

On Transmission Efficiency of the Multimedia Service over IEEE 802.15.4 Wireless Sensor Networks

Mu-Sheng Lin ^a, Jenq-Shiou Leu ^a, Wen-Chi Yu ^{a,b}, Min-Chieh Yu ^a, Jean-Lien C. Wu ^c

^a Department of Electronic Engineering, NTUST(National Taiwan University of Science and Technology), Taiwan, R.O.C.

^b Department of Computer Science and Communication Engineering, Army Academy, Taiwan, R.O.C.

^c Department of Computer and Communication Engineering, St. John's University, Taiwan, R.O.C.

amoos.lin@gmail.com, jsleu@mail.ntust.edu.tw, yuwenchi.tw@gmail.com, M9802114@mail.ntust.edu.tw, jcw@mail.ntust.edu.tw

Abstract—Multimedia services over resource constrained Wireless Sensor Networks (WSNs) face a performance bottleneck issue from the gateway node to the sink node. Therefore, the queue management at the gateway node is crucial for diversified messages conveyed from the front nodes to the sink node. In this study, we focus on the performance improvement upon different traffic loads over WSNs. A dynamic adaptation scheme based on adjusting Beacon Interval (BI) and Superframe Duration (SD) in the IEEE 802.15.4 MAC superframe accompanied with RED (Random Early Detection) queue management scheme is proposed to increase the transmission efficiency of multimedia over WSNs. Evaluation metrics include end-to-end delay, packet delivery ratio and energy consumption in IEEE 802.15.4 beacon enabled and non-beacon enabled mode. Simulation results show that RED scheme accompanied with an appropriate setting of BO, SO value can effectively decrease end-to-end delay and energy consumption compared to the DropTail (FIFO) scheme.

Keywords—Wireless sensor networks (WSNs), IEEE 802.15.4, DropTail (FIFO), random early detection (RED), beacon-enabled, non-beacon enabled

I. INTRODUCTION

IEEE 802.15.4 standard [1] defines the protocol and interconnection of devices via radio communication in a wireless personal area network (WPAN). The standard uses CSMA/CA medium access mechanism and supports star as well as peer-to-peer topologies. It provides applications such as home entertainment and control, security alarms, industrial monitoring and control, personal mobile healthcare and tele-assist, etc. Two types of device called the Full Function Device (FFD) and the Reduced Function Device (RFD) are used in a LR-WPAN network. FFD is a fully functional device which can be a PAN coordinator, a coordinator, or just a device. RFD is a device with reduced functionality which can only function as an end device. It can't communicate with any other device in addition to coordinator. We talk about the PAN-coordinator, which acts as a coordinator for the entire WPAN. It is authorized to provide synchronization services in an established network.

There are many popular queuing and scheduling mechanisms are implemented in NS-2 such as DropTail,

Random Early Detection (RED), priority and fair queuing to provide the facility to simulate the network operation. S. Patel et. al. proposed comparison between two queuing management system Random Early Detection (RED) and Drop tail for avoiding the congestion in high speed packet switched networks [3]. G. Epiphaniou focuses on three different mechanisms, DropTail (FIFO), RED and DiffServ, and their effects on real-time voice traffic [4]. N. T. Le et. al. evaluate the performance of their analytical on M/M/1 queuing model for IEEE 802.15.4 non-beacon-enabled mode at the 2.4GHz in NS-2 network simulator [5]. J. Mistic and V.B. Mistic analyze the performance of a personal area network operating under the IEEE Standard 802.15.4 in the beacon enabled mode, and derive the probability distribution of packet access delay and calculate the throughput [6]. C. Buratti proposed a mathematical model for the beacon-enabled mode of IEEE 802.15.4 [7]. B. Gao and C. He proposed an individual beacon order adaptation (IBOA) algorithm for IEEE 802.15.4 networks, which can individually adapt the beacon interval and duty cycle of each node at the same time to the node's individual performance requirements [8]. J. Jeon et. al. proposed a new duty-cycle adaptation algorithm for IEEE 802.15.4 beacon-enabled networks. They modify the reserved frame control field in the MAC layer header to deliver the end device's buffer occupancy and queuing delay [9]. Despite many researches study about the applications of 802.15.4 on industrial and MAC protocol, but little attention in the past has been given to how different queuing mechanisms, such as DropTail (FIFO) and RED (Random Early Detection), perform in terms of different settings of Beacon Order (BO), Superframe Order (SO) parameters on the Multimedia Service over IEEE 802.15.4 Wireless Sensor Networks.

