EFFICIENT COMMUNICATION THROUGH MULTI-CHANNEL TIME DIVISION MULTIPLE ACCESS FOR WIRELESS SENSOR NETWORK

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A thesis submitted in fulfillment of the
requirements for the award of the degree of
Master of Science (Computer Science)

Faculty of Computer Science and Information Systems
Universiti Teknologi Malaysia

JUNE 2012

Dedicated to my beloved mother

ACKNOWLEDGEMENT

All praise unto Allah for everything I have. I would like to thank the following persons who accompanied me during the time I was working for this degree.

In preparing this thesis, I was in contact with many people, researchers, academicians, and practitioners. They have contributed towards my understanding and thoughts. In particular, I wish to express my sincere appreciation to my thesis supervisor, Assoc. Prof. Dr. Kamalrulnizam Abu Bakar, for encouragement, guidance, critics and advice till the end of glorious successful work.

My fellow postgraduate students should also be recognized for their support. My sincere appreciation also extends to all my colleagues, En. Herman, Oon Erixno, Yoanda Alim Syahbana, M. Gary Shaffer, and others who have provided assistance at various occasions. Their views and tips are useful indeed. Unfortunately, it is not possible to list all of them in this limited space.

I am grateful to all my family members, especially my mother ‘Erlina’, and my brother ‘Aip’ for their prayers and moral support. I also deeply thanks to my wife ‘Asna Ningsih’ for her prayer, advice and moral support.

ABSTRACT

Network congestion is an essential issue to be addressed in Wireless Sensor Network (WSN). Congestion degrades network performance in terms of packet throughput and throughput fairness. This is mainly caused by collisions and traffic imbalance. To reduce network congestion, three mechanisms to minimize the problem are proposed. Firstly, a load balancing strategy is deployed into mechanism of network self-organizing. The strategy addresses the issue of traffic imbalance. Secondly, the implementation of hop by hop flow control allowing sensor nodes to detect congested nodes and suspend their data transmission until the congested nodes are ready to receive data. Finally, a mechanism for reducing collisions through multi-channel Time Division Multiple Access (TDMA) is deployed in the Medium Access Control (MAC) layer. These mechanisms are realized in a dedicated WSN protocol called Multi-Channel Time Division Multiple Access – Cross Layer Protocol (MT-XLP). Design of the MT-XLP involved the Medium Access Control (MAC) and routing layers. The first layer manages the mechanisms for channel assignment, time slot allocation, and time synchronization to provide communication links and reduce collisions in the network. The second layer manages the load balancing and hop by hop flow control mechanisms. A series of experiments to measure packet throughput and index of throughput fairness were conducted using a number of sensor nodes and one sink node that installed with the MT-XLP protocol. The results were compared with result from the identical experiments that use IEEE 802.15.4/ZigBee protocol. The comparison showed that MT-XLP is able to provide packet throughput that are two times larger and has a larger index of throughput fairness in comparison to IEEE 8021.5.4/ZigBee.

