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PERFORMANCE EVALUATION OF DATA TRANSPORT OVER DIFFERENT-NODE DENSITY OF ZIGBEE SENSOR NETWORK – AN OPNET SIMULATION STUDY

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Abstract. In this paper, we analyze the performance of different node density of Wireless Sensor Network (WSN) operating under the IEEE Standard 802.15.4 in the beacon-enabled mode. The motivation for evaluating the beacon-enabled mode is due to its flexibility for WSN applications as compared to the non-beacon enabled mode. The analysis is based on an accurate OPNET simulation model which supports slotted Carrier Sense Multiple Access Mechanism with Collision Avoidance (CSMA/CA) mechanism and Guaranteed Time Slot (GTS). The performance of the slotted CSMA/CA sensor network is evaluated and analyzed for different network settings to understand the impact of the protocol attributes, including super-frame order (SO), beacon order (BO), data packet size and maximum back-off number. Through the simulation results, high SO provides better network throughput, otherwise results in lower average latency. We also found that the MAC overheads on small MAC Service Data Unit (MSDU) are more significant than the overheads on large MSDU. And the back-off mechanism results in longer delays when the network traffic is heavy.

Keywords. Wireless sensor network, ZigBee network, network performance.

1 INTRODUCTION

During the last decade there has been an explosion of devices using sensor technologies for control and monitoring purposes. Wired sensors are now intended to be replaced with wireless technologies and wireless sensor networks have aroused much research interest. Most technologies designed so far, such as Bluetooth and Wi-Fi, primarily focus on the ability to support higher data rates and wider operating range, which have a direct impact on the power requirements, cost factor, size, complexity and feasibility [1]. ZigBee is a new wireless technology guided by the IEEE802.15.4 Personal Area Network (PAN) standard. It is primarily designed for the wide ranging automation applications and to replace the existing non-standard technologies. Compared to Long Range (LoRa) wireless radio frequency (RF) technology, the main features of ZigBee are low power consumption, low cost, low data rate, self-organization and flexible topologies [2][3].

Till this time, few accurate simulations and implementations have been done for ZigBee protocol. The OPNET Modeler is an industry leading discrete-event network modeling and simulation environment [4][5][6]. Two IEEE802.14.5 OPNET simulation models were researched. The first model is developed by the National Institute of Standards and Technology (NIST) [7]. This model implements only the first two levels of the International organization of Standardization (ISO)/ Open System Interconnection (OSI) stack and a few functions of the upper layer. Instead of using the accurate OPNET wireless library, it uses its own radio channel model and only supports un-slotted CSMA/CA MAC protocols. Compared to the NIST simulation model, the model developed by OPEN-ZB implements the both the application layer and the battery module [8]. Since the OPEN-ZB simulation model provides more features and uses the accurate OPNET wireless library, we used this model to evaluate the performance of the ZigBee sensor network.

Last but not least, from the best of our knowledge, there has not reported about the impact of node-density on Quality of Service (QoS) of ZigBee sensor network. And it is critical to have analytical model using parameters such as node-density, back-off number, retransmission limit, and packet size for the scalable-node ZigBee sensor network [9]. For better presentation of our results, we collect and classify all simulation results from OPNET, export them to spreadsheet to illustrate the final simulation results.

This paper divides into following primary sections. Section 2 will introduce the general concept of IEEE802.15.4 protocol and cover some relevant features of this protocol. Further details about the simulation models and simulation environment setup are explained in Section 3. Section 4 shows the collected simulation results based on simulation scenarios. Finally, Section 5 concludes this paper.

2 RELEVANT FEATURES OF THE IEEE802.15.4 PROTOCOL

The IEEE802.15.4 standard specifies the physical layer and MAC sub-layer for Low-Rate Wireless Personal Area Networks (LR-WPAs) [9]. The ZigBee standard is guided by the IEEE802.15.4 protocol and specifies the network and application layers [10][11]. According to [10], three different types of nodes can be used in a wireless sensor network: the coordinator, the router and the end device. The coordinator performances like the root of a tree. It initiates the network format and exchanges the parameters used by the other nodes to communicate. There is only one coordinator in each network. The router participates in multi-hop routing of messages and managers the routing tables. Both the coordinator and the router are called Full Function Devices (FFDs). On the other hand, the end device, which is also referred as Reduced Function Devices (RDFs), is only responsible for collecting data from sensors and sending them to FFDs.