In this study, we focus on the performance improvement upon different traffic loads over WSNs. Figure 1 shows a typical multimedia application over WSNs that a front sensor node equipped with a camera sends an emergent message containing the surveillance image to the sink node once it detects an urgent or intrusive event. Different traffic types demand different packet delivery ratio and end-to-end delay. Urgent messages always have a first priority with a minimum

end-to-end delay. On the other hand, keep-alive messages carrying small periodic data have a comparatively low priority which can tolerate a longer delay. Hence, a dynamic adaptation scheme based on adjusting Beacon Interval (BI) and Superframe Duration (SD) in the IEEE 802.15.4 MAC superframe is proposed to increase the transmission efficiency of multimedia over WSNs.

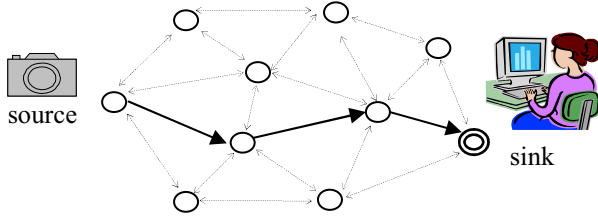


Figure 1. Multimedia service over IEEE 802.15.4 wireless sensor networks

A comprehensive simulation for the proposed scheme by using the NS-2 network simulator is also presented in this study. Evaluation metrics include end-to-end delay, packet delivery ratio and energy consumption using the beacon enabled and non-beacon enabled mode in IEEE 802.15.4 WSNs. Distinct network topologies like star, tree and chain architectures comprising one coordinator and some stationary nodes are considered in the simulation. Simulation results show that a suitable queuing management scheme accompanied with an appropriate setting of BO, SO can effectively achieve a better performance. If the BO value is fixed, a smaller SO value would incur a higher end-to-end delay and a lower packet delivery ratio. If the BO value is equal to the SO value, a larger BO can achieve a higher packet delivery ratio and a lower average end-to-end delay. Besides, the RED queue management scheme can decrease end-to-end delay compared to the DropTail scheme.

The remainder of the paper is structured as follows: in section II we introduce IEEE 802.15.4 MAC superframe structure and the concepts of Random Early Detection. In section III we introduce the network configuration and assumptions of our simulations. In section IV we present the results of our experimental simulations. Finally, in section V we present our main conclusions and suggest a number of areas for further work.

II. IEEE 802.15.4 MAC SUPERFRAME STRUCTURE AND RANDOM EARLY DETECTION

A. IEEE 802.15.4 MAC Superframe Structure

IEEE 802.15.4 MAC protocol supports the beacon enabled and non-beacon enabled modes. In beacon enabled mode, the access to the channel is managed through a superframe, starting with the beacon packet transmitted by the PAN coordinator. The superframe is subdivided into a contention access period (CAP), contention-free period (CFP) and an inactive part. Nodes in CAP use a slotted CSMA/CA to contention for channel and CAP containing a number of GTSSs that can be allocated by the PAN coordinator to specific nodes. In the non-beacon enabled mode, there are no regular beacons, but the coordinator may unicast beacons to a soliciting device.

Communication among devices in the non-beacon-enabled mode uses unslotted CSMA/CA for decentralized access. This paper considers CAP and inactive period only when the beacon-enabled mode is used. Figure 2 shows the IEEE 802.15.4 MAC superframe structure.