ABSTRAK

Kesesakan rangkaian merupakan satu isu penting dalam rangkaian sensor tanpa wayar (WSN). Ia mengurangkan prestasi rangkaian dalam jangka kadar purata keberhasilan penghantaran paket dan keadilan kadar purata keberhasilan penghantaran. Kesesakan rangkaian disebabkan oleh perlanggaran dan ketidakseimbangan trafik. Kajian ini telah menggabungkan tiga mekanisme untuk mengurangkan kesesakan rangkaian. Di dalam mekanisme pertama, ia mengurangkan kesesakan rangkaian dengan melaksanakan strategi pengimbangan beban ke dalam mekanisme penganjuran rangkaian sendiri. Strategi ini bertujuan untuk menangani isu ketidakseimbangan trafik. Seterusnya di dalam mekanisme kedua, ia mengurangkan kesesakan rangkaian dengan melaksanakan kawalan aliran secara bertingkat. Mekanisme ini membolehkan nod sensor mengesan kesesakan node dan menangguhkan penghantaran data sehingga nod bersedia untuk menerima data. Akhirnya, mekanisme ketiga mengurangkan kesesakan rangkaian dengan cara mengurangkan perlanggaran melalui berbilang saluran *Time Division Multiple Access* (TDMA) yang digunakan pada lapisan medium kawalan akses (MAC). Mekanisme ini direalisasikan dalam protokol khas WSN yang dipanggil *Multi-Channel Time Division Multiple Access - Cross Layer Protocol* (MT-XLP). Reka bentuk MT-XLP melibatkan lapisan medium kawalan akses (MAC) dan lapisan penghalaan. Lapisan MAC menguruskan mekanisme bagi penguntukan saluran slot masa, dan penyegerakan masa untuk menyediakan pautan komunikasi dalam rangkaian dan mengurangkan pelanggaran. Manakala, lapisan penghalaan menguruskan mekanisme untuk pengimbangan beban dan kawalan aliran secara bertingkat. Beberapa siri ujikaji telah di laksanakan untuk mengukur kadar purata keberhasilan penghantaran paket dan indeks keadilan kadar purata keberhasilan penghantaran dengan menggunakan beberapa nod sensor dan satu nod sink yang telah di lengkapi dengan protocol MT-XLP. Prestasi MT-XLP telah dinilai dalam jangka kadar purata keberhasilan penghantaran paket dan indeks keadilan kadar purata keberhasilan penghantaran. Ia juga telah ditanda aras berbanding dengan IEEE 802.15.4/ZigBee. Berdasarkan kaji yang dijalankan, MT-XLP dapat menyediakan kadar purata keberhasilan penghantaran paket dan indeks keadilan kadar purata keberhasilan penghantaran lebih daripada dua kali ganda jika dibandingkan dengan IEEE 8021.5.4/ZigBee.

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LIST OF ABBREVIATIONS

Ack	-	Acknowledgement
ADC	-	Analog to Digital Converter
APL	-	Application
AODV	-	Ad hoc On Demand Distance Vector
BFC	-	Breath First Search
CA	-	Collision Avoidance
CAP	-	Contention Access Period
CCA	-	Clear Channel Assessment
CDMA	-	Code Division Multiple Access
CFP	-	Contention Free Period
CHc	-	Child Channel
CHp	-	Parent Channel
CN	-	Child Nodes
CSMA	-	Carrier-Sense Multiple Access
CSMA/CA	-	Carrier Sense Multiple Access with Collision Avoidance
CTS	-	Clear to Send
DTROC	-	Distributed TDMA Receiver-Oriented Channeling
ED	-	Energy Detection
EEPROM	-	Electrically Erasable Programmable Read Only Memory
FDMA	-	Frequency Division Multiple Access
FFD	-	Full-Function Devices
FIFO	-	First In First Out
GTS	-	Guaranteed Time Slots
HC	-	Hop Count
ID	-	Identity
IEEE	-	Institute of Electrical and Electronics Engineers

ISM	-	Industrial, Scientific, and Medical
GPS	-	Global Positioning System
GT	-	Guard Time
JR	-	Joint Request
KB	-	Kilo Byte
Kbps	-	Kilo bit per second
LEACH	-	Low Energy Adaptive Clustering Hierarchy
LLC	-	Logical Link Control
L-MAC	-	Lightweight Medium Access Control
LQI	-	Link Quality Indication
MAC	-	Medium Access Control
Mbps	-	Mega bit per second
MINA	-	Multi-hop Infrastructure Network Architecture
MMSN	-	Multi frequency media access control for WSN
MT-XLP	-	Multi-channel TDMA-based Cross Layer Protocol
NWK	-	Network
O-QPSK	-	Offset Quadrature Phase Shift Keying
PAN	-	Personal Area Network
PHY	-	Physical
QoS	-	Quality of Service
RF	-	Radio Frequency
RFD	-	Reduce-Function Devices
RREP	-	Route Reply
RREQ	-	Route Request
RTP/RTCP	-	Real-time Trans- port protocol
RTS	-	Request to Send
SAP	-	Service Access Point
SB	-	Super-frame Beacon
SDMA	-	Space Division Multiple Access
SRAM	-	Static Random Access Memory
SSCS	-	Service Specific Convergence Sub-layer
TCP/IP	-	Transmission Control Protocol/ Internet Protocol
TDMA	-	Time Division Multiple Access
UART	-	Universal Asynchronous Receiver/ Transmitter

