DISTRIBUTED TIME DIVISION MULTIPLE ACCESS (DTDMA) MEDIUM ACCESS CONTROL PROTOCOL FOR WIRELESS SENSOR NETWORKS

by

WOON THEAN HUNG WILSON

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LIST OF ABBREVIATION

AC	Alternating Current
ACK	Acknowledgement (Message)
AP	Access Point
ASP	Application Support Package
awk	**A**lfred V. Aho, Peter J. **W**einberger, and Brian W. **K**ernighan
BDM	Background Debug Mode
BE	Backoff Exponent
BI	Beacon Interval
BO	Beacon Order
BS	Base Station
BSS	Basic Service Set
CAP	Contention Access Period
CCA	Clear Channel Assessment
CFP	Contention Free Period
CORSIM	Microscopic Traffic Simulation Model
CRC	Cyclic Redundancy Check
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
CTS	Clear To Send
CW	Contention Window
DTDMA	Distributed Time Division Multiple Access
DTSS	Distributed Time Slot Synchronization
ED	Energy Detection
ESS	Extended Service Set
EVB	Evaluation Board
EVK	Evaluation Kit
FCS	Frame Check Sequence

FFD	Full Function Device
GTS	Guaranteed Time Slot
IBSS	Independent Basic Service Set
ID	Identification
IEEE	Institute of Electrical and Electronic Engineers
IP	Internet Protocol
ISM	Industrial, Scientific, and Medical
LBT	Listen Before Talk
LR-WPAN	Low-Rate Wireless Personal Area Network
MAC	Medium Access Control
MCPS	MAC Common Part Sublayer
MEMS	Micro-electromechanical Systems
MLME	MAC Sublayer Management Entity
ns2	Network Simulator 2
OMNETT	Discrete Event Simulation System
OPNET	Optical Network Simulator
PAN	Personal Area Network
PARSEC	Parallel Simulation Environment for Complex System
PCF	Point Coordination Function
PDR	Packet Delivery Ratio
PHY	Physical
PLEN	Previous Length
POS	Point of Service
RAM	Random Access Memory
RBS	Reference Broadcast Synchronization
RFD	Reduced Function Device
RTS	Ready To Send
S-MAC	Sensor Medium Access Control

SARD	Sensor Application Board
SB-MAC	Slotted Beaconless Medium Access Control
SD	Superframe Duration
SO	Superframe Order
SYNC	Synchronization Packet
TcL	Tool Command Language
TDMA	Time Division Multiple Access
TRAMA	TRaffic Adaptive Medium Access
WLAN	Wireless Local Area Network
WPAN	Wireless Personal Area Network

LIST OF PUBLICATIONS

Wilson T.H. Woon and T.C. Wan. “Performance Evaluation of IEEE 802.15.4 Wireless Multi-Hop Networks: Simulation and Testbed Approach”. To appear in Int. Journal. of Ad Hoc and Ubiquitous Computing (IJAHUC).

Wilson T.H. Woon and T.C. Wan. “Performance Evaluation of IEEE 802.15.4 Ad Hoc Wireless Sensor Networks: Simulation Approach”. In Proc. of IEEE Int. Conf. on Systems, Man, and Cybernetics (SMC 2006), Taipei, Taiwan, 8-11 Oct. 2006.

PROTOKOL KAWALAN PENCAPAIAN MEDIA CAPAIAN BERBILANG PEMBAHAGIAN MASA TERAGIH (DTDMA) UNTUK RANGKAIAN SENSOR TANPA WAYAR

ABSTRAK

Rangkaian sensor tanpa wayar menerima perhatian yang memberangsangkan sejak beberapa tahun yang lalu disebabkan oleh peningkatan permintaan terhadap perisian kadar rendah, murah dan menjimatkan tenaga seperti operasi perkilangan, ketenteraan, kesihatan, pengawasan alam sekitar, sekuriti, operasi penyelamatan dan komunikasi tanpa wayar. Beberapa tahun kebelakangan ini, terdapat banyak usaha untuk memajukan sambungan tanpa wayar berbentuk sensor untuk komunikasi. Seperti kebanyakkan komunikasi tanpa wayar, protokol kawalan pencapaian media merupakan suatu cabaran yang penting dalam menyediakan kemudahan komunikasi yang lancar antara peralatan-peralatan tanpa wayar. Salah satu kriteria dalam protokol kawalan pencapaian media ialah penyediaan capaian medium yang efisien sambil mengurangkan perlanggaran antara data. Dalam konteks rangkaian sensor tanpa wayar, masalah utama yang dihadapi ialah kekurangan tenaga bateri. Oleh itu sesebuah protokol kawalan pencapaian media mesti mengambil kira masalah ini untuk memastikan sesuatu sensor berfungsi lama. Lain-lain keperluan termasuk fleksibiliti dalam mengatasi perubahan dalam rangkaian, menggalakkan sensor-sensor bekerjasama dalam menjalankan fungsi rangkaian, menyokong aplikasi mudah, pencapaian medium secara adil, tahap truput yang baik dan masalah lengah dalam penghantaran data yang minima. Penyelesaian kesemua masalah ini boleh dikatakan suatu matlamat yang agak sukar untuk dicapai. Oleh itu, sesebuah protokol kawalan pencapaian media biasanya hanya menyelesaikan sebahagian daripada masalah – masalah tersebut. Tesis ini menilai sejauh mana pencapaian piawaian IEEE 802.15.4 dalam pelbagai keadaan menggunakan simulator ns2 dan rangkaian sensor tanpa wayar yang mengandungi lima sensor. Tahap pencapaian piawaian yang baru sahaja diluluskan ini jarang mejadi fokus penyelidikan. Tesis ini turut mencadangkan Protokol Kawalan Pencapaian Media Tanpa Isyarat Bercelah (SB-MAC) untuk mengatasi kelemahan-kelemahan dalam protokol IEEE 802.15.4. Protokol ini adalah berdasarkan kepada konsep protokol kawalan pencapaian media capaian berbilang pembahagian masa teragih (DTDMA). Ia meliputi tiga fungsi iaitu capaian media, penyelarasan pembahagian masa dan komunikasi data tanpa perlanggaran. Protokol ini telah dilaksanakan dalam rangkaian sensor tanpa wayar yang mengandungi lima sensor dan dibandingkan dengan protokol IEEE 802.15.4. Hasil daripada penyelidikan ini didapati SB-MAC berfungsi lebih baik daripada protokol IEEE 802.15.4 dalam pelbagai rangkaian sensor tanpa wayar berbentuk sementara.