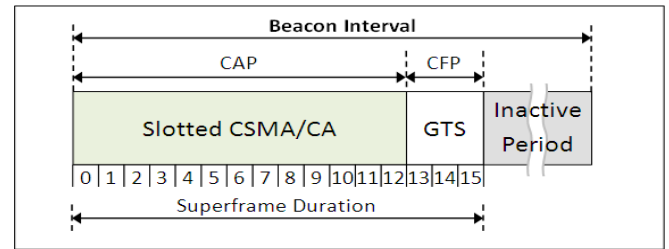


Figure 2. IEEE 802.15.4 MAC superframe structure [12]

The structure of this superframe is described by the values of macBeaconOrder (BO) and macSuperframeOrder (SO). The MAC PIB attribute macBeaconOrder, describes the interval at which the coordinator shall transmit its beacon frames. The superframe order is the variable which is used to determine the length of the superframe duration (SD) which is divided into 16 time slots. Similarly the Beacon Interval (BI) is determined by the variable BO.

Since the time of the superframe duration can not exceed the time of a beacon interval, the condition for both parameters is $0 \leq SO \leq BO \leq 14$. When BO is greater than SO, indicates there is an inactive portion present in the superframe. Also for $SO = BO$, the beacon interval is same as the superframe duration indicating there is no inactive portion.

The value of macBeaconOrder, BO, and the beacon interval, BI, are related as follows:

$$BI = aBaseSuperframeDuration \times 2^{BO}$$

$$SD = aBaseSuperframeDuration \times 2^{SO}$$

- $aBaseSuperframeDuration = 960$ symbols = 15.36 ms, each time slot has a duration of $15.36 / 16 = 0.96$ ms.
- Nonbeacon-enabled mode: $BO=SO=15$. If $BO = 15$, the coordinator will not transmit beacon frames except when requested to do so, such as on receipt of a beacon request command. The value of macSuperframeOrder shall be ignored if $BO = 15$.

Table 1 shows part of NS2 trace file in the beacon enabled mode. Node 0 is the coordinator and node 1 is a full function device that sends constant bit rate (CBR) traffic to node 0. We set the values of BO, SO equal to 3 so the value of beacon interval is $15.36\text{ms} \times 2^3 = 122.88\text{ms}$. From Table 1, we can observe node 0 send BCN (beacon) every 122.88ms (1.775232000-1.652352000).

TABLE 1. PART OF NS2 TRACE FILE (BO=SO=3)

s	1.652352000	_0_	MAC	---	0	BCN	12	[0	ffffff	0	0]
s	1.775232000	_0_	MAC	---	0	BCN	12	[0	ffffff	0	0]
s	1.789120000	_1_	MAC	---	0	CM1	17	[0	0	1	0]
r	1.789856033	_0_	MAC	---	0	CM1	17	[0	0	1	0]
s	1.790272000	_0_	MAC	---	0	ACK	5	[0	1	0	0]
r	1.790624033	_1_	MAC	---	0	ACK	5	[0	1	0	0]
s	1.898112000	_0_	MAC	---	0	BCN	20	[0	ffffff	0	0]

In the tree topology, data transmission can from a device to the coordinator or from the coordinator to the device. Node 1 sends an association request (CM1) to node 0. After node 0 receives the request and sends back an ACK. Connection is established. Then node 1 sends a data request (CM4) and node 0 sends an ACK.

B. Random Early Detection

Random early detection (RED), also known as random early discard or random early drop, is an active queue management algorithm. The operation of RED queue management is shown in Figure 3.

1) When packets income, it calculates their current occupied Average Queue Length (Avr).

2) If the Avr is smaller than MinThreshold (MinThres), the packet will be kept and sent to the queue waiting for the transmission.

3) If the Avr is longer than MaxThreshold (MaxThres), all of packets will be dropped.

