REAL-TIME CAPABLE MULTI-HOP MEDIA ACCESS CONTROL PROTOCOL FOR SMART HOME ENVIRONMENT

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by

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LIST OF ABBREVIATIONS

6LoWPAN	IPv6 over Low-Power Wireless PAN
ACK	Acknowledgment
AODV	Ad hoc On-Demand Distance Vector
API	Application Programming Interface
ASN	Absolute Slot Number
BFSK	Binary Frequency Shift Keying
BPSK	Binary Phase Shift Keying
BR	Border Router
CAP	Contention Access Period
CFP	Contention Free Period
CRC	Cyclic Redundancy Check
CS	Carrier Sense
CSMA	Carrier Sense Multiple Access
CSMA/CA	Carrier Sense Multiple Access Collision Avoidance
DSSS	Direct Sequence Spread Spectrum
EC	Embedded Computer
FCF	Frame Control Field
FDMA	Frequency-division multiple access
FFD	Fully Function Device
FHSS	Frequency Hopping Spread Spectrum
GFSK	Gaussian Frequency Shift Keying
GP	Guard Periods
GTS	Guaranteed Time Slot
IoT	Internet Of Things
LLC	Logical Link Control
LR-WPAN	Low-Rate Wireless Personal Area Network
MAC	Medium Access Control
MCU	Microcontroller Unit

MTU	Maximum Transmission Unit
O-QPSK	Orthogonal-Quadrature Phase Shift Keying
PAN	Personal Area Network
PIR	Passive Infrared Sensor
QoS	Quality of Service
RAM	Random Access Memory
RDC	Radio Duty Cycle
RSSI	Receive Signal Strength Indicator
RF	Radio Frequency
RFD	Reduced Function Device
ROM	Read-only Memory
SDCC	Small Device C Compiler
SMA	SubMiniature version A
SoC	System-on-Chip
TDMA	Time Division Multiple Access
TSCH	Time Slotted Channel Hopping
TSMAC	Time-Slot Medium Access Control
WLAN	Wireless Local Area Network
WPAN	Wireless Personal Area Network
WSN	Wireless Sensor Network

PROTOKOL KAWALAN MEDIA BERBILANG LOMPATAN DENGAN MASA NYATA BAGI PERSEKITARAN RUMAH PINTAR

ABSTRAK

Rangkaian Penderia Tanpa Wayar (WSN) merupakan teknologi yang kini kerap kali diketengahkan dan pelbagai kajian telah dilakukan untuk mengaplikasikan di dalam kehidupan seperti pemantauan persekitaran, aplikasi keselamatan dan ketenteraan. Ini termasuklah kajian terhadap *Internet of Things* (IoT) dan Rumah Pintar yang kini semakin diminati di dalam penyelidikan. Gabungan peralatan rumah seperti lampu, pintu pagar dan juga kamera litar tertutup mampu menjadikan rumah masa hadapan bukan sekadar bijak, tetapi jimat tenaga dan selamat. Namun begitu, untuk mengaplikasikan WSN di dalam persekitaran Rumah Pintar, protokol WSN perlu menyokong masa nyata. Protokol ini juga mesti berupaya untuk menghantar data yang sensitif kepada masa seperti audio dan video pada kadar bit yang rendah melalui rangkaian berbilang lompatan di mana liputan rangkaian dapat diperluaskan. Protokol MAC yang sedia ada tidak menyokong masa nyata dengan berbilang lompatan serta memenuhi keperluan penyaluran minimum 8 kilobit sesaat. Oleh itu, tesis ini mencadangkan protokol MAC TSMAC. Prestasi dibuat terhadap protokol CSMA. Hasil daripada eksperimen dapat membuktikan bahawa TSMAC mampu menyalurkan sehingga 18 kilobit sesaat untuk satu sumber dan 10 kilobit sesaat untuk dua sumber secara serentak di atas rangkaian 6LoWPAN dua lompatan menggunakan perkakasan sebenar.

REAL-TIME CAPABLE MULTI-HOP MEDIA ACCESS CONTROL PROTOCOL FOR SMART HOME ENVIRONMENT

ABSTRACT

The Wireless Sensor Network (WSN) is a technology that is now often highlighted and various studies have been done to apply in life such as environmental monitoring, security and military applications. These include the study of the Internet of Things (IoT) and Smart Home, where it is now gaining popularity in the research environment. The combination of home appliances such as lights, gates and closed circuit, would be able to make the future home not just smart, but smarter in energy consumption and secure. Nevertheless, to apply WSN in the Smart Home Environment, WSN protocols need to support real-time characteristics. This protocol must also be capable of transmitting time-sensitive data such as audio and video at low bit rates through a multi-hop network where coverage can be expanded. The existing MAC protocol does not support real-time with multiple-hop and meets the minimum throughput requirement of 8 kilobits per second. Therefore, this thesis proposes TSMAC MAC protocol. The performance is made against CSMA protocol. It was determined, real-time data such as low bit rate audio, capable to stream up to 18 kilobits per second for one source and 10 kilobits per second for two-source simultaneously over 6LoWPAN network over two-hop using the real hardware.