DISTRIBUTED TIME DIVISION MULTIPLE ACCESS (DTDMA) MEDIUM ACCESS CONTROL PROTOCOL FOR WIRELESS SENSOR NETWORKS

ABSTRACT

Wireless Sensor Networks (WSNs) received tremendous attention over the last few years due to increasing demand for low data rate, low-cost and low power applications in industries like factory automation, military, health and hospitality, environment monitoring, security, search and rescue, and wireless communications. In recent years, there have been intense efforts on developing wireless sensor networking for data communications. Like traditional wireless communications, medium access control (MAC) protocols remain a challenging problem in enabling seamless connection between devices. The basic requirement from a MAC protocol is efficient channel access with minimal packet collision. Within WSNs, sensor nodes are usually battery powered which incur limitations on energy availability. Therefore energy-saving mechanisms are vital to ensure longevity. Other requirements include scalability and adaptivity, distributed cooperation among nodes, low bandwidth, fair channel access, good throughput and channel utilization, and minimal latency. It is challenging to attempt to fulfill all requirements. Therefore, existing MAC protocols usually have one or more tradeoffs. This thesis evaluates the performance of IEEE 802.15.4 wireless networks under various environments using the ns2 simulator and a five-node wireless sensor network testbed. This recently released standard was designed specifically for WSNs but its actual performance has not been studied extensively. This thesis also proposes the Slotted Beaconless Medium Access Control (SB-MAC) protocol as an enhancement to the IEEE 802.15.4 protocol. This protocol is based on a Distributed Time Division Multiple Access (DTDMA) MAC scheme. It consists of three functions: channel access, time slot synchronization and collision-free data communications. This protocol is implemented in the five-node wireless sensor network testbed and

evaluated against the IEEE 802.15.4 protocol. It was found that SB-MAC performs better than the IEEE 802.15.4 protocol in various wireless sensor mesh network topologies.

CHAPTER 1
INTRODUCTION

The desire for a viable solution to the last-mile problem (Kennedy, 2003) resulted in a significant shift in computer communications paradigm from wired-based networking to wireless communications. Since the last few decades, wireless networking has become the preferred medium for communications. It provides ubiquitous connection that paves way for effective communications among wireless devices such as mobile phones, PDAs, laptops, personal computers, and many more. This development has significantly changed the way we live and has become an integral part of our daily life. For example wireless technologies are the enablers of various industries like military, healthcare, home appliances, consumer products, manufacturing, industrial process monitoring, weather forecasting, telecommunications, entertainment, transportation, and many more.

Recent advancement in wireless networking enabled the creation of Wireless Sensor Networks (WSNs) that support simple, low-rate, and low-power connectivity for short range communications. The performance of medium access control (MAC) protocols that govern channel access for WSNs is critical for the reliability and smooth operation of WSN.

1.1 Problems Statement

Existing MAC protocols for WSNs was rarely implemented in realistic testbed environment, i.e. on a real sensor, due to limited time and funding. As a result, majority of the proposed protocols was implemented and evaluated using network simulation software (NS2, 2006) (Corsim, 2006) (Parsec, 2006) (Omnet++, 2006) (OPNET, 2006). However simulators serve as platform for protocol verification which may not represent actual usage environments. Due to a lack of realistic implementation and performance studies, the suitability of existing MAC protocols for WSN remains vague.

In addition, existing MAC protocols for WSNs contain several deficiencies. One of them is the requirement for a centralized node to establish and manage the network. This is clearly expensive and inflexible. Besides that, MAC protocols for WSNs were designed specifically for wireless networks. This approach is too expensive for the resource-constrained WSNs. Finally most MAC protocols do not fulfill the fundamental requirement of a MAC protocol that is minimizing packet collision.

1.2 Objectives of the Thesis

The objectives of this thesis are as follows:

- Implement and test identical scenarios for IEEE 802.15.4 wireless sensor networks using both ns2 simulation and an actual testbed, to determine how well the simulation and measured results correspond to each other.
- Improve the performance of the IEEE 802.15.4 protocol for wireless sensor mesh network topologies via modifications to the MAC protocol.

The proposed MAC protocol could be implemented on ns2 simulator in future for large scale deployment and performance study. However before this can be realized, a comparison study between ns2 and testbed must be conducted to determine whether the results for both platforms are consistent with each other.

1.3 Scope of the Thesis

The scope of this research is as follows:

- Describe the WSN taxonomy and survey the MAC protocols for WSN with emphasis on the IEEE 802.15.4 standard.
- Propose a new MAC protocol for WSN to address channel access and packet collisions issues in WSN.
- Evaluate and compare the performance of IEEE 802.15.4 MAC protocol in various network settings using ns2 and testbed.

- Evaluate the performance of the proposed MAC protocol and IEEE 802.15.4 MAC protocol.
- Determine the effectiveness of the proposed MAC protocol over IEEE 802.15.4 MAC protocol.

1.4 Contributions of the Thesis

This thesis conducts extensive performance evaluation of IEEE 802.15.4 MAC (IEEE, 2003) protocol in various scenarios using the ns2 simulator (NS2, 2006) and the Freescale MC13193 Evaluation Kit (EVK) (Freescale, 2006c) which consists of five sensor motes. This experiment study not just provides realistic evaluation results but the mean to correlate results obtained from simulation and testbed experiments. The outcome of this performance study would give a better understanding of the nature of IEEE 802.15.4 as well as the disparity of experiment results obtained from simulated and actual environments.

This thesis also proposes the Slotted Beaconless Medium Access Control (SB-MAC) protocol for WSN. SB-MAC is based on the concept of Distributed Time Division Multiple Access (DTDMA). It consists of three parts, namely time slot assignment in Spatial TDMA, distributed time slot synchronization, and collision-free channel access. This protocol is simple, inexpensive, and effective in channel access while minimizing packet collisions.

1.5 Thesis Organization

This thesis is organized as follows:

Chapter 2 provides general introduction to WSN and survey existing MAC protocols for WSN. It also states the requirements for MAC protocol in WSN.

Chapter 3 gives an overview of the proposed MAC protocol and its variants.

Chapter 4 presents the experimental tools and methodologies. The former involves description of ns2 and Freescale MC13193 Evaluation Kit (EVK) while the latter covers network topologies and settings used in the experiments.

Chapter 5 gives the results, analysis, and discussions of the experiments conducted in Chapter 4.

Chapter 6 covers the overall conclusion, recommendation, and future work.

