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# *TRADE-OFF BETWEEN ENERGY EFFICIENCY AND COLLISIONS FOR MAC PROTOCOLS OF WIRELESS SENSOR NETWORK*

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# TRADE-OFF BETWEEN ENERGY EFFICIENCY AND COLLISIONS FOR MAC PROTOCOLS OF WIRELESS SENSOR NETWORK

By

**MOHAMMAD SAUKAT JAHAN**

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

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**Chairman: Associate Professor Aduwati Binti Sali, PhD**
**Faculty: Engineering**

Wireless sensor networks (WSNs) have the potential to connect the physical world with the virtual world by forming a network of sensor nodes (SN). In WSNs, efficient usage of resource is critical because sensor nodes are resource limited devices, also the network operations are often restricted the energy limitations. Hence, energy saving and reduce collision of sensor nodes are major design issue. Medium access control (MAC) protocols have a significant effect on the flexible, energy-efficient and collision free communication and performance of sensor networks. Therefore, it is necessary to develop a MAC protocol for trade-off between energy efficient and collision, which reduces delay, access collisions, resource consumption, and increases the system performance.

This research investigates energy and collisions efficiency MAC protocols designed to extend the lifetime and manage the resource of WSNs. This research makes several significant contributions to the WSNs based on the IEEE 802.15.4 standards. First, the proposed incomplete cooperative game theoretic based MAC (GT-MAC) protocol, improves on the existing wireless sensor MAC protocols by offering significant network performance and lifetime extensions over the existing IEEE 802.15.4\Zigbee standards based WSN protocols. In this game, each sensor node estimates the current state of the game by detecting the channel and changes its equilibrium strategy by tuning to local contention parameters for trade-off between energy efficient and collision. Secondly, this research introduces a geographical and power based clustering algorithm (GPCA) for WSNs. Trade-off between energy efficiency and collisions in these approaches can be obtained by cluster formation, cluster-head election, data

collecting at the cluster-head nodes to reduce data redundancy and thus, save energy. Finally, Cluster and Game Theory based MAC (CGT-MAC) algorithm manages the SNs resource efficiently by trade-off between energy efficiency and selecting a proper backoff period to eliminate the collisions among the SNs. In CGT-MAC, after geographically grouped into clusters, all SNs within a cluster based on current traffic conditions select a proper backoff period using the game theory for data transmission.

Simulation models have been developed and simulated to verify the performance improvements of the proposed algorithms. Results indicate that the energy consumption is decreased to 25% in a moderately loaded (1pkt/sec) network to a heavily loaded (10pkt/sec) network over the standard of IEEE 802.15.4, EBA-15.4MAC, G-MAC, LEACH and ADAPT protocol. The throughput also improves by 34% in most scenarios of interest. This proves the viability of trade-off between energy efficiency and collisions for IEEE 802.15.4 based MAC protocols of WSNs.

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

**TRADE-OFF ANTARA KECEKAPAN TENAGA DAN PERLANGGARAN UNTUK PROTOKOL MAC WAYARLES RANGKAIAN SENSOR**


**Oleh**

**MOHAMMAD SAUKAT JAHAN**

**Mei 2015**

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Rangkaian sensor tanpa wayar (WSNs) mempunyai potensi untuk menghubungkan dunia fizikal dengan dunia maya dengan membentuk rangkaian nod sensor (SN). Dalam WSNs, keberkesanan penggunaan sumber adalah penting kerana nod sensor peranti terhad sumber, juga operasi rangkaian sering terhad batasan tenaga. Oleh itu, penjimatan tenaga dan mengurangkan perlanggaran nod sensor adalah isu reka bentuk utama. Kawalan akses media (MAC) protokol mempunyai kesan yang besar ke atas fleksibel, cekap tenaga dan perlanggaran komunikasi percuma dan prestasi rangkaian sensor. Oleh itu, adalah perlu untuk membangunkan protokol MAC untuk trade-off antara cekap tenaga dan perlanggaran, yang mengurangkan kelewatan, perlanggaran akses, penggunaan sumber, dan meningkatkan prestasi sistem.

Kajian ini menyiasat tenaga dan perlanggaran kecekapan protokol MAC direka untuk melanjutkan hayat dan menguruskan sumber WSNs. Kajian ini membuat beberapa sumbangan penting kepada WSNs berdasarkan piawaian IEEE 802.15.4. Pertama, permainan teori yang tidak lengkap koperasi yang dicadangkan berdasarkan MAC (GT-MAC) protokol, meningkatkan pada protokol-protokol MAC sensor wayarles yang sedia ada dengan menawarkan prestasi rangkaian dan jangka hayat sambungan penting terhadap protokol WSN IEEE 802.15.4\ZigBee piawaian sedia ada berasaskan. Dalam permainan ini, setiap nod sensor menganggarkan keadaan semasa permainan dengan mengesan saluran dan perubahan strategi keseimbangan dengan penalaan kepada parameter perdebatan tempatan untuk trade-off antara cekap tenaga dan perlanggaran. Kedua, kajian ini memperkenalkan algoritma pengelompokan geografi dan kuasa berasaskan(GPCA) untuk WSNs. Trade-off antara kecekapan tenaga dan

perlanggaran dalam pendekatan ini boleh didapati dengan pembentukan kelompok, pilihan raya kelompok kepala, pengumpulan data pada nod kelompok kepala untuk mengurangkan pertindihan data dan dengan itu, menjimatkan tenaga. Akhirnya, Kluster dan Teori Permainan berasaskan MAC (CGT-MAC) algoritma menguruskan sumber SNs yang cekap oleh trade-off antara kecekapan tenaga dan memilih tempoh backoff yang betul untuk menghapuskan perlanggaran antara SNs. Dalam CGT-MAC, selepas geografi dikumpulkan ke dalam kelompok, semua SNs dalam kelompok yang berdasarkan kepada keadaan trafik semasa pilih tempoh backoff yang betul menggunakan teori permainan untuk penghantaran data.