UNPF	-	Unified Network Protocol Framework
USB	-	Universal serial Bus
WSN	-	Wireless Sensor Network

CHAPTER 1

INTRODUCTION

1.1 Overview of Wireless Sensor Network

Wireless Sensor Network (WSN) is a fully autonomous self-configuring ad-hoc network (Kohvakka, 2006). It comprises large number of sensor nodes which are capable to sense their environment, to process data, and to communicate with other sensor nodes (Jovanovic and Djordjevic, 2007; Wen *et al.*, 2011).

The sensor nodes are densely distributed in monitoring area. They collect data from the monitoring area and route the data back to sink node or base station. Data are routed back to the sink node by a multi-hop infrastructure-less network. Typical architecture of WSN is depicted in Figure 1.1.

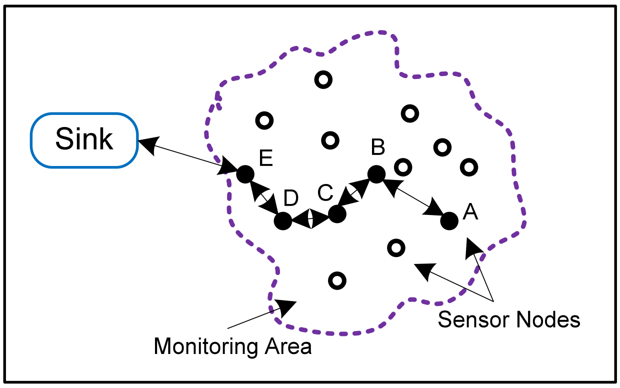

Figure 1.1 Typical architecture of WSN

A sensor node, also called node, typically contains a sensing unit, processing unit, communication unit, and power unit (Silva *et al*., 2004; Heinzelman, 2000; Al-Karaki and Kamal, 2004). The sensing unit comprises some kinds of sensor to sense physical parameters in monitoring area and convert the parameters' value into analog signal. Then, the analog signal is digitized by Analog to Digital Converter (ADC) to provide digital data for processing unit. In the processing unit, the digital data is processed to generate real value of the physical parameters. The processing unit generally consists of processor and memory. Data from processing unit is transmitted to sink node through communication unit that involves a wireless transceiver. The power unit is responsible to supply energy for the aforementioned units by utilizing energy from power supply. In addition, the sensor node may be optionally equipped with mobilizer and position finding system such as Global Positioning System (GPS). Figure 1.2 illustrates block diagram of sensor node components.

