ENERGY HARVESTING EFFECT ON PROLONGING WIRELESS LOW POWER LOSSY NETWORK LIFESPAN

BY

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ABSTRACT

Internet of Things (IoT) is a pillar technology for the next coming industrial revolution by enabling connections between deployed small devices wherever and whenever. However, these devices are often constrained in processor, memory, and energy. Usually known as sensor nodes, these devices are connected with each other to form a network of different nodes. As a matter of fact, routing the data in such environment is a challenge because of constrained sources of power. Therefore, Routing Protocol for Low-Power and Lossy Network (RPL) was formed by Internet Engineering Task Force (IETF) to develop an adapted routing solution for such networks, made up of large number of constrained nodes with limited processing power, memory, and energy. However, the overhead exchanged, to facilitate the routing process and maintain connectivity, drains these battery-operated nodes. This research examines a solar energy harvesting module to power such constrained network devices and quantifies the effect of using harvested energy on prolonging the network lifetime when RPL routing protocol is used. Simulation is conducted in three different scales (25 nodes, 50 nodes, 100 nodes) using Contiki Cooja simulator sporting Zolertia Z1 motes. Furthermore, the harvested energy was fed from an experimental power trace. All battery levels were set to 1% of their total capacity for all nodes in the network to expedite the process of observing the energy harvesting effect. The performance evaluation results showed that the network with no-energy harvesting operated for time duration of 4:08:04 time units (e.g., hour:minute:second) with a dramatic decrease in connection between nodes in the network. However, the same network, when using the harvested energy to back up the battery operation, lasted for 6:40:01 in time units with improved connectivity, a total extended network lifetime of 2:31:97-time units. Furthermore, for the RPL routing metrics, OF0 outperformed ETX in term of throughput, packet delivery ratio, energy consumption, and network connectivity.

ملخص البحث

تعتبر تقنية انترنت الاشياء Internet of Things اوIoT الثورة القادمة بقوة الى حيز الوجود في السنوات القليلة القادمة والتي من المتوقع ان تكون موجودة في كل مكان وزمان.هذه التقنية تحتوي على اجهزة صغيرة منتشرة في كل مكان لاجل تسهيل حياة الانسان ، وبالتالي غالباً ما تكون هذه الأجهزة مقيدة في المعالج والذاكرة والطاقة. تعرف هذه الأجهزة باسم عقد الاستشعار التي تتصل ببعضها البعض لتشكيل شبكة اتصال مع الانترنت. في الواقع ، كان توجيه البيانات في مثل هذه البيئة يمثل تحديًا نظرًا لمحدودية مصادر الطاقة وبالتالي ، تم تشكيل بروتوكول التوجيه القياسي RPL لشبكة الطاقة المنخفضة والضائعة LLNs . هذا البرتوكول طور من قبل فريق هندسة الإنترنت IETF لايجاد حل مناسب وفعال لتوجيه البيانات لمثل هذه الشبكات التي تحتوي على عدد كبير من العقد المقيدة مع طاقة معالجة محدودة ، والذاكرة ، وخصوصا عندما تكون تعمل بالبطارية. يقترح هذا البحث وحدة تجميع الطاقة الشمسية لتشغيل هذه الشبكة المقيدة التي تستخدم بروتوكول توجيه RPL ، وبالتالي دراسة التأثيرات على إطالة عمر الشبكة. بالإضافة إلى ذلك ، سيتم إجراء المحاكاة في ثلاثة سيناريوهات مختلفة باستخدام Contiki Cooja ، علاوة على ذلك ، سيكون هناك تقييم للعقد التي تعمل بالبطاريات والتي تعمل على حصاد الطاقة الشمسية لدراسة وتقديم التأثيرات في إطالة عمر شبكة تسخدم البروتوكل القياسي RPL. نتيجة لذلك ، أظهرت النتائج أن الشبكة التي تعمل بدون وحدة الطاقة الشمسية أشتغلت فقط حوالي 4:08:04 (اربع ساعات وثمان دقائق واربع ثوان) مع انخفاض كبير في الاتصال بين جميع العقد ، وعندما أضفنا نظام الطاقة الشمسية عملت الشبكة لحوالي 6:40:01 (ست ساعات واربعين دقيقة وثانية واحدة). لذلك ، قدمت وحدة حصاد الطاقة الشمسية عمر شبكة ممتد إجمالي هو 2:31:97 (ساعتان و 31 دقيقة وسبعة وتسعون ثانية). علاوة على ذلك ، خلال تقييم مقاييس RPL ، يتفوق OF0 على ETX من حيث الإنتاجية ونسبة تسليم الحزم واستهلاك الطاقة وكذلك استمرارية اتصال الشبكة.

APPROVAL PAGE

I certify that I have supervised and read this study and that in my opinion; it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Master of Science in (Computer and Information Engineering).