Model simulasi telah dibangunkan dan simulasi untuk mengesahkan peningkatan prestasi algoritma yang dicadangkan. Keputusan menunjukkan bahawa penggunaan tenaga itu menurun kepada 25% dalam sederhana dimuatkan (1pkt/sec) rangkaian kepada banyak dimuatkan (10pkt/sec) rangkaian lebih taraf IEEE 802.15.4, EBA-15.4MAC, G-MAC, Leach dan MENYESUAIKAN protokol. Pemprosesan ini juga meningkatkan sebanyak 34% dalam kebanyakan senario yang menarik. Ini membuktikan daya maju trade-off antara kecekapan tenaga dan perlanggaran untuk IEEE 802.15.4 protokol MAC berasaskan WSNs.

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# APROVAL

I certify that a Thesis Examination Committee has met on 14 May 2015 to conduct the final examination of Mohammad Saukat Jahan on his thesis entitled "Trade-Off between Energy Efficiency and Collisions for MAC Protocols of Wireless Sensor Network" 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 fulfillment of the requirements for the degree of Doctor of Philosophy. The members of the supervisory committee were as follows:

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| | |
|---|---|
| WSN | Wireless Sensor Network |
| LR-WPAN | Low Rate-Wireless Personal Area Network |
| MAC | Medium Access Control |
| ADC | Analog-to-Digital Converter |
| CPU | Central Processing Unit |
| GT-MAC | Game Theory based MAC |
| SN | Sensor Node |
| GPCA | Geographical and Power based Clustering Algorithm |
| CGT-MAC | Cluster and Game Theory based MAC |
| ACK | Acknowledgement |
| BO | Beacon Order |
| BE | Backoff Exponent |
| CW | Contention Window |
| CSMA/CA | Carrier Sense Multiple Access/Collision Avoidance |
| CCA | Clear Channel Assessment |
| CFP | Contention Free Period |
| CAP | Contention Access Period |
| BI | Beacon Interval |
| NB | Number of Backoff |
| PAN | Personal Area Network |
| PHY | Physical Layer |
| TDMA | Time Division Multiple Access |
| PER | Packet Error Rate |

| | |
|---|---|
| RF | Radio Frequency |
| RX | Receive or Receiver |
| SD | Superframe Duration |
| TRX | Transceiver |
| TX | Transmit or Transmitter |
| MHz | Megahertz |
| NAM | Network Animator |
| NS | Network Simulator |
| DSSS | Direct Sequence Spread Spectrum |
| RFD | Reduced-function device |
| FFD | Full-function device |
| MSDU | MAC service data unit |
| MFR | MAC footer |
| PHR | PHY header |
| LIFS | Long Inter Frame Spacing |
| SIFS | Short Inter Frame Spacing |
| POS | Personal Operating Space |
| FND | First Node Dies |
| HND | Half Nodes Dies |
| LND | Last Node Dies |
| PDR | Packet Delivery Ratio |
| RSSI | Receiving Signal Strength |
| MPDU | MAC Protocol Data Unit |
| BEB | Binary Exponential Backoff |
| KEB | Knowledge-based Exponential Backoff |

| | |
|---|---|
| IBEB | Improved Binary Exponential Backoff |
| IP | Interim Period |
| ECR | Enhanced Collision Resolution |
| EB | Enhanced Backoff |
| TB | Temporary Backoff |
| NTB | Next Temporary Backoff |
| EBA | Efficient Backoff Algorithm |
| SO | Superframe Order |
| EEUC | Energy-Efficient Unequal Mechanism |
| ECLEACH | Enhanced Centralized LEACH |
| ADAPT | Adaptive Access Parameters Tuning |
| CBR | Constant Bit Rate |
| PEC | Percent of Energy Consumed |
| FE | Final Energy |
| IE | Initial Energy |
| EC | Energy Consumption |
| DBR | Data Bits Received |
| ST | Simulation Time |
| TDT | Total Data Transmission |
| NRP | Number of Received Packets |
| NTP | Number of Transmitted Packets |
| LQI | Link Quality Indicator |
| VCH | Virtual Cluster Header |
| G-MAC | Game-Theoretic MAC |

# CHAPTER 1

# INTRODUCTION

## 1.1 Background

In recent years, Wireless Sensor Networks (WSNs) have gained worldwide attention due to the advances made in wireless communication, information technologies, and electronics field. The concept of WSN is based on a simple equation: Sensing + CPU + Radio = Thousands of potential applications [1]. The development of a small low cost sensor, known as the Sensor Node (SN) enables the applications to monitor, respond to events, and detect the environmental data. The data is routed hop by hop through the SNs until it reaches the Base Station (BS) in the WSN field. Moreover, simplicity of maintenance and flexibility of deployment enables the SN to be arranged in extremely poor conditions such as inside the incident or closely related to it. The individual SN's position does not have to be pre-determined or engineered. Random exploitation of the sensor networks can take place in inaccessible or hostile places. However, random exploitation of protocols and algorithms designed for sensor networks must have capabilities that are self-organising. In addition, SNs have the ability to perform simple computations locally and only transmit the necessary and partially processed data.