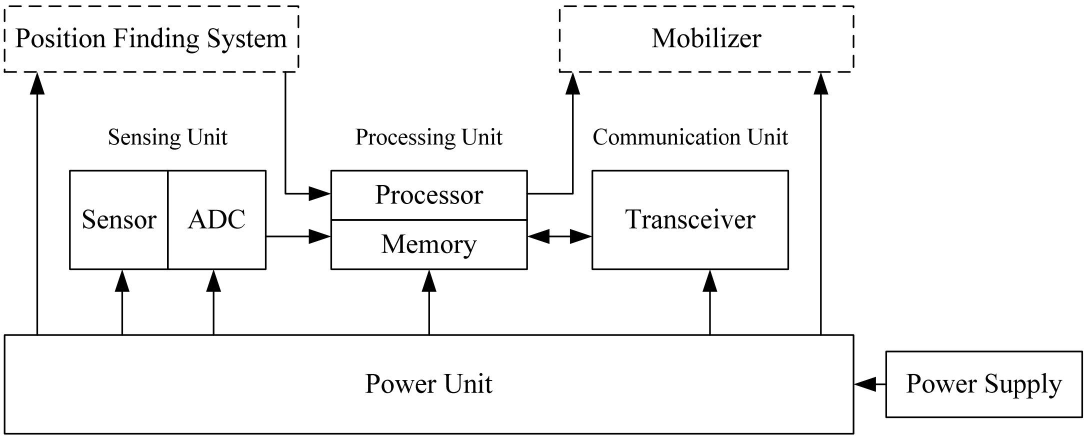

Figure 1.2 Sensor node components (Akyildiz *et al*., 2002)

Substantial progresses in micro-electronic devices, wireless communication, and embedded computing have encouraged the emergence of WSN technology. Several WSN researches have been widely studied and implemented in many applications and in various areas. Research by Mainwaring *et al.* (2002) implemented WSN to monitor behavior of nesting seabirds and their habitat in Great Duck Island, Maine, United States. Another research by Li and Liu (2007) developed a WSN system named Structure-Aware Self-Adaptive (SASA) for underground monitoring in coal mines. Wang *et al.* (2007) developed a WSN application for intensive irrigated agriculture. In 2008, Chi *et al*. researched and implemented WSN for surveillance system to monitor environmental condition in green house. The numerous research areas of WSN are summarized as shown in Figure 1.3.

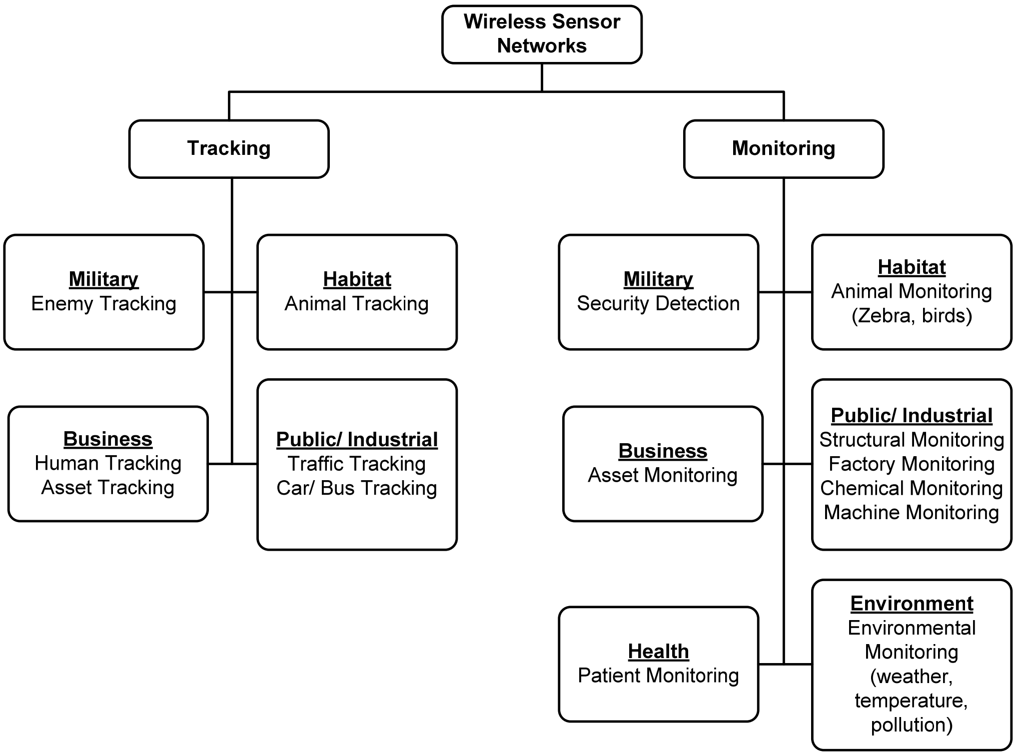

Figure 1.3 Various applications and areas of WSN implementation (Yick *et al*., 2008)

A WSN design should consider several issues (Li *et al*., 2007). Sensor node is scarce of energy since it is powered by battery. Hardware components that used should have low power consumption. However, the use of low power components such as low power processor and low power transceiver tends to decrease performance of sensor node. It is well known that low power processor has low computational capability and low memory capacity, while low power transceiver has short range of transmission.