CHAPTER 1

INTRODUCTION

Wireless Sensor Network (WSN) is a fast growing technology, which is widely used for different application, namely environmental monitoring, weather forecast, target tracking and military applications. Since WSN nodes are mainly used for outdoor applications, they mainly rely on their internal battery supply.

It has also enabled many new applications including Smart Home Environment. For example, incorporating WSN technology in home devices, such as lighting, air conditioning, security cameras will inspire future developers to be able to design and build not only smart but low-cost, secured, energy efficient and also network efficient.

A cloud capable network that is able to accommodate all these requirements and as well as supporting multi-hop ad-hoc network structure, provide scalability as well as efficiency in supporting such a household collection of smart electronic devices. With the use of multi-hop WSN, the coverage of the network can be extended, providing coverage to areas that are not easily accessible via network outlets, including entrances, windows as well as outdoor areas and garden.

However, the use of WSN for the Smart Home Environment creates a new challenge, where it requires the development of real-time data capable WSN protocols, which can support the transmission of time-sensitive data such as low bit rate audio for intercom systems and low bit rate video for video security camera. Besides, although the data rates required by the indoor ambience monitoring and control are relatively low, in certain circumstances for examples, smoke detectors and fire alarms require real-time response.

Current WSN protocols (EMAC (Hoesel, Nieberg, Kip, & Havinga, 2004), L-MAC (Van Hoesel & Havinga, 2004) and AI-LMAC (Chatterjea, Hoesel, & Havinga, 2004)) are not designed to support such real-time data transmission. The purpose of this research is to investigate suitable Medium Access Control (MAC) Protocols as well as a real-time capable routing protocol for WSNs, and its development for use in the Smart Home Environment.

1.1 Motivation

In the past few years, it has become a fact Smart Home technology is evolving. The idea of the Smart Home is to increase automation of the home, managing energy and reducing emissions to the environment. The early stage technology implemented in Smart Home Environment is using power line which is known as X10. This technology evolves from wired to wireless technology because it is easy to deploy the sensor in house area without worries on cabling and could extend the sensor to the location where there is no power outlet. Wireless technology gives several advantages and benefits to the users such as easiness of maintenance, mobility, and reliability (Sallinen, 2010). This include WSN which is base on the IEEE 802.15.4 standard which is easier to maintain and it is design for mobility.

Nevertheless, the wireless technology is quite fragile since it is easily threatened by interference and collision. Unlike sensor such as temperature, it should not be a problem, since the data size is relatively low, but when data size is bigger, for example, low bit rate audio or video, this could cause delay. Therefore real-time MAC protocol is needed and have to be considered to solve the problem.

In a normal deployment of WSN network, star topology is a choice. Nodes are categorized in two types: Fully Function Device (FFD) and Reduced Function Device (RFD). In a star network, a FFD is needed to be a coordinator, while RFD attaches with the sensor, join the network via FFD. There is a probability that sensor need to be placed in a location where there is no coverage area. The limitation with star network, an RFD node is unable to send data to the coordinator via another RFD. This happens because of RFD is a reduce function, and does not have a function to forward data from another RFD. The source node could not send the data to the sink. To solve the issue, multi-hop is needed and has to be done in a mesh topology, where an intermediate node is a FFD node.

These considerations are motivations for this thesis. The goal is to investigate suitable real-time capable multi-hop MAC protocol to be implemented in WSN for the use of Smart Home Environment, where even low bit rate video or audio could be transmitted in a multi-hop environment as well as real-time capable. This could enable application such as intercom, audio or video control through a WSN network.

1.2 Research Questions

Recently there are many studies of WSN involving physical, MAC protocols, network and also application layer to improve power efficiency and data delivery. There are many protocols being introduced but still no suitable protocol could be implemented in Smart Home Environment to address real-time transmission and response. In addition, limitation on the wireless coverage will also affect transmission from source to the receiver. The limitation could due by interference and also the wireless transmitter reaches to its maximum limit. This would require an implementation of multi-hop to be enabled in Smart Home Environment. Thus, research questions are as follows:

1. What is the suitable WSN architecture for Smart Home Environment that shall need multi-hop?
2. How to improve current wireless connectivity to support real-time transmission in multi-hop environment for WSN Network?