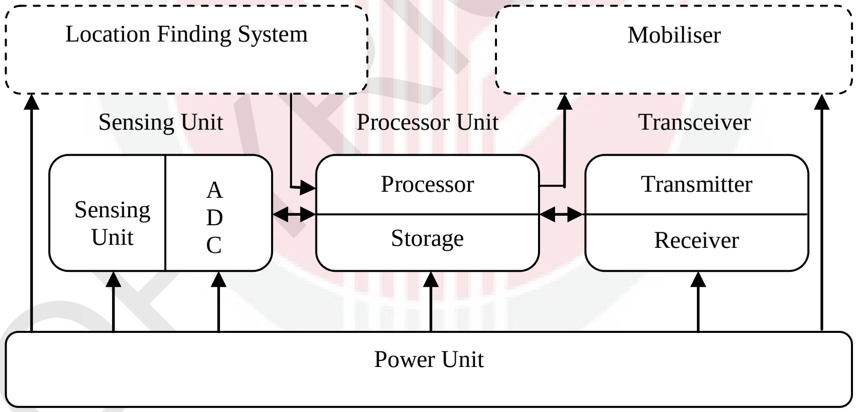


**Figure 1.1: The components of a sensor node [2]**

Figure 1.1 reveals the structure of the SN. It is observed that the SN usually consists of four fundamental units: a processing unit, a sensing unit, a power unit, and a transceiver unit. A location finder, a mobiliser, and a power generator that are application-based may also accompany the SN. The sensing unit controls the environment in terms of the humidity, temperature, pressure, sound, vibration, and image. The ADC converts the analog data that is collected into the digital data

(Analog-to-Digital Converter) which is examined and processed by the processor unit. The transceiver links the network to the SN. The power unit is the most important component. SNs may be battery-powered or they may utilize an energy-scavenging unit such as the solar cell. Most sensing tasks and routing protocols require precise location information. Thus, it is normal for SNs to contain a location finder. SNs may be found with a mobiliser to obtain various different sensing jobs based on applications.

WSNs may contain a few to thousands of heterogeneous or homogeneous SNs, which share the requirement to manage data collaboration or sink routing of the network data collection, as depicted in Figure1.2. In WSNs, the SNs must be self-organized in such a manner that they can perform cooperative processing to accomplish tasks that they cannot do individually. Given this situation, sensor networks experience a lot of challenges normally not found in other network types. Limited energy budget and processing resources, reduced reliability, and a normally higher density and number of SNs compared to conventional networks, are just some of the issues that need consideration when developing protocols for WSN [3]. Since technology shrinks the hardware, the research on WSN continues to develop energy-saving, innovative, techniques in the network protocol at all layers to design the sensor platforms that are able to operate unattended for months or years. Scalable WSN networks are necessary in order to manage sensor fields that are very dense. The applications for the WSN networks that are energy-efficient normally function in clustered and self-organizing environments, which support both the single or collaborative application.

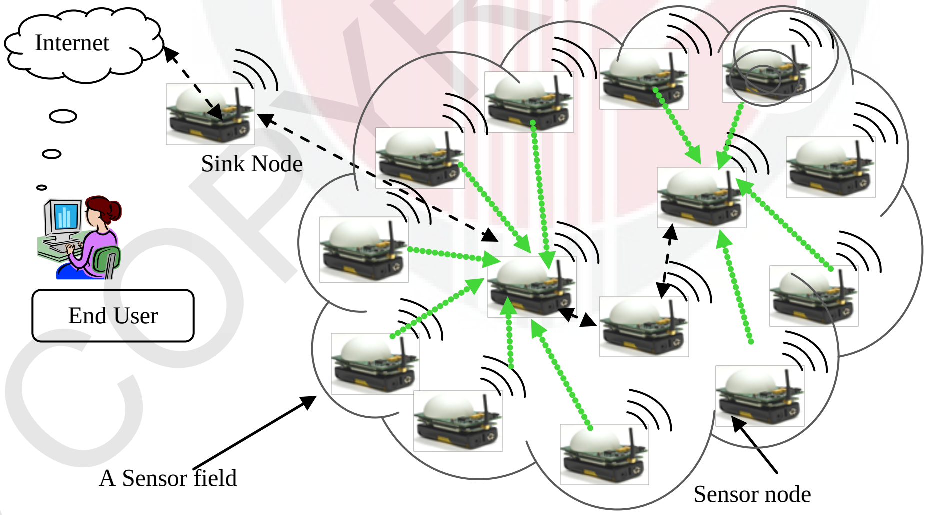


**Figure 1.2: Wireless sensor networks [4]**

Energy-efficient and collisions free WSN networks can be applied in several areas including military surveillance, biological, homeland defence nuclear, chemical sensing, environmental sensing, and precision farming (Figure 1.3). The applications normally function in clustered and self-organizing settings, which sustain a collaborative or single application. The design of the WSN network needs tradeoffs in the form of reduces collision to extend its network lifetime.

(a) UPM Farm (b) The Penang Bridge

**Figure 1.3: Precision farming and structural health monitoring of bridge using WSNs [5]**

Medium Access Control (MAC) protocol plays a vital role in the performance of WSNs. SNs are typically battery powered that makes change or replacement difficult due to the cost constraints. Therefore, energy efficient and collision free MAC protocol is considered a primary goal of the WSNs design [5]. There are some important key issues that need to be fulfilled in order to ensure a successful deployment of WSNs such as energy efficiency, reliability and scalability. To achieve energy-efficient requirements, collisions between the transmitting SNs should be minimised. This collision leads to packet drop thusly reducing throughput and causing energy wastes. In order to compute the required power for each SN, communication and computation of SNs are being considered. The communication energy usage is much higher than the computation energy usage. Communication in sensor networks is dependent on the connectivity of the network, where connectivity is defined as the ability to link between any pair of SNs.

In a general way, the task of a WSN consists of measuring a variable through the SNs, eventually (pre-) processing this information, and if opportune, transmitting the data to sink node. It has been [6] shown in various design case that some of the most power hungry tasks of sensors are related to communication: not only transmission (or re-transmission) and receive power, but the power needed while waiting (idle listening) and scanning the channel for collision can be significant. The channel access schemes are designed to save energy, so mechanisms are included to allow SNs to switch to low-power states and avoid expensive modes such as transmission, reception and channel listening. To save energy, SNs do not have to listen to the channel continuously, so it is possible to switch to low-power when the wake-up delay fits within the timing constraints of the medium access control. While contending for the channel, SNs delay their carrier sensing by a random backoff delay during which they got to low power modes. Only after that random delay, the contending SN wakes-up to listen to the channel during maximally two backoff slots. As a results, the power consumption during channel listening is minimized and trade-off with collisions.