Typical deployments of WSN involve large number of sensor nodes. A scalable WSN protocol should be able to keep its performance from small to large number of sensor nodes that deployed in monitoring area. It should be also resistant to the changes of network topology that frequently happened due to appearance or disappearance of sensor nodes. These characteristics lead the network scalability to become an essential issue in WSN.

Another issue that also essential is network performance. It relates to ability of the network to provide reliable data delivery service for sensor nodes. There are several parameters indicate the network performance, among of them are packet throughput, packet loss, packet delay, throughput fairness, and network reliability.

1.2 Motivation

The advanced development in microelectronics and communication technologies have emerged mass production of low power sensor node. Generally, the low power sensor node comprises lightweight processor and low power transceiver that also known as tiny node. This composition allows the tiny node to have lower energy consumption as well as production cost.

Tiny node is often used in many monitoring applications that involve large number of sensor nodes. The monitoring applications require data to be sent periodically. Traffic direction flows from sensor nodes to sink node (multi-to-one uplink traffic). In these applications, high traffic load may flows from sensor nodes to sink node because large number of sensor nodes periodically send their data to the sink node. The high traffic load in multi-to-one uplink traffic leads to cause network congestion, especially when it involves multi-hops data transmission. Sensor nodes that closer to sink node (in term of number of hops to sink node) are more potential to suffer from congested.

Network congestion occurs when available capacity at any point in a network cannot accommodate high traffic that flows in the network. According to Hull, *et al*. (2004) network congestion in wireless sensor network leads to the degradation of packet throughput and index of throughput fairness in data transmission. Good packet throughput is important because it indicates the number of packet that eventually received by sink node (also called useful packet). Similar to packet throughput, good index of throughput fairness is also important since it affects the validity of information received. It is better to receive small number of packets from N sensor nodes that spread out across monitoring area than receive large number of packets from one sensor node.

Considering the significant impact of network congestion to network performance, in term of packet throughput and index of throughput fairness, this research is carried out to study the network congestion. The study intends to design mechanisms for minimizing network congestion in order to provide an efficient communication for WSN.

1.3 Background of the Problem

Wireless Sensor Network (WSN) has been widely implemented in various monitoring applications. There are some specific characteristics of WSN in monitoring applications. Typically, a monitoring application uses large number of sensor nodes to derive information from the whole monitoring area. Information or packet data is sent from sensor node to sink node periodically. To conserve energy and to minimize production cost, the monitoring application usually uses tiny nodes that have lightweight processor and low power transceiver.

The lightweight processor copes with some limitations such as low processing speed and low memory capacity. Low computational capability is implication of these limitations. On the other hand, the low power transceiver cuts down sensor node coverage and communication range. To deal with low computational capability, the sensor nodes should be run with lightweight protocol. The lightweight protocol may be defined as a protocol with low complexity and relatively small control overhead. To address the communication range issue, the sensor nodes may use multi-hop short transmission. The multi-hop short transmission enables a sensor node to receive and forward data from other sensor nodes. In other words, besides sense their environment, the sensor node also acts as a router.

The characteristics of WSN, that are using large number of tiny nodes and transmitting data periodically through multi-hop short transmission, lead to the increase of network traffic. High traffic in the network may cause network congestion that will degrade network performance in term of packet throughput and throughput fairness. Figure 1.4 illustrates background of the problem.

