An Experiment on Performance Study of IEEE 802.15.4 Wireless Networks

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Abstract

IEEE 802.15.4 is an emerging standard specifically designed for low-rate wireless personal area networks (LR-WPAN) with a focus on enabling the wireless sensor networks. It attempts to provide a low data rate, low power, and low cost wireless networking on the device-level communication. In this paper, we have established a realistic environment for the preliminary performance evaluation of the IEEE 802.15.4 wireless networks. Several sets of practical experiments are conducted to study its various features, including the effects of 1) the direct and indirect data transmissions, 2) CSMA-CA mechanism, 3) data payload size, and 4) beacon-enabled mode. The data throughput, delivery ratio, and received signal strength indication (RSSI) are investigated as the performance metrics.

Index Terms – IEEE 802.15.4, low-rate wireless personal area networks (LR-WPAN), wireless sensor networks, ZigBee.

I. INTRODUCTION

Recently, for accessing networks and services without cables, wireless communications is a fast-growing technology to provide the flexibility and mobility [1]. Obviously, reducing the cable restriction is clearly one of the benefits of wireless with respect to cabled devices. Other benefits include the dynamic network formation, easy deployment, and low cost in some cases. In general, the wireless networking has followed a similar trend due to the increasing exchange of data in services such as the Internet, e-mail, and data file transfer. The capabilities needed to deliver such services are characterized by an increasing need for data throughput. However, other applications in fields such as industrial [2-3], vehicular, and residential sensors [4] have more relaxed throughput requirements. Moreover, these applications require lower power consumption and low complexity wireless links for a low cost (relative to the device cost). IEEE 802.15.4 [5] is the one that addresses these types of requirements.

Zheng and Lee [6-7] developed an NS-2 simulator for IEEE 802.15.4 to study its performance with various features. Also, Lu et al. [8] implemented the IEEE 802.15.4 MAC prototype in the NS-2 network simulator and provided simulation-based performance evaluations, focusing on its beacon-enabled mode for a star-topology network. Timmons and Scanlon [9] presented a mathematical analysis of the IEEE 802.15.4 performance in relation to medical sensor body area networks. However, most of the previous work on the IEEE 802.15.4 performance study is based on either the simulation or mathematical analysis, and so far there are no realistic experiments and results available for reference.

In this paper, after an overview of the IEEE 802.15.4 wireless networks, we attempt to make a preliminary performance study via several sets of practical experiments, including the effects of 1) the direct and indirect data transmissions, 2) CSMA-CA mechanism, 3) data payload size, and 4) beacon-enabled mode. Results of the experiments would be beneficial to the design and deployment of the IEEE 802.15.4 wireless networks.

The organization of the paper is as follows. Section II introduces the IEEE 802.15.4 communication protocols. Next, experimental hardware and configuration are illustrated in Section III. Then, experimental results of the performance study are described in Section IV. Finally, Section V gives the conclusions.

II. IEEE 802.15.4 WIRELESS NETWORKS

The IEEE 802.15.4 [5] defines the physical layer (PHY) and medium access control sublayer (MAC) specifications for supporting simple devices that consume minimal power and typically operate in the personal operating space (POS) of 10 m. Wireless links under 802.15.4 can operate in three license free industrial scientific medical (ISM) frequency bands, as shown in Fig. 1. These accommodate over air data rates of 250 kbps in the 2.4 GHz band, 40 kbps in the 915 MHz band, and 20 kbps in the 868 MHz. A total of 27 channels are allocated in 802.15.4, including 16 channels in the 2.4 GHz band, 10 channels in the 915 MHz band, and 1 channel in the 868 MHz band.

A. Function Devices

Two different device types can participate in an LR-WPAN network: a full-function device (FFD) and a reduced-function device (RFD). The FFD can operate in

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three modes serving as a PAN coordinator, a coordinator, or a device. An FFD can talk to RFDs or other FFDs, while an RFD can talk only to an FFD. An RFD is intended for applications that are extremely simple, such as a light switch or a passive infrared sensor. They do not need to send large amounts of data and would only associate with a single FFD at a time. Consequently, the RFD can be implemented using minimal resources and memory capacity. A device in an 802.15.4 network can use either a 64-bit IEEE address or a 16-bit short address assigned during the association procedure, and a single 802.15.4 network can accommodate up to 65536 (2^{16}-1) devices (the address 0xFFFF is hold for broadcast).

