UNIVERSITI PUTRA MALAYSIA

FIREFLY-INSPIRED TIME SYNCHRONIZATION MECHANISM FOR SELF-ORGANIZING ENERGY EFFICIENT WIRELESS SENSOR NETWORKS

ZEYAD GHALEB AQLAN AL-MEKHLAFI

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By

ZEYAD GHALEB AQLAN AL-MEKHLAFI

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfillment of the Requirements for the Degree of Doctor of Philosophy

October 2017

DEDICATIONS

This thesis is dedicated to my father Dr. Ghaleb Aqlan Al-Mekhlafi who has taught me that “if I make a wish and work hard, it would come true”. He has also exerted his precious effort in making my life successful. My work is also dedicated to my mother Marum Othman who has taught me to how to use what I have learned in helping other people.

To all those lovely ones who have taught me to be brave and patient.

To my sister, my lovely wife, and my wonderful Kids Shahd, Rahf and Tariq.

I also should express my gratitude to my supervisor Associate Prof Dr. Zurina and the entire committee, including Prof Dr Mohammed and Associate Prof Dr. Zuriati.

Finally, my thankfulness should be dedicated to my lovely friends and all those close people who have supported me during my PhD.

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfillment of the requirement for the Degree of Doctor of Philosophy

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October 2017

Chairman : Associate Professor Zurina Mohd Hanapi, PhD
Faculty : Computer Science and Information Technology

One major issue faced by Wireless Sensor Network (WSN), which is based on pulse-coupled oscillators (PCOs) is the energy consumption and loss of data due to the deafness, high packet collision and high power in the application. Therefore, to overcome this problem this research proposes a technique for the efficient minimization of energy usage among WSNs, particularly during transmission scheduling (sender state) for time synchronization in WSNs. Specifically, the current work focuses on three decentralized methods of energy efficiency with scalability and robustness. Among the mechanisms used is the traveling wave pulse coupled oscillator (TWPCO), which is a self-organizing technique for energy efficient WSNs by adopting a traveling wave phenomenon based on phase locking of the PCO model regarding sensor nodes as observed in the flashing synchronization behaviors of fireflies and secretion of radio signals as firing to counteract deafness. The second mechanism is a self-organizing energy efficiency pulse coupled oscillator (EEPCO) mechanism for WSNs, which combines both the biologically inspired and non-biologically inspired network systems to counteract packet collision. The third proposed mechanism is the random traveling wave pulse coupled oscillator (RTWPCO), which reduces high-power to the smallest level by using phase-locking travelling wave in biologically inspired of the PCO model and random method based on anti-phase in non-biologically inspired of the PCO model.

The performances of the proposed algorithms were studied using a simulation analysis. The results showed significant improvement in terms of reaching the steady state after a certain number of cycles, obtaining superior data gathering ratio, and reducing the energy consumption ratio of sensor nodes. Specifically, the TWPCO mechanism showed superior performance compared to other mechanisms with a deduction on the total energy consumption by 25 %, while improving the performance by 13 % in terms of data gathering. On the other hand, the EEPCO mechanism improved data collection by

up to 100% when the number of sensor nodes is below 40. In such a scenario, the energy efficiency also improved by up to 15%. Finally, the proposed RTWPCO mechanism achieved up to 53% and 60% reduction in the energy usage mainly due to the increase in the number of sensor nodes as well as the increase in the data packet size of the transmitted data. In addition, the mechanism improved the data gathering ratio by up to 75% and 73% respectively.

These mechanisms help to avoid deafness that occurs in the transmit state in WSNs, to counteract packet collision during transmission in WSNs and minimize the high-power utilization in the network and as well increase the data collection throughout the transmission states in WSNs.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk Ijazah Doktor Falsafah

MEKANISME PENYEGERAKAN MASA BERINSPIRASIKAN KUNANG-KUNANG BAGI PENGATURAN KENDIRI UNTUK KECEKAPAN TENAGA JARINGAN PENGESAN TANPA

Oleh

ZEYAD GHALEB AQLAN AL-MEKHLAFI

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Pengerusi : Profesor Madya Zurina Mohd Hanapi, PhD
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Satu isu utama yang dihadapi oleh Rangkaian Sensor Tanpa Wayar (WSN), yang berdasarkan pengayun denyutan nadi (PCOs) adalah penggunaan tenaga dan kehilangan data yang disebabkan oleh kurang deria pendengaran, perlanggaran paket yang tinggi dan kuasa yang tinggi dalam aplikasi. Oleh itu, untuk mengatasi masalah ini, penyelidikan ini mencadangkan teknik untuk mengurangkan penggunaan tenaga di kalangan WSN, terutamanya semasa penjadualan penghantaran (state sender) untuk penyelarasan masa di WSN. Khususnya, kerja semasa yang dijalankan memberi tumpuan kepada tiga kaedah yang berpusat untuk penggunaan tenaga yang cekap dengan skala dan ketahanan. Antara mekanisme yang digunakan ialah pengayun denyutan nadi menggunakan gelombang radiasi (TWPCO), yang merupakan teknik penyelenggaraan kendiri untuk WSNs yang merupakan cekap tenaga dengan menggunakan fenomena gelombang radiasi berdasarkan fasa kunci oleh model PCO mengenai nod sensor seperti yang diperhatikan dalam kelipan kunang-kunang dan rembesan isyarat radio adalah sebagai cara untuk mengatasi kurang deria pendengaran. Mekanisme kedua adalah mekanisme pengayunan denyutan nadi berdasarkan penyelenggaraan kendiri yang cekap tenaga (EEPCO) untuk WSN, yang menggabungkan kedua-dua sistem berdasarkan biologi dan bukan biologi untuk mengatasi masalah perlanggaran paket. Mekanisme ketiga yang dicadangkan ialah pengayun denyutan nadi gelombang radiasi secara rawak (RTWPCO), yang mengurangkan penggunaan kuasa yang tinggi ke tahap terendah dengan menggunakan gelombang radiasi fasa kunci secara biologi dari model PCO dan kaedah rawak berdasarkan kepada anti-fasa secara biologi dari model PCO.

Prestasi algoritma yang dicadangkan telah dikaji menggunakan analisis simulasi, yang menunjukkan peningkatan yang ketara dari segi mencapai keadaan yang stabil setelah beberapa kitaran tertentu, dapat memperoleh nisbah perhimpunan data yang lebih baik, dan mengurangkan nisbah penggunaan tenaga nod pengesan. Khususnya, skim TWPCO

menunjukkan prestasi unggul berbanding dengan mekanisme lain dengan pengurangan jumlah penggunaan tenaga sebanyak 25%, sementara peningkatan prestasi sebanyak 13% dari segi pengumpulan data. Sebaliknya, skema EEPCO meningkatkan pengumpulan data sehingga 100% apabila bilangan nod pengesan berada di bawah 40. Untuk senario sedemikian, kecekapan tenaga juga meningkat sehingga 15%. Akhirnya, skim RTWPCO yang dicadangkan mencapai 53% dan pengurangan 60% penggunaan tenaga terutamanya disebabkan oleh peningkatan bilangan nod pengesan serta peningkatan saiz paket data data yang dihantar. Di samping itu, skim ini meningkatkan nisbah pengumpulan data masing-masing sehingga 75% dan 73%.

Skim ini membantu mengelakkan kepekakan yang berlaku semasa proses penghantaran di WSN, sejurus mengatasi perlanggaran paket semasa penghantaran di WSN dan dapat meminimumkan penggunaan kuasa tinggi dalam rangkaian dan juga mampu meningkatkan pengumpulan data semasa proses penghantaran di WSN.

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I certify that a Thesis Examination Committee has met on 24 October 2017 to conduct the final examination of Zeyad Ghaleb Aqlan Al-Mekhlafi on his thesis entitled "Firefly-Inspired Time Synchronization Mechanism for Self-Organizing Energy Efficient Wireless Sensor Networks" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Doctor of Philosophy.