2.1 IEEE802.15.4 physical and MAC layers

The physical layer is responsible for data transmission and reception using a certain radio channel. The IEEE802.15.4 is currently operating in three frequency bands: 868MHz band at a data rate of 20kbps in Europe, 915MHz band at 40kbps in the North America, and 2.4GHz band at a data rate of 250kbps in worldwide [10].

Table 1. ZigBee physical layer specifications.

Attribute	2450MHz band	915MHz band	868MHz band
Gross data rate	250 kbps	40 kbps	20 kbps
Number of Channel	16	10	1
Modulation	O-QPSK	BPSK	BPSK
Chip pseudo-noise sequence	32	15	15
Bit per symbol	4	1	1
Symbol period	16 micro-sec	24 micro-sec	49 micro-sec
Access scheme	DSSS	DSSS	DSSS

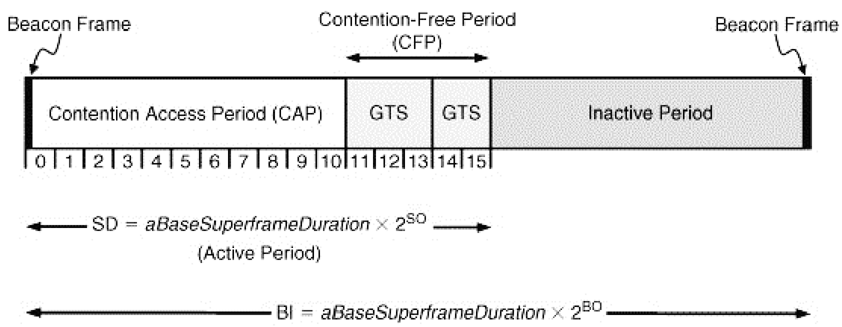

Figure 1: Frame structure of the beacon signal [10].

The Medium Access Control (MAC) protocol supports two operation modes that can be selected by a coordinator in the Personal Area Network (PAN): beacon enabled mode and non-beacon enabled mode. In beacon-enabled mode, the beacon frames are periodically generated and sent by the PAN coordinator to identify its PAN and synchronize devices that are associated with it. When beacon enabled mode is selected, the PAN coordinator uses super-frame structure to communicate the end devices which are associated to that PAN. Each super-frame begins with the transmission of a network beacon followed by an active portion and an optional inactive portion as shown in fig. 1. Therefore, the Beacon Interval (BI) is the time between two consecutive beacon frames.

The active period, referred to the Super-Frame Duration (SD), is divided into 16 equally sized time slots. Data can be transmitted during these time slots. The BI and the SD are determined by two parameters, the Beacon Order (BO) and the Super-Frame Order (SO) respectively.

$$BI = aBaseSuperframe\ Duration \times 2^{BO} \text{ for } 0 \leq BO \leq 14 \quad (1)$$

$$SD = aBaseSuperframeDuration \times 2^{SO} \text{ for } 0 \leq SO \leq BO \leq 14 \quad (2)$$

In these two equations (1) and (2), the "*aBaseSuperframeDuration*" refers to the minimum duration of the super-frame. This duration is 15.36ms if the assumption of 250kbps in the 2.4GHz frequency band is made [3]. Each active period can be further divided into a Contention Access Period (CAP) and an optional Contention Free Period (CFP). Slotted Carrier Sense Multiple Access mechanism with Collision Avoidance (CSMA-CA) can be used within the CAP.

The CFP is activated when a device sends to the PAN coordinator a request. Upon receiving the request, the PAN coordinator checks whether there are sufficient resources to allocate the requested time slots. These slots are referred to as Guaranteed Time Slots (GTS). In non-beacon enabled mode, super-frame structure is not used and the un-slotted CSMA/CA mechanism is used. Therefore, GTS is not provided by the non-beacon enabled mode. In this paper, we only interest with the beacon-enabled mode due to its flexibility for Wireless Sensor Network (WSN) applications as compared to the non-beacon enabled mode.

2.2 Slotted CSMA/CA mechanism

The slotted CSMA/CA mechanism is based on a basic time unit called Back-off Period (BP) and is used in beacon-enabled mode during the CAP. The BP is the basic time unit of the MAC protocol. The access to the channel can only occur at the boundary of the back-off slots. The back-off slot boundaries must be aligned with the super-frame slot boundaries. When a device wants to transmit frames during the CAP, it first locates the boundary of the next back-off slot and then waits for a random number of the back-off slots. If the channel is busy, following this random back-off, the device will wait for another random number of back-off slots before trying to access the channel again. This can be repeated for several times. If the channel is idle, the device can begin transmitting on the next available back-off slot boundary.