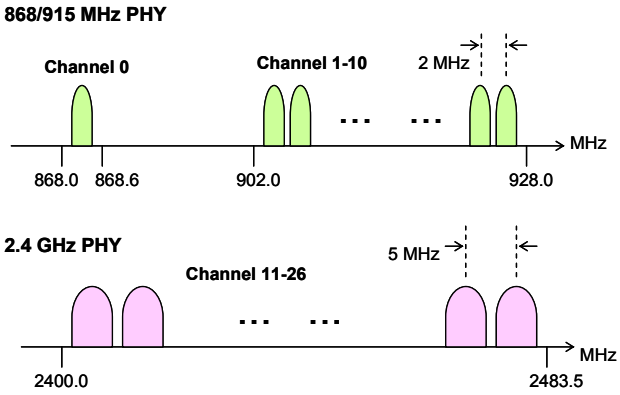


Fig. 1. The IEEE 802.15.4 channel structure.

B. Network Topology

Two types of topologies are supported in 802.15.4: a one-hop star or a multihop peer-to-peer topology. The basic structure of a star network can be seen in Fig. 2 (a). After an FFD is activated for the first time, it may establish its own network and become the PAN coordinator. All star networks operate independently from all other star networks currently in operation. This is achieved by choosing a PAN identifier, which is not currently used by any other network within the radio sphere of influence. Once the PAN identifier is chosen, the PAN coordinator can allow other devices (FFDs and RFDs) to join its network. On the other hand, in a peer-to-peer topology, each device is capable of communicating with any other device within its radio sphere of influence. One device will be nominated as the PAN coordinator, for instance, by virtue of being the first device to communicate on the channel.

Further network structures can be constructed out of the peer-to-peer topology and may impose topological restrictions on the formation of the network. An example is the cluster-tree network, as shown in Fig. 2 (b), which is a special case of a peer-to-peer network in which most devices are FFDs. An RFD may connect to a cluster tree network as a leave node at the end of a branch, because it may only associate with one FFD at a time. Any of the FFDs may act as a coordinator and provide synchronization services to other devices or other coordinators. Only one of these coordinators can be the overall PAN coordinator, which may have greater computational resources than any other device in the PAN.

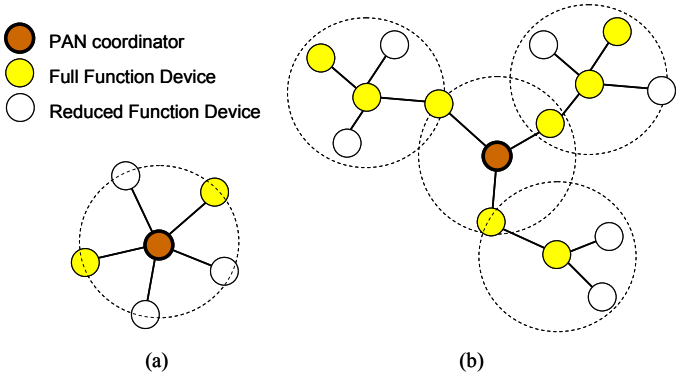


Fig. 2. (a) Star and (b) cluster tree topologies of the IEEE 802.15.4 network.

C. Beacon and Superframe Structure

The IEEE 802.15.4 standard allows the optional use of a superframe structure. The superframe is bounded by network beacons sent by the coordinator and is divided into 16 equally sized slots. All transactions shall be completed by the time of the next network beacon. The beacons are used to synchronize the attached devices, to identify the PAN, and to describe the structure of the superframes. The format of the superframe is defined by the coordinator. The superframe can have an active and an inactive portion, as shown in Fig. 3. The active portion of each superframe is composed of three parts: a beacon, a contention access period (CAP) and a contention-free period (CFP). The beacon shall be transmitted, without the use of carrier sense multiple access with collision avoidance (CSMA-CA), at the start of slot 0, and the CAP shall commence immediately after the beacon. Any device wishing to communicate during the CAP between two beacons shall compete with other devices using a slotted CSMA-CA mechanism. The CFP, if present, follows immediately after the CAP and extends to the end of the active portion of the superframe. No transmissions within the CFP shall use a CSMA-CA mechanism to access the channel.

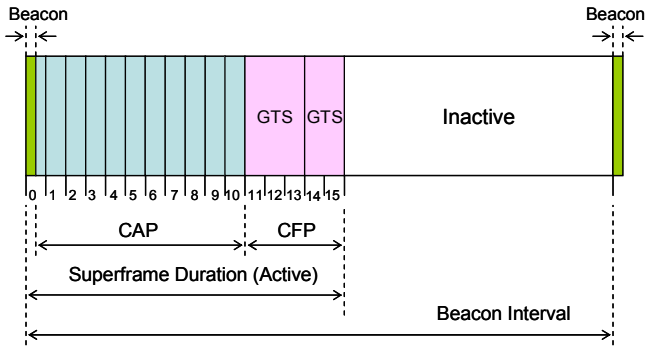


Fig. 3. The IEEE 802.15.4 superframe structure.