1.3 Objectives

This research of this thesis is to address the following issues to support a Smart Home Environment:

1. To propose a suitable WSN architecture for Smart Home Environment which require multi-hop.
2. To develop a new real-time capable multi-hop MAC protocol for Smart Home Environment.
3. To investigate the performance of proposed MAC protocol using experimental test-bed.

1.4 Scope

This research proposes an algorithm for a new MAC protocol to support real-time data transmission in WSN network. In this research, experimental method used was tested on a test-bed. The test-bed only involve up to two hops of WSN network.

1.5 Contributions

This thesis proposed a new MAC protocol algorithm that base on time slotted algorithm to support real-time capable multi-hop MAC protocol. The proposed protocol is to reduce, and some cases completely prevent the issues of packet collision. The proposed protocol could be implemented in Smart Home Environment, hence inspire house developer to use WSN for Smart Home implementation in house development. This protocol has been experimented in real WSN nodes.

CHAPTER 2

LITERATURE REVIEW

This chapter has three segments: an introduction to the Smart Home Environment, literature on existing wired and wireless technology for a Smart Home Environment and literature on existing real-time MAC protocol.

In Section 2, several existing Smart Home technology such as X10, INSTEON, Wavenis, Z-Wave, ZigBee and 6LoWPAN Network will be discussed. The discussion defines the wireless operation frequency, maximum data transmission and how it operates. In Section 3, a literature review on existing real-time MAC protocol for WSN such as TOMAC, SUPPORT, RRMAC and RTH-MAC discussed.

2.1 Smart Home Environment

Smart Home Environment is a home environment that uses sensors and network equipment to enable the occupant to remotely control and automate home devices. The main objective of the Smart Home is to increase automation of the home, managing energy and reducing emissions to the environment (Al-Sumaiti, Ahmed, & Salama, 2014). In order to improve home automation, enhancement on communication could be established via power line network (X10), network radio signal or Internet protocol standard that uses twisted pair or fiber optics.

Smart devices have been around for a long time, and limited use due to the constraints of intercommunication. The solution to this problem is to connect all the equipment of smart devices using a cable. However, there is an issue in certain circumstances to use a wire to connect these devices. The portability and mobility of devices, especially equipment that is difficult to be connected by cable due to the location of the equipment raise an issue which wired is not an option for communication. Thus, it has created a demand for devices and solutions that need to support the wireless for home automation network.

2.2 Wireless Sensor Network (WSN)

WSN consist of a large number of small, inexpensive sensor nodes which are distributed over a geographical area for monitoring and tracking such as temperature, speed. A sensor normally is simple, compact and has limited memory, power, and processing capabilities. Over the last few years, WSN received much attention due to increasing demand for inexpensive, simple, low-rate, and low power applications such as environmental monitoring, surveillance, motion detection, data collection, health monitoring, disaster recovery, and data communications. Lately, applications like factory automation and also home automation are also trying to implement WSN. The crucial part of this application is, time constraint for message delivery where information must reach on destination on the specified time.

2.3 Existing Technology

There are several existing technologies to support Smart Home Environment. In this section, existing technology from the wired to the wireless technology will be discussed.

2.3.1 X10

X10 (*Transmission Of Data Using Power Line Carrier Communication System*, n.d.) is a communication protocol developed by Pico Electronics. It is an open standard that is used in communication equipment used for home automation. With the use of power line wiring, X10 implement signalling and control, in brief radio frequency bursts, representing digital information. The advantage of using the X10 protocol is, all components are designed to operate with existing power lines. Data transmission speed could be achieved up to 14 Mbps and has 256 possible addresses that can be used. However, the problem of this protocol is, that some of the equipment requires portability and mobility, still unsolved because not every place has a power outlet.

2.3.2 INSTEON

INSTEON (Darbee, 2006) defines mesh topology with a combination of Radio Frequency (RF) and power line links. A node could be RF-only or power-line only or could support both. This technology is developed by SmartLabs for home automation. For RF, it uses frequency shift keying (FSK) modulation with the 904 MHz band. This technology supports bit rate up to 38.4 kilobits per second.

INSTEON device can play any role either sender, receiver or relayer since it works as peers. If communication between devices is out of range, it could be achieved through a multi-hop approach which the maximum number of hops for each message limited to four. Transmission is executed using time slot synchronisation, which means, only certain device is permitted to transmit in a certain time slot, and all devices within the same range do not transmit different messages at the same time.

This technology defines time slot by a number of power line zero crossing. RF devices without power line transmit asynchronously, while a related message will be transmitted synchronously with a device attached to the power line. INSTEON define simulcast, where devices within the same range are allowed to transmit the same message simultaneously.