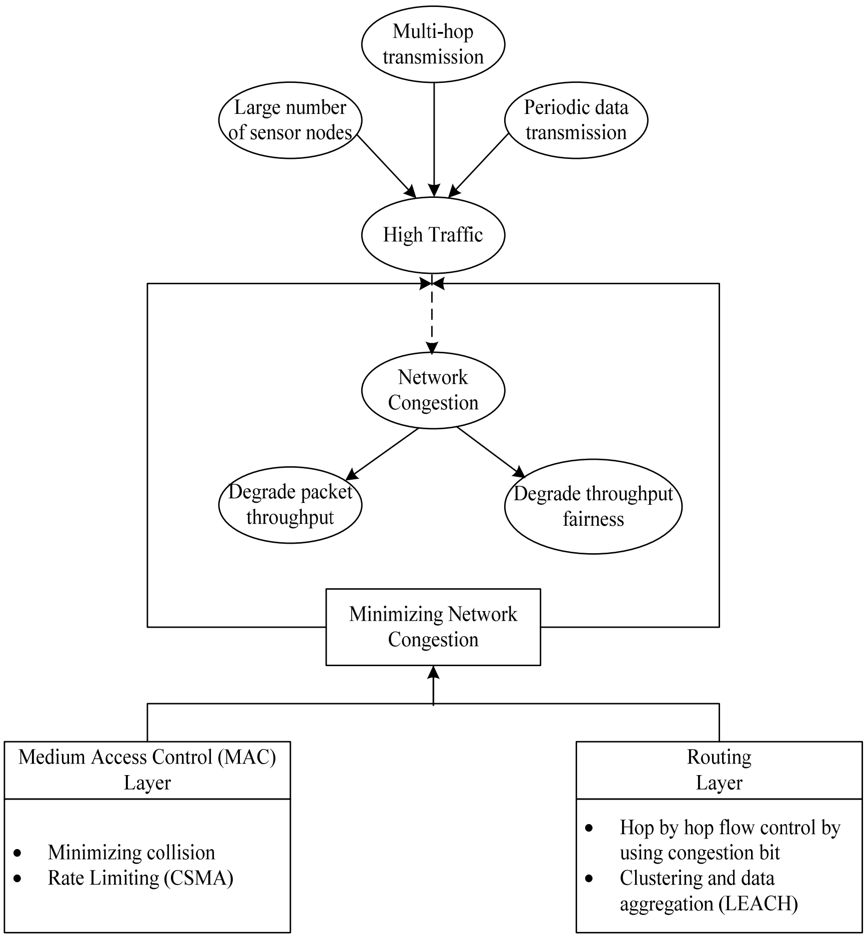

Figure 1.4 Background of the problem

Researches on WSN have proposed some mechanisms to minimize network congestion. Among of the mechanisms involved in Medium Access Control (MAC) layer or routing layer. The first mechanism for minimizing network congestion is by reducing collisions. Collision is taken place when two or more data packets are concurrently received by a node. The collision causes the data packets to become damaged. The damaged data packets must be dropped and re-transmitted. The re-transmission of damaged data packets will delay transmission of the next data packets in node's reception buffer. This leads to increase possibility of network congestion.

There are some mechanisms of Medium Access Control (MAC) proposed to control collisions. The first mechanism uses Carrier Sense Multiple Access (CSMA). This is a contention-based mechanism for accessing transmission medium. In CSMA, every node must listen to a common channel before transmitting its data. If the common channel is idle, then the transmission can be started. Otherwise, the node must listen again the common channel after certain back off time until it finds the channel is idle or the node may abort the transmission.

Although CSMA has mechanism to reduce collisions, it cannot assure a collision-free network due to "hidden terminal" issue (Heinzelman, 2000). There are two techniques proposed to reduce collision risk that caused by the hidden terminal issue. They are by using Request to Send/Clear to Send (RTS/CTS) handshake or using Collision Avoidance (CA) as used by IEEE 802.15.4/ZigBee (Al-Mahdi *et al*., 2009).