CHAPTER 2
LITERATURE SURVEY

2.1 Wireless Sensor Networks

Wireless Sensor Networks or WSN(s) were invented due to rapid development in wireless technologies. It received tremendous attention over the last few years due to the advancement of micro-electromechanical systems (MEMS) and wireless communications. This enabled the development and subsequently the release of wireless-based sensor nodes or motes that are usually compact, simple, and inexpensive. Furthermore a particular sensor has limited power, processing, and storage capabilities that made it suitable for simple low-rate applications such as environmental monitoring, surveillance, motion detection, data collection, health monitoring, disaster recovery, and data communications.

WSNs were designed specifically for short distance communications within the range of 100 meters. Since limited energy is one of the characteristics of wireless sensor, limiting the transmission range could reduce energy consumption. In fact this encourages nodes in typical WSNs to collaborate with each other in data collection and processing, in addition to coordination and management of sensing activities.

The topology of WSNs is either *infrastructure* or *infrastructureless* depending on the application requirement. The former is a traditional method for establishing WSNs where a collection center or sink is deployed to collect data gathered by sensors scattered all over the network. However wireless sensors are inexpensive thus the production of these devices could easily span from hundreds to thousands. Therefore it is predicted that future deployment of WSNs would be infrastructureless i.e. without the sink. The concept of infrastructureless network is similar to *ad hoc network* or *mesh network*. In this network, all devices are equipped with wireless communications and networking capabilities to enable communications with immediate neighbors (nodes within transmission range). This networking framework is flexible, easy to establish, temporal in nature, self-organizing, and inexpensive. All nodes are considered homogeneous, communicate on the same channel and frequency, and use their physical or hardware address for identification purpose.

2.2 Medium Access Control Protocol for WSN

A medium access control (MAC) protocol serves as an integral component in computer communications. It enables nodes in a particular network, both wired and wireless, to coordinate with each other in a shared medium (channel) to efficiently and effectively handles channel access (ownership) and other management activities such as sleep-and-wake periods, neighborhood identification and updates, packet collision avoidance, security, and error detection.

2.2.1 Types of MAC Protocols

The first category of MAC protocols is known as *contention* access. All nodes in a network compete with each other for channel access. The basic mechanism is such that channel reservation is made when it is free of activities. Otherwise, a node will go into silent mode and reassesses the channel state after some time. This is repeated until the channel is secured or the maximum number of permitted attempts is reached. The second category is known as *contention-free* access whereby each node is allocate certain time period to access the channel. This allocation is either through a dedicated centralized node or base station (BS) or through distributive resolution among nodes involved in communications. *Scheduled* access is another example of MAC protocol where nodes broadcast their activities schedule (sleep, awake, transmission, and receiving) to all immediate neighbors. Receiving nodes would adjust their schedules to ensure collision-free communications in the network. The fourth method is known as h*ybrid* approach. It combines two or more of the previously mentioned techniques. A brief survey on existing MAC protocols is provided in the section on literature survey.

2.2.2 Requirements of WSN MAC Protocols

One of the basic requirements of MAC protocol for WSNs is **minimizing packet collisions** which occur when two or more nodes attempts control of the channel at the same time. The solution to this is by establishing effective and efficient channel access mechanisms. Generally collision cannot be overcome completely in wireless network. However a decent MAC protocol should minimize such occurrence. Sources of packet collision include simultaneous access and 'hidden node' problem (Toh, 2001) (Ng *et al.*, 2005).

Another requirement of a WSNs MAC protocol is **energy efficiency**. As mentioned earlier, WSNs are constrained by finite energy source. In order to prolong the lifetime of a sensor node, sources of energy waste must be minimized. They include packet collision, idle listening, overhearing, overemitting as well as receiving and transmitting messages (Wei *et al*., 2004) (Demirkol *et al.*, 2006). Reducing packet collision is the most basic requirement in order to reduce idle random 'backoffs' (listening) and packet retransmission. Furthermore the MAC protocol should also minimizes transmission of control packets and allows nodes to go into sleep mode during inactive period. The latter has to be efficiently scheduled because frequent transition from sleep to active state and vice versa consumes relatively large amount of energy (Wei *et al*., 2004).

In an ad hoc network, nodes **cooperate** with each other in a distributed manner to accomplish a particular function which includes channel access. This requirement is critical in the absence of central controlling node or gateway to coordinate the nodes. Even when a gateway is employed, cooperation among nodes is also necessary because the gateway may not have sufficient resources to support large population of nodes and in case it fails, total network failure could be prevented. Therefore sensor nodes must be flexible and fault-tolerant.

Scalability and adaptivity refer to the ability of the MAC protocol to accommodate changes in network size, density, and topology. Nodes in WSNs are not expected to be highly mobile but changes to the network topology could occur when nodes become active and inactive or when new nodes are added to the network.

Other characteristics include **latency**, **throughput**, **fairness**, and **channel utilization**.

2.2.3 Problems in Wireless Channel Access

2.2.3.1 Collision Detection

Packet collision occurs when two or more nodes attempt to access the channel simultaneously. It is detected when there is excessive noise in the channel or acknowledgement from destination is not received. However collision detection based on these techniques may be inefficient because packets may go missing or corrupted in the wireless medium. There is no solution to these problems and assumption that collision occurs has to be made for these cases.

2.2.3.2 Hidden Node Problem

‘Hidden node’ (Toh, 2001) (Ng *et al.*, 2005) is a classical problem in wireless networks where two or more nodes that are 'hidden' or out of transmission range of each other attempts to communicate with the same destination simultaneously. Collision is undetected because it occurs at the destination, not the source, and acknowledgement from destination may be disabled. Figure 2.1 depicts this problem.

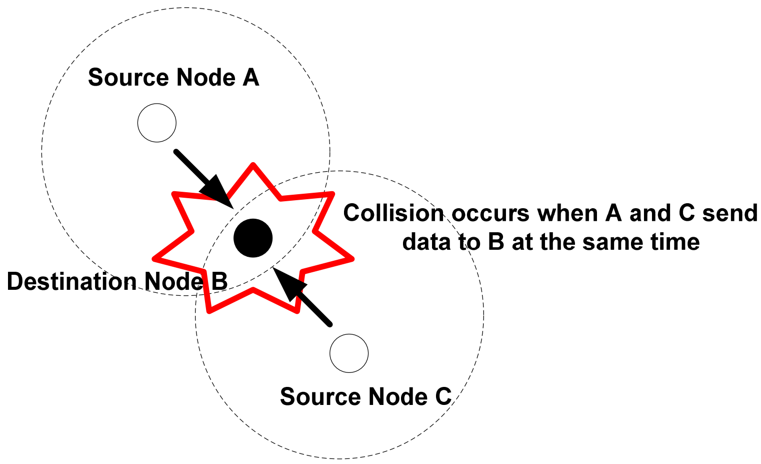

Figure 2.1: Hidden Node Problem

To avoid collision due to this problem, the Ready-To-Send and Clear-To-Send (RTS/CTS) handshake (Karn, 1990) was introduced. A particular node with data message to send will broadcast an RTS message to the destination. If the destination is ready for communications, a CTS message is returned. Since message exchange is broadcast in nature, all nodes within range would be notified about the channel reservation. However this method does not avoid collision completely especially in multihop networks. Figure 2.2 depicts the deficiency of RTS/CTS handshake.