For low-latency applications or applications requiring specific data bandwidth, the PAN coordinator may dedicate portions of the active superframe to that application. These portions are called guaranteed time slots (GTSs). Any allocated GTSs shall be located within the CFP. The PAN coordinator may allocate up to 7 of these GTSs, and a GTS may occupy more than one slot period. However, a sufficient portion of the CAP shall remain for contention-based access of other networked devices or new devices wishing to join the network. All contention-based transactions shall be complete before the CFP begins. Also, each device transmitting in a GTS shall ensure that its transaction is complete before the time of the next GTS or the end of the CFP. Then, during the following inactive portion, the coordinator shall not interact with its PAN and may enter a low-power mode.

The structure of the superframe is described by the values of beacon order (BO) and superframe order (SO). The length of the superframe, i.e. beacon interval (BI), and the length of its active part, i.e. superframe duration (SD) are defined as follows:

$$BI = aBaseSuperframeDuration \times 2^{BO},\ 0 \le BO \le 14.$$
$$SD = aBaseSuperframeDuration \times 2^{SO},\ 0 \le SO \le 14.$$

Where, *aBaseSuperframeDuration*, the number of symbols forming a superframe when the superframe order is equal to 0, is 960 symbols. For those PANs that do not wish to use the superframe structure (referred to as a nonbeacon-enabled PAN) shall set both *BO* and *SO* to 15. In this case, a coordinator shall not transmit beacons and GTSs shall not be permitted.

D. CSMA-CA Mechanism

The CSMA-CA algorithm shall be used before the transmission of data or MAC command frames transmitted within the CAP. The IEEE 802.15.4 uses two types of channel access mechanism, depending on the network configuration.

- *Unslotted CSMA-CA*: Nonbeacon-enabled networks use this channel access mechanism. Each time a device wishes to transmit data frames or MAC commands, it shall wait for a random period. If the channel is found to be idle, following the random backoff, the device shall transmit its data. If the channel is found to be busy, following the random backoff, the device shall wait for another random period before trying to access the channel again.
- Slotted CSMA-CA: Beacon-enabled networks use this channel access mechanism, where the backoff slots are aligned with the start of the beacon transmission. Each time a device wishes to transmit data frames during the CAP, it shall locate the boundary of the next backoff slot and then wait for a random number of backoff slots. If the channel is busy, following this random backoff, the device shall wait for another random number of backoff slots before trying to access the channel again. If the channel is idle, the device can begin transmitting on the next available backoff slot boundary.

In both cases, the algorithm is implemented using units of time called backoff periods, where one backoff period shall be equal to a constant, i.e. *aUnitBackoffPeriod* (20 symbols) [5]. The maximum number of backoffs the CSMA-CA algorithm will attempt before declaring a channel access failure, i.e. *macMaxCSMABackoffs*, can be varied between 0 and 5 (4 in default). Note that the CSMA-CA algorithm shall not be used for the transmission of beacon frames, acknowledgment frames, or data frames transmitted in the CFP.

E. Data Transfer Models

The mechanisms for data transfer depend on whether the network supports the transmission of beacons. A beacon-enabled network is used for supporting low-latency devices, such as PC peripherals. If the network does not need to support such devices, it can elect not to use the beacon for normal transfers.

- *Direct data transmission*: This data transfer transaction is the mechanism to transfer data from a device to a coordinator. In a beacon-enabled network, when a device wishes to transfer data to a coordinator, it first listens for the network beacon, as shown in Fig. 4 (a). When the beacon is found, the device synchronizes to the superframe structure. At the appropriate point, the device transmits its data frame, using slotted CSMA-CA, to the coordinator. The coordinator acknowledges the successful reception of the data by transmitting an acknowledgment frame. On the other hand, in a nonbeacon-enabled network, when a device wishes to transfer data, it simply transmits its data frame, using unslotted CSMA-CA, to the coordinator. The coordinator acknowledges the successful reception of the data by transmitting an acknowledgment frame, as shown in Fig. 4 (b).

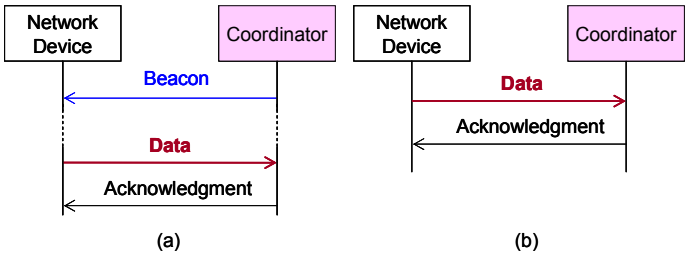


Fig. 4. Direct data transmission in (a) beacon-enabled, and (b) nonbeacon-enabled networks.