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This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as a fulfillment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

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Date:

Declaration by graduate student

I hereby confirm that:

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Declaration by Members of Supervisory Committee

This is to confirm that:

- the research conducted and the writing of this thesis was under our supervision;
- supervision responsibilities as stated in the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) are adhered to.

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Name of Member of Supervisory Committee:	Professor Dr. Mohamed b Othman

Signature:	
Name of Member of Supervisory Committee:	Associate Professor Dr. Zuriati bt Ahmad Zukarnain

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LIST OF ABBREVIATIONS

ADC	Analog-Digital Converter
aMaxBE	Maximum Backoff Exponent
BS	Base Station
CBR	Constant Bit Rate
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
CTS	Clear-To-Send
DAC	Digital-Analog Converter
DES	Discrete Event Simulator
DESYNC	Desynchronization Method
DCTS	Directional Clear to Send
DIFS	Distributed interframe spacing
DRTS	Directional Request to Send
DS	Distributed System
DU-MAC	Directional Ultra-Wideband MAC
EEPCO	Energy-Efficient Pulse-Coupled Oscillator
EIDLE	Expected IDLE Count
EL	Energy Level
ERX	Expected Receive Count
ESLEEP	Expected SLEEP Count
ESIF	Explicit Synchronization Intelligent Feedback
ETX	Expected Transmission Count
FDMA	Frequency-Division Multiple Accesses
FTSP	Flooding Time Synchronization Protocol
GloMoSim	Global Mobile System Simulator

GUI	Graphical User Interface
IEEE	Institute of Electrical and Electronic Engineers
IP	Internet Protocol
MAC	Medium Access Control
macMinBE	Minimum Backoff Exponent
MEMS	Micro-Electrical Mechanical Systems
MS	Millisecond
OOP	Object Oriented Programming
OPNET	Optimized Network Engineering Tool
PBS	Pairwise Broadcast Synchronization
PCO	Pulse-Coupled Oscillator
PHY	Physical Layer
PRC	Phase Response Carve
QIF	Quadratic-Integrate and Fire
QoS	Quality of Service
RBS	Reference-Broadcast Synchronization
RF	Radio Frequency
RIC	Radial-Isochron-Clock
RIDMAC	Receiver-Initiated Directional MAC
RT	Routing Table
RTS	Request-To-Send
RTWPCO	Random Traveling Wave Pulse Coupled Oscillator
SN	Sensor Node
SOM	Self-Organizing Mechanism
SWAMP	Smart antenna-based Wider-range Access MAC Protocol
TCP	Transmission Control Protocol

TDMA	Time Division Multiple Access
TWPCO	Traveling Wave Pulse Coupled Oscillator
WSNs	Wireless Sensor Networks

CHAPTER 1

INTRODUCTION

This chapter semantically illustrates a common background of the work reported in this thesis and recognizes details of the motivation and research problems. It also highlights the research significance, presents the research objectives, and then describes the scope of this research. The chapter also provides a brief description of the organization of the thesis.

1.1 Background

Over the last few years, micro-electrical mechanical systems (MEMS), especially wireless sensor networks (WSNs) have attracted considerable attention from researchers. WSNs are small and inexpensive devices with sensing, processing and transmitting capabilities of environmental phenomena of interest. They have various application prospects, including military, industrial and agricultural monitoring systems . In addition, the limited processing capability and communication radius are two important features characterizing the WSN technology . Since these restrictions are crucial to the overall lifetime of the WSN, they need to be considered when designing a routing protocol [4]. Because the failure of individual nodes directly represents the whole network with time, it is more likely for packet relaying and regular sensing to the base station to be exposed to serious jeopardization. This is more possible especially because more and more sensors will cease operating due to their exhausted energy [5]. Each routing protocol algorithm transmits data from the sources to the destinations, and it is expected to increase the network exposure even if the propagation value decreases [6]. Yet, one of the most serious issues faced by the WSN technology is the issue of coverage-holes [7]. Thus, the only remaining feasible deployment option or alternative in medium and large deployments in hostile regions is random dropping of Sensor Nodes (SNs) by unmanned vehicles or low flying helicopters. Even when there is a possibility of deterministic deployment, the issue of coverage-holes will be faced especially because of the sensors running out of battery energy. Such issue gets more evidently challenging, particularly for those nodes situated within close proximity to the base station. Such nodes usually represent the system bottleneck because of their high data-relaying task. In addition, sensor nodes are left to operate independently after they are initially deployed, thus complicating the issue of coverage.

As described by Sharma et al. [8], WSN represents a group of thousands of tiny sensor nodes which are capable of performing wireless communication, limited calculation, and sensing. A WSN encompasses a sensor, node, base station, gateway, and coordinator. These elements of WSN are illustrated in Figure 1.1. Its sensors serve as the heart of network devices because they play an important role in obtaining the data from the medium and converting it into wireless signals. Nodes are regarded as the fundamental units of WSN, which also play a role in obtaining the data from the sensors nodes and relaying the information to the base station [5, 9, 10]. As shown in Figure 1.2, nodes are small devices, which comprise a few kilobytes of memory, MHz processors, a radio scope of a few meters, and one or two batteries. In addition, the gateway functions as an entrance or a proxy server and firewall to another network. As gateways, they are important in facilitating intelligent WSN network-data and network connection (TCP/IP). Furthermore, base stations (BS) have a centralized point in controlling the network. The information extracted from the network as well as disseminate control information is usually returned into the network [5].

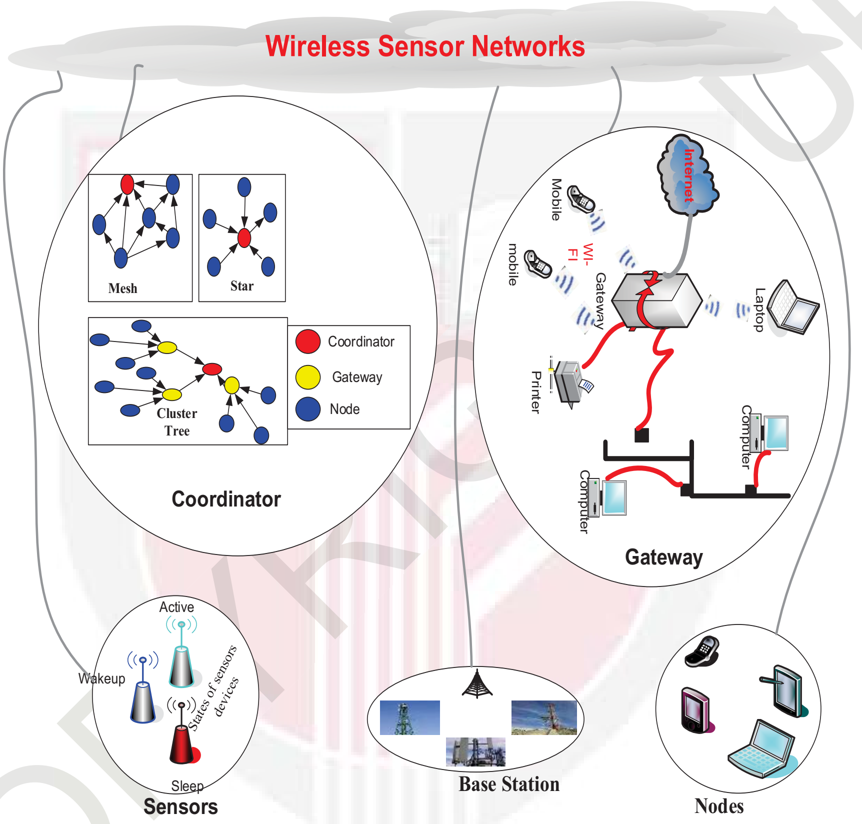

Figure 1.1 : WSN elements

They also serve as collectors of data, and they common computer-based or embedded system-based. For the coordinator, it plays an important role in parsing and buffering messages as well as reading raw sensor data broadcasted from the sensor networks. It also allocates a configuration and a port for the gateway for each connection request [11].