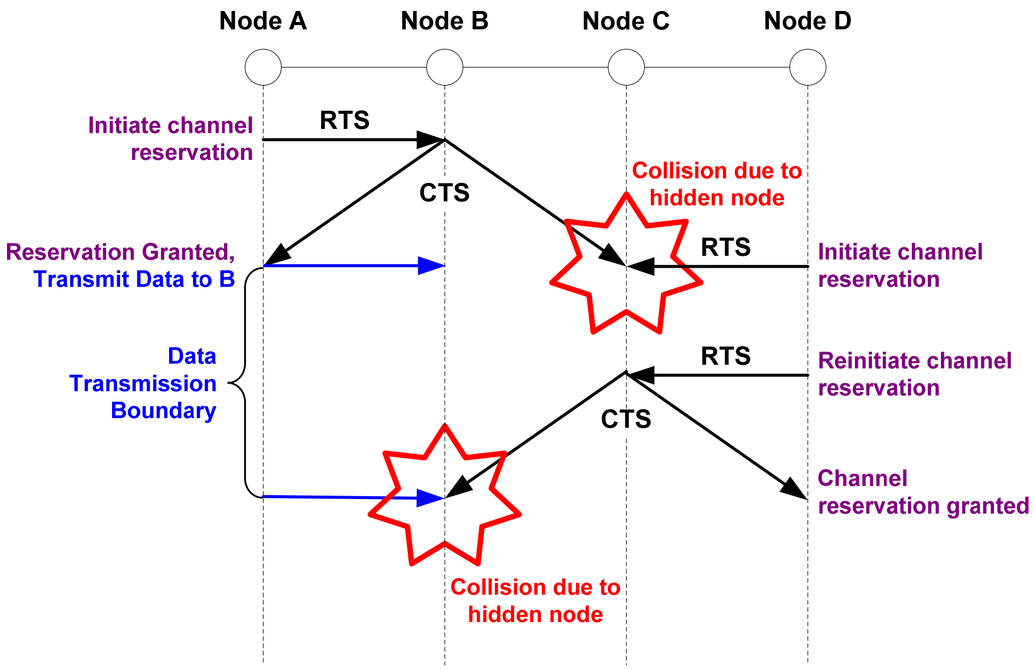

Figure 2.2: Deficiency of RTS/CTS Handshake

2.2.3.3 Exposed Node Problem

Since communications in wireless networks is usually broadcast-based, nodes that are not involved in the communications would be able to intercept the messages being exchanged. This inadvertently prevented these exposed nodes from accessing the channel, thus lowers network availability and channel throughput. This is known as the exposed node problem (Toh, 2001). Figure 2.3 illustrates this problem.

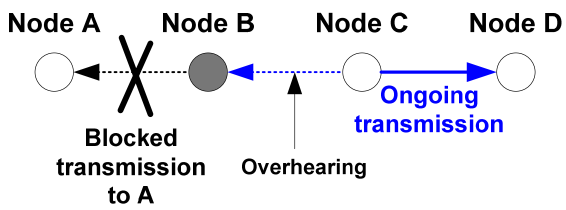

Figure 2.3: Exposed Node Problem

2.3 Literature Survey on MAC Protocols for WSN

In this section, a review of existing MAC protocols for wireless networks is presented by describing their basic concept, access method, and ability in supporting the requirements of WSN. Readers are directed to (Akyildiz *et al*., 2002) (Demirkol *et al.*, 2006) (Kurose *et al*., 1988) (Sachs, 1988) for comprehensive collections of MAC protocols for wireless networks.

2.3.1 IEEE 802.11

2.3.1.1 Basic Concept

The IEEE 802.11 standard was designed for wireless local area network (WLAN). It was first released in 1997 (IEEE, 1997) and revised in 1999 (IEEE, 1999). It supports *infrastructure* and *infrastructureless* networks. The basic building block of an IEEE 802.11 WLAN is *Basic Service Set* (BSS). There could be several BSSs in the network thus forming an extended service set (ESS). In infrastructure network, a base station (BS) or access point (AP) is strategically deployed to manage the BSS. In infrastructureless network, the I*ndependent Basic Service Set* (IBSS) forms an ad hoc network. This standard supports *contention-free* and *contention* access mechanisms.

2.3.1.2 Access Method

The basic IEEE 802.11 access mechanism is known as C*arrier Sense Multiple Access with Collision Avoidance* (CSMA/CA), categorized as a *contention-based* protocol. CSMA/CA is a 'listen before talk' (LBT) mechanism. It consists of two portions, the carrier sensing (CSMA) and collision avoidance (CA). In the CSMA operation, a particular node with message to send will not transmit immediately. Instead it 'listens' to the channel for any ongoing activities. If the channel is busy, then the transmission is delayed for a random time period. After the delay period is over, the channel is reassessed and if it is still busy, the delay duration would be incremented. At the same time, the number of access attempts ('backoff' counter) will be increased until a threshold value is met. If the maximum transmission attempt is met, then the transmission is considered failed and must be aborted. If the channel is free, transmission does not take place until CA mechanism completes. CA is a *virtual carrier sensing* mechanism for reducing the probability of collision. It basically delays the transmission further. The packet transmission is initiated if the channel is free during this process. The protocol will return to CSMA mode with longer delays in case the channel is not free during CA or if collision occurs.

Point coordination function (PCF) is a poll and response protocol for *contention-free* access. It is only applicable in infrastructure network where the AP manages it. Basically devices with data to send would first register with the AP. The AP would then poll these devices regularly for traffic sources and at the same time delivers data to the devices. This function contains several limitations in the legacy IEEE 802.11 standard (IEEE, 1997), which leads to better enhancements in the subsequent release (IEEE, 1999).

