then it's because of chance.

In table 6.4**,** the comparison of mean AQI values between EMRSN and existing methods, at each 1 hour in the duration of 24 hours shows statistically significant difference for 11 hours, time points (1 am, 5 am, 8 am, 9 am, 10 am, 11 am, 12 pm, 1 pm, 2 pm, 3 pm, and 4 pm), where the mean AQI values are statistically significantly higher by EMRSN method than existing method. Whereas the data does not show the statistically significant difference in the mean AQI values between the EMRSN and existing methods for the other 13 hours, time points for the duration of 24 hours. In table 6.5, the comparison of mean AQI values between the two methods, of each day during 31 days of October 2017 shows the statistically significant difference for 25 days, where the mean AQI values are statistically significantly higher by EMRSN method than the existing method. And no statistically significant difference was observed in the mean AQI values between the EMRSN and existing methods for the remaining 6 days of October 2017. Table 6.6**. *From this analysis, it can be inferred that the 'EMRSN values of AQI' are much better in most of the times, and in few instances, it was almost same with that of 'Existing system's values of AQI'.*** This means that the operational time of the AQI sensors for the proposed system was found to be more efficient when compared to the existing systems which couldn't record the values during few instances of the day due to poor functioning of the installed AQI sensors. According to the statistical analysis that was carried out, data were entered in MS Excel and analyzed using SPSS version 21.0 statistical software (IBM Inc., Chicago, USA). Descriptive statistics (mean and standard deviation) were used to describe the Air Quality Index (AQI) values. Student's t-test for independent samples was used to compare the mean values of AQI between the EMRSN and existing methods. A p-value of <= 0.05 and 95% confidence intervals for difference of mean was used to report the statistically significant and precision of the results. 95% Confidence interval is for obtaining the precision of the results to know the reliability and repeatability of the system. Basically, to assess the precision of results. If the same experiment is repeated for 100 odd times, then there is a fair chance that we get the same results for about 95%. That is 95 times, the same results get repeated between the lower limit and upper limit.

The proposed EMRSN system is also compared with other existing RSN approaches for performance evaluation in terms of average delay and RF source velocity towards the node to recharge it according to the triggered events as depicted in Figure 6.36 and 6.37 respectively. The description about NCS, TBR and TDC has been specified in Chapter 4. The readers can refer the research contribution by Farris et al. (2016) for clear understanding about the working of each of the existing RSN approaches.

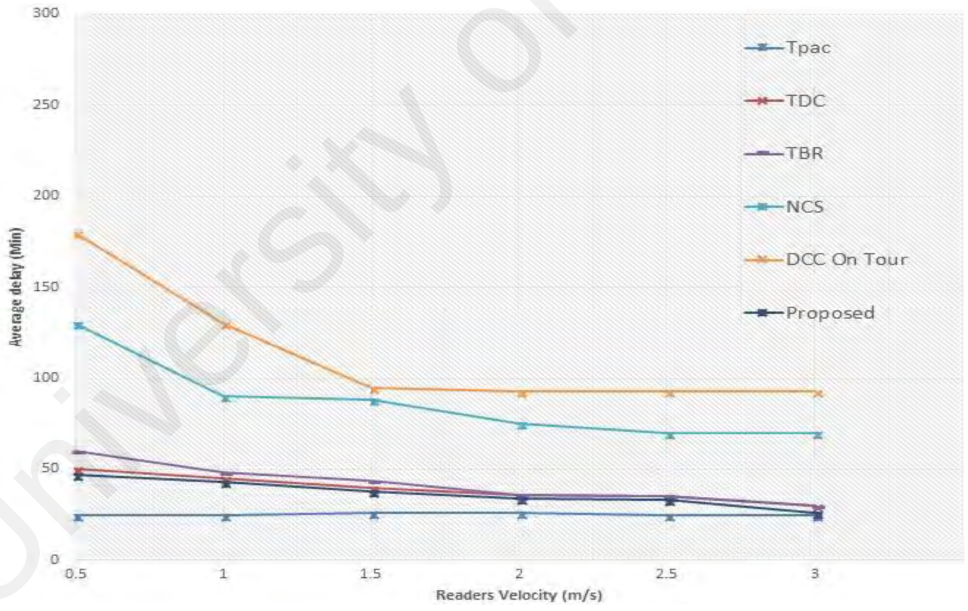


Figure 6. 36: **Performance evaluation of the proposed system in terms of average delay**