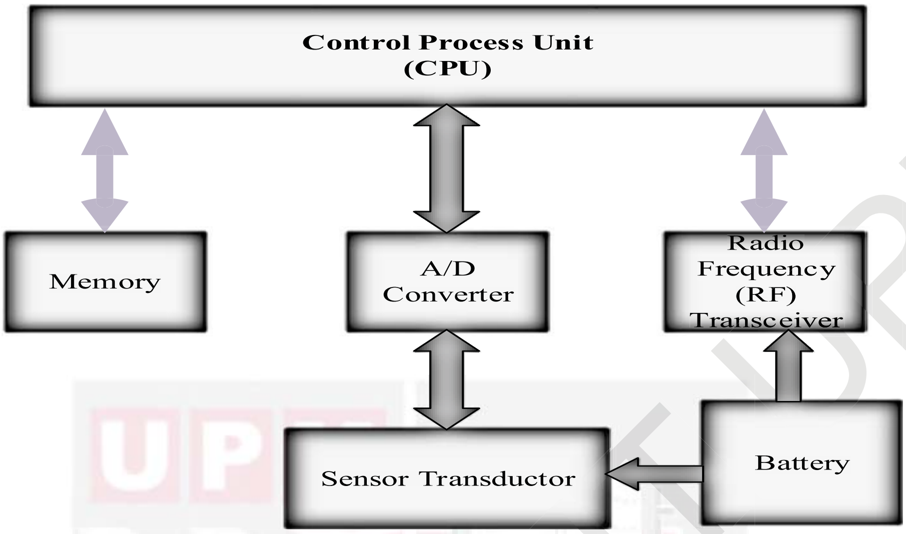

Figure 1.2 : Sensor node architecture

Typically, the sensor node consists of four major factors: power supply unit, sensing unit, computing unit, and communication unit (Figure 1.3). Thus, a power supply encompasses the battery that provides all other units with power. This means that power of the battery must be controlled. Controlling the power is important, especially when there is a need for maximizing the lifetime of the sensor network because batteries cannot be easily replaced after being deployed in the field. Controlling such power is achieved through adoption of various techniques at different layers, thus saving the energy in these most exhausting units. High-energy costs on the sensor nodes are incurred by a radio communications unit of sensor nodes, particularly in the active mode (transmit and receive). The sensor functions as a monitor of the physical events as well as producers of the analog signals. It also serves as a converter of signals into digital while at the same time passing them to the computing unit for more processing. Generally, the computing unit involves a processor and memory storage, both of which play a key role in providing a smart control of the node. The communication unit is inclusive of a short range radio that receives and transmit data, thus consuming the highest level of energy in the node [12]. Usually, the sensing unit is inclusive of one or more sensors, a digital-analog converter (DAC) and an analog-digital converter (ADC). As a matter of fact, the energy which is consumed in the transmit and receive modes is higher than that consumed in the sleep and idle modes [13].

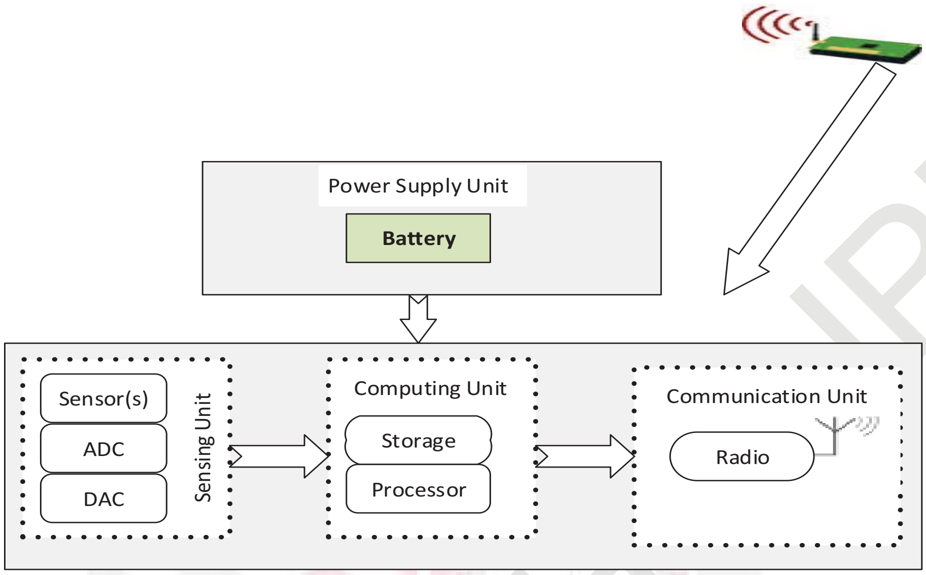

Figure 1.3 : Paradigm diagram of a characteristic sensor node

Time synchronization is considered as a serious problem that hinders the operation of any distributed WSN. Synchronization sets up the same limit of time for diverse sensor nodes. In this way, it achieves unification of functions for voice data and video, organization of diverse sleep or wake-up node scheduling mechanisms and distribution of time-based channels [14].

Time synchronization is advantageous over unsynchronized systems [15]. It is also naturally assumed to facilitate certain techniques and algorithms in Physical layer (PHY) and Medium Access Control (MAC) layers. From the PHY perspective, slot synchronization is capable of advancing cooperative transmission technologies. From the perspective of the MAC layer, slot synchronization is capable of coordinating packet transmission of nodes, thus attaining optimal throughput and power efficiency (Figure 1.4). Moreover, transmission of data based on synchronization can be achieved by optimizing the periodic use of energy in the WSN.

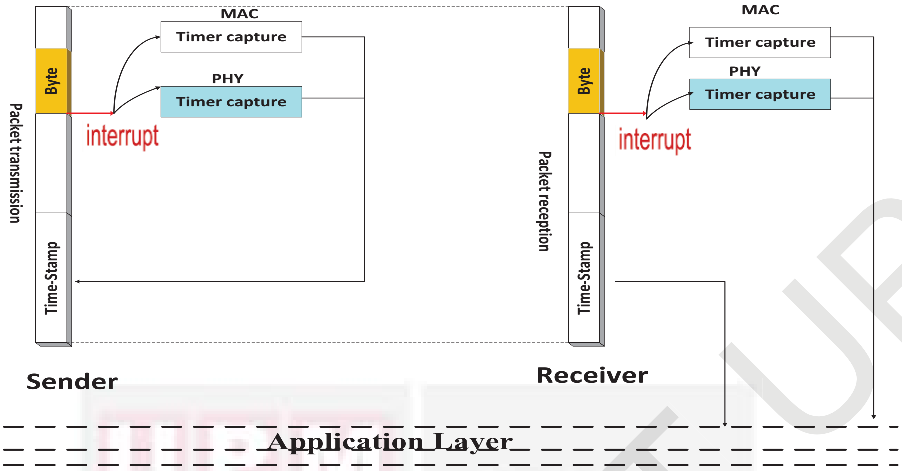

Figure 1.4 : Time synchronization in MAC and PHY layers

What often constrains the sensor nodes is the restricted energy in addition to the processing and storage capacity, which leads to transmitting the sensed data to a more resource-rich node, known the BS. Therefore, in a network of sensor nodes, the wireless sensors collaboratively sense the environment, detect the phenomenon of interest and eventually forward the data to a dedicated base station in synchronization. This synchronization between the nodes is required for coordinating the cycles of power or efficiency of energy and for the stable functioning of sensors in real-time monitoring scenarios [16]. One of the techniques that may be employed to model the behaviour of WSN is the Pulse-Coupled Oscillator (PCO) algorithm, where sensor nodes as observed in the flashing light emission synchronization behaviors of fireflies and secretion of radio signals are regarded as firing to attract mating partners [3, 16]. Wireless sensor nodes are associated with strict energy requirements and dynamic topology changes. Thus, the proposed PCO technique must cater for these dynamics in order to afford a successful implementation (for the avoidance of the deafness, collision problems and hidden terminal at the sender state); thereby enhancing not only the packet drop rate but also the network lifetime [17, 18]. Nevertheless, WSNs are unable to afford simultaneous transmission and reception of data, and for most scenarios, the battery replacement is impossible upon the exhaustion of a node's battery energy [19]. Thus, energy efficient protocols constitute vital design requirements for the WSN as a whole. Another important requirement of WSNs is the self-organizing capability, which enables sensor nodes to re-discover their new neighbours (due to battery exhaustion or abrupt malfunction of some nodes in the network) in the face of dynamic network topology changes.