- *Indirect data transmission*: This data transfer transaction is the mechanism for transferring data from a coordinator to a device. In a beacon-enabled network, when the coordinator wishes to transfer data to a device, it indicates in the network beacon that the data message is pending. The device periodically listens to the network beacon and, if a

message is pending, transmits a MAC command requesting the data, using slotted CSMA-CA. The coordinator acknowledges the successful reception of the data request by transmitting an acknowledgment frame. The pending data frame is then sent using slotted CSMA-CA. The device acknowledges the successful reception of the data by transmitting an acknowledgment frame. Upon receiving the acknowledgement, the message is removed from the list of pending messages in the beacon. This sequence is summarized in Fig. 5 (a). On the other hand, in a nonbeacon-enabled network, when a coordinator wishes to transfer data to a device, it stores the data for the appropriate device to make contact and request the data. A device may make contact by transmitting a MAC command requesting the data, using unslotted CSMA-CA, to its coordinator at an application-defined polling rate, as shown in Fig. 5 (b). The coordinator acknowledges the successful reception of the data request by transmitting an acknowledgment frame. If data are pending, the coordinator transmits the data frame, using unslotted CSMA-CA, to the device. If data are not pending, the coordinator transmits a data frame with a zero-length payload to indicate that no data were pending. The device acknowledges the successful reception of the data by transmitting an acknowledgment frame.

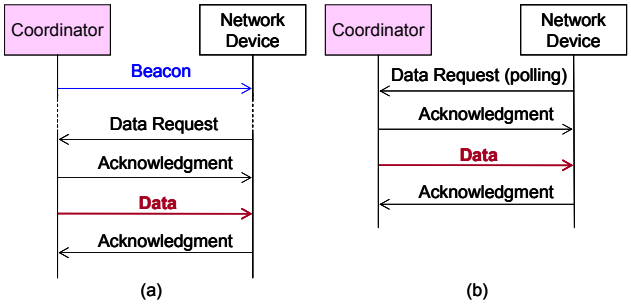


Fig. 5. Indirect data transmission in (a) beacon-enabled, and (b) nonbeacon-enabled networks.

F. Data Frame Format

IEEE 802.15.4 defines four frame types, including the beacon, command, acknowledgment, and data frames. The data packet is the major one that affects the data throughput of the network. The format of the 802.15.4 data frame is shown in Fig. 6. The MAC frame, i.e. the MPDU, is composed of an MAC header (MHR), MAC service data unit (MSDU), and MAC footer (MFR). The first field of the MAC header is the frame control field. It indicates the type of MAC frame being transmitted, specifies the format of the address field, and controls the acknowledgment. In short, the frame control field specifies how the rest of the frame looks and what it contains. A data frame may contain both source and destination information with the size of the address field between 4 and 20 bytes. The payload field is variable in length. However, the maximum MAC data payload, *aMaxMACFrameSize*, is equal to *aMaxPHYPacketSize* (127 bytes) – *aMaxFrameOverhead* (25 bytes) = 102 bytes [5]. The MPDU is passed to the PHY as the PHY data frame payload, i.e., PSDU. The PSDU is prefixed with a synchronization header (SHR) and a PHY header (PHR), together with PSDU to form the PHY data packet, i.e., PPDU.

III. PERFORMANCE EXPERIMENTS

In this section, we establish experiments on the performance study of the IEEE 802.15.4 wireless networks.

A. Experimental Hardware

As shown in Fig. 7, two CC2420DBs (development boards) from Chipcon [10] are used as a coordinator and a network device (Device 1), respectively, continuously transferring the data so as to perform the measurements. The CC2420 is a single-chip IEEE 802.15.4 compliant and ZigBee ready RF transceiver. It provides a highly integrated, flexible low-cost solution for applications using the 2.4 GHz frequency band. The CC2420DB boards contain a CC2420 with necessary support components, an Atmel Atmega128L AVR microcontroller with 128K flash and 4K SRAM, 32K external RAM, a PCB antenna, as well as a joystick, buttons and LEDs that can be used to implement a visual user application interface.

