Performance Study of ZigBee Based Wireless Sensor Networks

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***Abstract*—**The IEEE 802.15.4 standard is designed for low-rate wireless personal area networks (LR-WPAN) with focus on enabling wireless sensor networks. It aims to give a low data rate, low power consumption, and low cost wireless networking on the device-level communication. The objective of this study is to investigate the performance of IEEE 802.15.4 based networks using simulation tool. In this project the network simulator 2 NS2 was used to several performance measures of wireless sensor networks. Three scenarios were considered, multi hop network with a single coordinator, star topology, and an Ad hoc on demand distance vector AODV. Results such as packet delivery ratio, hop delay, and number of collisions are obtained from these scenarios.

***Keywords*—** ZigBee, wireless Sensor networks, IEEE 802.15.4, low power, low data rate.

I. Introduction

RECENTLY, wireless technology has become a good choice among the clients for communication. In fact, it is used everywhere when the wired communications are hard to implement. Many of the wireless technologies are constantly evolving and changing the world of telecommunications. Due to the progress in wireless communications over the last few years, the improvement of networks of low-cost, low-power, multifunctional sensors have received increased interest. These sensors have small size and can sense, process data, and communicate with each other, typically over a radio frequency (RF) channel. The design of a sensor network is able to sense events or phenomena, collect and process data, and transmit sensed information to interested clients.

A wireless sensor network (WSN) is a configuration that include sensing (reading or measuring), computing, and communicating elements that gives an administrator the ability to measure, observe, and respond to actions in a particular space. The supervisor is usually the entity of civil or commercial or industrial. The space can be the physical world (factory, green houses, etc.), or biological system. It includes typical applications as well, such as data collection, monitoring, and medical telemetry [13].

A sensor network is a type of network which is made up of a huge number of sensor nodes. These nodes are spread to perform different types of operations to get the readings of different types of attributes such as temperature acceleration, humidity, etc. in particular field. So, there is no need to have a big computer setup to evaluate all these tasks, merely cheap small sensor devices are used.

The wireless sensor networks are used in logistic telemetry applications in which one wishes to know the condition of goods through transfer and to know the condition of different attributes associated with the goods [5], [6].

There are four different components of a sensor node [1]; sensing unit, power unit, transceiver, and processing units. Furthermore, there are other components in a sensor node such as location finding system, power generator and mobilizer. WSNs give a type of ways in the physical world to solve some problems which were not available before evolution of WSNs. Some of the important features concerning the wireless sensor networks are [1], [2]:

- Due to the small battery requirements, it is important for a sensor node to conserve energy to stay alive for a longer period of time. That is why it goes to sleeping mode sometimes during operation to conserve energy.
- Communicating nodes are attached to each other by wireless medium in the multihop sensor networks, so the medium which will be used should be available worldwide.
- Encryption methods are used to carry out the security operations in these networks.
- Physical layer in the sensor network protocol stack is responsible for the detection of signals, modulation and generating carrier frequency.
- Compared to the wired networks, WSNs require less maintenance.
- WSNs are easy to install and if some configuration needs to be done, it is also easy to carry out. These networks consist of cost effective sensor nodes which can be replaced by new nodes if they experience some problem.

The main aim of the LR-WPAN technology is quite different from other personal wireless networks. Instead of offering very high rates at long distances with the requirements of high Quality of Service (QoS), it is intended to serve industrial, residential and medical applications with very low power consumption and cost. This can be achieved as a result of the low data rate supported; for some applications a battery lifetime of 6 months up to several years is possible. In addition, ZigBee networks may be implemented with several different flexible network structures [9].