In general, energy efficiency is ensured in WSNs by explicitly embedding energy-minimization protocols into the underlying sensing model of the sensors (such as reducing the per packet energy consumption) or avoiding the high energy usage of any single node within the network [19].

1.2 Motivation

The work in this thesis is motivated by the idea of suggesting various decentralized energy-efficient methods, which are common and suitable for most of WSN applications [3, 19]. Such applications need minimize energy usage and, consequently, rising the potential for enhancing the lifetime of a sensor network. This would take into account the energy of sensor nodes as the most important factor to avoid rapid energy depletion. In these mechanisms, the transfer load is a regular interval and a lowly energy-efficient control mechanism over the sensor nodes throughout transmitting, which would reduce the average energy in the network. Almost all sensor nodes die simultaneously, thus leading to optimizing the overall network lifespan.

1.3 Research Problem

In analysing the various discussion deliberated in the previous section, there are several debates negotiated in the former part, while there are also relevant problems that occur during transmitting (in the sender state). These problems are specified in this thesis as follows:

- PCO can be used in firefly time synchronization but cannot be used in real sensor networks because the sensor nodes cannot receive messages while transmitting (deafness problem). Many researchers have proposed deafness in the original PCO model in order to improve the main problem of time synchronization. However, the proposed methods should reduce energy consumption and loss of data.
- The PCO model is also not suitable for sensor networks because WSNs are unable to afford simultaneous transmission and reception of data, and for most scenarios, replacement of the battery is impossible upon the exhaustion of a node's battery energy method because of packet collision. Packet collision usually occurs when a sensor node misses the control packet, which indicates that the channel is idle, and then it attempts to transmit on the channel while another node is busy transmitting on the same channel. This results into collision and dropping of packets. Therefore, in this case, none of the packets is successfully received. At the same time, the energy consumption should be reduced to a certain level.
- The importance of WSN applications is recognized in most various fields, which leads to dramatically varying requirements and features. Thus, it is more suitable and more hard to identical demands in all applications. The PCO mechanism causing delayed and uncharitable applications would prefer to reduce energy consumption to the smallest level.

1.4 Research Significance

The use of wireless sensor network is inspiring for improving a mechanism that can conserve more power at each sensor node due to the transmit state. In contrast, energy efficient pulse coupled oscillator confirms to be the quickest method to conserve power at each sensor node. However, even with reduced energy consumption, every sensor node is consumed more quickly to offer services to other nodes through a data transmission state. In this study, the wireless sensor network element and energy efficient pulse coupled oscillator are together considered. We proposed improving energy efficiency in terms of a data gathering ratio and an energy consumption ratio and reaching the transient steady state [3]. The significance of this research stems from the challenge of proposing an energy efficiency mechanism that reduces the energy consumption, makes the data-gathering ratio superior and maximizes their lifetime at the same time.

1.5 Research Objectives

The main objective of this study is to develop and adopt distributed energy efficient pulse coupled oscillator mechanisms for time synchronization in WSNs that will maximize their lifespan. This is achieved by considering the remaining batteries of sensor nodes that are responsive to the breakdown incidence using efficient and dependable methods. To accomplish this objective, the following specific objectives are recognized:

1. To propose a mechanism called Traveling Wave Pulse Coupled Oscillator (TWPCO) using self-organizing mechanism energy efficient WSNs by adopting a traveling wave phenomenon based on phase locking of the PCO model to observe in the flashing synchronization behaviors of fireflies in order to counteract deafness. For this objective, TWPCO was implemented to overcome the deafness by distributing the synchronized message through a random offset, even as the detailed offset is transmitted through the message. Afterwards, the receiver can immediately re-establish synchronization and change the time as a result of the received offset costs.
2. To propose a mechanism called an Energy-efficient Pulse Coupled Oscillator (EEPCO) which is a self-organizing method for energy efficient WSNs by combining both the biologically inspired and non-biologically inspired network systems to utilize the desynchronization method based on the anti-phase of PCO in order to counteract packet collision during transmission and to minimize energy consumption among the sensor nodes. In order to overcome this problem, EEPCO was implemented by enabling the sensor node though self-organization and allocating equally spaced timeslots regardless of the topology or the network size.
3. To propose a mechanism called Random Traveling Wave Pulse Coupled Oscillator (RTWPCO) mechanism, which is a self-organizing technique for energy efficiency WSNs using the phase-locking travelling wave and the random method based on anti-phase of the PCO model. This mechanism was proposed in order to minimize the high-power utilization in the network and get better data gathering of the sensor nodes during data transmission. For this objective, RTWPCO was implemented to overcome the high power by randomly selecting the offset τ_i between 0 and τ^{max}.

1.6 Research Scope

This research concentrates on the energy efficient pulse coupled oscillator as the main task in WSNs, where there are biological inspired system network synchronization behavior and non-biological inspired system network synchronization behavior as a self-organizing method among node communication. The work in this thesis focuses on two types of synchronization behavior among oscillators: phase locking synchronization and anti-phase synchronization.

Moreover, this research used a travelling wave phenomena, desynchronization and random mechanisms, while for desynchronization, it was employed in the three suggested mechanisms. It was also slightly utilized in the second method (EEPCO) during the transmission state process to minimize the energy consumption ratio and make the data-gathering ratio superior.

Finally, all the suggested mechanisms in this research are based on the PCO model that takes into account sensor nodes as observed in the flashing synchronization behaviors of fireflies and secretion of radio signals as firing to counteract the problem that occurs in the transmission state processing.

1.7 Thesis Organization

The rest of the thesis is organized as follows:

Chapter 1 provides a common background of the work reported in this thesis, the motivation and the research problems. It also highlights the research significance and research objectives, and then, it describes the scope of this research.

Chapter 2 introduces a review of state of the art literature of energy efficiency based on the Pulse Coupled Oscillator model for wireless sensor networks. This chapter also gives a summary and organization of energy efficiency issues that operate at different layers. Moreover, it provides the main techniques: non-biologically inspired network systems and biologically inspired network systems by fireflies phenomenon that suits sensor networks, and concentrates on time synchronization that uses the transmission scheduling in WSNs. Furthermore, the chapter explains the concepts and ideas used in previous related work and emphasizes the strengths and limitations of these models.

Chapter 3 describes the research methodology used in this thesis. The chapter also explains our suggested algorithms. In this chapter, the system of the suggested mechanisms is give described through a clarification starting from the pre-process of the current mechanisms to the estimations. The chapter also gives an outline of the environmental resources, experimental parameters, and performance metric used.

Chapter 4 provides a detailed discussion of the structural design and evaluation of the proposed TWPCO method. This chapter also discusses the framework and the most important operations of the traveling wave. It is concluded with the results and the observations of some experiments conducted to confirm and test the proposed method in terms of the transmitting state, efficiency and gathering.