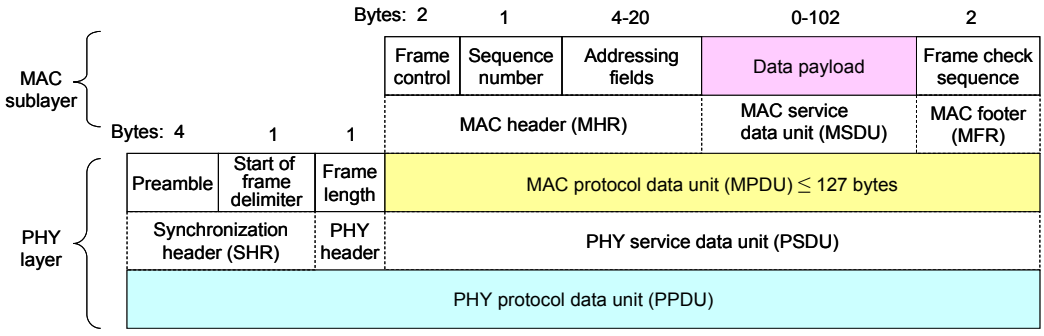


Fig. 6. Data frame format of the IEEE 802.15.4.

Also, one CC2400EB (evaluation board) that together with a CC2420EM (evaluation module) is used as the packet sniffer for monitoring [11]. It provides a USB port. Both the CC2420DB and CC2400EB have a serial port for easily connecting with a PC or notebook, where the real-time data could be stored.

The other three Freescale MC13192 evaluation boards [12] are used as the traffic load generators (Device 2-4). The boards contain an MC9S08GT60 microcontroller with 60K flash and 4K RAM, a PCB antenna, as well as buttons and LEDs as the user interface.

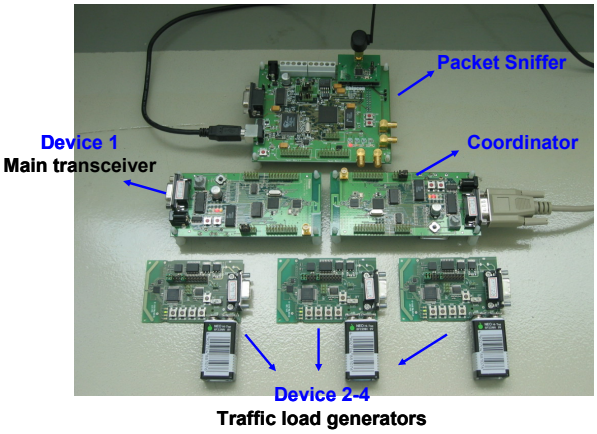


Fig. 7. Experimental equipment.

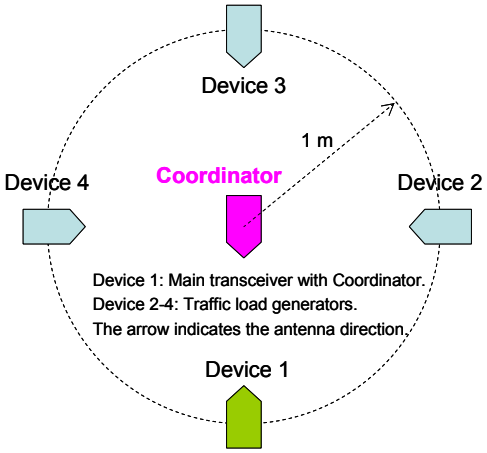


Fig. 8. Experimental setup as a star topology.

B. Experimental Configuration

Four sets of experiments are designed to evaluate the various performance behaviors of IEEE 802.15.4, including the effects of 1) the direct and indirect data transmissions, 2) CSMA-CA, 3) data payload size, and 4) beacon-enabled mode. The experiments were run in a one-hop star topology, as shown in Fig. 8. The distance between the coordinator and each device is 1 meter. Device 1 is the main transceiver continuously sending or receiving data packet to or from the coordinator. The other Device 2-4 are traffic load generators in the following Experiment B and C. In each experiment, the frame retransmission was disabled and 10000 data packets were transmitted by either the coordinator (indirect transmission) or the Device 1 (direct transmission). During the data transfer, the addressing mode used is the 16-bit short address. In addition, if all transmissions are successful, another 10000 acknowledgment packets would be transmitted so as to respond to each data packets. The performance study was for a steady state network, i.e. after all the devices finish channel scanning and the association procedure to join the PAN.

IV. EXPERIMENTAL RESULTS

In this section, the realistic data rate, received signal strength indication (RSSI), and delivery ratio are measured under the mentioned experimental sets.

A. Direct and Indirect Data Transmissions

In this experiment, the raw data rate is defined as

$$R_{\text{rawData}} = \frac{\sum_{x} N_x \cdot (L_{\text{PPDU}})_x}{T_{\text{end}} - T_{\text{start}}}, \qquad (1)$$

where, $x = \{\text{data, acknowledgment, command, beacon}\}$.

N_x is the number of transmitted packets for each type of frames, $(L_{\text{PPDU}})_x$ is the PPDU packet length (in byte) for each type of frames, while T_{start} and T_{end} is the time to start and end the transmission.