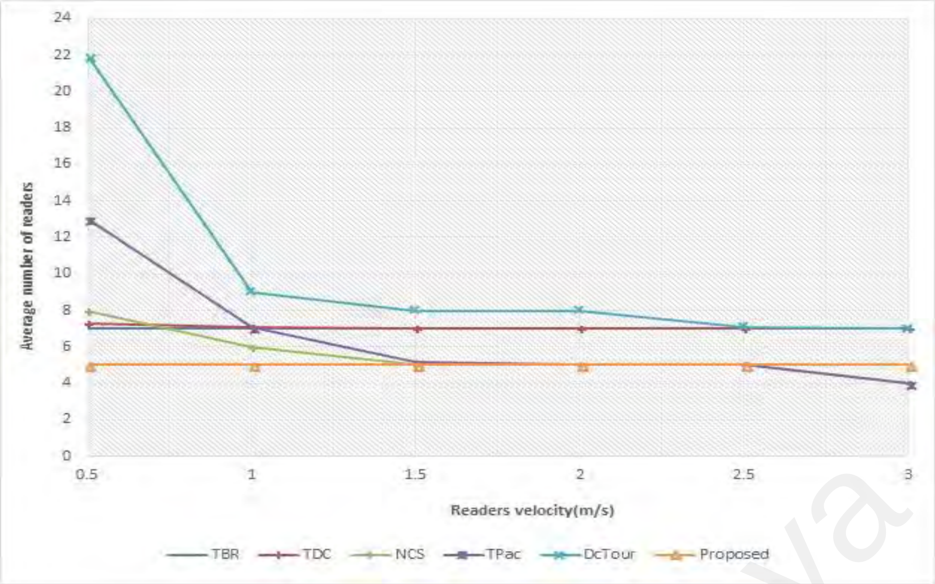


Figure 6. 37: **Performance evaluation of the proposed system in terms of RF source velocity**

6.7 Summary and chapter conclusion

This chapter has presented the description of the experimental settings in which simulations and hardware model deployment is carried out along with the assumptions made for the proposed system model. In section 6.3, the simulation results were presented for evaluating the performance of the proposed EMRSN model and techniques. The remainder of the chapter focused on validation of the proposed model and simulated techniques using hardware model, followed by the description of results obtained from the validation in section 6.5. Finally, in section 6.6, the application of the proposed hardware model for an IoT application to monitor the AQI levels and mitigate the air pollution caused by congested traffic has been presented. The monitored values are further statistically analyzed and validated with the current methods that have been adopted for measuring the AQI values in Malaysia. This chapter presents and discusses the results obtained through simulation, real-time deployment, and statistical analysis. Finally, the chapter is concluded in section 6.7.

CHAPTER 7: CONCLUSION AND FUTURE WORK

This chapter presents and discusses the concluding remarks of this research work. Hence, in section 7.1, it gives an overview of the problem statement which serves as the motivation behind this research. Furthermore, a review of the achieved objectives has been presented in section 7.2 followed by a discussion on the research findings, contributions and some future directives in section 7.3 and 7.4 respectively.

7.1 Overview

The primary focus of this research is to solve and address the issue of energy consumption. Firstly, it focuses to address the uncertainty behind the traditional WSNs which completely rely upon the energy that is stored in batteries and capacitors. Rather, energy harvesting using renewable energy resource such as RF signals has been utilized for powering the circuitries of the sensor node, followed by employing the methods of energy harvesting and transfer via backscattering as energy saving techniques in the proposed scenario. Therefore, a two-way approach of handling the issue of energy consumption in this research is that – improving the lifetime of the network (by not completely and primarily relying on energy stored in batteries/capacitors) through ambient RF energy harvesting followed by proposing energy saving techniques - EHRSN and ETRSN to handle the high energy consumption when two enabling technologies of IoT such as RFID and WSN are integrated. The problem analysis carried out in this research has major findings that higher energy consumption in sensor networks is the primary matter of concern to ensure reliability and longevity of a network. The state-of-the-art research contributions have seldom focused upon the issue of energy management. Therefore, it was also analyzed that the major causes for higher energy consumption in sensor networks are – communication protocol, network topology, routing mechanism and energy transmission/storage techniques. The impact of each of these mentioned causes and factors have been studied and analyzed for systematic qualitative review for energy management of RSN. The issues such as node failure, interference management, a lifetime of the network and time delay are focused upon and addressed in this research. Thereafter, to solve each of the said drawbacks, the research objectives with regards to energy harvesting, energy transfer and controlling/handling of the energy levels of the nodes have been proposed and achieved in this research. The next section presents the accomplished achievements related to each of the research objectives.

7.2 Reappraisal of achieved objectives

This thesis had presented and described an energy management model for RF-enabled sensor networks in IoT contexts. To accomplish the research goal, four objectives have been proposed and achieved. The first objective was to enable energy optimization for controlling and handling the energy levels of nodes through SMDP energy modeling and dynamic programming approach. The second objective was to design and develop an EHRSN algorithm using event-triggered programming approach. The third objective was to design and develop an enhanced stochastic backscattering mechanism for energy transmission to improve the throughput of network and to avoid the recurring interferences. Finally, the fourth objective was to experimentally evaluate and test the proposed EM techniques using simulations, followed by validating the energy management model using real hardware system and further deploy it in an IoT application of air quality monitoring. The proposed system has also been compared for performance analysis with existing approaches of the literature. The objectives that were achieved and described throughout the course of this chapter are detailed as follows:

- *Enabling energy optimization:* The energy model is optimized through dynamic programming by solving the SMDP. The various states of a node are modeled to achieve maximum efficiency. The node's state transitions are modeled based on both EH and ET framework and the total utilization factor is calculated according to which the sensors are calibrated and configured for further and suitable experimentation.