There are three parameters in the slotted CSMA/CA mechanism, the Back-off Exponent (BE), the Contention Window (CW) and the Number of Back-offs (NB). The BE enables the computation of the back-off delay, which is a random variable between 0 and $(2^{BE}-1)$. The CW represents the number of back-off period and the NB represents the number of times that the slotted CSMA/CA mechanism was required to back-off while attempting to access the channel.

3 IEEE802.15.4 SIMULATION MODELS

3.1 OPEN-ZB simulation model features

As shown in fig. 2a about the OPNET simulation model of IEEE802.15.4, the physical layer consists of the IEEE802.15.4 compliant radio transmitter and receiver, which are operating at 2.4GHz frequency band with the data rate of 250kbps. The transmission power of the transmitter and the receiver is set to 1mW.

The MAC layer implements the slotted CSMA/CA and the GTS mechanisms. When the GTS is active, the GTS data traffic generated from the application layer is stored in a buffer with a specified capacity and dispatched to the network. The MAC layer also managers the generation of beacon frames when the node is a PAN coordinator.

The application layer consists of three parts, a traffic source, a GTS traffic source and a traffic sink. The traffic source and the GTS traffic source can generate both the unacknowledged and acknowledged data frames during the CAP and CFP periods. The traffic sink receives data frames from lower layers and performs network statistics. The batter module computes and energy consumption and the remaining energy levels.

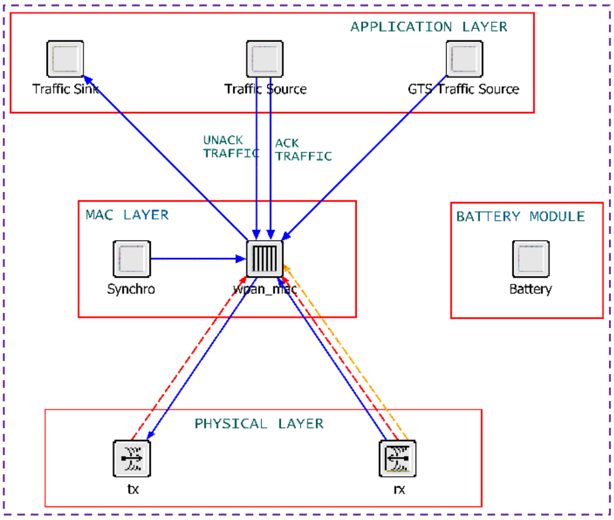

Figure 2a: IEEE802.15.4 OPNET simulation model.

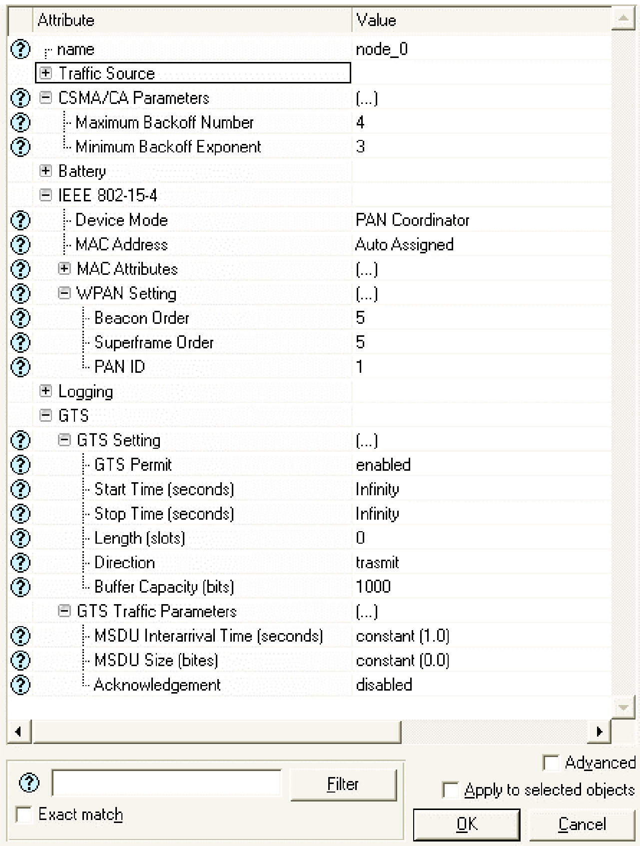

Figure 2b: User-defined attributes.