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DECLARATION

I hereby declare that this dissertation is the result of my own investigation, except where otherwise stated. I also declare that it has not been previously or concurrently submitted as a whole for any other degree at IIUM or other institutions.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVATIONS

AODV	Ad Hoc On-Demand Distance Vector
BPDs	Battery Powered Devices
DAO	Destination Advertisement Object
DIO	DODAG Information Object
DIS	DODAG Information Solicitation
DODAG	Destination Oriented Directed Acyclic Graph
DSR	Dynamic Source Routing
EH	Energy Harvesting
ETX	Expected Transmission Count
FND	First Node Dead
HND	Half Nodes Dead
ICMP	Internet Control Message Protocol
IEEE	Institute of Electrical and Electronics Engineers
IETF	Internet Engineering Task Force
INC	Incremental Conductance
IP	Internet Protocol
LLN	Low Power and Lossy Network
JNI	Java Native Interfaces
LND	Last Node Dead
MAC	Medium Access Control
MCU	Microcontroller Unit

MRHOF	Minimum Rank with Hysteresis Objective Function
MPPT	Maximum Power Point Tracking
NSA	Node State Attribute
OCV	Open Circuit Voltage
OF	Objective Function
OF0	Objective Function 0
OS	Operating System
P&O	Perturbation and Observation
RDC	Radio Duty Cycling
RPL	Routing Protocol for LLN
SEEOF	Smart Energy Efficient Objective Function
SEPAs	Solar Energy Prediction Algorithms
ROLL	Routing Over Low-power and Lossy
TORA	Temporally Order Routing Algorithm
UDP	User Datagram Protocol
UDGM	Unit Disk Graph Model
VM	Virtual Machine
WSN	Wireless Sensor Network

LIST OF SYMBOLS

FND	First Node Dead Round
$T_{\square}$	Time When First Node Dead
$T_{\square}$	Time When Simulation is Started
HND	Half Nodes Dead Round
T_{h}	Time When Half of Nodes are Dead
LND	Last Node Dead Round
$T_{\square}$	Time When Last Node is Dead
PDR	Packet Delivery Ratio
I	Current Draw at Different Mode in the Mote Components
V	Voltage Available for the Battery in Use

CHAPTER ONE

INTRODUCTION

1.1 OVERVIEW

Internet of things (IoT) is one of the most important technologies of the future that are expected to make a big difference in the world around us by allowing communication between objects “things” to do daily activities for us instead of humans. Wireless Sensor Network is consisted of many heterogeneous devices (sensors) which communicate autonomously. Nowadays, the usage of these technologies is rapidly increasing in the industrial field, by using sensors to monitor the ambient conditions, working parameters, and to send the data to the sink node that also knows gateway. Such kind of technology could be more effective in our daily life by making many tasks easily conducted especially in industrial area and security surveillance systems. For instant, bridge collapse might be a tragedy incident if it happens over populated area however, monitoring the bridges using WSN can reduce or prevent the occurrence of such tragedy through giving an information about the situation of the bridge in early stages or expectation of any accident, as it will be more helpful to evacuate the surrounded area timely and conveniently (Yetgin, Cheung, El-Hajjar, Hanzo, & Tutorials, 2017).

Wireless Sensor Networks which is known as WSN is a technique which has recently adopted as a medium of communication and as a mean to set a well efficient network. So basically, WSN is a network made by tremendous number of sensor nodes in which each and every sensor is linked to a node. The sensor node has several parts responsible for receiving, processing and sending data to a server or even to a cloud computing service host. These nodes usually have small scale radio transceiver, possessing their own antennas to initiate the process of sending data, a microcontroller for the purpose of data acquisition and processing. It also has a built-in analogue/digital electronic circuit known as signal conditioner circuit meant to make an analogy between the nature of sensed data signal and the microcontroller acquisition ability. Aside from that, the node has its own power source, usually batteries, supercapacitors or any sort of energy harvesting system for making its own power supply. The reading acquired by sensor nodes is gathered by a gateway to be passed on to a server or host (Rawat, Singh, Chaouchi, & Bonnin, 2014). In addition, routing the data in such environment has been a challenge because of constrained sources of power therefore, Routing Protocol for Low-Power and Lossy Network (RPL) has been formed by Internet Engineering Task Force (IETF) to develop an adapted routing solution for such networks that contain large number of constrained nodes with limited processing power, memory, and sometimes energy when they are battery operated or energy harvesting). This kind of network called low power lossy network (LLNs). It is terminology used by to explain the focus of routing over low-power and lossy (ROLL) group. RPL is IPv6 routing protocol for low-power and Lossy network that focuses in path selection with considering the routing behaviour, the objective function is the metric that is used to determine the perfect way to route the packets of data from node to other node , and on the way to sink node, from child node to parent node. The node with small rank called child while the node with high rank called parent. Each node wanting to send data can communicate with ambient nodes and choose the one that close distance to it and links it to other nodes to the sink node. Two main Objective Functions have been utilized nowadays in RPL, namely; (OF0), and (MRHOF). (Kim, Ko, Culler, & Paek, 2017). Objective Function Zero (OF0) uses ranks to estimate the hope count to the root. Minimum Rank Objective Function with Hysteresis (MRHOF) dynamically uses the