This experiment was taken under a nonbeacon mode and the frame retransmission was disabled. The data size of MSDU is set to the *aMaxMACFrameSize* (102 bytes) as mentioned in Section II-F. Fig. 9 shows the raw data rate for both direct and indirect data transmission. The data rate has a slight variation with an average as 153.02 kbps for direct data transfer and 65.69 kbps for indirect data transfer, respectively. Based on a theoretical gross data rate of 250 kbps, the utilization rate is 61.21 % and 26.28%, respectively. For indirect data transfer, the data rate is greatly reduced because of the network device's polling rate (sending data request periodically). In all the experiments of this paper, the QUEUED_POLL_RATE, which is used to poll immediately for the next queued message when receiving a data indication (i.e. frame pending subfield in the frame control field is true), is 10 ms.

The RSSI is measured for each received packet. The PHY layer uses receiver energy detection (ED), a signal-to-noise ratio, or a combination of these to measure the strength and/or quality of a link from which a packet is received. The RSSI value could be used to produce the link quality indication (LQI) value. The LQI value is required by [5] to be limited to a range [0, 255] with at least 8 unique values. Fig. 10 shows the RSSI for both the direct and indirect data transmissions with an average as -34.35 dBm and -40.87 dBm, respectively.

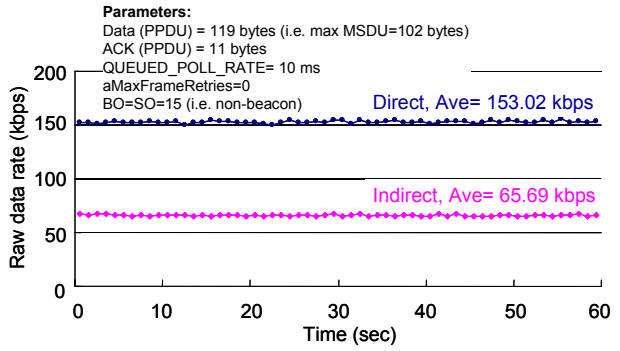


Fig. 9. Raw data rate for the direct and indirect data transmissions in a nonbeacon-enabled network.

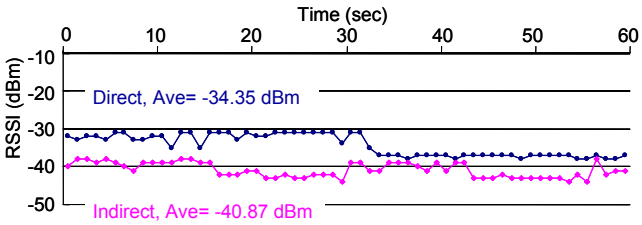


Fig. 10. RSSI value for the direct and indirect data transmissions in a nonbeacon-enabled network.

B. Effects of CSMA-CA Mechanism

During the CSMA-CA, data packets may be undeliverable as the channel is extremely busy, or be erroneous (e.g. CRC failed), or even be lost. In this paper, the effective data rate is defined as

$$R_{\text{effData}} = \frac{N_{\text{data}} \cdot (L_{\text{MSDU}})_{\text{data}}}{T_{\text{end}} - T_{\text{start}}}, \qquad (2)$$

where, N_{data} is the number of usable data packets, and $(L_{\text{MSDU}})_{\text{data}}$ is the MSDU length (i.e. MAC payload size) of the data frame.

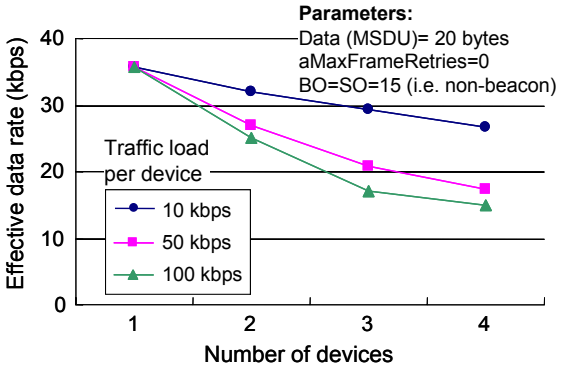


Fig. 11. Effective data rate of CSMA-CA with varied traffic load in a nonbeacon-enabled network.

In this experiment, the data MSDU size was fixed to 20 bytes. 10000 data packets were transmitted from the Device 1 to the coordinator (direct data transmission). The *macMaxCSMABackoffs* was set to 4 and the backoff exponent was 3. Fig. 11 and 12 show the effective data rate and delivery ratio between the coordinator and Device 1 for different number of devices with varied traffic load (generated by Device 2-4). The results show that with the increase of devices, both the effective data rate and delivery ratio decreased due to the presence of collisions and random backoffs. Moreover, with the larger traffic load from other devices, both the effective data rate and delivery ratio were also reduced because the collision possibility increased.