Chapter 5 discuses the proposed EEPCO mechanism and its organization. The EEPCO is a self-organized method. It also presents a new mechanism to deal with the dynamic changes in WSN to counteract packet collision and at the same time, increase the data gathering and minimize the energy efficiency of the system. This chapter also introduces the performance evaluation of the EEPCO developed in this thesis.

Chapter 6 introduces the proposed RTWPCO mechanism by integrating the PCO mechanism with the random method that is based on the application requirements. It also presents and discusses the results and observations of several experiments performed with simulations.

Chapter 7 concludes the whole thesis by describing the main features and capabilities of the proposed methodologies. It also provides several promising directions as guidelines for researchers to carry out future research in this area.

REFERENCES

[1] R. R. Choudhury and N. H. Vaidya. Deafness: A MAC problem in ad hoc networks when using directional antennas. in *Network Protocols, 2004. ICNP 2004. Proceedings of the 12th IEEE International Conference on*, pp. 283-292, 2004.

[2] V. Jain, A. Gupta, and D. P. Agrawal. On-demand medium access in multihop wireless networks with multiple beam smart antennas. *Parallel and Distributed Systems, IEEE Transactions on,* vol. 19, pp. 489-502, 2008.

[3] Y. Taniguchi, G. Hasegawa, and H. Nakano. Self-organizing Transmission Scheduling Considering Collision Avoidance for Data Gathering in Wireless Sensor Networks. *Journal of Communications,* vol. 8, 2013.

[4] A. M Shamsan Saleh, B. Mohd Ali, M. F. A Rasid, and A. Ismail. A Self-Optimizing Scheme for Energy Balanced Routing in Wireless Sensor Networks Using SensorAnt. *Sensors,* vol. 12, pp. 11307-11333, 2012.

[5] M. R. Senouci, A. Mellouk, H. Senouci, and A. Aissani. Performance evaluation of network lifetime spatial-temporal distribution for WSN routing protocols. *Journal of Network and Computer Applications,* vol. 35, pp. 1317-1328, 2012.

[6] R. Hylsberg Jacobsen, Q. Zhang, and T. Skjødeberg Toftegaard. Bioinspired principles for large-scale networked sensor systems: An overview. *Sensors,* vol. 11, pp. 4137-4151, 2011.

[7] L.-H. Zhao, W. Liu, H. Lei, R. Zhang, and Q. Tan. The detection of boundary nodes and coverage holes in wireless sensor networks. *Mobile Information Systems,* vol. 2016, 2016.

[8] G. Sharma, S. Bala, A. Verma, and T. Singh. Security in Wireless Sensor Networks using Frequency Hopping. *International Journal of Computer Applications (0975-8887),* p. 1, 2012.

[9] W. Hui, L. KeZhong, and L. XiaoHui. On Energy-Efficient Node Deployment in Wireless Sensor Networks. *Int'l J. of Communications, Network and System Sciences,* vol. 1, pp. 241-245, 2008.

[10] J. Figueiras and S. Frattasi. Encyclopedia of Wireless and Mobile Communications. 2007.

[11] B. Carter and R. Ragade. Message transformation services for wireless sensor networks (mts-wsn). in *ICWN*, pp. 3-7, 2006.

[12] N. A. Pantazis and D. D. Vergados. A survey on power control issues in wireless sensor networks. *IEEE Communications Surveys and Tutorials,* vol. 9, pp. 86-107, 2007.

[13] S. C. Ergen and P. Varaiya. On multi-hop routing for energy efficiency. *Communications Letters, IEEE,* vol. 9, pp. 880-881, 2005.

[14] Y.-C. Wu, Q. Chaudhari, and E. Serpedin. Clock synchronization of wireless sensor networks. *Signal Processing Magazine, IEEE,* vol. 28, pp. 124-138, 2011.

[15] W. Chu, C. J. Colbourn, and V. R. Syrotiuk. The effects of synchronization on topology-transparent scheduling. *Wireless Networks,* vol. 12, pp. 681-690, 2006.

[16] F. Núñez, Y. Wang, D. Grasing, S. Desai, G. Cakiades, and F. J. Doyle. Pulse-coupled time synchronization for distributed acoustic event detection using wireless sensor networks. *Control Engineering Practice,* vol. 60, pp. 106-117, 2017.

[17] K.-H. Phung, B. Lemmens, M. Mihaylov, L. Tran, and K. Steenhaut. Adaptive Learning Based Scheduling in Multichannel Protocol for Energy-Efficient Data-Gathering Wireless Sensor Networks. *International Journal of Distributed Sensor Networks,* vol. 2013, p. 11, 2013.

[18] S. Wieser, P. L. Montessoro, and M. Loghi. Firefly-Inspired Synchronization of Sensor Networks with Variable Period Lengths. in *Adaptive and Natural Computing Algorithms*, ed: Springer, 2013, pp. 376-385.

[19] A. M. S. Saleh, B. M. Ali, H. Mohamad, M. F. A. Rasid, and A. Ismail. RRSEB: A Reliable Routing Scheme for Energy-balancing Using a Self-adaptive Method in Wireless Sensor Networks. *TIIS,* vol. 7, pp. 1585-1609, 2013.

[20] A. A. Babayo, M. H. Anisi, and I. Ali. A Review on energy management schemes in energy harvesting wireless sensor networks. *Renewable and Sustainable Energy Reviews,* vol. 76, pp. 1176-1184, 2017/09/01/ 2017.

[21] K. S. Kim, S. Lee, and E. G. Lim. On enery-efficient time synchronization based on source clock frequency recovery in wireless sensor networks. *arXiv preprint arXiv:1508.02708,* 2015.

[22] M. K. Stojčev, L. R. Golubović, and T. R. Nikolić. Clocks, power and synchronization in duty-cycled wireless sensor nodes. *Facta universitatis-series: Electronics and Energetics,* vol. 24, pp. 183-208, 2011.

[23] P. Gainer, S. Linker, C. Dixon, U. Hustadt, and M. Fisher. The Power of Synchronisation: Formal Analysis of Power Consumption in Networks of Pulse-Coupled Oscillators. *arXiv preprint arXiv:1709.04385,* 2017.

[24] I. Bekmezci and F. Alagöz. Energy efficient, delay sensitive, fault tolerant wireless sensor network for military monitoring. *International Journal of Distributed Sensor Networks,* vol. 5, pp. 729-747, 2009.

[25] Y. Wang, K. Mosalakanti, F. Núñez, S. Deligeorges, and F. J. Doyle III. A kernel module for pulse-coupled time synchronization of sensor networks. *Computer Networks,* vol. 127, pp. 161-172, 2017.

[26] A. K. Tripathi, A. Agarwal, and Y. Singh. An approach towards secure and multihop time synchronization in wireless sensor network. in *Information and Communication Technologies*, pp. 297-302, 2010.

[27] Mei.L. New advances in clock synchronization for wireless sensor networks. Doctor of Philosophy, Department of Electrical and Electronic Engineering, The University of Hong Kong, 2010.

[28] B. Sundararaman, U. Buy, and A. D. Kshemkalyani. Clock synchronization for wireless sensor networks: a survey. *Ad Hoc Networks,* vol. 3, pp. 281-323, 2005.

[29] T. Schmid, R. Shea, Z. Charbiwala, J. Friedman, M. B. Srivastava, and Y. H. Cho. On the interaction of clocks, power, and synchronization in duty-cycled embedded sensor nodes. *ACM Transactions on Sensor Networks (TOSN),* vol. 7, p. 24, 2010.

[30] D. Mills. Network Time Protocol (Version 3) specification, implementation and analysis. 1992.

[31] D. Mills. Modelling and analysis of computer network clocks. *Electrical Engineering Department Report,* vol. 9252, 1992.

[32] S. B. Moon, P. Skelly, and D. Towsley. Estimation and removal of clock skew from network delay measurements. in *INFOCOM'99. Eighteenth Annual Joint Conference of the IEEE Computer and Communications Societies. Proceedings. IEEE*, pp. 227-234, 1999.