This study examines the wireless medium access control approach to reduce collision, enhance energy usage efficiency and to lengthen the lifetime of the WSN networks. The general research endeavours are elaborated in this chapter. Section 1.2 of this chapter provides the research's problem statement and the motivation for the WSN protocols are described. The following Section 1.3 reveals the research objectives. A brief overview of the thesis scope and the study module in terms of a block diagram is demonstrated in Section 1.4. Section 1.5 introduces the research contributions and process flow. Finally, the thesis organisation is in Section 1.6.

## 1.2 Problem Statement and Motivation

WSN SNs are remarkably constrained in terms of their resources, i.e., energy, computational power, and radio bandwidth. Moreover, the wireless channel is a shared medium that is interference limited. In WSNs, SNs' energy resources are quickly drained by a host that is malicious by select same backoff period and maintaining the SNs' radios active when otherwise they would go into sleep mode to conserve energy. Communication in a WSN is classified into various layers. One of the layers is the Medium Access Control (MAC), which allows for a successful network operation by reducing collision between SNs. The MAC protocol attempts to prevent classes by not permitting the two interfering SNs to transmit simultaneously. The MAC protocol provides more priority in minimizing the energy consumption compared to the QoS specifications.

Currently, MAC protocols based on contention have been suggested and implemented for WSNs that aim to tradeoffs between energy consumption and collision by maintaining the radios in suitable sleep mode as much as possible. IEEE 802.15.4 is one of the most widely used short-range, low-complexity, and low-power communication protocols. In the CSMA/CA technique, the main aspects to cause an effect on the performance of the network and the general efficiency of energy usage of the MAC protocol are the number of active SNs and the backoff period. The CSMA/CA technique utilizes the parameter configuration that is static without supporting the various services and networks, self-adaptively. In addition, the techniques used by these protocols to minimize energy consumption and collision can be manipulated by users with malicious intent who realize the characteristics of the MAC protocols, even in networks that utilize authentication and encryption to secure the network's traffic. Therefore, this research examines the current problems of the suggested tradeoff between energy-efficient and collision for WSN MAC protocols that do not provide a network control technique that is effective in lowering idle listening, increasing sleep duration, and controlling the amount of overhead cluster control traffic. Moreover, the current carrier sense medium access with the collision avoidance (CSMA/CA) algorithm mechanism has some drawbacks:

1. In CSMA/CA, idle listening takes place when a SN found in the WSN, listening to an inactive medium, overtakes the loss of power in the networks recognized as limited sleep cycles and scarce traffic. This CSMA/CA updates the backoff periods without taking into consideration the number of competing SNs in the wireless medium. Therefore, the CSMA/CA has been proven to be insufficient in terms of system throughput and packet delivery ratio;
2. A collision in the frame takes place when the wireless SN sends a MAC protocol message that clashes with the time of another message. CSMA/CA uses a very limited random number of Backoff Exponents (BE) that increase the probability of two SNs selecting the same number of backoff periods. This will give rise to more collisions among the contending SNs and subsequently, affect the overall system's performance; and
3. In the conventional approach for backoff control for the IEEE 802.15.4 MAC, a SN is unable to transmit packets when there are inactive parts in the superframe. Thus, the SN's stored packets should access the channel concurrently at the start of the next active part (CAP); hence, the channel access congestion should take place at the start of the CAP. This causes lower resource (i.e., channel) utilisation and a longer average delay of the WSNs employing the IEEE 802.15.4 MAC.

Motivation for this research is derived from the delay performance degradation due to the conventional backoff control approach in the WSNs that are cluster based with non-uniformity in the spatial and temporal traffic. This research intends to design, execute, and examine a WSN MAC protocol that is collision free and energy efficient with the wireless SNs transmissions to lengthen the sleep duration and conserve energy in power and resource limited devices. Specifically, here is proposed an incomplete cooperative game theoretic MAC protocol mechanism called the Game Theory based MAC (GT-MAC) as a feasible solution to the aforementioned problems. Protocols based on contention and reservation, which address some of the issues related to the sources of energy loss, but not all. With minimum overhead control, the GT-MAC protocol selects the backoff period dynamically and permits the other related SNs to sleep for longer periods, reduce SNs transmission collision and lengthen the network's lifetime. In addition, the power based and geographical clustering algorithm exploits the additional opportunities for reduce SNs packet collision and increased the performance of WSNs that come together with the generation of faster cluster and rotates the Cluster Head (CH) duties among all the SNs, for distribution of energy costs management. Finally, here advocates the use of cluster-based game theory to address the issue of dynamic resource adaptation in IEEE 802.15.4 based WSN. Here proposes a bottom-up approach based on the cluster and game theory that allows the development of autonomous WSN applications with dynamic adaptation, minimal or distributed processing for task allocation, and limited communication overhead. Moreover, the Cluster and Game Theory based MAC (CGT-MAC) algorithm manages the SNs resource efficiently by eliminating the collisions among the SNs. In addition, SNs are tradeoffs between the energy efficiency and collisions. Here shows that higher anonymity comes at a cost - either higher communication/energy overhead or at higher latency to reduce collision. The choice of the parameters is left to the WSN and depends on level of accuracy needed and the traffic in the network.