2.3.3 Wavenis

Wavenis (García-Hernando, Martínez-Ortega, López-Navarro, Prayati, & Redondo-López, 2008) is a wireless protocol stack developed by Coronis System. It defines the functionality of Physical Layer, Link Layer, and Network Layer. It's services could be accessed through Application Programming Interface (API) which are located on the upper layer.

Wavenis operates in the 433 MHz, 868 MHz, and 915 MHz. Some of the product also supports 2.4GHz band. Bit rates offered by Wavenis is 4.8 kilobits per second, 19.2 kilobits per second and 100 kilobits per second. Data are modulated using Gaussian Frequency Shift Keying (GFSK) and Frequency Hopping Spread Spectrum (FHSS) for over 50 kHz bandwidth channels.

This technology offers two types of MAC sublayer which are synchronised and non-synchronised. In a synchronised network, the node is given the mix of Carrier Sense Multiple Access (CSMA) and Time Division Multiple Access (TDMA). Each of nodes allocates a time slot calculated randomly based on its address. When the right time slot arrives for that node to make a transmission, the node performs Carrier Sense (CS). If the channel is busy, transmission is discarded, and the node computes a new time slot for transmission.

For non-synchronised networks, Carrier Sense Multiple Access Collision Avoidance (CSMA/CA) is used. On Logical Link Control (LLC) sublayer, it manages flow and error control by offering per-frame or per-window Acknowledgment (ACK)s. It has only one type of device. The Wavenis network layer specifies four-level virtual hierarchical tree. The root of the tree play the role as the gateway and also collect the data. A new device that wants to join the network needs to broadcast the request for a device of a certain level and a sufficient Quality of Service (QoS) value. QoS value is determined by Receive Signal Strength Indicator (RSSI), battery energy, and the number of devices attached to the solution.

2.3.4 Z-Wave

Z-Wave (Jfr, 2006) is a wireless protocol architecture develop by ZenSys. The main objective of Z-Wave is to allow reliable transmission of a short message from a control unit to one or more nodes. The protocol proposes five primary layers which are Physical Layer, MAC Layer, Transfer Layer, Routing Layer and Application Layer.

Z-Wave operates in 868 MHz, 908 MHz and also 2.4 GHz. It allows transmission at 9.6 kilobits per second, 40 kilobits per second data rates using Binary Frequency Shift Keying (BFSK) modulation for 868 MHz and 902 MHz bands. For 2.4 GHz band, bit rates support up to 200 kilobits per second.

Z-Wave defines a collision avoidance mechanism which allows transmission frame when the channel is available. If not, transmission attempt is deferred for a random period of time. The transfer layer provides an optional retransmission mechanism based on ACK so that it could manage communication between two nodes.

There are two types of devices in Z-Wave which are controllers and slaves. The controllers poll and send a command to the slaves, which reply to the controllers or execute instructions. A controller maintains information which represents the full topology of the network. For routing layer, it performs routing based on a source routing approach. A packet could be transmitted up to four hops.

2.3.5 ZigBee

ZigBee (García-Hernando et al., 2008) is a wireless networking technology developed by ZigBee Alliance. This technology is used for a low-rate and short-range application. The protocol proposed four primary layers which are the Physical Layer, MAC Layer, Network Layer and Application Layer. For Physical Layer and Network Layer are defined by the IEEE 802.15.4 standard, while the other layers are proprietary of ZigBee.

ZigBee operates in the 868 MHz, 915 MHz and 2.4 GHz bands which is based on IEEE 802.15.4. The data rates could be achieved are 20 kilobits per second, 40 kilobits per second and 250 kilobits per second, respectively. For 868 MHz and 915 MHz, Binary Phase Shift Keying (BPSK) is used while 2.4GHz signal uses Orthogonal-Quadrature Phase Shift Keying (O-QPSK). As ZigBee is meant on IEEE 802.15.4, it has two methods for channel access which is Beacon-enabled and Beaconless.

For Beacon-enabled, there is one node which plays a role as the Personal Area Network (PAN) coordinator. This node transmits a beacon for network synchronisation. The time between beacons is separated into three periods:-

- Contention Access Period (CAP) – Use CSMA/CA.
- Contention Free Period (CFP) – Node could transmit packet base on allocated Guaranteed Time Slot (GTS).
- Inactive Period – nodes will go into sleep mode.

In the Beaconless mode, plain CSMA/CA scheme is employed. For unicast transmission, ACK frames are used. ZigBee defines three device roles: ZigBee Coordinator, ZigBee Router, and ZigBee End Device.