[33] W. Yuan, S. V. Krishnamurthy, and S. K. Tripathi. Synchronization of multiple levels of data fusion in wireless sensor networks. in *Global Telecommunications Conference, 2003. GLOBECOM'03. IEEE*, pp. 221-225, 2003.

[34] E. Waltz and J. Llinas. Multisensor Data Fusion. Norwood, MA, Artech House. Inc, 1990.

[35] S. Madden, R. Szewczyk, M. J. Franklin, and D. Culler. Supporting aggregate queries over ad-hoc wireless sensor networks. in *Mobile Computing Systems and Applications, 2002. Proceedings Fourth IEEE Workshop on*, pp. 49-58, 2002.

[36] D. L. Hall and J. Llinas. An introduction to multisensor data fusion. *Proceedings of the IEEE,* vol. 85, pp. 6-23, 1997.

[37] F. Heidarian, J. Schmaltz, and F. Vaandrager. Analysis of a clock synchronization protocol for wireless sensor networks. *Theoretical Computer Science,* vol. 413, pp. 87-105, 2012.

[38] O. Chipara, C. Lu, J. Stankovic, and C.-G. Roman. Dynamic conflict-free transmission scheduling for sensor network queries. *Mobile Computing, IEEE Transactions on,* vol. 10, pp. 734-748, 2011.

[39] C. Gao, I. Kivelä, X. Tan, and I. Hakala. A transmission scheduling for data-gathering wireless sensor networks. in *Ubiquitous Intelligence & Computing and 9th International Conference on Autonomic & Trusted Computing (UIC/ATC), 2012 9th International Conference on*, pp. 292-297, 2012.

[40] F. Ferrante and Y. Wang. Robust Almost Global Splay State Stabilization of Pulse Coupled Oscillators. *IEEE Transactions on Automatic Control,* vol. 62, pp. 3083-3090, 2017.

[41] M. K. Maggs, S. G. O'Keefe, and D. V. Thiel. Consensus clock synchronization for wireless sensor networks. *Sensors Journal, IEEE,* vol. 12, pp. 2269-2277, 2012.

[42] F. Sivrikaya and B. Yener. Time synchronization in sensor networks: a survey. *Network, IEEE,* vol. 18, pp. 45-50, 2004.

[43] A. P. Probability. Random Variables and Stochastic Processes. McGraw-Hill International Editions, 1991.

[44] A. Leon-Garcia. *Probability and random processes for electrical engineering* vol. 2: Addison-Wesley Reading, 1994.

[45] C. Bovy, H. Mertodimedjo, G. Hooghiemstra, H. Uijterwaal, and P. Van Mieghem. Analysis of end-to-end delay measurements in Internet. in *Proc. of the Passive and Active Measurement Workshop-PAM'2002*, 2002.

[46] H. S. Abdel-Ghaffar. Analysis of synchronization algorithms with time-out control over networks with exponentially symmetric delays. *Communications, IEEE Transactions on,* vol. 50, pp. 1652-1661, 2002.

[47] G. J. Pottie and W. J. Kaiser. Wireless integrated network sensors. *Communications of the ACM,* vol. 43, pp. 51-58, 2000.

[48] H. Cho, J. Kim, and Y. Baek. Enhanced precision time synchronization for wireless sensor networks. *Sensors,* vol. 11, pp. 7625-7643, 2011.

[49] I. Skog and P. Handel. Synchronization by Two-Way Message Exchanges: Cramér-Rao Bounds, Approximate Maximum Likelihood, and Offshore

Submarine Positioning. *Signal Processing, IEEE Transactions on,* vol. 58, pp. 2351-2362, 2010.

[50] S. Ganeriwal, R. Kumar, and M. B. Srivastava. Timing-sync protocol for sensor networks. in *Proceedings of the 1st international conference on Embedded networked sensor systems*, pp. 138-149, 2003.

[51] J. Van Greunen and J. Rabaey. Lightweight time synchronization for sensor networks. in *Proceedings of the 2nd ACM international conference on Wireless sensor networks and applications*, pp. 11-19, 2003.

[52] P. Jinlin, Z. Li, D. McLernon, and W. Jibo. A novel receiver-receiver time synchronization scheme for femtocells. in *Wireless Communication Systems (ISWCS), 2010 7th International Symposium on*, pp. 937-940, 2010.

[53] J. Elson, L. Girod, and D. Estrin. Fine-grained network time synchronization using reference broadcasts. *ACM SIGOPS Operating Systems Review,* vol. 36, pp. 147-163, 2002.

[54] H. Dai and R. Han. TSync: a lightweight bidirectional time synchronization service for wireless sensor networks. *ACM SIGMOBILE Mobile Computing and Communications Review,* vol. 8, pp. 125-139, 2004.

[55] K.-L. Noh, E. Serpedin, and K. Qaraqe. A new approach for time synchronization in wireless sensor networks: Pairwise broadcast synchronization. *Wireless Communications, IEEE Transactions on,* vol. 7, pp. 3318-3322, 2008.

[56] M. R. Kosanovic and M. K. Stojcev. Delay compensation method for time synchronization in wireless sensor networks. in *Telecommunication in Modern Satellite Cable and Broadcasting Services (TELSIKS), 2011 10th International Conference on*, pp. 623-629, 2011.

[57] M. Maróti, B. Kusy, G. Simon, and Á. Lédeczi. The flooding time synchronization protocol. in *Proceedings of the 2nd international conference on Embedded networked sensor systems*, pp. 39-49, 2004.

[58] S. Ganeriwal, C. Pöpper, S. Čapkun, and M. B. Srivastava. Secure time synchronization in sensor networks. *ACM Transactions on Information and System Security (TISSEC),* vol. 11, p. 23, 2008.

[59] D. Mills, J. Martin, J. Burbank, and W. Kasch. Network time protocol version 4: Protocol and algorithms specification. 2070-1721, 2010.

[60] J. Reis and N. B. Carvalho. Synchronization and syntonization of wireless sensor networks. presented at the Wireless Sensors and Sensor Networks (WiSNet), 2013 IEEE Topical Conference on, 2013.

[61] H. Karl and A. Willig. *Protocols and architectures for wireless sensor networks*: Wiley-Interscience, 2007.

[62] C. Olariu, J. Fitzpatrick, P. Perry, and L. Murphy. A QoS based call admission control and resource allocation mechanism for LTE femtocell deployment. in *Consumer Communications and Networking Conference (CCNC), 2012 IEEE*, pp. 884-888, 2012.

[63] D. Kielpinski, C. Monroe, and D. J. Wineland. Architecture for a large-scale ion-trap quantum computer. *Nature,* vol. 417, pp. 709-711, 2002.

[64] D. M. Ingram, P. Schaub, and D. A. Campbell. Use of Precision Time Protocol to Synchronize Sampled-Value Process Buses. *Instrumentation and Measurement, IEEE Transactions on,* vol. 61, pp. 1173-1180, 2012.

[65] M. Kassouf, L. Dupont, J. Béland, and A. Fadlallah. Performance of the Precision Time Protocol for clock synchronisation in smart grid applications. *Transactions on Emerging Telecommunications Technologies,* vol. 24, pp. 476-485, 2013.

[66] P. Moinzadeh, K. Mechitov, R. Shiftehfar, T. Abdelzaher, G. Agha, and B. F. Spencer. The time-keeping anomaly of energy-saving sensors: Manifestation, solution, and a structural monitoring case study. in *Sensor, Mesh and Ad Hoc Communications and Networks (SECON), 2012 9th Annual IEEE Communications Society Conference on*, pp. 380-388, 2012.