## 1.3 Objectives of the Research

The fundamental objectives for this research are to identify the MAC-layer resource-consumption issues in WSN. Also, develop a MAC protocol to tradeoffs between energy efficiency and collisions to extend the network lifetime of the SNs. The incomplete cooperative game theory extends the SN's lifetime that is faced with resource consumption issues that reduce collision and keep the radio off when it ought to be sleeping for conservation of energy. These mechanisms have low overhead when it comes to added network traffic, energy consumption, and memory and processing requirements. They integrate easily into the current WSN protocol stack implementations. Also, select the appropriate backoff period depending on the network traffic by trade-off between energy efficiency and collisions to. Then incorporate these models into other protocols propose to enhance the performance and to adapt to the prevailing network conditions. The GT-MAC protocol presented in this research leverages the game-theory based efficiency technique to lower message overhearing, idle listening, and contention of energy costs. In addition, the GT-MAC extends the energy-saving by trade-off collisions, high-tech methods by concentrating on the set up of the traffic rhythm to maximise the period of sleep opportunities, reduce the traffic overhead control, and enhance the network's lifetime. The designing and implementing of a distributed WSN network cluster management system that organizes the SNs and increases the throughput in the current WSN MAC protocols are also included in this research. To achieve these improvements, the following objectives are studied and accomplished:

1. To improve throughput and packet drop rate usage in IEEE 802.15.4 MAC by enhancing the backoff process precision to trade-off between energy efficiency and collision for CSMA/CA algorithm with the game theory based algorithms(demonstrated in Chapter 3);
2. To design and validate a clustering algorithm for WSNs based on geographical location and remaining energy, for reducing energy consumption and collision of SNs and trade-off between them(demonstrated in Chapter 4); and
3. To minimise access collision, average packet delay, resource consumption and trade-off between energy and collision of the SNs in large scale WSNs by using geographical and power based clustering and incomplete cooperative game theory (demonstrated in Chapter 5).

## 1.4 Thesis Scope and Study Module

The study area of this research focuses on WSNs. Traditional wireless communication can be broadly classified into six categories: Ad Hoc, WSN, Wi-Fi, Bluetooth, Cellular, and WiMax as shown in Figure 1.4. Depending on the mobility of SNs, WSN can be further classified into static networks and mobile networks. The present MAC design for WSNs can be divided broadly into (S-MAC, T-MAC, IEEE 802.15.4) [7], hybrid protocols (Z-MAC, B-MAC) [8], and scheduling-based (TRAMA, LEACH) based on contention [9]. In each category, the approaches taken for individual access control to the shared medium differ according to the assumptions regarding quality assurance, traffic patterns, complexity, and fairness. Scheduling-based protocols possess the expected advantage of conserving energy in comparison to contention-based protocols, as the radio's duty cycle is decreased and no collision that are contention-induced and overhead are present. Nevertheless, sustaining a schedule (time synchronisation) in a WSN is a complicated job that will result in complications in the SN. A normal hybrid protocol can integrate the Time Division Multiple Access's (TDMA) strengths and the carrier sense multiple access (CSMA). Nevertheless, the present protocols of a hybrid nature have to decrease further the weaknesses of the protocols that have been incorporated. The summary of the general steps studied in this research is illustrated in Figure 1.4.

Contention-based MAC protocols are widely used because of their simplicity and flexibility [10]. These protocols employ contention mechanism rather than clock synchronisation and hybrid protocols. For that matter, there is a need to distinguish between protocols that use a reservation of medium access and those that use a contention mechanism. Even though, most studies show that the contention-based WSN solutions need a lot of idle listening and face frame collisions [11], many of the WSN usages are designed incorporating customized protocols that are contention-based referred to as slotted protocols. The schemes that are schedule-based provide essential conservation of energy; however, they are rather complicated and face inefficiency of bandwidth. The slotted protocols provide alternative schemes, and have the advantage of contention-based and scheduled protocols [12, 13].

Slotted schemes are similar to the conventional protocols that are contention-based MAC, but the channels are divided into frames with duty cycles that allow synchronization of the functions of the network and permit wireless SNs to sleep without the need for coordination of wakeup times actively. The slotted CSMA/CA communication offers further opportunities to sleep when the other SNs have completed the transmissions during the frame period, but it enhances the probabilities of collision as SNs begin competing for the medium at the start of the next frame duration simultaneously. In addition, as each SNs can sleep after all the exchanges of a message, the slotted protocols lower idle listening. Network lifetimes are extended by the wireless sensor network MAC protocols via lowering the function of the highest component of energy-demand of the sensor platform in the radio. Energy-efficient MAC protocols use synchronization of the network communication by trading off network throughput and latency (delay) to develop opportunities for radios to sleep with active duty cycles as low as 2.5% under minimal traffic situations [14]. It is essential to understand both the sources of malicious and normal energy loss in the design of a power control system. The normal sources of energy loss in the WSNs involve frame collisions, idle listening, message overhearing, and protocol overhead.