On network layer, it supports addressing and routing for the tree and mesh topologies. For tree topology, route information is rooted at the coordinator while in a mesh topology, routes are created on demand and maintained base on Ad hoc On-Demand Distance Vector (AODV) routing protocol. ZigBee supports up to 30 hops maximum with the usage of mesh routing.

2.3.6 6LoWPAN

IPv6 over Low-Power Wireless PAN (6LoWPAN) (Shelby & Bormann, 2011) is an IP-based solution defined by Internet Engineering Task Force (IETF). IETF has been carrying out the standardisation of mechanisms for extending the Internet for sensor and actuator network. The frame format and several mechanisms are needed for the transmission of IPv6 packets on top of IEEE 802.15.4 defined by IETF Working Group

(WG). 6LoWPAN offers mechanism such as:

- Fragmentation - By nature of IPv6, minimum Maximum Transmission Unit (MTU) is 1280 bytes, while the maximum frame size for IEEE 802.15.4 is 127 bytes. This mechanism is the ability to encode a datagram using multiple link frames.
- Header compression - IPv6 header fields are eliminated from a packet when adaptation layer information carried in 802.15.4 frame or based on simple assumptions of shared context. By using this mechanism, it can compress 40 bytes of IPv6 header to a 2 byte header.

Since it is based on IEEE 802.15.4, 6LoWPAN operates in the 868 MHz, 915 MHz, and 2.4 GHz. The data rates achieved are 20 kilobits per second, 40 kilobits per second and 250 kilobits per second. For 868 MHz and 915 MHz, BPSK is used while 2.4Ghz signal O-QPSK is used. As it is based on IEEE 802.15.4, it has two methods for channel access which is Beacon-enabled and Beaconless. Compared with ZigBee, the role played by 6LoWPAN are as follows: Edge Router, Node (Mesh-Under), Router (Router-Over) and Host.

Edge Router enables interconnection of a LoWPAN with another network. In Mesh-Under, routing is being done on Layer 2 which uses IEEE 802.15.4 addresses. By using this configuration, only single IP link appears for the whole LoWPAN. While in Route Over, each of the radio hops is equal to an IP hop and routing occurs at Layer 3 or IP level. A Host is a simple node that can only be a source or sink for IPv6 packets.

2.4 Existing Standards

2.4.1 IEEE 802.11

IEEE 802.11 (IEEE802.11, 2012) is the standard for Wireless Local Area Network (WLAN). The standard adopts the standard 802 LLC protocol but provides an optimised Physical Layer and MAC Layer for wireless communication. It has specified two physical layers which Direct Sequence Spread Spectrum (DSSS) and FHSS. It operates on the 2.4 GHz band, with transmission rate at this early stage is 2 Mbps.

Access mechanism used by IEEE 802.11 is CSMA/CA. Each sender listens for traffic. If there is a traffic, the sender waits for a random amount of time, and will recheck back for the traffic. If there is no traffic more than a present amount of time, the packet sends without waiting. This method used by CSMA/CA is to avoid collisions which could result in transmission failure. The receiver will immediately send back an ACK packet. If the sender does not receive the ACK, the packet will be put in a queue, so that CSMA could retransmit the packet.

Although the throughput is getting bigger and could support portability and mobility, it is not energy efficient, and it is expensive on deployment.

2.4.2 IEEE 802.15.1

IEEE 802.15.1 (IEEE802.15.1, 2005) is the standard for Wireless Personal Area Network (WPAN). It is used to exchange information over short distances among a private, intimate group of participant devices. Compared to WLAN, to connect through WPAN involve a little or no infrastructure. This will enable small, power-efficient, inexpensive solution to be implemented. IEEE 802.15.1 technology is also known as Bluetooth. It could be operated in a point of service within the range of 10 meters and could be extended to 100 meters.

On Network Layer, it supports addressing and routing for the tree and mesh topologies. For tree topology, route information is rooted at the coordinator while in a mesh topology, routes are created on demand and maintained base on the AODV routing protocol.

2.4.3 IEEE 802.15.4

IEEE 802.15.4 (IEEE802.15.4, 2011) is a network, suitable for simple applications. It only requires low rate connectivity, bandwidth and also low power consumption. The standard defines protocol on the Physical Layer and MAC Layer for Low-Rate Wireless Personal Area Network (LR-WPAN). It operates in 868 MHz, 915 MHz, and 2.4 GHz frequencies. The data rates could be achieved 20 kilobits per second with one channel, 40 kilobits per second for ten channels and 250 kilobits per second for 16 channels, respectively. Each of hardware comes with a 64-bit IEEE address known as PHY address. The standard also uses 16-bit short address. It is assigned by PAN Coordinator during association phase.