2.3.1.3 Suitability for WSN

Earlier development of WSN assumes the use of this conventional IEEE 802.11 MAC (Intanagonwiwat *et al*., 2003). However there are several ramifications with this approach. The power saving mechanism defined in IEEE 802.11 requires the intervention of AP in order to be efficient. However deploying AP(s) in WSN is too costly and restricts flexibility. The collision avoidance mechanisms are incomplete because they do not take into account the impact of ‘hidden node’ problem. The standard also did not tackle the exposed node problem. Nevertheless the IEEE 802.11 MAC is scalable and adaptive because changes to network topology do not affect its operation. However in the event of increasing traffic loads, latency would increase while throughput and channel utilization would decrease due to intense contention and frequent ‘backoffs’.

2.3.2 IEEE 802.15.1

2.3.2.1 Basic Concept

IEEE 802.15.1 (IEEE, 2005) standard defines the MAC and physical (PHY) layer protocols for wireless personal area networks (WPANs). It is also known as Bluetooth (Bluetooth, 2006). It operates in a point of service (POS) of within 10 meters but may be extended to 100 meters. It was designed for short-range communications and supports simple, low-rate, and low energy applications commonly found in mobile phones, PDAs, and headsets (just to name a few). IEEE 802.15.1 MAC is a *contention-free* protocol based on centralized TDMA scheme. In this scheme, a central node known *master* is responsible of allocating time slot for each associated node or *slave* for accessing the channel.

2.3.2.2 Access Method

The IEEE 802.15.1 WPAN defines two types of nodes, namely *master* and *slave*. All nodes in the network can take on either role but only one can become the master. Though IEEE 802.15.1 standard does not restrict the number of slaves, but according to Bluetooth specification (Bluetooth, 2006) up to seven **active** slaves can be found in the network. Note that there can be more than seven slaves in the network but only seven can be actively involve in a communication process.

The access scheme is based on poll-and-response mechanism where the master will poll each slave in a round-robin manner. Figure 2.4 shows the TDMA scheme adopted by the standard as well as how the poll-and-response scheme works. The odd-numbered slots are reserved by the master for polling purpose while the slots the precede each of the polling slot are used by specific slave to communicate with the master.

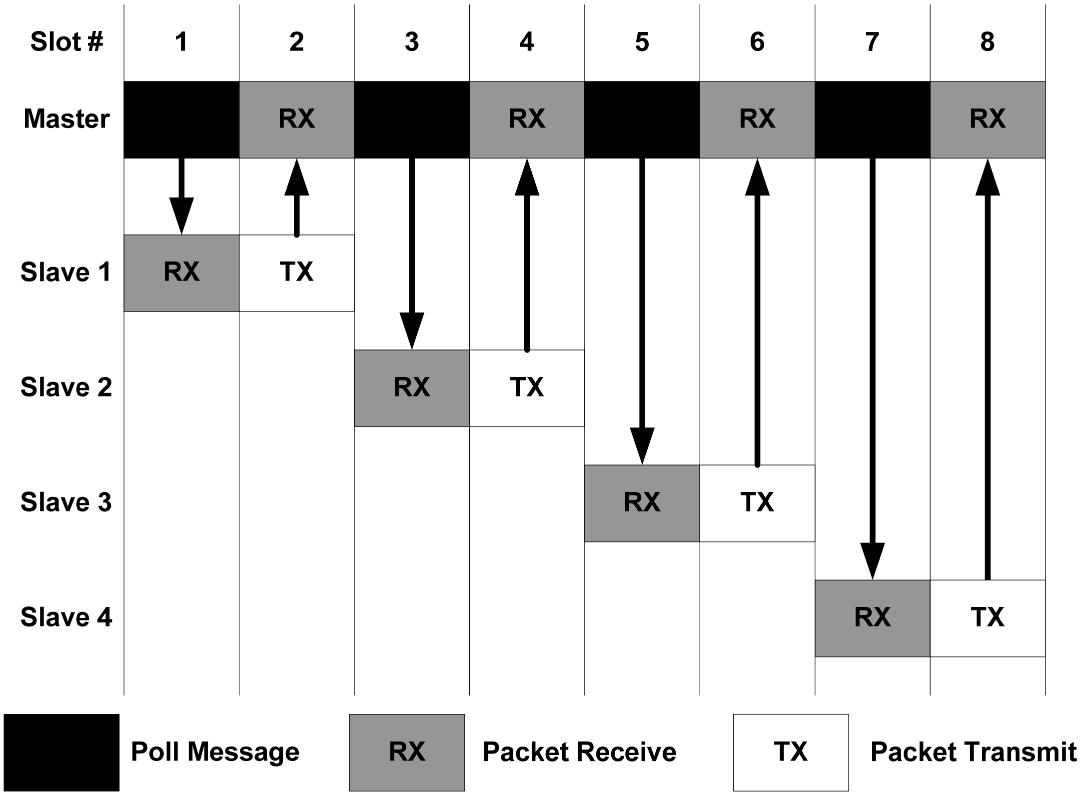

Figure 2.4: Bluetooth Slot Timing and Packet Transmission Operation

2.3.2.3 Suitability for WSN

IEEE 802.15.1/Bluetooth was designed for WSNs. However there are distinct disparities between the two, which fall into application and network architecture. IEEE 802.15.1 or Bluetooth is mainly used for ultra short distance applications that are within Body Area Network (Jovanov *et al*., 2005) range while WSNs is commonly used by applications requiring wider coverage. Besides that Bluetooth only supports limited number of nodes (seven) whereas WSN requires population of several magnitudes larger than that. As a result, the IEEE 802.15.1 MAC is not scalable and adaptive.

Other requirements such as energy efficiency and collision avoidance are well fulfilled in IEEE 802.15.1. The master node is responsible of putting inactive nodes to sleep while the centralized TDMA access scheme guarantees collision-free access.

2.3.3 Sensor MAC (S-MAC)

2.3.3.1 Basic Concept

S-MAC (Wei *et al*., 2004) was explicitly designed for WSNs. Its primary goal is to reduce energy consumption. It also has good collision avoidance mechanism and is scalable. S-MAC tackles all sources of energy waste, which include idle listening, collision, overhearing, and control overhead. The basic idea behind S-MAC is the use of scheduling and contention. It allows node to schedule sleep and listen periods and exchange it with other nodes. The CSMA/CA channel access scheme with RTS/CTS handshake is also adopted.