3.2 User-defined attributes

This section introduces some important user-defined attributes of our simulation model. As shown in fig. 2b, the MSDU Size attribute specifies the size of the MAC Service Data Unit. Since the MAC header is 104 bits and the maximum allowed size of the overall frame is 1016 bits, the MSDU Size value can be from 0 to 912 bits. The Maximum Back-off Number attribute specifies the maximum number of retransmissions that the slotted CSMA/CA mechanism will attempt before the mechanism terminates with a channel access failure status. The range of this value is from 0 to 5.

The Minimum Back-off Exponent attribute specifies the minimum value of the BE in the slotted CSMA/CA. As mentioned in previous section, the BE is related to how many back-off periods a device must wait before attempting to access the channel activity.

The BO and SO attributes are related only to the PAN coordinator. The setting of BO and SO must satisfy the relationship $0 \leq SO \leq BO \leq 14$. If *SO* is equal to *BO*, then according equations (1) and (2) from Section 2, the Beacon Internal is equal to the super-frame duration. Therefore, the super-frame is always active. According to the IEEE802.15.4 standard, the super-frame will not be active following the beacon if *SO* is equal to *15*. Thus, in order to operate in beacon-enabled mode, the SO and BO attributes in the PAN coordinator must be set to a value between 0 and 14.

The GTS Permit attribute allow the PAN coordinator to accept or reject the GTS allocation request from end devices. This attribute only applies to the PAN coordinator. From the end device side, each device can specify the time when the GTS allocation and deallocation requests are sent to the PAN coordinator by setting the Start Time and Stop Time attributes.

4 SIMULATION AND RESULTS

Our objective is to evaluate the performance of the ZigBee wireless sensor network. The performance of the un-slotted CSMA/CA mechanism was evaluated in [7] by using the NIST simulation model, however the slotted CSMA/CA mechanism was not addressed. In order to carry out this task, we developed a simulation environment for the IEEE802.15.4 slotted CSMA/CA mechanism using the OPNET simulator. We consider a typical star wireless sensor network with one PAN coordinator surrounded by numbers of identical nodes within the radio coverage. The node density is sequentially simulated as 1,2,3,4,5,10,20,30,40,100,130 and 150 RDFs end-nodes, respectively. One of our provision network topology simulation with 40 ZigBee end-nodes is pictured in fig. 3.

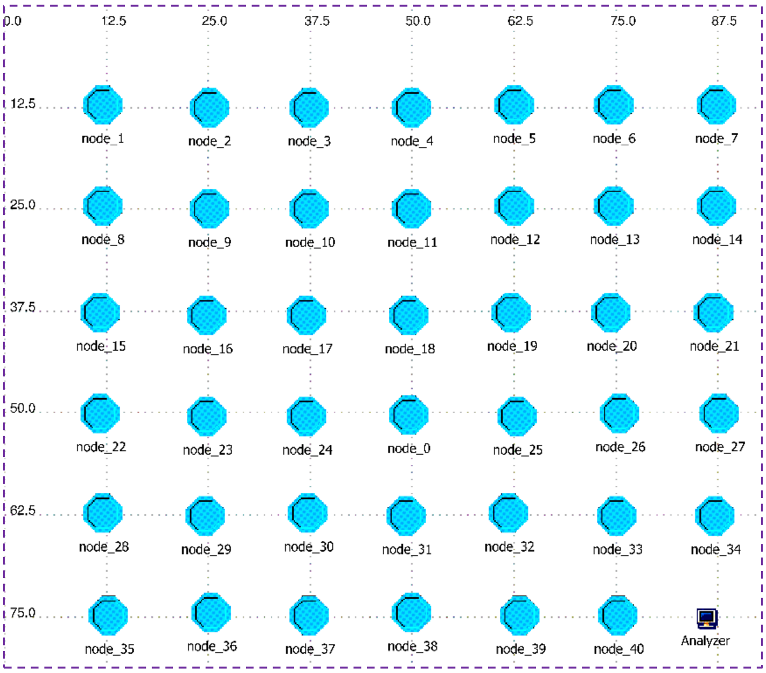

Figure 3: Example of star topology with 40 ZigBee end-nodes inside 100m^2 room.

We particularly interest in three performance parameters, the average end-to-end delay, the network output load and the probability of success. The end-to-end delay is the transmission delay between two consecutively received packets. The probability of success is the probability of the packets being successfully received during the CAP. In order to understand the impact of the protocol attributes, including the super-frame order, beacon order, maximum back-off number and the frame size, on the network performance, we set up four primary simulation scenarios as follows.