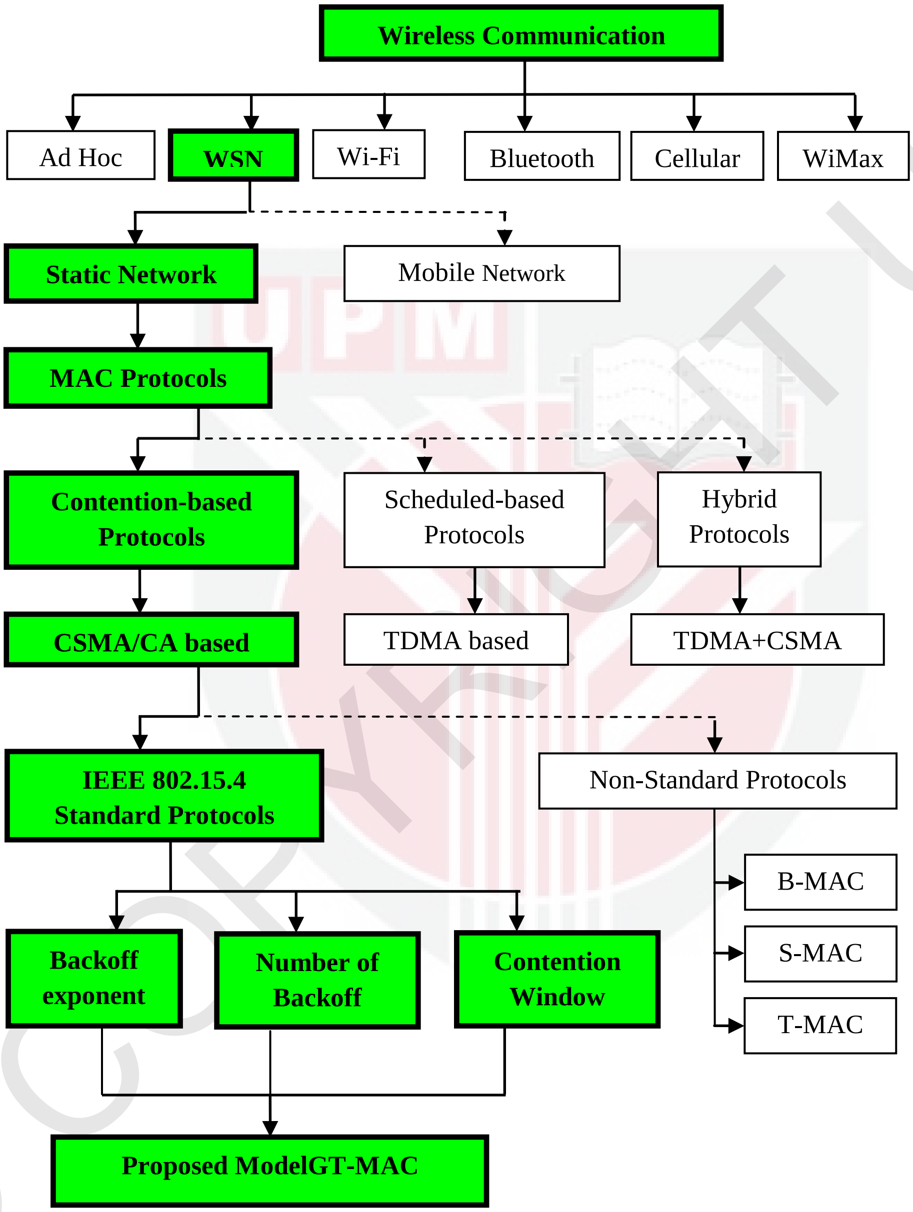


**Figure 1.4: Study module: taxonomy**

WSN interfaces the SNs without constraints of energy continuously monitor the medium for incoming transmissions. Idle listening happens when a SN in the WSN, listens to an inactive medium and dictates losses of power in the identified networks by limited sleep cycles and limited traffic. As an example, by using the Chipcon CC2420 250kbps transceiver [15], the SN is able to transmit the wireless personal area network maximum-sized 128-byte message in 4.1ms. If a SN transmits and receives one 5ms message each second, and for the remaining 990ms listens to an idle channel, that particular SN spends 99% of its duty cycle using energy without receiving or sending any messages. As most wireless sensor radios use as much energy or more during the idle listening time compared to the transmission time, the WSN MAC protocols that are energy-efficient try to coordinate network traffic so that the transmissions only start in the time slots that are predetermined. After all the transmissions in the network are completed for a specific cycle or duration, the protocols permit SNs to go back to sleep until the next time for transmission. The following section demonstrates four approaches to lowering idle listening in WSNs: dynamic sleep scheduling, preamble sampling, static sleep scheduling, and scheduling for off-line periods.

When a wireless SN sends a MAC protocol message or frame, frame collision takes place at that point as it overlaps or collides in time with another message. Data will be corrupted at the receiving end if the strength of the interfering signal is sufficiently high. The radio cannot simultaneously receive during transmit mode in many single-channel radios. Thus, the sender of message's only signal of a collision is the lack of an acknowledgement message from the receiver. Frame collision takes place in wireless networks naturally because of the space and time extensions in the distributed radio networks. The main reasons for wireless frame collisions are: propagation delays between distant SNs; finite radio receive-to-transmit transition times (the capture effect) that range from 250µs to 500µs after sensing a clear channel; and hidden SNs out of range from the sender, but within the range of the receiver. Both the sending and receiving SNs have to use up extra energy due to resending messages. Frame collisions are reduced by protocol designers through using contention-based backoff algorithms or contention-free scheduling protocols to decrease the collision probabilities.

MAC protocols that are cluster-oriented TDMA demonstrate the possible conservation in obtained energy using these schemes that are synchronized. The LEACH or the Low-energy adaptive clustering hierarchy [16] is a self-organizing, cluster-based protocol that utilizes a passive technique to choose a CH node randomly. LEACH's assumption is that all SNs are homogeneous and deployed simultaneously with equal energy. The main features of LEACH are energy-conservation data fusion/aggregation that reduces the quantity of data messages sent back to the BS, randomized rotation of the local BS or CH nodes, and localized coordination for cluster setup and operation. This novel "off-line" CH election utilizes an algorithm that is probability-based to select passively the next round's CH without passing any control messages. After the self-election is completed, the CH utilizes the CSMA to broadcast a clustered advertisement message to all local SNs within radio range. Other SNs listen to the entire CH broadcasts and try to connect to the CH that indicates the highest receiving signal strength (RSSI). The least amount of energy is needed by this cluster for intercommunication. The CH compiles the requests for cluster membership and constructs a schedule for every SN to send its data up to the CH for aggregation and to be forwarded to the network sink. This pattern of traffic only works for data moving out of the network, and does not allow communication of SNs with each other.