2.3.3.2 Access Method

The basic periodic sleep-and-wake scheme adopted by S-MAC is shown in Figure 2.5. Each node has certain time durations for sleep and wake. S-MAC encourages centralized coordination by allowing an *initiator* node to broadcast its sleep-and-wake schedule in the form of SYNC packet for others (*followers*) to adhere. However one or more initiators may exist in the network because they are hidden from each other. Therefore follower nodes may adopt more than one schedule, which means more energy consumption through longer idle listening and overhearing periods.

Figure 2.5: S-MAC's Periodic Sleep-and-Wake

Communications between two nodes occurs when the destination starts listening. S-MAC uses the CSMA/CA mechanism with RTS/CTS handshake for channel access.

Figure 2.6 presents a sample of S-MAC communications scheme. Another important feature of S-MAC is the concept of dividing long message into shorter frames and sent in burst. This feature is part of the protocol effort in reducing power consumption by minimizing overheads.

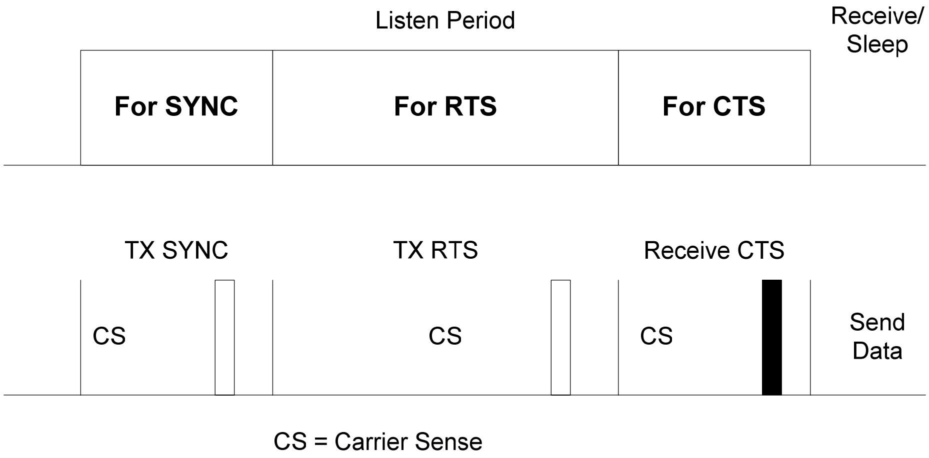

Figure 2.6: S-MAC Communications Scheme (Demirkol *et al.*, 2006)

2.3.3.3 Suitability for WSN

Since S-MAC was designed specifically for WSNs, it has fulfilled some of its properties. However this protocol introduces high latency especially in multihop networks due to different sleep and listen schedules adopted by the intermediate nodes. The fragmentation of long packets also contributes to this problem. The SYNC packet may take more time to propagate in the network thus reduces the protocol's efficiency. Therefore S-MAC is not suitable for applications that require immediate or punctual response such as fire detection, emergency search and rescue efforts, location identification, and so on.

2.3.4 WiseMAC

2.3.4.1 Basic Concept

WiseMAC (El-Hoiydi, 2002) is based on spatial TDMA and CSMA with Preamble Sampling protocol where all nodes use two communication channels, one for TDMA-based data transmission while the other for CSMA control access. The core technique of WiseMAC is the use of preamble sampling to reduce idle listening.

2.3.4.2 Access Method

Each data transmission is preceded with a preamble packet for alerting receiving node. In WiseMAC, all nodes have similar sleep-and-wake schedule but their relative schedule offset is different. If the channel is found to be busy after waking up, the node continues sampling (listening) the channel until the data packet is received or the medium becomes idle again. However the receiver may not be ready for receiving the packet due to interference. This causes the problem of energy waste due to overemitting.

A solution to this is through dynamically determining the length of the preamble. To determine the sleep schedule of immediate neighbors, a particular node keeps a table of this information and updates it whenever a data transmission is detected on the channel. Based on this information, the sender schedules transmissions so that the destination's sampling time corresponds to the middle of the preamble. Figure 2.7 illustrates the WiseMAC concept.

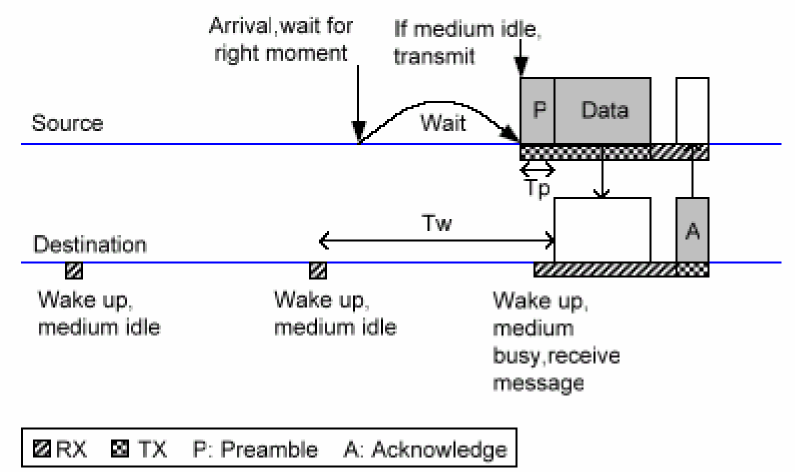

Figure 2.7: WiseMAC Concept (El-Hoiydi, 2002)

2.3.4.3 Suitability for WSN

WiseMAC is another MAC protocol designed for WSNs. It has energy saving and collision avoidance capabilities. However using CSMA does not prevent collision due to 'hidden node' from occurring. This protocol offers no solution to this predicament. Since the sleep-and-wake schedules of all neighbors (potential destinations) are not synchronized, the potential problem for broadcast packet is such that this message will be stored and broadcasted many times as the destinations wakeup at different time. This is clearly inefficient and waste energy.

2.3.5 TRaffic Adaptive Medium Access Protocol (TRAMA)

2.3.5.1 Basic Concept

TRAMA (Rajendran *et al.*, 2006) is an example of hybrid TDMA and scheduled MAC protocol. It was designed to minimize energy waste through collision-free transmission and dynamic sleep during inactive period. These are achieved through announcement of activity schedules and turning off the radio transceiver when not involve in data communications. Communications, both data and schedule broadcasting is strictly time-slotted.

2.3.5.2 Access Method

TRAMA is divided into three core functions, namely random access, schedule transmission, and data exchange. The former refers to exchanging information about 1-hop neighbors to obtain information of 2-hop nodes and to acquire slots for communications. This is initiated through random time slot selection. The purpose of this is to keep the neighborhood list updated to accommodate slot selection later. This stage is prone to packet collision. Therefore to guarantee consistent neighborhood information with some degree of confidence, the length of random access period and the number of retransmission are set accordingly (Demirkol *et al.*, 2006).