- *Development of EHRSN technique*: This objective is achieved through implementing the technique using NS2. The event-triggered algorithm invokes the EHRSN mechanism whenever an event is triggered. The focus and outcome of this objective are to avoid and mitigate the node failure that is caused due to inefficient handling of node's energy levels.
- *Development of enhanced stochastic backscattering mechanism:* This objective is achieved through simulative implementation. The node which gets depleted in energy levels and is away from the RF energy source gets the energy from its neighbor node that is selected in a stochastic manner. The focus and research outcome is the control and efficient handling of the energy levels of the nodes. Thereafter, the issue of interferences is also addressed through interference management technique which provides the research deliverable of mitigation of recurring interferences during EH and ET processes. The network lifetime is eventually increased through the proposed EMRSN modeling and EHRSN, ETRSN techniques.
- *Testing, evaluation, and validation:* This objective is accomplished through 3 aspects- firstly, the proposed techniques (EH and ET) are experimentally tested and evaluated through simulation tools. Secondly, the proposed system is comparatively evaluated in terms of performance with existing methods in the literature. Thirdly, the proposed EMRSN model is validated using deployment of a real hardware system and sensor motes followed by obtaining the validation results. Finally, the proposed methodology is applied in an IoT

application/context and the results obtained from this are analyzed statistically using SPSS.

7.3 Research findings and contributions

This research has derived and concluded the following findings-

- When RFID is integrated and combined with other technologies, it behaves differently with distinctive MAC interfaces.
- The arrival of data packets during energy transmission follows a poisson distribution.
- When RF and WSN are integrated together, the network lifetime is increased by nearly 80% rather than WSN without RF harvesting.
- The runtime of the sensors using this research has provided an operational run time of about 30 mins per cycle and the obtained energy efficiency is higher when compared to its counterparts.
- The amount of energy consumption during transmission was 0.5W and for receiving 0.3W which is comparatively lesser when compared with the existing approach with energy consumption of 1.83W for both transmitting and receiving.
- The cost of the deployed hardware model of this research was nearly MYR 814 which is more cost effective when compared to the existing device of WISP which costs around MYR 8020.
- The MAC and physical layer parameters along with the upper layers can play a significant role in identifying the energy profile of a sensor node.
- The rate at which harvesting takes place depends upon the size of the node which is getting recharged.

- When the sensors are programmed on low power for EH, the number of packets generated are also considerably lesser when compared to the ones which are configured to high power ratings, for heavy sensing operations.
- The EH and ET processes cannot be carried out when the distance between the RF source and the sensor node is higher. In order to investigate in this regard, more research efforts need to be done.

The application of the proposed methodology in IoT contexts in the major research contribution. The application of monitoring the AQI values of the atmosphere states that the proposed EM model can produce greener environment by mitigating the air pollution. When these AQI values are monitored, they are communicated to the commuters through a mobile application to avoid the route/area that is heavily congested and polluted due to traffic induced air pollution. In this way, the proposed research makes a significant contribution to the welfare of society and environment. The technical research contributions with regards to publications have been specified after the reference section of this thesis.

7.4 Future enhancements

In this thesis, there are many assumptions made relative to the development and implementation of the proposed model. However, the system may not work well in larger scenarios/networks such as environmental monitoring, smart buildings, habitat monitoring and IoT applications with wider coverage areas. The future directive of this research is focused upon the employment of reinforcement learning technique, which learns the system using artificial intelligence and adopts the best optimal policies depending upon the history of energy profile of the network. In this case, the energy modeling will be carried out by considering the discounted reward factor as well. The distance between the nodes and the RF energy source is limited in this research.

Therefore, research efforts to increase this distance has to be carried out for the further efficiency of the system. The IoT sensor based on the IoT layered stack can be modeled and optimized for efficient energy utilization as means for further extending this research. Moreover, the concept of machine learning can also be embedded to further extend the proposed concept for complex and mission critical IoT systems.

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- Shaik Shabana Anjum, Rafidah Md Noor, Ismail Ahmedy, Nornazlita Hussin, Miss Laiha Mat Kiah, Fawad Ali Khan & Nasrin Agha Mohammadi, Bronze medal, "A Step Closer towards Pollution-free and Traffic-free Malaysia, International invention and innovative Competition (InIIC 1/2017), 6th May 2017.
- Shaik Shabana Anjum, Rafidah Md Noor, Ismail ahmedy, Nornazlita Hussin and Miss Laiha Mat Kiah, Gold Medal, "Go Green Malaysia: Mitigation of traffic congestion based on air quality index, Invention, Innovation and design exposition (iidex 2017), 25th September 2017.