If the IEEE 802.15.4 standard is a Low-Rate Wireless Personal Area Network (LR-WPAN) standard. The ZigBee alliance was formed to the structure of the IEEE 802.15.4 group, the both were aiming at the same goal. Then, the ZigBee Alliance and the IEEE 802.15.4 group decided to join forces

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and ZigBee is today the commercial name for this technology [3]. "The IEEE 802.15 Task Group 4 is chartered to investigate a low data rate solution with multi-month to multi-year battery life and very low complexity. It is intended to operate in an unlicensed, international frequency band". The scope of the task group is to define the physical- (PHY) and the medium access control (MAC) layers [4], whereas the ZigBee alliance focuses on the improvement of the higher layers and the overall improvement. Fig. 1. shows the ZigBee protocol layers and the relations between IEEE 802.15.4 and the ZigBee Alliance in terms of the protocol.

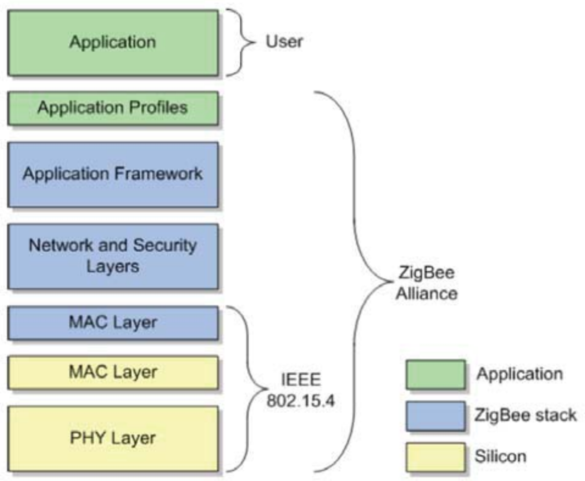

Fig. 1 ZigBee Protocol Layers

The rest of this paper is organized as follows. In section 2, the researcher presents overview of WSNs technology. The emphasis in this section is on both PHY and MAC layers of IEEE 802.15.4 standard. The numerical results and discussions are presented in section 3. The results are based on simulation performed by NS2. The conclusion and highlight for future work is presented in section 4.

II. Theoretical Background

A. ZigBee Overview

There are great numbers of applications in the industrial markets that require the wireless technology which allocate low data rates, less difficulty, and provide batteries to stay alive for longer time. At the present time, the industrial markets require wireless standards that are dependable, economical, and use low power. This technology addresses the standard in the WSN needs and low data rate wireless control.

For all those types of needs to be fulfilled, IEEE has developed a standard which is called IEEE 802.15.4 [task group 4], to search a low data rate solution with a battery life that will last for months and with less difficulty [11], [12]. The aimed applications are WSN, interactive toys, home automation, and remote control.

The technology of ZigBee defines several layers such as network, security, and applications framework profile for a system supported on IEEE 802.15.4 standard. This standard is very important in the PHY layer to define the construction of the RF and ZigBee topology. The description of technology in this standard is very important for the common reader to understand what factors are or features that make up ZigBee, it shall define the layers such as (network, security, and application framework profile layers), above the PHY and MAC layer. ZigBee will be a standard use for sensor and control application.

- Low cost: ZigBee is an economical technology with low cost of the devices and in the installation, maintenance processes. Another characteristic in this standard is by using primary cells, these cells can reserve the batteries alive for months.
- Great number of nodes per network: ZigBee allows to use any number of nodes or devices which important larger control networks are, and larger arrays of sensors.
- Very low power consumption and simple implementation: The included duty cycle provides the batteries, so they stay alive for months, even years, this cycle gives a low power consumption to the batteries.
- Simplicity of protocol and global implementation: ZigBee uses the IEEE 802.15.4 PHY which operates at different frequency bands involving 915 MHz for Australia, North America, and for Europe is using 868 MHz band and 2.4 GHz band globally for worldwide approximately. There are about one fourth compared to Bluetooth at ZigBee protocol code stack, this simplicity adds to the low cost and maintenance in this standard.
- Use two different states: ZigBee uses two different kinds of states in operation, i.e. the active and inactive states to conserve energy and power.
- Low duty cycle: In ZigBee, duty cycle is less than 0.1 % which is extremely low, it depends on the increment and decrement of requirements of application.
- Dual PHY: The frequency bands which use on PHY are 868/915 MHz, and 2.4 GHz. Data rates supported on 868MHz, 915MHz, and 2.4GHz are 20kbps, 40 Kbps and 250 Kbps in orders.
- Channel access mechanism: Here, CSMA-CA is used which results in larger throughput for controls and sensors applications.
- Hand-shake protocol: ZigBee provides a fully handshake protocol which makes sure that the transfer is reliable.
- Capable address space: Address space provides up to 18,450,000,000,000,000,000 devices using 64 bits IEEE address whereas about 65,535 networks can be supported (for each network can be 255 devices.)
- Optional guaranteed time slot: This option is available in case of some failure or need.
- Range: The range covered is typically about (1-100) m which is based on the setting of the surrounding environment.