Expected Transmission Count (ETX) as the default metric to calculate the rank. It selects the path that minimizes the metrics used, and uses hysteresis to reduce the churn “change of parent” caused by small metric changes over time.

In term of constrained energy in low power lossy networks (LLNs), many research works have been reported to provide an efficient energy solution for RPL protocol. Most of these studies are concerned to investigate RPL metrics in order to provide optimal solution for energy efficient and prolonged and lasting network lifetime. However, typical power sources in such constrained devices are batteries which deplete its energy to get drained out over short time. Furthermore, change of these batteries periodically is very difficult process particularly in remote areas, and where there are huge number of sensor nodes deployed. Therefore, energy harvesting for WSN (Kanoun, 2018) is considered a good solution to convert ambient energy into electric energy that can be used to power low power devices to prolong battery life. Energy harvesting also known as energy scavenging is a term used to describe the process of capturing ambient energy such as, wind, thermal, vibration, RF signals, and solar energy. This small captured energy is stored into power banks to be used for powering senor nodes in WSN. Energy storage devices in WSN are fitted often with reachable batteries as well as supercapacitors.

In this research, we provide energy harvesting module (EH-Module) to study the effects of energy harvesting on prolonging network lifespan when RPL routing protocol is in use. EH-module is developed to simulate RPL network in Contiki Cooja simulator (Österlind, Dunkels, Eriksson, Finne, & Voigt, 2006). This module is an extension of PowertraceK that used to provide Neutral Operation of the Minimum Energy Node in Energy-Harvesting Environments (Riker, Curado, & Monteiro, 2017).

However, our developed module combines three sub-modules into one. These sub-modules are consumption sub-module, storage sub-module, and harvesting sub-module. We develop this module to use real data of solar energy accumulated by Colombia University (Gorlatova et al., 2011). Furthermore, this study provides a comprehensive evaluation for RPL standard objective functions in term of energy harvesting. This is to our best knowledge is the first RPL evaluation with and without energy harvesting for both OF0 and ETX. In order to evaluate RPL metrics performance in term of prolonged network life time, three network configurations of 100 nodes, 50 nodes, and 25 nodes are designed. Each network scale will cover both objective functions of; ETX and OF0 with and without energy harvesting as power source.

1.2 PROBLEM STATEMENT

Recently, the use of wireless sensor networks (WSNs) is one of the most popular technologies that has been taking place in various domains of our life. It can be used in a health care, secured surveillance premises, and military operations. As a man-made utility, WSN have several challenges and issues related to power consumption and network lifetime such as collisions, overhearing, protocol overhead and idle listening, depending on node’s transceiver (Ezhilarasi & Krishnaveni, 2018). The IETF routing over Low power and Lossy network (ROLL) working group has developed a routing protocol called RPL based on IPv6 for low power and Lossy Networks (LLNs).

The critical issue of this study is battery-powered node that has limited time of function before the power is drained. Such kind of nodes deployed and connected to form a heavy density networks. It able to work with hundreds and millions of nodes and, thus it is difficult to change the batteries periodically in such scenario. In addition, some constrained nodes are deployed in a remote and unreachable areas which reflect on the difficulties related to accessing these areas occasionally to change the batteries. Consequently, several studies have proposed solutions for such challenges by investigating RPL routing protocol from different prospective such as link quality and energy consumption metrics; however, this research explores the power supply source itself and proposed a harvested solar energy as additional power source.

1.3 RESEARCH OBJECTIVES

This study aims to prolong lifetime of self-powered sensor nodes in Low Power Lossy Networks (LLNs) by making PRL routing protocol is in use. Additionally, energy harvesting module is considered as additional power resource in situation where battery is concurrently used. This research focuses only on using harvested solar energy to power sensor-nodes and to investigate its effect on RPL performance. In order to achieve that, the following specific objectives are to be met:

1. To develop an energy harvesting module that uses real data traces to power constrained sensor nodes on low power lossy wireless network utilizing RPL routing protocol.
2. To evaluate and benchmark the performance of RPL routing protocol in term of the effect of energy harvesting in prolonging network lifespan when powered with solar energy harvesting.