(i) The purpose of the first scenario is to evaluate the impact of the network load.

(ii) The second scenario is to evaluate the impact of super-frame order and beacon order.

(iii) The third scenario is to evaluate the impact of the frame size.

(iv) And the last scenario is to evaluate the impact of maximum back-off number.

Unless it is mentioned differently, following settings apply to all the simulation scenarios.

- BO and SO are always set to equal
- Maximum Back-off Number is set to 4
- Minimum Back-off Exponent is set to 3
- Only acknowledge data frame are generated
- GTS are enabled
- MSDU Inter-arrival Time and MSDU Size are constants

- Simulated period is 50 seconds
- Buffer size is 1000 bits

4.1 Impact of number of end devices

In order to evaluate the impact of the network load on the performance of ZigBee wireless sensor network, the average delay, the probability of success and the network throughput are collected as functions of the number of end devices in the network. In this scenario, each identical end device sends packets with a packet size of 100 bits (MSDU size) and a constant generation interval (MSDU Inter-arrival Time) of 0.1s during the CAP. The GTS is enabled from the 0.2s to 1.5s of the simulation period and it sends packets with a packet size of 100 bits and a constant generation interval of 0.2s during the CFP. The super-frame order and beacon order are set to 7. The arrival data rate is defined as MSDU size over MSDU Inter-arrival Time. Thus, the arrival data rates are 1kbps during the CAP and 0.5kbps during the CFP. Since GTS is enabled only at the beginning of the simulation period (from 0.2s to 1.5s), the arrival data rate is 1kbps after 1.5s. When we increase the number of end devices in the network, we increase the network load accordingly.

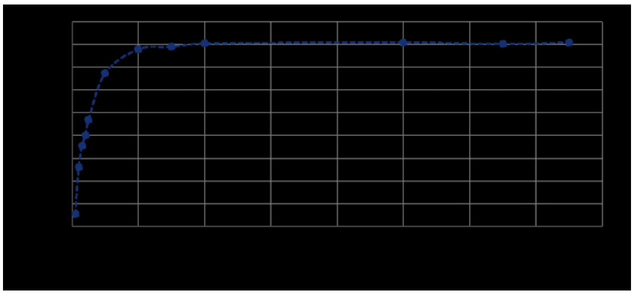

Figure 4a: Average delays as a function of the number of end devices.

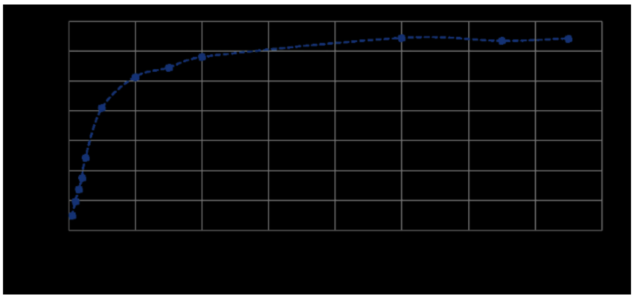

Figure 4b: Average network throughputs as a function of the number of end devices.

Figures 4a and 4b present the impact on the end-to-end delay and the network throughput when step-by-step increasing the end-device number from 1 to 150. Figures 4a and 4b show that initially both the network throughputs and the delays increase with the number of end devices. When the number of end devices reaches 50, the curves become flat. The floor level of the network throughput is about 32kbps and the delay is about 0.016s. The floor level is determined by the data rate limitation of the IEEE802.15.4. Although theoretically the IEEE802.15.4 protocol can provide a capacity of 250kbps, our simulation results show that in fact the data rate is limited to 32kbps, which is 12.8% of the theoretical value.

To further investigate the difference between the theoretical value and the simulation value, the percentage of successful acknowledged transmission packets are captured. As shown in fig. 5, the percentage is 100% when there is only one end device in the network. When more end devices are added to the network, more packets are dropped during the transmission due to the heavy network load and the limited buffer size. From the simulation result, we can observe that a network with 150 end nodes (each node has a data arrival rate of 1kbps) is able to successfully transmit 75% of the generated data.