4) If the Avr is between MinThres and MaxThres, the drop probability of the packet will be a linear function of a number between 0 and MaxP (Max. probability).

$$P_b = (Avr - MinThres) / (MaxThres - MinThres)$$

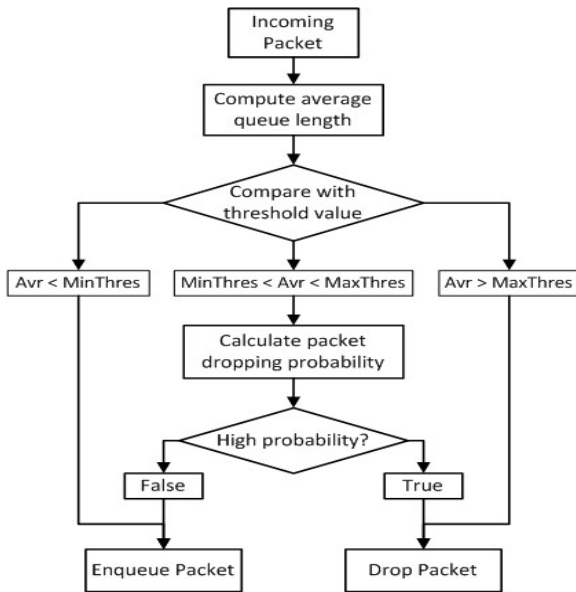


Figure 3. The operation of Random Early Detection [2]

RED's performance is highly dependent on the settings of its control parameters. We choose several control parameters offered by NS2, which includes Qlen, MaxP, MinThres, MaxThres and q_w that users may according the requirements to adjust RED's performance. However, the impact of the individual parameter on the queue's performance is dependent on the others too. The parameters setting in our simulations show as follows.

- Qlen: queue size, we set it to 50 packets.

- MaxThres: maximum threshold for queue, $MaxThres = queue_size / 2$. Here we set it to 25.
- MinThres: minimum threshold for queue, $MinThres = Max_thresh / 3$. We set it to 8.
- MaxP: maximum value for P_b , $MaxP = 2 * packet_loss_rate$. Here we set it to 0.1.
- q_w: queue weight, NS-2 default value is 0.002. Here we use the default value.

Despite RED algorithm is designed to accompany a transport-layer congestion control protocol such as TCP. We try to apply RED in IEEE 802.15.4 wireless sensor networks.

III. NETWORK CONFIGURATION AND ASSUMPTIONS

The solution performance evaluation is carried out under the NS2 simulator [11]. We use the ns2 module developed by Jianliang Zheng and Myung. J. Lee for IEEE 802.15.4 (NS-2.28) in our simulation [12]. In all simulation we have considered the following.

- The physical layer consists of IEEE 802.15.4 compliant radio transmitter (tx) and receiver (rx) that operate in the ISM band at 2.4GHz, with raw data rate 250kbps. The modulation technique is Quadrature Phase Shift Keying (QPSK).
- The MAC sub-layer implements the slotted/unslotted CSMA/CA.
- The application layer includes three CBR traffic sources with different data rate and one sink in this paper.
- Different scenarios may have different parameter values setting.
- Burst traffic is generated from the camera that capturing event photo and sending it to sink immediately. We dynamically adapt BO, SO value to investigate the performance.

Performance metrics measured in this paper are the following.

A. Average End-to-End Delay

Average end-to-end delay is one of the most important metrics to emergent events. In WSNs, the end-to-end delay is the total time delay to deliver a packet from source to sink node. It is the sum of delays at all links within the end-to-end path. The delay at an intermediate node usually includes the following components: processing delay, queuing delay, transmission delay, propagation delay and retransmission delay. We mainly consider the average end-to-end delay for all source traffic along a multi-hop path to sink node. By decreasing the packet retransmission, we can decrease the average end-to-end delay.