2.4.4 IEEE 802.15.4e

IEEE 802.15.4e IEEE802.15.4e (2012) standard is a variation of IEEE 802.15.4-2006 standard which amends the MAC sublayer. It introduces Time Slotted Channel Hopping (TSCH), to allow distributed implementation and propose flexibility to minimise the interference.

The protocol divides time into time slots, and all nodes are synchronised to a given slot frame. There are two methods defined in IEEE 802.15.4e for allowing a device to synchronise in a TSCH network: Acknowledgment-based and Frame-based synchronisation. For the latter, the receiver uses the calculated delta for adjusting its clock. In this position, it is the receiver node that synchronises to the clock of the sender. For the former, the receiver provides such information to the sender node in its ACK. In this case, it is the sender node that synchronises to the clock of the receiver (Watteyne, Palattella, and Grieco (2015)).

Schedule cell is a single element of the schedule which is described by a slotOffSet and channelOffSet, and reserved for one node to transmit to another node as well as receive from another node within a given timeslot. TSCH defines a timeslot counter called Absolute Slot Number (ASN). When a new network is created, the ASN is initialized to 0; from then on, it increments by one at each timeslot (Watteyne et al. (2015)). Thus, all scheduled cells define the matrix cells. Each node follows a communication schedule as programmed in the matrix of cells.

2.5 Type of Devices

IEEE 802.15.4 defines three types of nodes, which is PAN Coordinator, Coordinator and Sensor device. It also categorised device into two, namely FFD and RFD. PAN Coordinator and Coordinator are classified as FFD, which is design to have all functionalities of an RFD, and greater resources like power, memory, and processor. FFD always play a major role in the formation of the core network and management or scheduling tasks. The PAN Coordinator is responsible for selecting a channel, assigning a short address to joined devices to start communication. It is also responsible for starting the Beacon-enable network. The RFD is a simple node and does not have functionalities as FFD. It depends on FFD to communicate and function. The FFD need to be powered to maintain an uninterruptible network, while RFD is a simple sensor device that sends and receive the message and could only be powered up by the battery.

2.6 Protocol Frame Format

Frame format used for the proposed MAC is derived from IEEE 802.15.4-2006 standard. It defines two frames, which is Data and ACK. Figure 2.1 depicts Data frame format for IEEE 802.15.4-2006 standard. The MAC Layer frame could increase up to the defined 802.15.4 MTU size of 127 octets. The standard defines MAC frame into three sections which are MAC Header, MAC Payload, and MAC Footer. MAC Header consists of 6 fields. The first field is a Frame Control Field (FCF) which allocated 2 bytes. FCF determine the type of packet, for this case two type of packet: Data and Ack.

The sequence number in the field normally contains a random number. This number will increase every time the frame is sent. The function of this field is to protect the frame from duplicated frame sent. The field is allocated 1-byte space. The third to the sixth fields occupy source and destination PAN IDs and addresses. PAN ID occupies 16 bits and address field depends on whether using a short or long address, occupying 16-bits, and 64-bits, respectively. The Payload field stores the data that need to be sent. The occupied space varies since it depends on the size of the data. The maximum occupied space, is the balance of the total 127 octets after deduct MAC Header and MAC Footer. The MAC Footer contains Cyclic Redundancy Check (CRC). This field occupies 16 bits. It is used to determine whether frame is valid or corrupted.

MAC Header						MAC Data Payload	CRC
Frame Control Field (2 bytes)	Sequence Number (1 byte)	Destination PAN ID (2 bytes)	Destination Address (0-8 bytes)	Source PAN ID (2 bytes)	Source Address (0-8 bytes)	Payload	Checksum (2 bytes)

Figure 2.1: Data Frame Format (IEEE 802.15.4-2006)

Each node composes the frame based on this format before sending out the packet to the destination over the air. When the packet is received, received node sends back the ACK packet. ACK packet is formed based on defined frame as in Figure 2.2. It has to be requested by the sender, where it also need to be defined in the FCF.