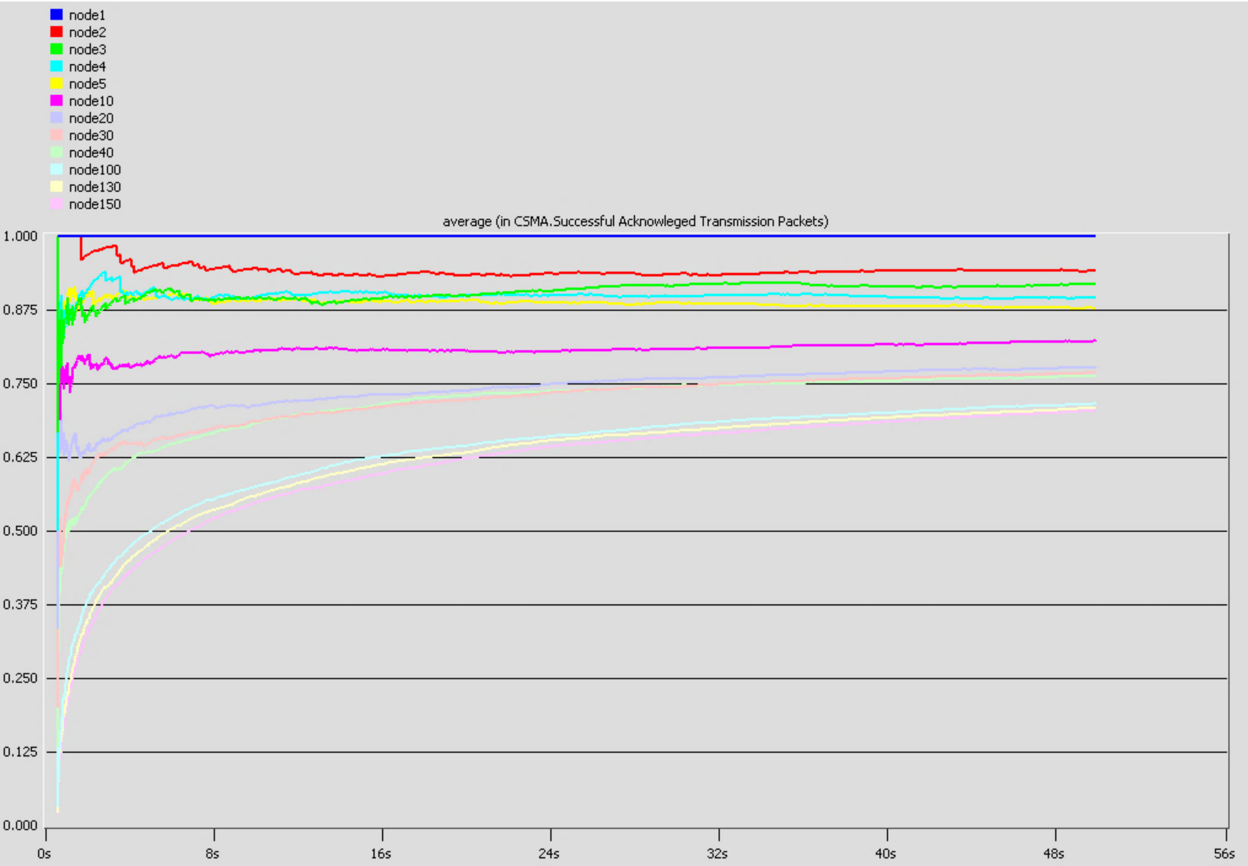

Figure 5: Average successful acknowledged transmission packets for different numbers of end nodes.

4.2 Impact of SO and BO

The objective of this part is to evaluate the impact of super-frame order and beacon order on the performance of slotted CSMA/CA. The results are collected based on different values of SO and BO. We consider a network with 20 end devices and each of them has a data arrival rate of 3.5kbps.

From fig. 6a, as we expected, low SO values produce lower network throughput. This is basically due to two reasons. First, the overhead of the beacon frame is more significant for lower SO values because beacons are more frequent. Second, in case of lower SO values, there are more collisions at the start of each super-frame. Furthermore, although the increase in the super-frame order from 0 until 4 has significant impact on the network throughput, the increase of SO from 5 to 14 has little impact on the network throughput. If *SO* equals to *4* as a threshold value, for SO values above the threshold, the probability of collisions is quite low. As a result, it leads to higher network throughputs but no further increases.