ZigBee has three traffic types as followed:

- Periodic data: In this type, the application defines the data rate for instance the sensors.

- Intermittent data: In this type stimulus or applications define the data externally for instance light switch.
- Repetitive low latency data: In this type the time slots are allocated.

All these three types can deal with IEEE 802.15.4 MAC. by mechanism of beaconing, this technology can deal with the periodic data in which active sensor looks for the messages and returns to the sleep mode. The optional guaranteed time slot can be given by the low latency data rate applications.

B. Physical Layer

The PHY layer provides an interface between the MAC sublayer and the physical radio channel via the RF firmware and RF hardware. The management entity of the PHY layer is called the PLME which is responsible for maintaining a database of managed objects pertaining to the PHY layer that is referred to as the PHY PAN information base (PIB). The entity of PHY management provides the layer management service interface through which layer management functions might be invoked. Fig. 2 shows the components and interfaces of the PHY [4].

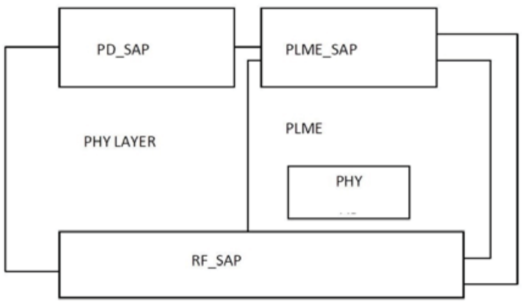

Fig. 2 PHY Reference Model

There are two services, accessed through two SAPs by the PHY layer. (PHY data service, PHY management service).

- The PHY data service accessed through the PHY data SAP (PD-SAP), which its service enables the transmission and reception of PHY protocol data units (PPDUs) across the physical radio channel.
- The PHY management service accessed through the SAP of PIAME (PIAMESAP).

In IEEE 802.15.4 standard radio communication is used in the personal area network (PAN) to carry out the communication between devices, it defines protocols for establishing connection between devices it also uses slotted carrier sense multiple access with collision avoidance (CSMA-CA) which helps avoid the collusion. In the PAN, the superframe structure uses to reserve time slots of devices, this procedure controlled by the coordinator at the medium access layer. There are three license-free frequencies of the IEEE 802.15.4 standard contain 16 channels at 2.4 GHz, 10 channels at 915 MHz, and one channel at 868 MHz. The maximum data rates for each band are 250 kbps, 40 kbps and 20 kbps, respectively. The air interface is direct sequence spread spectrum (DSSS) using binary phase shift keying (BPSK) for 868 MHz and 915 MHz and offset-quadrature phase shift keying (OQPSK) for 2.4 GHz. Table I describes the frequency bands and data rates and totally 27 channels are available across the different frequency bands, as described in Table I [14].