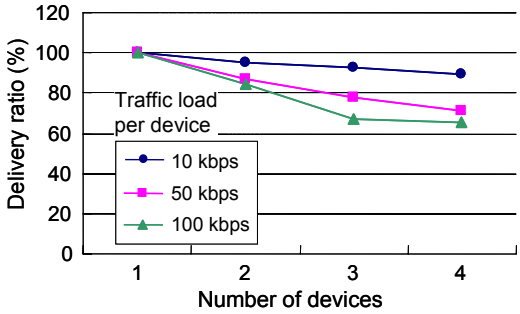


Fig. 12. Delivery ratio of CSMA-CA with varied traffic load in a nonbeacon-enabled network.

C. Effects of Data Payload Size

Fig. 13 and 14 show the effective data rate and delivery ratio between the coordinator and Device 1 for different number of devices with varied data payload (MSDU) size. The traffic load generated by Device 2-4 was fixed to 100 kbps. Similarly, 10000 data packets were transmitted from the Device 1 to the coordinator (direct data transmission).

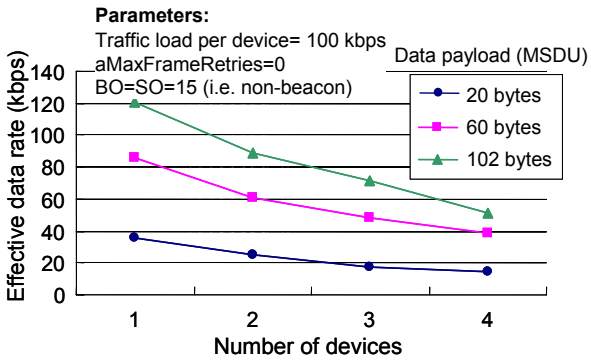


Fig. 13. Effective data rate of CSMA-CA with varied data payload size in a nonbeacon-enabled network.

The results show that with the increase of payload size, the data rate also increased since the effect of overhead was reduced leading to a raise of data coding efficiency. On the other hand, the delivery ratio has only a slight variation when the data payload varies. The delivery ratio of 102-byte payload is the lowest one when 4 devices generate the traffic load. This is because as the number of devices increases, a larger packet size will has more possibility to collide and to be destroyed.

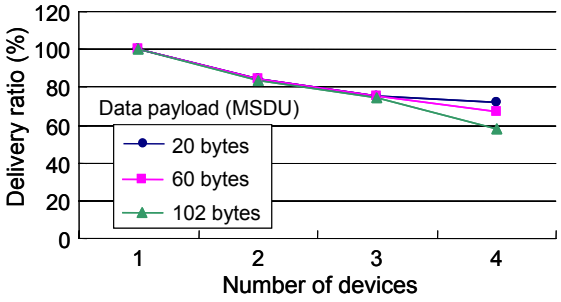


Fig. 14. Delivery ratio of CSMA-CA with varied data payload size in a nonbeacon-enabled network.

D. Effects of Beacon-Enabled Mode

This experiment was taken under Device 1 continuously sending data packet to the coordinator. The beacon MPDU size and the data MSDU size were fixed to 16 and 20 bytes, respectively. Similarly, 10000 data packets were transmitted (direct data transmission). As the beacon order varies, we make the BO and SO equal, which leads to the duty cycle to be 100% (i.e. the active superframe duration is equal to the beacon interval). Fig. 15 shows the effective data rate between the coordinator and Device 1 for different number of beacon order. The result shows that with the increase of beacon order, the data rate also increased. Note that the beacon order 15 indicates a nonbeacon mode. Thus, from this experiment, we found that the nonbeacon-enabled network would have larger data rate than the beacon-enabled one. Also, as the beacon order becomes smaller and leads to a shorter beacon interval, it may result in a "beacon storm" effect and thus reduce the data rate.

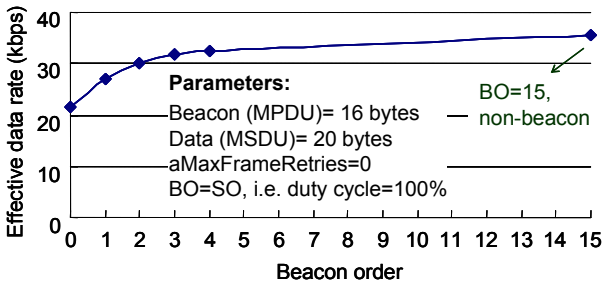


Fig. 15. Effective data rate in a beacon-enabled network.