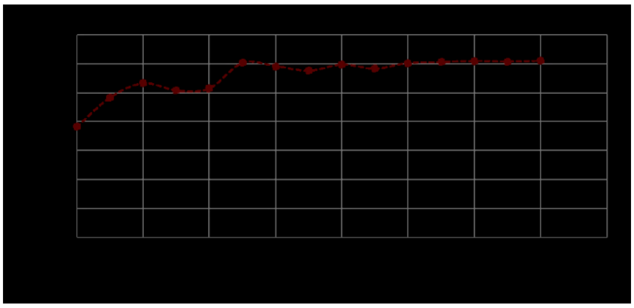

Figure 6a: Network output load as a function of different BO, SO values.

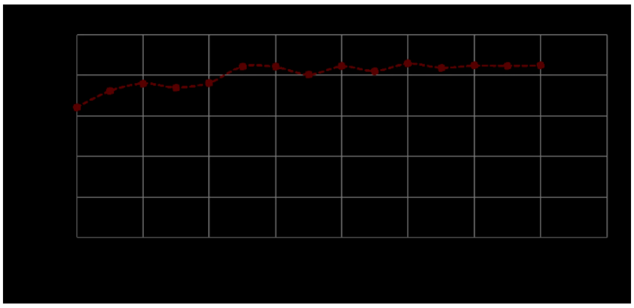

Figure 6b: The average delay as a function of different SO, BO values.

Figure 6b shows the average delay as a function of different SO, BO values. It is basically consistent with the network throughputs. There are more collisions in the beginning of a new super-frame due to the high probability of Clear Channel Assessment (CCA). Therefore, the back-off delays will not increase too much due to this frequent collision in case of low SO values. For high super-frame orders, the back-off algorithm will have less impact and the end-to-end delay will not be further increased.

4.3 Impact of packet size

This part studies the impact of packet size on the performance of slotted CSMA/CA. According to the IEEE802.15.4 standard specification, the size of the MAC header is 104 bits because only 16-bit short addresses are used for communication. The maximum allowed size of the overall frame is equal to 1016 bits. Thus, the MSDU size is limited to 912 bits. In order to generate the constant data arrival rate when varying the MSDU size, for each configuration, we vary the inter-arrival times as well. The following table shows the corresponding settings of MSDU sizes and intervals.

Table 2: MSDU size and interval settings

MSDU Size (bit)	MSDU Interval (s)	Data Arrival Rate (bps)
100	0.2	500
200	0.4	500
300	0.6	500
400	0.8	500
500	1	500
600	1.2	500
700	1.4	500
800	1.6	500
900	1.8	500

As shown in fig. 7, the network output loads increase when large MSDUs are generated. When the MSDU size is small, the impact of the MAC header on the network throughputs is significant. We can observe that there is only 21kbps network throughput when the MSDU size is 100 bits as compared to the 36kbps network throughput when the MSDU size is 900 bits. A great amount of the network bandwidth is wasted by carrying MAC headers. When the MSDU size becomes larger, we need less MAC headers to frame the generated data. Consequently, more bandwidth is used to carrying data and results in a higher network throughput.

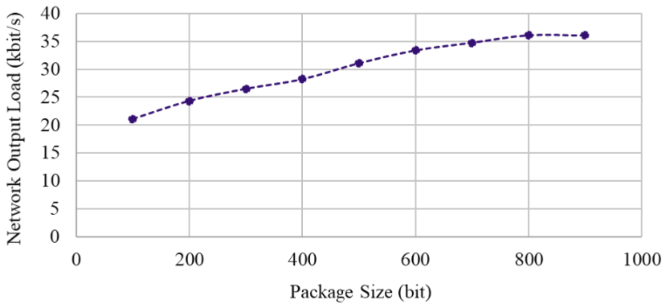

Figure 7: Network output load as a function of packet size.

4.4 Impact of maximum Back-off Number

This part investigates the impact of maximum back-off number on the performance of slotted CSMA/CA. Our preliminary studies show that the maximum back-off number has no impact on the network performance when the network load is light because the retransmission occurs very quickly. In order to study the impact on a heavy network, we consider a network with 30 end nodes and each node sends packets with a data arrival rate of 0.7kbps. As shown in fig. 8a, the delay is about 0.005s when no retransmission is allowed. Then it increases abruptly to reach 0.03s when five retransmissions are allowed. Therefore, we can conclude that the node has to wait for a longer time before attempting to retransmit in case of heavy traffic load.