The second mechanism for controlling collisions is by using Time Division Multiple Access (TDMA) or Frequency Division Multiple Access (FDMA). Both mechanisms use fixed-allocation technique for reducing collision. TDMA allocates a unique timeslot to each node and allows the node to transmit its data only within the allocated timeslot. This mechanism can provide a collision free network, but it requires strict time synchronization (Heinzelman, 2000). On the other hand, FDMA assigns different channel to each node and allows the node to transmit its data through the assigned channel. This mechanism also can provide a collision free network, but it requires much bandwidth. To obtain advantages from both contention-based and fixed-allocation based MACs, some works combine the two mechanisms into hybrid MAC.

The second mechanism reduces network congestion by using rate limiting (Hull *et al*., 2004). This mechanism uses token bucket to detect network congestion. A node accumulates one token every time it hears its parent forward packet. The node is allowed to send packet only when its token count is above zero, and each transmission costs one token. This approach limits node to transmit data at the same rate as each of its descendants. However, this mechanism is very costly in term of energy consumption since it requires transceiver always listens to transmission medium.

In routing layer, a mechanism of hop by hop flow control is proposed by Hull *et al*. (2004) to minimize network congestion. In this mechanism, every sensor node will set a congestion bit when it is congested. The congested bit is put in the header of every outgoing packet to inform the congested state to other nodes. Nodes that receive the information of congested node will suspend data transmission through the congested node. This mechanism is not costly and simple to be applied.

Another mechanism in routing layer minimizes network congestion by using network clustering technique. This technique was formerly used in Low-Energy Adaptive Clustering Hierarchy (LEACH) that proposed by Heinzelman (2000). This technique groups sensor nodes into several clusters which every cluster is managed by a cluster head. The cluster members send their data to cluster head. Then, the cluster head will perform data aggregation in order to reduce number of data that wants to be transmitted to sink node. Thus, it can minimize network congestion.

1.4 Research Problems

Based on previous works, this research combines some mechanisms for minimizing network congestion to provide an efficient communication in WSN. The first mechanism is involved in network self-organizing. In this mechanism, a load balancing strategy is deployed during formation of network topology to balance traffic across the network. The second mechanism minimizes network congestion through hop by hop flow control. This mechanism involves a technique for detecting congested node and advertising the information of congested node. The last mechanism minimizes network congestion by reducing collisions through Medium Access Control (MAC) layer. Combining the three mechanisms for minimizing network congestion raises some issues in this research as follows:

1. Mechanism of network self-organizing that used to build communication link in a network topology should be able to minimize network congestion. A load balancing strategy should be deployed in the network self-organizing mechanism in order to balance traffic load.
2. Hop by hop flow control minimizes network congestion by suspending data transmission until congested nodes are ready to receive the data. This mechanism requires a technique for detecting congested node and advertising the information of congested node.
3. Collisions that happened during accessing transmission medium lead to increase possibility of network congestion. Frequency Division Multiple Access (FDMA) and Time Division Multiple Access (TDMA) are well known mechanisms that can provide collision free network. Assigning limited frequency channels to large number of nodes is a challenging issue in FDMA. In TDMA, time slots allocation and time synchronization becomes the next issues that should be addressed.

1.5 Research Questions

Based on the explained issue in the previous sections, several research questions are addressed in this research as follows:

1. How to design a mechanism of network self-organizing that includes load balancing strategy?

2. How to design a mechanism of hop by hop flow control that can detect congested nodes and advertise information of the congested nodes?
3. How to design a mechanism of multi-channel Time Division Multiple Access (TDMA) in order to reduce collisions?

1.6 Purpose of the Research

The main goal of this research is to combine some mechanisms for minimizing network congestion in order to provide efficient communication in WSN. The mechanisms are network self-organizing with load balancing strategy, hop by hop flow control, and collisions reduction. To realize the combined mechanisms, this research designs a new WSN protocol that called Multi-Channel Time Division Multiple Access – Cross Layer Protocol (MT-XLP). Design of this cross layer protocol integrates Medium Access Control (MAC) layer and network/routing layer. MAC layer deals with channel assignment and time slot allocation to provide communication link in the network and reduce collisions. Network/routing layer deals with mechanism for load balancing and hop by hop flow control. By means of MT-XLP, performance of the combined mechanisms in minimizing network congestion is evaluated. The performance evaluation is conducted by measuring packet throughput and index of throughput fairness. Finally, performance evaluation is benchmarked with IEEE 802.15.4/ZigBee.