IEEE 802.15.4 standard is a well-known contention-based MAC protocol that is used in this research [17]. The standard uses an asynchronous and random access method to control the access to the communication medium. Only BS requiring transmissions compete for the bandwidth and in general can divide the bandwidth resources. These protocols are decentralized and function well when the SNs have irregular, bursty, traffic patterns, and do not function well under heavy loads of traffic as increased probabilities of frame collision may cause instability in the network. Collisions in WSNs lower the throughput, and their retransmissions decrease the valuable battery power. Extra energy losses in the contention-based protocols involve message overhearing and idle listening. Most performances of the SN design attempt to achieve the best attribute from both the contention and schedule approaches; however, they are forced to make some ultimate design tradeoffs. Contention-based MAC protocols can be further classified into IEEE 802.15.4 standard protocols and non-standard protocols. CSMA/CA based IEEE 802.15.4 protocols maintains three parameters: Number of Backoffs (NB), Contention Window (CW), and Backoff Exponent (BE).

There are two different procedures for a channel access method where the standard can operate: beacon enabled mode and non-beacon enabled mode. In this work, the beacon-enabled mode is evaluated owing to its simplicity for WSNs applications in comparison to the non-beacon enabled mode. In addition, most of the unique features of IEEE 802.15.4 MAC such as synchronisation, sleeping techniques, and employing CSMA/CA mechanism, are found within this mode. The beacon-enabled mode utilises the slotted CSMA/CA mechanism for accessing wireless medium.

The slotted CSMA/CA algorithm uses insufficient random access method. In other words, when the SNs have data to transmit, they first wait for a random backoff period selected within the range [0, $2^{BE}$ *-1*]; BE is the backoff exponent that determines the number of backoff periods the SN will wait for before trying to access the communication medium [18]. During the channel access procedure, the CSMA/CA algorithm is allowed to use a very small range of BE (*macMinBE – aMaxBE*), where the minimum BE is indicated by *macMinBE* = 3 and the maximum by *aMaxBE* = 5. This limited number of BEs that is allowed by the standard increases the probability of SNs choosing the identical number of backoff periods and this causes more collisions among the contending SNs.

The slotted CSMA/CA algorithm updates the backoff periods without taking into consideration the current traffic in the wireless medium: defining the number of backoff periods that need to be waiting before transmission can begin. In addition, CW value is initialised at two, prior to each transmission attempt, and reset to two, each time the channel is identified to be busy. The problem starts when more numbers of SNs try to access the channel to send their data. CSMA/CA neither chooses the appropriate size of the contention window nor takes into consideration the number of contending nodes in the communication medium. Hence, network throughput and delivery ratio reduces due to an increase in the probability of collision during data transmission. As such, the proposed enhancement in this thesis must serve to solve the aforementioned problem.

The focus of this thesis is to develop and analyze efficient mechanisms to extend the network lifetime by reducing collision for wireless SNs. There is a great need to enable these systems to work and withstand this transition as centralized communication networks make way for distributed systems. The loss of control over networks may reduce the general network performance; thus, bridging this loss of performance is of major importance. Game-theoretic methods are distributed naturally, as entities aim to maximize their individual performances. However, application of the game theory to the distributed back-off period control has not received much attention. The possibility of rather complex interactive system between the various network elements is opened up with modern network combined with network heterogeneity, network dynamics, and the wireless medium's shared nature. Moreover, the network elements in the distributed systems are usually limited in their scope and must deal with partial and limited knowledge regarding the network's operating state. These limitations namely the selfish SN optimizations and their interdependencies, and the insufficient information may have an effect on the end-to-end system's performance drastically. Game theory offers a flexible and natural framework to examine and predict the result of the interactions between selfish rational network SNs that optimize their performance when dealing with the limited network knowledge. The proposed solution's approaches are discussed in the next chapter.

### 1.5 Research Contributions

This research's main contribution is the game theoretic MAC protocol that improves the carrier sense multiple access with tradeoff between energy efficiency and collisions mechanism for IEEE 802.15.4 MAC (CSMA/CA) protocol by proposing the cluster based game theoretic MAC algorithm. The main accomplishments of this work are:

1. The first contribution of this thesis is related to designing a game theory based MAC (GT-MAC) protocol to trade-off between energy efficiency and collision suitable for a WSN. This protocol has been shown to have a higher throughput, energy consumption, and link quality than other MAC protocols such as the IEEE 802.15.4 and EBA-15.4MAC;
2. The second contribution of the thesis is related to the use of Energy-Efficient Geographical and Power Based Clustering Algorithm (GPCA), firstly, for WSNs in organizing and trade-off between energy and collision of the network in the sensor nodes. Simulations had been carried out using MATLAB to validate the algorithm. The results of the simulation showed the superior performance of GPCA in comparison with the other clustering protocols such as the LEACH based on performance metrics such as stability

of the network, total energy wastage, and the number of alive SNs in the system; and

3. The third contribution is the cluster and game theory based MAC protocol's (CGT-MAC) ability to carry out resource management analysis of performance by trade-off between energy efficiency and collision for large-scale IEEE 802.15.4 networks based on the star and mesh topologies. The performance has been evaluated using simulations for the WSN reactive MAC protocols like ADAPT, IEEE 802.15.4and EBA-15.4MAC in NS2. Performance evaluations metrics such as packet delivery ratio (PDR), and energy consumption, which include transmission, reception, idle, sleep mode, etc., were considered. From the simulation studies and analysis, it can be seen that the (Cluster based game theoretic - MAC) CGT-MAC protocol is far superior to the IEEE 802.15.4 standard, EBA-15.4MAC, and ADAPT for different traffic load rates and hop distance. Hence, it suits most application in the WSNs, which require constant monitoring and sending of sensed data packets to a sink at regular intervals of time.

The protocol (CGT-MAC) models were developed in NS2 using the uplink (nodes-to-coordinator) approach. Most of the communication is uplink, and not downlink (coordinator-to-nodes). Because of this, the analysis is only focused on the uplink mode. The wireless sensor MAC protocol models possess variables that collect statistics and monitor the usage of energy of each radio state, incorporating latency costs and transition energy. Each protocol's performance is assessed based on throughput, energy consumption and data rate.