[67] B. Kusy, P. Dutta, P. Levis, M. Maroti, A. Ledeczi, and D. Culler. Elapsed time on arrival: a simple and versatile primitive for canonical time synchronisation services. *International Journal of Ad Hoc and Ubiquitous Computing,* vol. 1, pp. 239-251, 2006.

[68] B. Lemmens, K. Steenhaut, P. Ruckebusch, I. Moerman, and A. Nowe. Network-wide synchronization in Wireless Sensor Networks. in *Communications and Vehicular Technology in the Benelux (SCVT), 2012 IEEE 19th Symposium on*, pp. 1-5, 2012.

[69] J. Wu, L. Jiao, and R. Ding. Average time synchronization in wireless sensor networks by pairwise messages. *Computer Communications,* vol. 35, pp. 221-233, 2012.

[70] K. Keswani and A. Bhaskar. WIRELESS SENSOR NETWORKS: A SURVEY. *Futuristic Trends in Engineering, Science, Humanities, and Technology FTESHT-16,* p. 1, 2016.

[71] S. Zahurul, N. Mariun, I. V. Grozescu, H. Tsuyoshi, Y. Mitani, M. L. Othman, H. Hizam, and I. Z. Abidin. Future strategic plan analysis for integrating distributed renewable generation to smart grid through wireless sensor network: Malaysia prospect. *Renewable and Sustainable Energy Reviews,* vol. 53, pp. 978-992, 2016/01/01/ 2016.

[72] F. K. Shaikh and S. Zeadally. Energy harvesting in wireless sensor networks: A comprehensive review. *Renewable and Sustainable Energy Reviews,* vol. 55, pp. 1041-1054, 2016/03/01/ 2016.

[73] S. S. R. Kawale and A. Makandar. Enhancing Energy Efficiency in WSN. *International Research Journal of Engineering and Technology (IRJET),* vol. 02, 2015.

[74] S. Watwe and R. Hansdah. Improving the energy efficiency of a clock synchronization protocol for WSNs using a TDMA-based MAC protocol. in *2015 IEEE 29th International Conference on Advanced Information Networking and Applications (AINA)*, pp. 231-238, 2015.

[75] N. Nokhanji, Z. M. Hanapi, S. Subramaniam, and M. A. Mohamed. An Energy Aware Distributed Clustering Algorithm Using Fuzzy Logic for Wireless Sensor Networks with Non-uniform Node Distribution. *Wireless Personal Communications,* pp. 1-25, 2015.

[76] L. S. Annabel and K. Murugan. Energy-Efficient Quorum-Based MAC Protocol for Wireless Sensor Networks. *ETRI Journal,* vol. 37, pp. 480-490, 2015.

[77] L. Robert and E. Wilfried. Firefly clock synchronization in an 802.15. 4 wireless network. *EURASIP Journal on Embedded Systems,* vol. 2009, 2009.

[78] M. A. Sarvghadi and T.-C. Wan. Message passing based time synchronization in wireless sensor networks: a survey. *International Journal of Distributed Sensor Networks,* vol. 12, p. 1280904, 2016.

[79] I. L. M. S. Committee. Wireless LAN medium access control (MAC) and physical layer (PHY) specifications. *IEEE Standard,* vol. 802, p. 999, 1999.

[80] E. Karapistoli, I. Gragopoulos, I. Tsetsinas, and F.-N. Pavlidou. A MAC protocol for low-rate UWB wireless sensor networks using directional antennas. *Computer Networks,* vol. 53, pp. 961-972, 2009.

[81] G. EkbataniFard and R. Monsefi. A detailed review of multi-channel medium access control protocols for wireless sensor networks. *International Journal of Wireless Information Networks,* vol. 19, pp. 1-21, 2012.

[82] C. A. Richmond. Fireflies flashing in unison. *Science,* vol. 71, pp. 537-538, 1930.

[83] R. E. Mirollo and S. H. Strogatz. Synchronization of pulse-coupled biological oscillators. *SIAM Journal on Applied Mathematics,* vol. 50, pp. 1645-1662, 1990.

[84] A. Tyrrell and G. Auer. Imposing a reference timing onto firefly synchronization in wireless networks. in *Vehicular Technology Conference, 2007. VTC2007-Spring. IEEE 65th*, pp. 222-226, 2007.

[85] N. Wakamiya and M. Murata. Synchronization-based data gathering scheme for sensor networks. *IEICE Transactions on Communications,* vol. 88, pp. 873-881, 2005.

[86] O. Babaoglu, T. Binci, M. Jelasity, and A. Montresor. Firefly-inspired heartbeat synchronization in overlay networks. in *Self-Adaptive and Self-Organizing Systems, 2007. SASO'07. First International Conference on*, pp. 77-86, 2007.

[87] R. R. Choudhury, X. Yang, R. Ramanathan, and N. H. Vaidya. Using directional antennas for medium access control in ad hoc networks. in *Proceedings of the 8th annual international conference on Mobile computing and networking*, pp. 59-70, 2002.

[88] T. Korakis, G. Jakllari, and L. Tassiulas. A MAC protocol for full exploitation of directional antennas in ad-hoc wireless networks. in *Proceedings of the 4th ACM international symposium on Mobile ad hoc networking & computing*, pp. 98-107, 2003.

[89] M. Takata, K. Nagashima, and T. Watanabe. A dual access mode MAC protocol for ad hoc networks using smart antennas. in *Communications, 2004 IEEE International Conference on*, pp. 4182-4186, 2004.

[90] M. Takata, M. Bandai, and T. Watanabe. A receiver-initiated directional MAC protocol for handling deafness in ad hoc networks. in *Communications, 2006. ICC'06. IEEE International Conference on*, pp. 4089-4095, 2006.

[91] V. Jain and D. P. Agrawal. Mitigating deafness in multiple beamforming antennas. in *Sarnoff Symposium, 2006 IEEE*, pp. 1-4, 2006.

[92] T. Korakis, G. Jakllari, and L. Tassiulas. CDR-MAC: A protocol for full exploitation of directional antennas in ad hoc wireless networks. *Mobile Computing, IEEE Transactions on,* vol. 7, pp. 145-155, 2008.

[93] O. Lanford III and S. Mintchev. Stability of a family of travelling wave solutions in a feedforward chain of phase oscillators. *Nonlinearity,* vol. 28, p. 237, 2015.

[94] G. Lv and M. Wang. Traveling waves of some integral-differential equations arising from neuronal networks with oscillatory kernels. *Journal of Mathematical Analysis and Applications,* vol. 370, pp. 82-100, 2010.

[95] F. Nunez, Y. Wang, A. R. Teel, and F. J. Doyle. Synchronization of pulse-coupled oscillators to a global pacemaker. *Systems & Control Letters,* vol. 88, pp. 75-80, 2016.

[96] F. Nunez, Y. Wang, and F. Doyle. Bio-inspired hybrid control of pulse-coupled oscillators and application to synchronization of a wireless network. in *American Control Conference (ACC)*, pp. 2818-2823, 2012.

[97] P. Goel and B. Ermentrout. Synchrony, stability, and firing patterns in pulse-coupled oscillators. *Physica D: Nonlinear Phenomena,* vol. 163, pp. 191-216, 2002.

[98] J. Nishimura. Frequency adjustment and synchrony in networks of delayed pulse-coupled oscillators. *Physical Review E,* vol. 91, p. 012916, 2015.

[99] P. Chatterjee and N. Das. A cross-layer distributed TDMA scheduling for data gathering with minimum latency in wireless sensor networks. in *Wireless Communication, Vehicular Technology, Information Theory and Aerospace & Electronic Systems Technology, 2009. Wireless VITAE 2009. 1st International Conference on*, pp. 813-817, 2009.

[100] T. Anglea and Y. Wang. Phase Desynchronization: A New Approach and Theory Using Pulse-Based Interaction. *IEEE Trans. Signal Processing,* vol. 65, pp. 1160-1171, 2017.