TABLE I
FREQUENCY BANDS AND DATA RATES FOR IEEE 802.15.4

Spreading Parameters				Data Parameters		
PHY (MHz)	Frequency band (MHz)	Chip rate (Kchips/s)	Modulation	Bit rate (Kb/s)	Symbol rate (Ksymbol/s)	Symbols
868	868-868.6	300	BPSK	20	20	Binary
915	902-928	600	BPSK	40	40	Binary
2450	2400-2483.5	2000	O-QPSK	250	62.5	16-ray Orthogonal

TABLE II
THE ZIGBEE CHANNELS

Frequency (MHz)	Number of channels (N)	Channel (numbering)	Channel center frequency (MHz)
868	1	0	868.3
915	10	1-10	906+2(k-1)
2450	16	11-26	2450+5(k-11)

The forms of the PHY are activation and deactivation of the radio transceiver, energy detection (ED), link Quality Indication (LQI), channel selection, clear channel assessment (CCA) and transmitting as well as receiving packets across the physical medium.

C. MAC Layer

The MAC layer provides two services as the following:

- The MAC data service which enables the transmission and reception of MAC Protocol Data Unit (MPDU) by the PHY data service.
- The MAC management service interfacing to the MAC Sub-Layer Management Entity (MLME) service access point (SAP) (MLME_SAP).

The headers of MAC sub layer are beacon management, channel access, GTS management, frame validation, acknowledged frame delivery, association, and disassociation [7], [8], [10].

III. RESULTS AND DISCUSSION

In this section, the simulation results are presented and discussed. The simulation aims to evaluate the performance of IEEE 802.15.4 networks. The performance was studied in terms of wireless network characteristics such as packet delivery ratio, packet delivery latency, and transmission collision, in addition to specific characteristics of LR-WPANs such as association. The simulation can be divided into three different scenarios as follows:

A. First Scenario

This scenario was designed to study the association performance of IEEE 802.15.4 networks by using a multi-hope topology. With a two-ray ground reflection signal propagation model and pan-coordinator in the network. Both modes (beacon enabled mode and non-beacon enabled mode) are used in this scenario. Fig. 3 illustrates the association scenario environment. Table III shows the parameters that are used in the experiments.

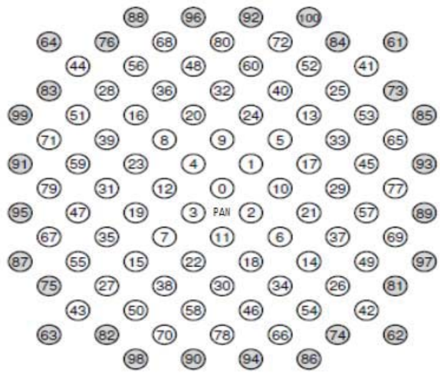

Fig. 3 Association Scenario Environment

Node 0, which is the PAN coordinator, and the leaf nodes depicted in grey, which are pure devices (RFD), all the other nodes (FFD) serve as both a coordinator (to its children) and a device (to its parent). So, 73 coordinators and 100 devices are available.

TABLE III
FIRST SCENARIO PARAMETERS

Parameter	Description
Number of node	101 nodes equally spaced in 80 x 80 m2 area
Transmission range	9 meterS
Data rate	250 kbps
Type of traffic	Poisson
Application traffic	1 pps
Beacon order	1, 2, 3, 4, 5, 6 and 10

B. Second Scenario

In the second scenario the transmission collision has been evaluated. The scenario run in a star topology environment with beacon enabled mode as shown in Fig. 4. With single pan-coordinator placed in the network, although this scenario run in beacon enabled mode, most of the metrics are general and can be used for non-beacon enabled mode.

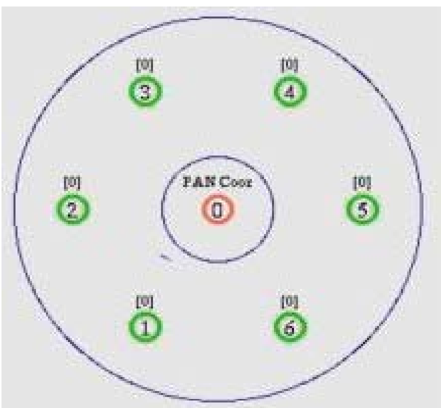

Fig. 4 Star Topology

Table IV shows the parameters that are used in the experiments for the second scenario.