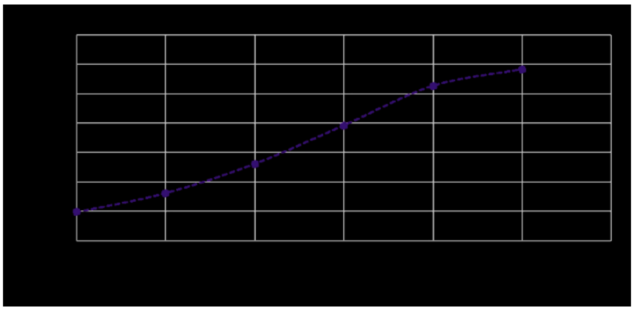

Figure 8a: Simulation values of delay as a function of maximum back-off number

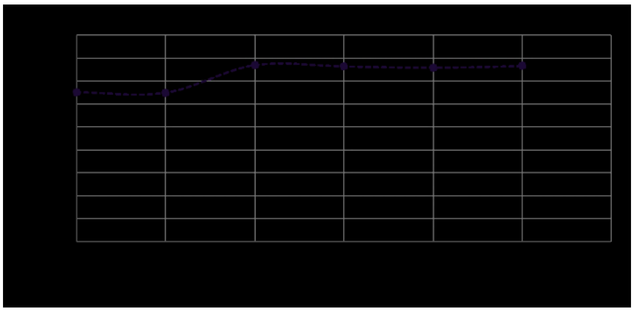

Figure 8b: Simulation values of Network Output Load as a function of maximum back-off number

Figure 8b shows the impact on the network output load when increasing the maximum back-off number. We can observe that if the maximum back-off number becomes larger (bigger than 1) the network output load reaches a higher level. When we use a small back-off value, such as 0 or 1, all the nodes which sense a collision will try to retransmit after a short interval. Consequently, the collision probability is high and the packets may be dropped. When a high back-off value is used, the retransmission interval becomes longer and as a result, the total number of successful transmissions increases.

5 CONCLUSIONS

In this paper we have evaluated the performance of the slotted CSMA/CA mechanism deployed by the IEEE802.15.4 protocol in beacon-enabled mode. We built a simulation environment to evaluate the impact of the following parameters on the performance of slotted CSMA/CA: *(i)* the network load, *(ii)* the beacon order and the super-frame order, *(iii)* the packet size, and *(iv)* the maximum back-off number. The simulation results show that that high super-frame orders provide better network throughput than lower super-frame orders. On the other hand, low SO values result in lower average delays. The MAC overheads on small MSDUs are more significant than the overheads on large MSDUs. The back-off mechanism results in longer delays when the network traffic is heavy. The actual data transmission rate of the IEEE802.15.4 protocol cannot reach the theoretical value of 250kbps due to the finite buffer size and traffic collisions.

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ĐÁNH GIÁ HIỆU SUẤT VẬN CHUYỂN DỮ LIỆU QUA MẠNG CẢM BIẾN ZIGBEE VỚI MẬT ĐỘ NODE KHÁC NHAU- NGHIÊN CỨU TRÊN MÔ PHỎNG OPNET

Tóm tắt. Trong bài báo này, chúng tôi phân tích hiệu suất của mạng cảm biến không dây có số lượng node khác nhau hoạt động theo tiêu chuẩn IEEE802.15.4 với chế độ beacon. Nguyên nhân đánh giá theo chế độ beacon là do tính linh hoạt đối với nhiều ứng dụng trong mạng cảm biến không dây (WSN) so với chế độ non-beacon. Phân tích dựa trên mô hình chính xác trong mô phỏng OPNET hỗ trợ cơ chế đa truy cập tránh xung đột (CSMA/CA) và khe thời gian được đảm bảo (GTS). Hiệu suất của mạng cảm biến CSMA/CA theo khe thời gian được đánh giá và phân tích thông qua việc cài đặt các thông số mạng khác nhau để hiểu tác động của các thuộc tính giao thức, bao gồm thứ tự siêu khung (SO), thứ tự beason (BO), kích thước gói dữ liệu và số lượng backoff tối đa. Thông qua kết quả mô phỏng, thông số SO lớn cung cấp thông lượng mạng tốt hơn, ngược lại dẫn đến độ phản hồi trung bình thấp hơn. Chúng tôi cũng nhận thấy rằng overhead trên MAC Service Data Unit (MSDU) nhỏ có ý nghĩa quan trọng hơn so với trên MSDU lớn. Và cơ chế backoff dẫn đến sự chậm trễ lâu hơn khi lưu lượng mạng tăng cao.

Từ khóa. Mạng cảm biến không dây, mạng ZigBee, hiệu suất mạng.

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