The second part of TRAMA is schedule exchange. The information broadcasted includes the identities of nodes to be communicated and the slots involved. Initially the transmitter determines the number of slots to be reserved for this purpose based on the application. Of all these slots, only those that has highest priorities or “winning slots” among the contention nodes that will be selected and announced. One of the "winning slots" would be reserved for broadcasting future schedule, usually the last slot. For example assume a transmitter selects 100 slots between slots number [1000, 1100] for schedule exchange but only slot number 1008, 1056, and 1098 are the "winning slots". Therefore slot number 1098 is used for announcing future schedule.

Finally a transmitter would have a set of destination nodes to communicate with. The list is sorted based on certain algorithm found in (Rajendran *et al.*, 2006).

2.3.5.3 Suitability for WSN

TRAMA is energy efficient while maintaining good throughput, latency, and fairness. Energy waste is reduced through dynamic schedule announcement and sleep periods for inactive nodes. Channel access is considerably fair through effective dynamic scheduling and channel reuse is allowed when not needed by the owners. Collision is reduced not just through good scheduling scheme but also the knowledge of 2-hop neighbors. However the frequent neighborhood and schedule exchange cause additional processing load (higher duty cycle) to the sensor, which may incurs additional energy consumption. The protocol assumes the use of GPS receiver and existing clock synchronization methods (Elson, 2002) (Younis, 2005) (Greunen *et al.*, 2003). The previous is too expensive for WSN while the latter was not studied in the literature. As a result the impact of clock drift especially on latency is not known. It is also observed that TRAMA incurs heavy packet overheads in its operation, which consumes more power.

2.4 IEEE 802.15.4

IEEE 802.15.4 (IEEE, 2003) standard defines the physical (PHY) and medium access control (MAC) protocol for low-rate wireless personal area networks (LR-WPANs). This network is suitable for simple applications that require low rate connectivity, low bandwidth, and low power consumption. It operates in a domain of 10 meters or less and may be extended to 100 meters depending on application requirement. It accommodates over-the-air data rates of 250 kb/s (2.4Ghz ISM band), 40 kb/s (915 MHz ISM band), and 20 kb/s (868 MHz ISM band). The 2.4 GHz ISM band offers 16 channels for communications while 915 MHz and 868 MHz ISM bands offer 10 and one channels respectively. Since only one channel is used at a time, additional channels in the 2.4 GHz and 915 MHz ISM bands provide the flexibility of switching channels in case of interference. Each hardware device (sensor node) comes with a default 64-bit IEEE address or commonly known as physical address. The standard also allows the use of 16-bit short address, which is assigned by the PAN coordinator during association phase. The use of the 64-bit addressing scheme introduces additional overhead. This standard is widely available in commercial products (Freescale, 2006c) (Chipcon, 2006) (Dust, 2006) (Crossbow, 2006) as well as in ns2 simulator (Zheng *et al*., 2006).

2.4.1 Types of Devices

The IEEE 802.15.4 standard consists of three types of devices (nodes), namely PAN coordinator, coordinator, and sensor device. The first two are categorized as full function device (FFD) while the latter reduced-function device (RFD). An FFD has all the functionalities of an RFD, in addition to greater resources such as power, memory, and processing capability. As a result, it usually plays a pivotal role in forming the core network and handling network management duties. The RFD refers to simple device that must depend on FFD to function. The PAN coordinator must be FFD because it is responsible of selecting a channel for communications, assigning short addresses to associated devices, and starting a beacon-enabled network. This node must be mains powered to maintain continuous network operation. On the other hand, the sensor device is a crude device that accepts short address and sends and receives messages to/fro the PAN coordinator. An ordinary coordinator is elected by the PAN coordinator to start another WPAN.

2.4.2 Network Topologies and Formations

There are two possible network topologies supported by IEEE 802.15.4 standard. They are simple star topology and peer-to-peer topology. For both, at least one PAN coordinator must exist and nodes communicate on all-wireless environment.

In a simple star network depicted in Figure 2.8 (a), communications occurs between the PAN coordinator and associated devices, which could be RFDs or FFDs. The PAN coordinator must be the first to exist and start the network by selecting the appropriate channel, setting the PAN ID, allowing other nodes to associate to it, and broadcast beacons periodically in beacon-enabled mode. It is possible to have two or more PAN coordinators within communication range of each other, thus the formation of numerous star networks. However they are independent of each other. Each PAN coordinator must select a unique PAN ID and communication channel. Devices must associate with only one PAN coordinator at a time.

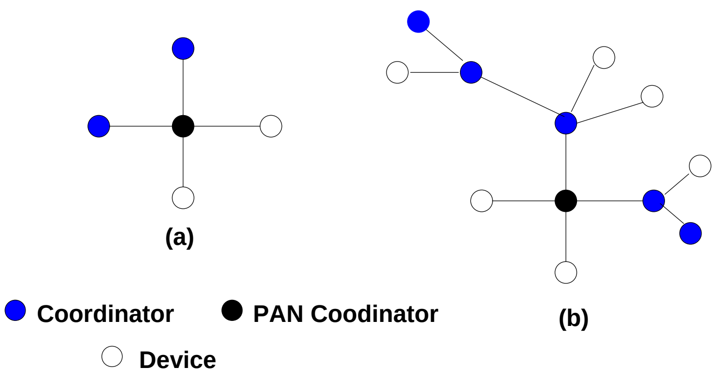

Figure 2.8: (a) Simple 1-hop Star Network (b) Cluster-Tree Network

Peer-to-peer topology is depicted in Figure 2.8 (b). The base structure consists of the previously described star topology. In order to allow multi-hop communications, one of the FFDs associated to the PAN coordinator could be elected as the coordinator node to manage its own cluster or WPAN. As a result, the coordinator functions like the PAN coordinator in allowing devices to associate to it, assigning short addresses to them, selecting PAN ID, and so on. The extension of this network is permissible through the election of FFDs as coordinators thus obtaining a cluster tree network as shown in Figure 2.8 (b).