TABLE IV
SECOND SCENARIO PARAMETERS

Parameter	Description
Number of node	7 nodes form a star with a radius of 10 meters
Transmission range	15 meter
Data rate	250 kbps
Poisson traffic	1 pps
Application sessions	Six, one for each device, are setup from the devices to the coordinator
Beacon order	changes from 0 to 8
Area	50 x 50 m2

C. Third Scenario

This scenario runs in an AODV over LR-WPAN using multi-hop environment with beacon enabled mode. The following characteristics have been evaluated:

1. Packet delivery ratio,
2. Hop delay,
3. End to End delay.

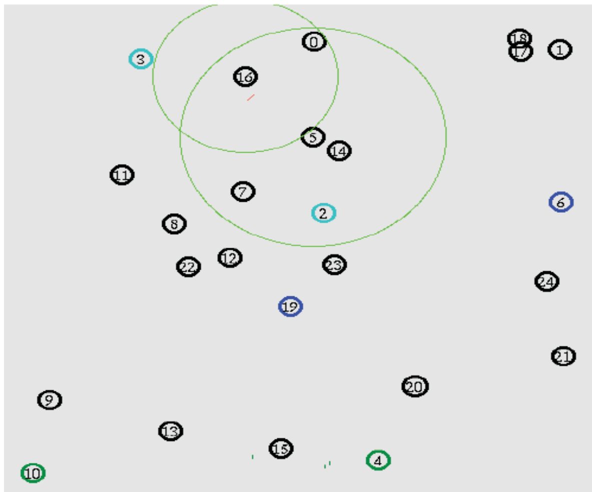

Fig. 5 Multi-hop Environment

Table V shows the parameters that are used in the experiments:

TABLE V
THIRD SCENARIO PARAMETERS

Parameter	Description
Number of node	25 nodes evenly distributed in a 50 x 50 m2 area
Transmission range	15 meter
Data rate	250 kbps (in the 2.4 GHz ISM band)
CBR traffic (average packet rates)	0.1 pps 0.2 pps 1 pps 5 pps 10 pps
Application sessions of traffic	19 - 6 10 - 4 3 - 2

General Parameters: Table VI shows general parameters which are used in all scenarios.

D.Experimental Results

Association: In a densely distributed unattended wireless sensor network, there are highly recommended features such as self-configuration in deployment and auto-recovery from failures. This type of networks is the typical scenario of an LR-WPAN.

Therefore, ZigBee network (IEEE 802.15.4) includes, in its design, an association and disassociation mechanism together with an orphaning and coordinator relocation mechanism. In the following subsection, the experimental results can be shown.

TABLE VI
GENERAL PARAMETERS

parameter	Description
bit error rate	10−6 to 10−5 link bit error rate (BER),
packet error rate (PER)	0.2%
simulation duration	100 seconds
application traffic duration	from 20 to 90 second
radio propagation model	two-ray ground reflection

A device needs to perform one of two types is an active channel scan or passive channel scan. In the active channel scan, a beacon request frame is sent in order to locate a suitable coordinator. In a passive channel scan, a beacon request frame is not sent in order to locate a suitable coordinator.

In these experiments the device needs to request beacons in non-beacon enabled environment. As a result, the active channel scan is used in these experiments. The coordinator receives the beacon request frame and handles it differently depending on its mode, which is in a beacon mode or non-beacon mode. If the coordinator is in a beacon mode, it rejects the frame silently, because beacons will be bent periodically anyway. But If the coordinator is in a non-beacon mode, it unicasts a beacon to the device soliciting beacons. In this experiment, the beacon order should be varied.

Fig. 6 Association Attempts vs. Beacon Order

The association Attempts are shown in Fig. 6 in terms of attempts per successful association and beacon order. As it can be seen from the figure as the beacon order increases the association attempts drops. For example, with 1 beacon order the association attempts per successful association are about 3.33. but when the beacon order increases to 8 the association attempts per successful association are about 1.06.