[101] H. Gao and Y. Wang. Analysis and design of phase desynchronization in pulse-coupled oscillators. *arXiv preprint arXiv:1603.03313,* 2016.

[102] R. Srivastava and C. E. Koksal. Energy optimal transmission scheduling in wireless sensor networks. *Wireless Communications, IEEE Transactions on,* vol. 9, pp. 1550-1560, 2010.

[103] A. Kamimura and K. Tomita. A self-organizing network coordination framework enabling collision-free and congestion-less wireless sensor networks. *Journal of Network and Computer Applications,* vol. 93, pp. 228-244, 2017/09/01/ 2017.

[104] J. Buck. Synchronous rhythmic flashing of fireflies. II. *Quarterly Review of Biology,* pp. 265-289, 1988.

[105] A. Tyrrell, G. Auer, and C. Bettstetter. Biologically inspired synchronization for wireless networks. *Advances in Biologically Inspired Information Systems,* pp. 47-62, 2007.

[106] A. Tyrrell, G. Auer, and C. Bettstetter. Biologically inspired synchronization for wireless networks. in *Advances in Biologically Inspired Information Systems*, ed: Springer, 2007, pp. 47-62.

[107] G. Werner-Allen, G. Tewari, A. Patel, M. Welsh, and R. Nagpal. Firefly-inspired sensor network synchronicity with realistic radio effects. in *Proceedings of the 3rd international conference on Embedded networked sensor systems*, pp. 142-153, 2005.

[108] R. Leidenfrost and W. Elmenreich. Establishing wireless time-triggered communication using a firefly clock synchronization approach. in *Intelligent Solutions in Embedded Systems, 2008 International Workshop on*, pp. 1-18, 2008.

[109] R. Pagliari and A. Scaglione. Scalable network synchronization with pulse-coupled oscillators. *Mobile Computing, IEEE Transactions on,* vol. 10, pp. 392-405, 2011.

[110] Y. Wang, F. Nunez, and F. J. Doyle. Energy-efficient pulse-coupled synchronization strategy design for wireless sensor networks through reduced idle listening. *Signal Processing, IEEE Transactions on,* vol. 60, pp. 5293-5306, 2012.

[111] J. Degesys, I. Rose, A. Patel, and R. Nagpal. DESYNC: self-organizing desynchronization and TDMA on wireless sensor networks. in *Proceedings of the 6th international conference on Information processing in sensor networks*, pp. 11-20, 2007.

[112] D. Buranapanichkit, N. Deligiannis, and Y. Andreopoulos. Convergence of desynchronization primitives in wireless sensor networks: A stochastic modeling approach. *Signal Processing, IEEE Transactions on,* vol. 63, pp. 221-233, 2015.

[113] Y. Taniguchi, N. Wakamiya, and M. Murata. A traveling wave based communication mechanism for wireless sensor networks. *Journal of Networks,* vol. 2, pp. 24-32, 2007.

[114] H. Yamamoto, N. Wakamiya, and M. Murata. An Inter-Networking Mechanism with Stepwise Synchronization for Wireless Sensor Networks. *Sensors,* vol. 11, pp. 8241-8260, 2011.

[115] F. Wang and J. Liu. Networked wireless sensor data collection: issues, challenges, and approaches. *Communications Surveys & Tutorials, IEEE,* vol. 13, pp. 673-687, 2011.

[116] A. Díaz, P. Sanchez, J. Sancho, and J. Rico. Wireless sensor network simulation for security and performance analysis. in *Proceedings of the Conference on Design, Automation and Test in Europe*, pp. 432-435, 2013.

[117] P. Neves, J. Fonsec, and J. Rodrigue. Simulation tools for wireless sensor networks in medicine: a comparative Study. in *International Joint Conference on Biomedical Engineering Systems and Technologies, Funchal, Madeira-Portugal*, 2007.

[118] M. Fernandez, S. Wahle, and T. Magedanz. A new approach to ngn evaluation integrating simulation and testbed methodology. in *Proceedings of the The Eleventh International Conference on Networks (ICN12)*, 2012.

[119] E. Weingärtner, H. Vom Lehn, and K. Wehrle. A performance comparison of recent network simulators. in *Communications, 2009. ICC'09. IEEE International Conference on*, pp. 1-5, 2009.

[120] A. Rastegarnia and V. Solouk. Performance evaluation of castalia wireless sensor network simulator. in *Telecommunications and Signal Processing (TSP), 2011 34th International Conference on*, pp. 111-115, 2011.

[121] Crossbow: Mica, Mica2, Mica2Dot, MicaZ Datasheets. http://www.xbow.com.

[122] M. Fruth. Probabilistic Model Checking of Contention Resolution in the IEEE 802.15.4 Low-Rate Wireless Personal Area Network Protocol. in *Leveraging Applications of Formal Methods, Verification and Validation, 2006. ISoLA 2006. Second International Symposium on*, pp. 290-297, 2006.

[123] K. Kim, S.-h. Shin, and B.-h. Roh. Firing Offset Adjustment of Bio-Inspired DESYNC-TDMA to Improve Slot Utilization Performances in Wireless Sensor Networks. *KSII Transactions on Internet & Information Systems,* vol. 11, 2017.

[124] F. Ishmanov, A. S. Malik, and S. W. Kim. Energy consumption balancing (ECB) issues and mechanisms in wireless sensor networks (WSNs): a comprehensive overview. *European Transactions on Telecommunications,* vol. 22, pp. 151-167, 2011.

[125] Y. Taniguchi, G. Hasegawa, and H. Nakano. Self-organizing transmission scheduling mechanisms using a pulse-coupled oscillator model for wireless sensor networks. in *Digital Information Processing and Communications (ICDIPC), 2012 Second International Conference on*, pp. 84-89, 2012.

[126] Y. D. Sato, K. Okumura, A. Ichiki, and M. Shiino. Thermal effects on phase response curves and synchronization transition. in *Advances in Neural Networks–ISNN 2011*, ed: Springer, 2011, pp. 287-296.

[127] S. Achuthan and C. C. Canavier. Phase-resetting curves determine synchronization, phase locking, and clustering in networks of neural oscillators. *The Journal of Neuroscience,* vol. 29, pp. 5218-5233, 2009.

[128] G. B. Ermentrout, L. Glass, and B. E. Oldeman. The shape of phase-resetting curves in oscillators with a saddle node on an invariant circle bifurcation. *Neural Computation,* vol. 24, pp. 3111-3125, 2012.

[129] Y. Taniguchi, N. Wakamiya, and M. Murata. A communication mechanism using traveling wave phenomena for wireless sensor networks. in *World of Wireless, Mobile and Multimedia Networks, 2007. WoWMoM 2007. IEEE International Symposium on a*, pp. 1-6, 2007.

[130] Y. Wang and F. J. Doyle. Optimal phase response functions for fast pulse-coupled synchronization in wireless sensor networks. *Signal Processing, IEEE Transactions on,* vol. 60, pp. 5583-5588, 2012.

[131] C. Z. Zulkifli, N. M. Noor, A. Zamzuri, M. Ali, and S. N. Semunab. UTILIZING ACTIVE RFID ON WIRELESS SENSOR NETWORK PLATFORM FOR PRODUCTION MONITORING. *JURNAL TEKNOLOGI,* vol. 78, pp. 63-72, 2016.

[132] O. D. Incel, A. Ghosh, and B. Krishnamachari. Scheduling algorithms for tree-based data collection in wireless sensor networks. in *Theoretical aspects of distributed computing in sensor networks*, ed: Springer, 2011, pp. 407-445.

[133] G. Lu, B. Krishnamachari, and C. S. Raghavendra. An adaptive energy-efficient and low- latency MAC for tree- based data gathering in sensor networks. *Wireless Communications and Mobile Computing,* vol. 7, pp. 863-875, 2007.