2.4.3 Network Modes and Superframe Structure

IEEE 802.15.4 networks operate in either beacon-enabled or beaconless mode. The latter is a straightforward communication mode where each node attempts to secure the channel using CSMA/CA mechanism (section 2.4.7). All nodes must remain active during the entire communication process. This causes significant loss of energy during idle periods. The former is an optional feature that requires periodic broadcasting of beacon messages by the PAN coordinator. The beacon-mode is in the form of Superframe structure as depicted in Figure 2.9. Beacon messages are used to indicate the start and end of the beacon mode. The Superframe structure consists of two portions, namely active and inactive. The latter is the duration where devices enter into sleep mode. The former can be further divided into contention-access period (CAP) and contention-free period (CFP). Devices compete with each other to secure the channel for communications during CAP while CFP consists of special reserved sessions known as guaranteed time slots (GTS) for a particular application to access the channel without competition. The duration for CAP, CFP as well as inactive period are specified in the beacon frames and strictly controlled by the PAN coordinator.

Beacon messages contain information regarding the PAN coordinator such as PAN ID, PAN coordinator short address, allowable association with the coordinator, channel ID, Superframe structure, and so on. These details are important when passive scan (section 2.4.6) is adopted in locating the PAN coordinator. Besides that, beacon frames also provide information regarding pending messages for a particular device.

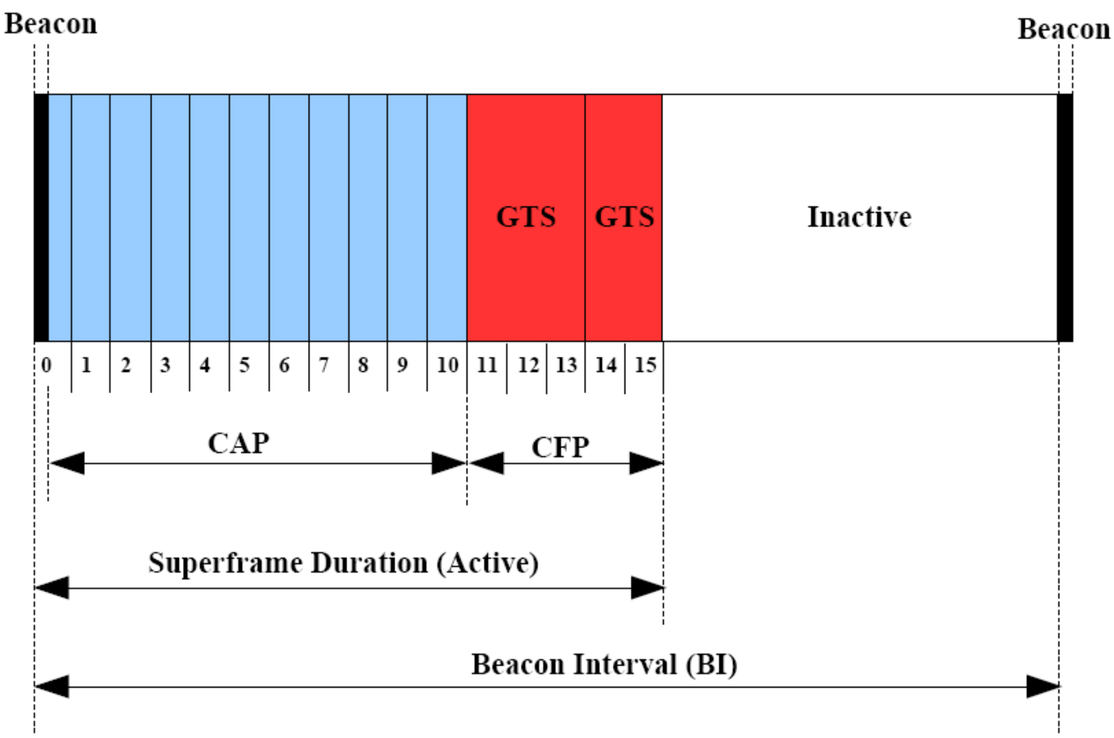

Figure 2.9: Superframe Structure for Beacon-Enabled Network

Superframe structure is described by values of *macBeaconOrder (BO)* and *macSuperframeOrder (SO)*. The latter defines the length of active portion of the Superframe, which includes beacon frames while the earlier refers to interval for beacon frames transmission. The relationship between *BO* and *Beacon Interval* (*BI*) is as follows: for $0 \leq BO \leq 14, BI = aBaseSuperframeDuration * 2^{BO}$ symbols where $\mathrm{aBaseSuperframeDuration} = \mathrm{aBaseSlotDuration} * \mathrm{aNumSuperframeSlots}$ symbols.

The relationship between *SO* and *Superframe Duration* (*SD*) is as follows: for $0 \leq SO \leq BO \leq 14, SD = aBaseSuperframeDuration * 2^{SO}$ symbols. If SO = 15, then the entire Superframe structure consists of inactive period. If BO = 15, then the network operates in beaconless mode.

The active portion (defines by *SO*) of the Superframe is divided in *aNumSuperframeSlots* equally spaced slots of duration $2^{SO} * aBaseSlotDuration$. The default value for *aNumSuperframeSlots* is 16 while *aBaseSlotDuration* is 60. This gives a value of 960 symbols or 15.36 ms for *aBaseSuperframeDuration*. If the values for *BO* and *SO* are similar, then the entire Superframe structure consists of active portion only. GTS feature is always requested by the device and is allocated when there is a request. The standard specifies up to seven GTS and a GTS may occupy more than one slot. A GTS request is granted when there are sufficient slots for CAP as well as CFP. GTS is deallocated when there is no data transmission for specific number of Superframes.

2.4.4 Data Transmission Modes

The PAN coordinator could choose to operate in either beacon-enabled or non-beacon mode. In both cases, data transmissions are classified into the following three types:

- Direct data transmission. It involves data transmission from device to PAN coordinator. Since the PAN coordinator is AC powered, associated devices could communicate with it directly upon successful channel reservation. Each data packet received is followed by an optional acknowledgement (ACK) message. In beacon-enabled mode, a device wishes to communicate with the PAN coordinator shall 'listen' for the beacon, synchronize with it, and transmit using slotted CSMA/CA. In non-beacon mode, devices must compete for the channel using unslotted CSMA/CA.
- Indirect data transmission. This refers to data transmission from coordinator to device. In beacon-enabled network, the PAN coordinator indicates the availability of data packets in the beacons. A device shall request for the data packet by sending a message using slotted CSMA/CA and waits for an ACK from the PAN coordinator. Finally the data message is transmitted using slotted CSMA/CA. Upon receiving the data message, an ACK frame is returned and the data packet is removed from the packet list. In non-beacon network, a particular device is responsible of polling the PAN coordinator for any pending messages using