Simulation parameters were chosen according to the measurements retrieved from the state-of-the-art wireless sensor platforms. The technical parameters taken into consideration in the simulation include the MAC protocols, traffic distributions, and the radio power management algorithm. The times of the CGT-MAC algorithm transition threshold were achieved by programming each radio power state transition into the Chipcon CC2420 platforms' radios and measuring the energy levels and transition times. Figure 1.5 illustrates the process flow diagram of the general steps involved in this research. It also includes the summary of the problem, solution, contribution, and the benchmark that compared our proposed protocols with from the related work to evaluate the performance.

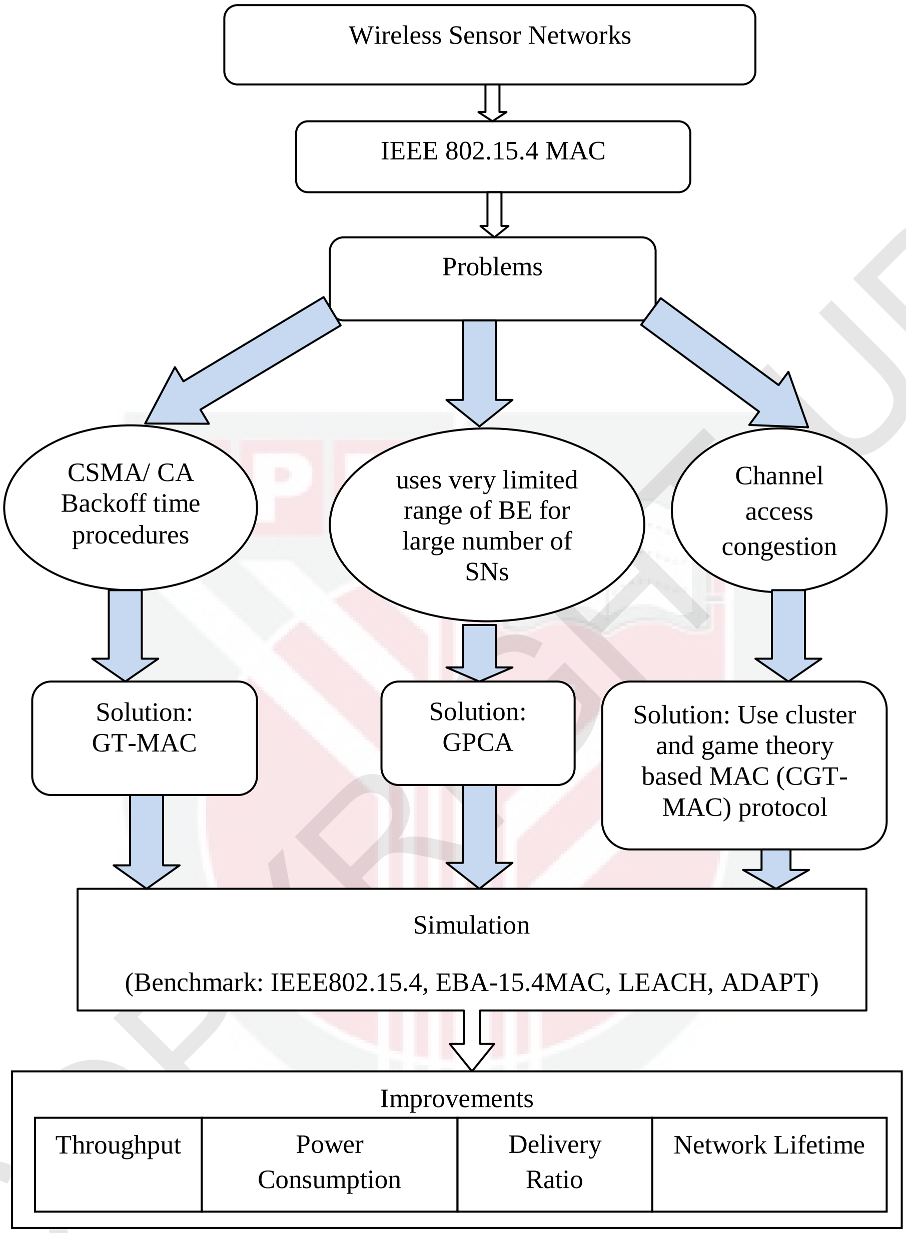


**Figure 1.5: Process flow diagram**

## 1.6 Organization of Thesis

This thesis is divided into six significant chapters. Chapter 1 incorporates the overview of wireless sensor networks (WSNs), the state of the problem and motivation, aims and objectives of the research, thesis scope and study module, and it highlights the main contributions of this research. Chapter 2 discusses the background of the research and presents a literature review of the available MAC schemes for tradeoff between energy efficiency and collisions avoidance, game theory, and cluster algorithms for WSNs. In Chapter 3 discuss the proposed game theoretic MAC protocol for WSNs and examine the analytical and simulation (NS2) findings based on the system's performance metrics. Performance evaluation of metrics such as throughput, link quality and energy consumption will be revealed. Star topology based IEEE 802.15.4 networks' performance will also be examined for the various traffic loads. The following, which is Chapter 4, elaborates on the GPCA algorithm in detail. For validation of the algorithm, simulations will be carried out in the MATLAB and a comparison will be made with well-known protocol such as the LEACH. Results of the simulation demonstrate GPCA's better performance in comparison to LEACH based on the performance metrics such as the system's number of alive SNs, total energy wastage, stability of the network. Chapter 5 presents the design and performance of the cluster and game theory based resource management algorithm of the CGT-MAC. The simulation results showed the superior Packet Delivery Ratio (PDR), throughput and energy consumption than ADAPT, IEEE 802.15.4 and EBA-15.4MAC in NS2. The thesis concludes with Chapter 6, which explains the limitations of the research and describes the scope for further research in the future.

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