Also, an indirect data transmission was conducted and 10000 data packets were transmitted from the coordinator to the Device 1. A comparison of the beaconing effects in both the direct and indirect data transmission is shown in Fig. 16. Note that in the indirect data transfer, when the beacon order increased, the data rate decreased (except BO=15, i.e. the nonbeacon mode). This is opposite to the "beacon storm" in the direct one. Since in the indirect data transfer, the device has to periodically listen to the network beacons and check if a message is pending so as to send the MAC command to request the data. Hence, as the beacon order becomes larger and leads to a longer beacon interval, it may take more time to inform the device of a pending message and the data rate is thus reduced.

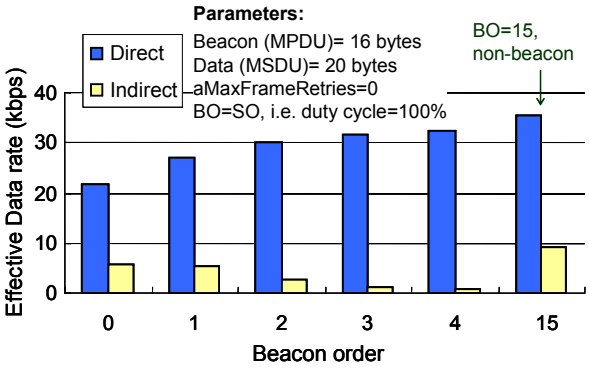


Fig. 16. Effective data rate of direct and indirect data transmission in a beacon-enabled network.

E. Discussions

During our experiments, we found that the highest raw data rate achieved is 156 kbps in the first experiment, where there is only one device. Note that this is substantially below the nominal value of 250 kbps because of the presences of packet overheads, random backoffs, ACK messages, as well as a large setting for inter-frame spacing. Also, note that the CAMA/CA mechanism in 802.15.4 automatically backs off initially when a transmission is imminent, i.e. each data and command frame transfer will at least have one backoff. This would also reduce the performance.

In the beaconing experiment, one of the reasons that the nonbeacon-enabled network has better performance than the beacon-enabled one may be the timing of acknowledgment frames. As shown in Fig. 17, in a nonbeacon-enabled network or in the CFP, the transmission of an acknowledgment frame shall commence *aTurnaroundTime* symbols after the reception of the last symbol of the data or command frame. This is a maximum time for RX-to-TX or TX-to-RX turnaround. On the other hand, in the CAP of a beacon-enabled network, it shall commence at a backoff slot boundary. In this case, the transmission of an acknowledgment frame shall commence between *aTurnaroundTime* and the sum of *aTurnaroundTime* and *aUnitBackoffPeriod* symbols after the reception of the last symbol of the data or command frame. The constant *aTurnaroundTime* and *aUnitBackoffPeriod* is defined as 12 and 20 symbols, respectively [5].

Other 2.4GHz ISM-band signals, such as Wi-Fi, Bluetooth, and microwave ovens, may interfere with the IEEE 802.15.4 performance. Also, when the distance between the transmitter and receiver was longer than around 10 m, we found that the PCB antenna had strong dependency of its angle direction and hence resulted in large relative deviations. Moreover, while experimenting in an outdoor environment, the disturbances and uncertainties from the weather, walkers, and vehicles

also affect the measurements. These issues may lead to non-reproducible results in some cases.

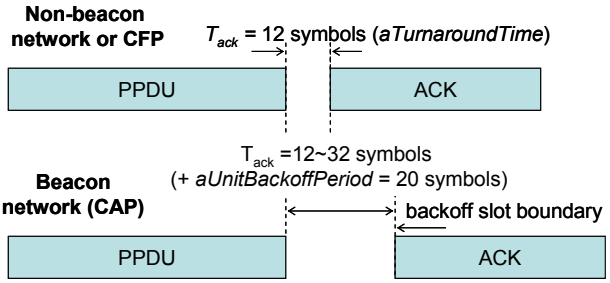


Fig. 17. Timing of acknowledgment frames

V. CONCLUSIONS

This paper has presented a brief overview of the emerging wireless standard, IEEE 802.15.4, with a preliminary performance study via a practical experiment. Featuring its simplicity, low power consumption, low cost connectivity, and device-level networking would make IEEE 802.15.4 suitable for wireless sensor network applications [13] in the practical industry.

Future work includes the evaluation of the power consumptions, association time, under different duty cycles, longer distances, multi-hop conditions, a tree or a peer-to-peer topology, and more device nodes. Also, the interference issues should be further investigated. Moreover, base on 802.15.4 (defines PHY and MAC only), ZigBee Alliance [14] defines the protocol stack to application layer. Another research direction is to evaluate features of the ZigBee platform stack, such as the security, binding time, and routing performance.

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