B. Packet Delivery Ratio

Packet loss may occur at any stage of a network transmission, mainly due to link failures, CSMA/CA channel access mechanism, RED problems. We use packet delivery ratio (PDR) to denote the performance.

$$PDR = \text{received packets} / \text{sent packets}$$

C. Energy Consumption

The coordinator consumes the energy when it transmits beacon and ACK packet, receives data packet, and listens the channel. Where rxPower is power consumption in receiving a packet, txPower is power consumption in transmitting a packet, sleepPower is power consumption in sleep state, and idlePower is power consumption in idle state. To measure the energy consumption in our scenarios, we use the energy model in NS-2. For accelerating the power consumption in our simulation, we modify the default values of the NS-2 default value [11]. We only measure the energy consumption on coordinator node in beacon-enabled/non-beacon-enabled mode.

IV. PERFORMANCE EVALUATION

There are three scenarios in this study. They are chain topology, tree topology and star topology. The simulation parameters are summarized in Table 2. Simulation duration is set to 60 seconds of which the first 5 seconds allow the nodes to associate with the PAN coordinator, and the remaining time is used for sending application traffic.

TABLE 2. SIMULATION PARAMETERS

simulation tool	NS-2
radio range	25m
data bit rate	250 Kbps
routing protocol	AODV
scale	50m x 50m
nodes	3, 4, 5 wireless static nodes
simulation time	60s
TX power	13.132 mW,
RX power	13.528 mW,
Idle power	712e-7 mW
Sleep power	144e-8 mW
node's initial energy	10J
packet size	50 bytes
traffic type	CBR

A. Chain Topology

Figure 4 illustrates the network topology with two FFD nodes (n1, n2) and one PAN coordinator (node 0). Each sensor node is set 20 meters away from the other nodes. Three constant bit rate traffic flows (Cbr1, Cbr2 and Cbr 3) enter node 1 and then send with the average data rate 2 packets/s along coordinator (node 0) to sink node (node 2). Each node's queue size sets to 50 packets.

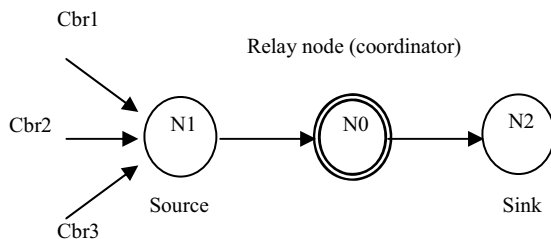


Figure 4. Chain topology

1) Impact of Different BO, SO for Traffic Loads (beacon-enabled mode)

For each configuration, we vary the inter-arrival time of the flows in source node to have different offered loads, assuming a constant packet size. With high offered loads, it causes higher packet loss due to the queue full. With low offered loads, it causes the increase in the average end-to-end delay.

Table 3 shows the PDR and average end-to-end delay (Avg. delay) using DropTail queue management scheme when SO value is fixed to 0. The PDR values are all zero when BO is greater than 5. Source node can't transmit data successfully due to long beacon interval and inactive period.

TABLE 3. PDR AND AVG. DELAY (DROPTAIL, 2 PKTS /s, SO=0)

BO	PDR (%)	Avg. delay (s)
0	100	0.051798
2	100	0.273113
3	100	0.773140
4	1.67	12.413684
5	0	N/A

We run the simulation for different values of SO (and BO = SO) as Table 4 shown. When BO equals to SO, less SO value will result in average end-to-end delay increased. When BO value is small, the probability of collision is increased. The bottom of Table 4 shows when BO is fixed, higher SO values have lower average end-to-end delay because of inactive period decreased. Sensor nodes don't change into sleep mode when BO equals to SO.