MAC Header		CRC
Frame Control Field (2 bytes)	Sequence Number (1 byte)	Checksum (2 bytes)

Figure 2.2: ACK Frame Format (IEEE 802.15.4-2006)

Frame Control Field Details								
Frame Type (3 bits) 0 = Beacon 1 = Data 2 = ACK 3 = Command 4-7 = Reserved	Security Enabled (1 bit)	Frame Pending (1 bit)	ACK Request (1 bit)	PAN ID Compression (1 bit)	Reserved (3 bits)	Destination Address Mode (2 bits) 00 = Address not present 01 = Reserved 10 = 16-bit Address 11 = 64-bit Address	Frame Version (2 bits)	Source Address Mode (2 bits) 00 = Address not present 01 = Reserved 10 = 16-bit Address 11 = 64-bit Address

Figure 2.3: Frame Control Field Details (IEEE 802.15.4-2006)

The details for FCF are show in Figure 2.3. The first field is to determine the type of frame. For the proposed MAC, frame type Data and ACK is used. This field occupies 3 bits. The second field is security enabled, to determine whether to use any encryption process on MAC Payload. The Frame Pending is occupies 1 bit and is used if the frame is incomplete and there are other packets after this packet. ACK Required is the field used by data frame to ask for acknowledgement. The receiver which receives a packet with ACK Required, send the ACK packet if the Checksum is valid. PAN ID Compression field occupies 1 bit, specifies whether the MAC frame is to be sent containing only one of the PAN identifier fields when both source and destination addresses are present. If the field is set to 1, both source and destination PAN ID are identified as same, and the frame should contain only the Destination PAN ID, and the Source PAN ID shall be assumed equal to the destination.

The Source and Destination Address fields occupies 2 bits. If there is no need for address, this field could contain 0 value. If this frame is used for broadcast messages the short address is assigned with the value 2, while if it used for Point to Point communications, the value 3 is used since there is a need to use a long address and it occupies 16 bits and 64 bits, respectively.

2.7 Network Topologies

The IEEE 802.15.4 support two possible network topologies, which is simple star topology and peer-to-peer topology. Both topologies require at least one PAN Coordinator. In simple star topology as shown in Figure 2.4, the PAN Coordinator is required to allow communication between nodes. It must be first to exist, to start the network by selecting a channel and set the PAN ID, thus allowing other nodes to join the network. Beacons also broadcast periodically in the network if the network mode is Beacon-enabled. Each device can only associate with one PAN Coordinator at a time.

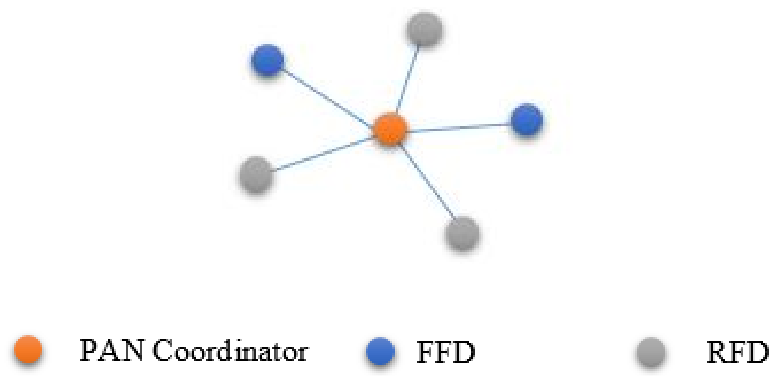

Figure 2.4: Star Topology

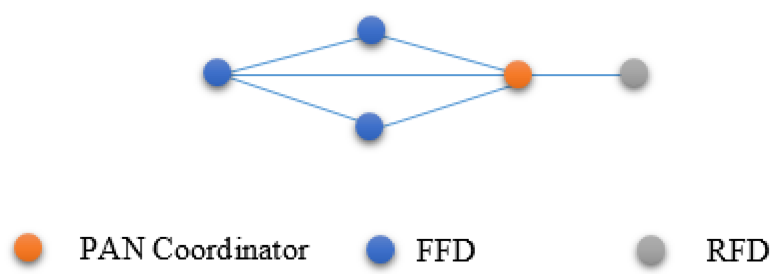

Figure 2.5: Peer-to-peer topology

Figure 2.5 shows peer-to-peer topology. In this topology, PAN Coordinator does not only work as same as termed in a star topology, but also communication could be made by involving between different nodes which are not PAN Coordinator in a peer-to-peer topology. By using this topology, multi-hop could be enabled by electing one of FFD to work as a Coordinator, and manage its own WPAN. Hence, this coordinator

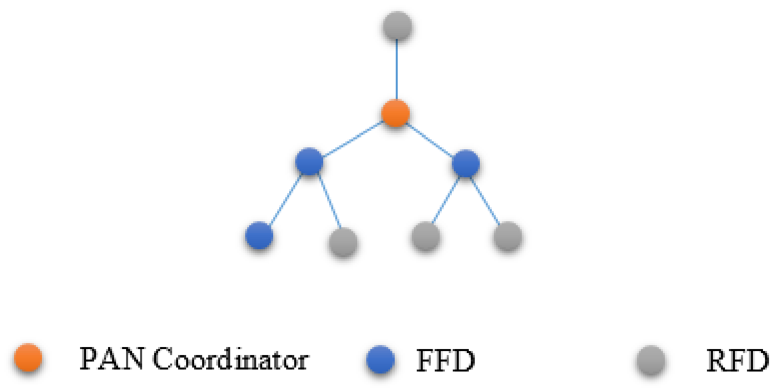

Figure 2.6: Cluster Tree topology

could allow devices to join this network cluster, assigning addresses and so on. Figure 2.6 depicts a cluster tree topology. This topology allows the extension of the network where it involves multiple FFD elected to be a Coordinator.