1.4 RESEARCH SCOPE

In order to enhance the energy efficiency and stability of RPL routing protocols, many research works have been addressed such issues and proposed solutions based on selecting an appropriate route to the sink node by investigating the objective function (Alvi, ul Hassan, & Mian, 2017). Accordingly, evaluating the performance for such objective functions in different environment and based on various metrics have been carried out by some studies like (Qasem, Altawssi, Yassien, & Al-Dubai, 2015), and (Gaddour, Koubâa, Baccour, & Abid, 2014) so as to promote RPL protocol in term of energy efficiency and network lifetime. The foremost aim of this dissertation is to prolong the lifespan of network using RPL routing protocol depending on solar energy harvesting as additional power source. Furthermore, this dissertation encompasses studying the effects of solar energy in prolonging the network lifespan by applying this concept into three different scenarios of WSN using RPL routing protocol. This has been done by developing energy harvesting module to use real date of solar energy. We have implemented the simulation using Contiki Cooja by using collected real data of power traces for PV cells. The research has suggested rechargeable battery as a power storage device but will not deepen into the power management for these circuits as well as the power distribution all over the nodes. However, other ambient energy such as, thermal, RF signals, vibrations, and wind are not our concerns in this work. Furthermore, other energy storage like supercapacitor is not included in this study.

1.5 DISSERTATION STRUCTURE

This dissertation is organized as consisting of six chapters. Chapter 1 describes the conceptual layout with motivation and terms used in the state of art technology to justify the reason of conducting this research. It presents a detailed background of RPL as well as energy harvesting. Chapter 2 presents a critical review of related work reported in contemporary literature, justifying thus the reason for undertaking this research. Chapter 3 presents research methodology to investigate research objectives by elaborating the way and technique for achieving these objectives. It also presents the tools and equipment used in this work. Chapter 4 discusses the developed energy harvesting module with its technical details, elaborating the essential design steps and implementation procedure of EH-Module. Chapter 5 discusses and analyses the obtained results in order to evaluate RPL metrics. The results are evaluated against similar results in the benchmarked papers for validation and preferential contribution of the achievements. Finally, Chapter 6 presents conclusions, describing the work as mix of already stated techniques by re-stating the methodology for marked results. It also suggest avenues using which how the research can be continued further.

CHAPTER TWO

LITERATURE REVIEW

2.1 INTRODUCTION

Basically, this chapter provides an outline information and summary of general ideas of tools and techniques used in this research. Literature review has highlighted the main concepts in the state-of-the art related to the research topic. It precisely clarifies the ideas to give more understanding for the research subject. This chapter is divided into two sections. Firstly, it is discussing the background of Low Power and Lossy Networks (LLNs) from the architecture perspective as well as its routing protocol. Thereafter, Contiki operating system is highlighting as the one of the most common operating systems in field of WSN. And we are going to elaborate its functions with respect to programming and simulation details. Cooja simulator is defined as a part of Contiki operating system, it works to simulate Contiki motes (nodes implemented with Contiki operating system). Subsequently, since RPL routing protocol is the used protocol in our network simulation, we are going to discuss it from different perspectives to provide clear understanding about its functions for routing data though a wireless network. Furthermore, Energy harvesting is also very important concept in this study since we are going to use a harvest solar energy as power source besides to the battery. Therefore, energy harvesting is going to be clarified in term of energy sources, power management, and so on. Secondly, the related works done by different contemporary research is going to be discussed. Likewise, a table of comparison among all these studies investigating priorities, features and limitations of each reported work, is presented.

2.2 BACKGROUND

2.2.1 Low-Power and Lossy Networks

Wireless Sensor Networks, also named Low Power Lossy networks (LLNs) are networks with huge number of constrained devices called nodes. These nodes have the ability to sense the ambient area parameters for communication as collected data to parent node over server. Typically, such kind of networks are used to monitor certain environmental situation or any other physical conditions in various places. Often, each node is considered a separated hardware device that contains very small embedded devices such as microcontroller, transceiver, sensor, and power sources as shown in figure 2.1. The node function begins by sensing a particular parameter such voltage, temperature, light, and so on, which is considered to be the task a specific node is deployed for. Microcontroller is the unit to process and store the sensed data for being sent by the sensor output. These data items need to be sent to the sink node through a wireless communication by using transceiver that works to generate radio waves to carry these data over the air. In order to turn on these sensor nodes by electrical energy which needs to be supplied to them from on-node power supply source. Usually, rechargeable batteries and ultracapacitors work as power source however, these sources are not renewable and hence are perishable. Therefore, energy harvesting is a promising solution for powering constrained devices in wireless sensor networks. These devices (nodes) have got very limited memory, processing power, and energy. These router nodes are dealing with very low data rates and the traffic patterns are not simply which could be point –to- multipoint or multipoint -to –multipoint. In addition, these networks may be coming thousands of nodes. Such kind of features require a routing solution.