TABLE 4. IMPACT OF TRAFFIC LOADS (DROPTAIL)

BO	SO	50 pkts/s Avg. delay (s)	100 pkts/s Avg. delay (s)
0	0	1.424160	1.430937
1	1	0.764768	0.781810
2	2	0.612112	0.621294
3	3	0.539826	0.570217
4	4	0.526245	0.552005
5	5	0.536100	0.559807
6	6	0.535082	0.542379
7	7	0.551991	0.518774
3	0	8.071928	8.064701
3	1	5.832748	5.825045
3	2	1.691801	1.690489
3	3	0.539826	0.570217

2) Impact of Traffic Loads (non-beacon-enabled mode)

In this simulation, we send a CBR packet every 5 second for keep-alive traffic, the traffic with data rate 2 packets/s stands for normal traffic, and the traffic which sending 20 packets/s is defined as emergent multimedia traffic load. We set BO, SO value to 15 to evaluate the performance in the non-beacon-enabled mode. Simulation time is 60 seconds and queue size is 50 packets.

Table 5 shows that all metrics (packet delivery ratio, end-to-end delay and energy consumption) haven't any differences between DropTail and RED algorithm. Due to unslotted

CSMA/CA doesn't use beacon to coordinate devices. Node which acquires the channel can transmit data immediately, so the queue length always is empty. RED mechanism doesn't work in the non-beacon-enabled mode. The PDR value is only 39.27 % with 20 packets /s traffic load because of the energy of node 0 runs out at 26.808665200s.

TABLE 5. DROPTAIL VS. RED WITH DIFFERENT TRAFFIC LOADS

Traffic load (packets/s)	DropTail			RED		
	PDR (%)	Avg. delay (s)	Energy	PDR (%)	Avg. delay (s)	Energy
0.2	100	0.022207	9.712956	100	0.022207	9.712956
2	100	0.019916	7.442435	100	0.019916	7.442435
20	39.27	0.018763	0.005730	39.27	0.018763	0.005730

B. Tree Topology

In the second set of experiments, we study the affect of dynamic adaptation scheme. Figure 5 illustrates the network topology with four nodes defined using NS-2 (n0, n1, n2, n3). Each sensor node is set 20 meters away from the other nodes. We assume node 1, node 2 doesn't affect each other. Simulation parameters are all the same as Table 2.

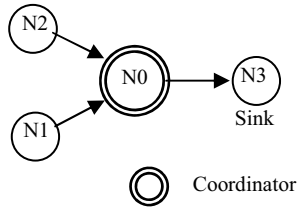


Figure 5. Tree topology

We run the simulation for different values of BO, SO where BO equals to SO from 0 to 9 with burst traffic. DropTail is the queue management scheme. Node 2 sends CBR traffic with 2 packets/s from 10s to 55s. Following node 1 sends burst traffic with 100 packets/s from 25s to 45s. All nodes are setting the same BO=SO=3 value in default simulation. Dynamic adaptation scheme changes vary BO, SO values when burst traffic load comes.

TABLE 6. PERFORMANCE OF DYNAMIC ADAPTATION SCHEME

BO=SO	Avg. delay (s)	PDR(%)	Residual Energy (node 0 lifetime)
0	0.431532	25.68	Runs out at 35.987584067s
1	0.256503	26.16	Runs out at 35.430432000s
2	0.426992	24.63	Runs out at 59.960032000s
3	0.313196	25.97	Runs out at 33.130784000s
4	0.615563	25.11	Runs out at 43.386624067s
5	0.467911	20.66	1.557760 J
6	0.299833	25.78	3.655319 J
7	0.841543	14.97	3.289051 J
8	4.010992	14.16	3.008140 J
9	0.287230	14.16	3.552419 J

Table 6 shows the comparison of default BO, SO value with dynamic adaptation scheme in the average end to end

delay, PDR and energy consumption metrics. The average end-to-end delay is 0.313196s and PDR is 0.2597 in default scheme. We observe that when setting BO=SO=6, PDR is similar with default scheme but average end-to-end delay can effectively decrease in dynamic adaptation scheme. When the simulation ends, coordinator node 0 still remain 3.655319J power in dynamic adaptation scheme. Conversely, residual energy of coordinator node 0 runs out at 33.130784000s in default scheme. Simulation result shows suitably chooses BO, SO value can get longer lifetime and less average end to end delay than default setting of BO, SO values.