In the case of multiple non-beacon coordinators being around, each one them will try to unicast a beacon using unslotted CSMA-CA to the device asking for beacons. So the sent beacons may collide at the device because of the hidden terminal problems due to the lack of RTS/CTS. That is, even the first stage of the association might fail.

In the case of multiple beacon coordinators being around, the situation is better, because they will continue beaconing even if a beacon request is received. The association attempts will go down if beacons are sent with low beacon order, due to an increase in the collisions. In other words, the beaconing coordinators can affect all the steps of the association process, but non-beaconing coordinators are likely to affect the first step. These experimental results revealed that beaconing coordinator is better in terms of association attempts.

Collision: In this case of experiments target the collision behavior of IEEE 802.15.4.

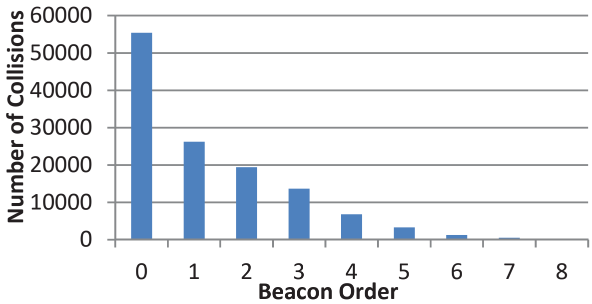

Fig. 7 Collisions vs. Beacon Order

The collisions and beacon order shown in Fig. 7. As it can be seen from the figure as the beacon order increases the collision drops. For example, with 0 beacon order the collision is about 55385. However, when the beacon order increases to 8 the collision is about 243.

In the low beacon orders the collisions occur more than in high beacon orders. The large number of collisions leads the network to virtually lose its control. This type of “Beacon Storm” problems is alleviated in high order beacons.

The broadcast-based storm is not a rare phenomenon, because of the broadcast nature of wireless networks. Most of the collisions between two devices not adjacent to each other in these experiments occur between hidden terminals as expected. However, the probability of collisions between non-hidden terminals in low beacon orders is not trifling either. This means that when the beacon order is very small, the slotted CSMA-CA can no longer work effectively and the chance that two non-hidden terminals jump to the channel simultaneously is significantly increased.

Some of the major collisions that occur during this simulation are defined by the coordinator (COO):

Many full-function devices in the network transmitting beacons at vary beacon order, which are colliding with each-other. This means that un-wanted beacons were dropped by devices prompting COO flag in the trace file. Consequently, it can be observed that the packet drops due to COO is much more than the packet sent or received.

Packet Delivery Ratio, Packet Delivery Latency, and e2e Delay: In this case of experiments target the packet delivery ratio for studying the performance of IEEE 802.15.4. The ratio of packets which is received successfully to packets sent in MAC.

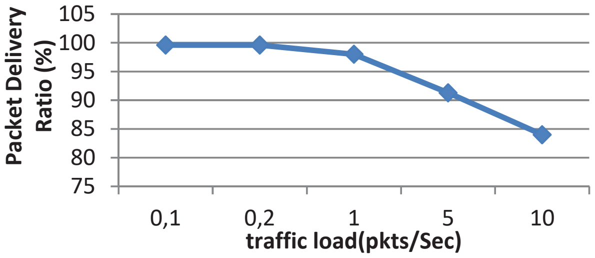

Fig. 8 Packet Delivery Ratio

The packet delivery ratio verses traffic load shown in Fig. 8. As it can be seen from the figure as the traffic load increases the packet delivery ratio drops. For example, with 0.1 pkts/Sec traffic load, the percentage of delivered packets is about 100%. but when the traffic load increases to 5 the percentage of delivered packets is about 92%.

In ZigBee network, the former does not use RTS/CTS mechanism, and this leads to the decrease of packet delivery ratio of the network. This RTS/CTS overhead proves to be useful when traffic load is high but obviously too expensive for ZigBee, because it is designed to be LR-WPANs.