1.7 Objectives of the Research

The precise objectives of this research as follows:

1. To design a mechanism of network self-organizing that includes load balancing strategy.

2. To design a mechanism of hop by hop flow control that can detect congested nodes and advertise information about the congested nodes.
3. To design a mechanism of Multi-channel Time Division Multiple Access that can minimize collisions.
4. To evaluate performance of MT-XLP in minimizing network congestion by measuring packet throughput and index of throughput fairness and benchmark the performance of MT-XLP against with IEEE 802.15.4/ZigBee.

1.8 Research Scope

The efficient communication through multi-Channel Time Division Multiple Access – Cross Layer Protocol (MT-XLP) is developed under the following scope and key assumptions:

(i) Design and development of MT-XLP focuses to integration of only two essentials layers in communication protocol stack, namely data link/MAC layer and network/routing layer.

(ii) MT-XLP is designed and optimized for WSN applications that have unique characteristics as the following:

- *Multi to one uplink traffic:* traffic comes from a number of sensor nodes towards a single sink node.
- *Small packet size:* a data packet contains sensor based data that only comprises several bytes (less than 30 bytes).
- *Data transmission occurs periodically:* every sensor node senses its environment and transmits the sensor-based data periodically to sink node.
- *Delay tolerance:* data is not transmitted in real-time.

(iii) Wireless Sensor Network is assumed to operate without any interference with other wireless networks.

(v) Performance of the MT-XLP is practically evaluated using prototype of tiny node and benchmarked toward IEEE 802.15.4/ZigBee protocol as familiar WSN protocol that has been commercialized.

1.9 Research Contributions

The philosophy of this research is to provide efficient communication for Wireless Sensor Network (WSN) by minimizing network congestion. The philosophy is realized by design a new protocol that called Multi-channel Time Division Multiple Access – Cross Layer Protocol (MT-XLP). This protocol involves several mechanisms for minimizing the network congestion. The main contributions of this research are summarized as follows:

1. The design of mechanism for network self-organizing that includes load balancing strategy. This mechanism can balance traffic load, thus it can minimize network congestion.
2. The design of mechanism for hop by hop flow control that can detect congested nodes and advertise information of the congested nodes.
3. The design of mechanism for multi-channel Time Division Multiple Access (TDMA) in Medium Access Control (MAC) layer that can minimize possibility of collisions.

1.10 Definition of Terms

- *Global synchronization*: All nodes in a network refer to a common clock source and synchronize their clock to the clock source. Nodes are synchronized in whole network.

- *Local time synchronization*: Nodes synchronize its clock with local clock source. Nodes are only synchronized in a local area network.
- *Packet throughput*: Rate of packet that eventually successfully reach its destination.
- *Index of Throughput Fairness*: Determines how fair is the total throughput that is achieved respect to throughput of individual nodes.
- *Protocol*: Set of rules that specify interactions between the communicating entities. In network, protocol is needed in each communication layer to specify how the layer works and how the layer interacts with other layers.
- *Hybrid (in term of medium access control):* Integrate two or more mechanisms in order to take advantages from each of mechanism and at the same time to cover limitations form each of mechanism.

1.11 Organization of Thesis

This thesis is organized into six chapters. Chapter 1 serves an essential introduction to the research, while Chapter 2 provides a review of related literature that leads to the formulation of this thesis. Chapter 3 describes the research methodology and its rationale. Chapter 4 explains the design and implementation of the MT-XLP. Experiments to test and to evaluate performance of the MT-XLP are presented in Chapter 5. Chapter 6 concludes the thesis by discussing the major significance of the proposed protocol including its benefits and drawbacks. This chapter also presents some discussions for further research.

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