2.8 Network Operation Mode

In IEEE 802.15.4 network operates in two modes which are Beacon and Beaconless. In Beacon mode, it is required to broadcast beacon message periodically. PAN Coordinator does the process to broadcast the beacon message. Beacon mode work in the form of Superframe structure. Beacon messages are used to determine the start and the end of the Beacon mode.

In a Beaconless mode, the communications between nodes are done by CSMA/CA mechanism, where each node will compete to secure the channel. Each of the nodes needs to be active.

2.9 Real-Time System

A real-time system is a system that needs to be acting on time directly proportional to the requirements in an environment. Deadline (Zheng & Ki-Il, 2010) is the main function in a real-time computer system, where maximum time to execute any instruction need to be completed within the given time. For a certain critical application, data is considered invalid when it arrives at the destination over the period of given time.

Real-time system provides following features to support the critical applications which are:

- Timeliness – Message transmitted at destination within dateline of the time domain.
- Designed for peak load – The real-time system should not collapse when it encounter heavy traffic.
- Predictability – To maintain and guarantee the performance, a real-time system needs to be able to predict consequences of any decision.
- Fault tolerance – The real-time system need to prevent itself from crashing.
- Maintainability – The architecture for real-time system need to be designed so that possible modification could be easy to perform.

2.10 Global Time Synchronisation and Slotted Time Synchronisation

Every WSN nodes need to sync with each other, which means nodes wake up or sleep at given time and communicate with each other without collisions happening.

Normally, each WSN node has its internal clock. Time synchronisation mechanism is needed to ensure the internal clock for each node has the same time.

GTS is one of the mechanisms for time synchronisation, usually one master clock as the time source. All other resources in the network will retrieve and synchronize the time based on the master. The issue of using GTS is there is no guarantee all nodes will receive the beacon at the same time. One of the factors is due to the distance. To solve this issue, there are several techniques proposed.

In contrast, Slotted Time Synchronization (STS), each node depends on its own clock to get synchronised with other nodes. STS works in distributed manner where time is divided into slots. Each of the nodes negotiates to book a time slot. It is independent and does not rely on master time source.

GTS has many constraints, such as in the topology, different classification of nodes and bandwidth. STS uses less energy since it transmits less beacon packet. STS provides more flexibility which makes suitable for WSN nodes.

2.11 Slotted Aloha

Aloha (Abramson, 1970) is a contention protocol developed in the 1970s for a packet radio network. In an Aloha, a single broadcast channel is shared by a number of communicating devices. Every device transmits its packets independent of any other device or any specific time. The device transmits the whole packet at a random point in time. The device then times out for receiving an acknowledgement (Roberts, 1975).

Slotted Aloha is proposed based on the Aloha where time is divided into fixed-size slots, where slot sizes are equal to packet transmission time. The protocol requires the devices to transmit the packet at the beginning of a time slot (Roberts, 1975). Each node has to wait until the start of the next slot before sending a packet.

2.12 Existing Real-Time MAC Protocol

In this thesis, four recent real-time MAC protocols are discussed. Real-time MAC protocol for wireless sensor network could be divided into two types which are hard real-time MAC protocol and soft real-time protocol. For hard real-time, the design is based on TDMA MAC protocol, while for a soft real-time MAC protocol it is developed based on S-MAC.

TDMA (Havinga & Smit, 2000) is a channel access method for shared medium network. This protocol uses hardware clock, where time access directs to the hardware. TDMA protocol can be group into two categories which are centralised and distributed. In the centralised approach, one active node will be a leader, responsible to assign who can access the channel and how long a node is allowed to control the channel. All sensor nodes will depend on the central node manager waiting for a time slot to be allocated within the cluster. This approach has disadvantages such as lack of scalability, fault tolerance and high latency.

Sensor-MAC (S-MAC) (Ye, Heidemann, & Estrin, 2002) was developed to reduce energy consumption from all sources that is identified to cause energy waste, for examples idle listening, collision, overhearing and control overhead. The protocol consists of three major components which are periodic listen and sleep, collision overhearing avoidance and message passing. With S-MAC, each node goes to sleep for some time,