In this case, the experiments target the hop delay and e2e delay for studying the performance of IEEE 802.15.4. The transaction time of passing a packet to one hop neighbor, including time of all necessary processing, backoff as well as transmission, averaged over all successful end-to-end transmissions within a simulation run.

The hop delay and e2e delay verses traffic load shown in Figs. 9 and 10. As it can be seen from the figure as the traffic load increases the hop delay increases. For example, with 0.1 pkts/Sec traffic load, the hop delay is about 0.004480037. but when the traffic load increases to 5 the hop delay is about 0.004480039 and there is difference between hop delay and e2e delay specially when the traffic load increases to 10 the e2e delay drops from 0.018634129 to 0.018527462 as illustrated in Fig. 10.

The RTS/CTS mechanism affects network latency as well. In these experiments, the average hop delay for IEEE 802.15.4 can be calculated, and the results are shown in Fig. 9. The increment of delay is expected, because all the traffic flows now need to converge on the sink node.

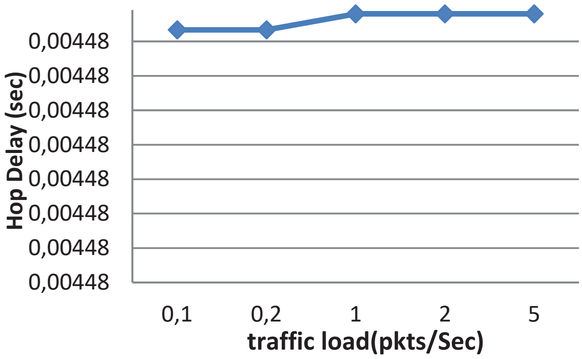

Fig. 9 Hop Delay

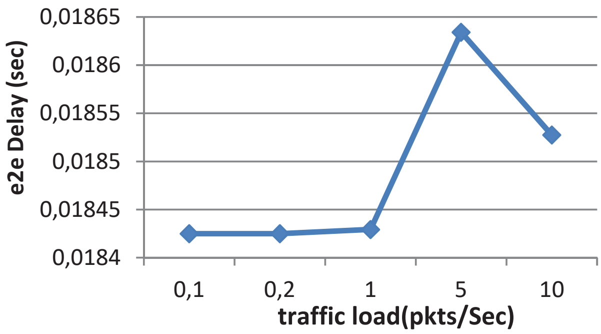

Fig. 10 E2e Delay

IV. Conclusions and Future Works

The IEEE 802.15.4 standard, which is designed for LR-WPANs, is an enabling standard the lighting of a host of new applications as well as changes many other existing applications is brought by this standard. Simple sensors and actuators to share a single standardized wireless platform are allowed by it.

An NS2 simulator is used to evaluate the general performance of IEEE 802.15.4 standard. It covers all the IEEE 802.15.4 PHY and MAC primitives, and carries out three sets of experiments, that is, experiments of:

1. Association mechanism study.
2. The collision scenario (examination of unslotted CSMA-CA and slotted CSMA-CA behaviors).
3. Evaluate the performance of IEEE 802.15.4 as the packet delivery ratio, hop delay, and End to End delay.

In IEEE 802.15.4, the Association mechanism in both beacon enabled, and non-beacon enabled modes are proceed smoothly, this mechanism implies that IEEE 802.15.4 possesses a good self-configuration feature and is able to shape up efficiently without human intervention.

IEEE 802.15.4 is expected to suffer from hidden terminal problems as a result to the lack of RTS/CTS. This expectation is matched by experiment results which have been done. But the performance degradation is minor for low data rates up to one packet per second. In this standard the default CSMA-CA backoff period is too short, which leads to frequent repeated collisions.

The experimental results showed that IEEE 802.15.4 a rather solid technical basis for many applications, the success of this standard in marketing still bears watching. For new technology, the success is determined by not only the technology itself, but many other factors as well.

In this paper, only a simulation study was conducted. In future work practical kits can be used to conduct the study. The simulated results in a future work might be compared to the real-world experimental. The closest simulation result to reality is found out by help of the real-world experiments.

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