C. Star Topology

For investigating the effect of our scheme in multihop environment, the modified star topology is used. We design three traffic flows along coordinator to sink node not only one hop to coordinator like standard. The topology of this scenario shows in Figure 6. Four full function devices (node 1 to 4) are placed symmetrically around the PAN coordinator (node 0) with an equal distance of 20 meters. The traffics generated by node 1, 2 and 3 send CBR traffics with 50 packets/s along coordinator (node 0) to sink node (node 4). Node 1 sends CBR traffic from 10s to 55s. Node 2 sends CBR traffic from 25s to 40s. Node 3 sends CBR traffic from 40s to 55s. The focus of the experiment is the head of the bottleneck link between n0, n4 and its buffer in particular. Node 0 is the intermediate gateway node with DropTail (FIFO) or RED queue implemented, with a buffer capacity of 50pkts and a queue fully monitored during the simulation.

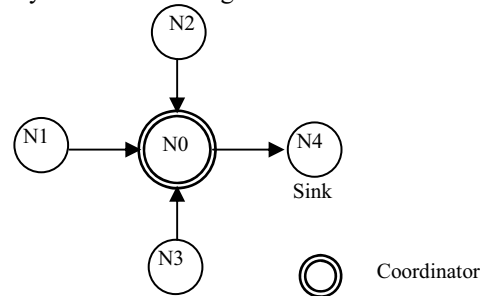


Figure 6. Star topology

1) Simulation Study in Queue Management scheme

A similar investigation has been conducted by changing the actual queue mechanism to RED for all nodes. RED operation is based on the principle that as the probability of a packet being dropped increases, the possibility of this packet being enqueued decreases. Figure 7 shows the RED scheme has lower queue length than Droptail. We observe queue length at the gateway node 0 which is closest to the sink node and measuring the end-to-end delay from source node to sink node. By measuring the queue length of coordinator node (n0), we can observe that queue occupy is not heavy. If the traffic load is getting heavier, the amount of packets stay in the queue will increase. RED can lessen the congestion by early detecting the queue status to drop packet to decrease the retransmission of arriving packets.

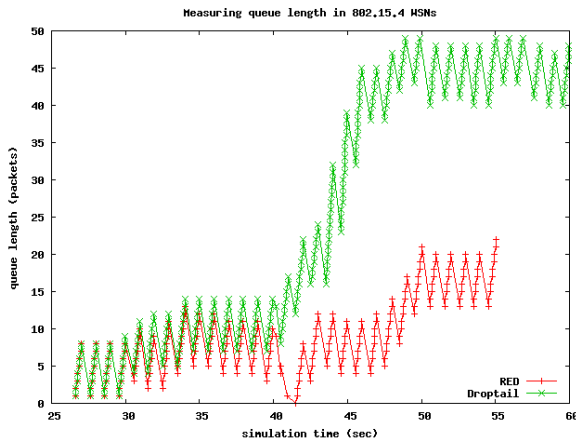


Figure 7. Queue length of coordinator node, traffic load 50 packets/s

2) Simulation Study in PDR, Average End-to-End Delay

Simulation results show that light traffic load with RED can get the same as DropTail in PDR and average end to end delay. When traffic load is getting heavier, despite the PDR is slightly lower than DropTail, but RED can get lower average end-to-end delay than DropTail. Table 7 shows the results.

TABLE 7. DROPTAIL VS. RED WITH DIFFERENT TRAFFIC LOADS

Traffic load	DropTail		RED	
	PDR (%)	Avg. delay (s)	PDR (%)	Avg. delay (s)
1	40	0.666688	40	0.666688
50	6.85	7.357023	6.59	3.115317
100	3.43	7.276406	3.29	3.027992

3) Simulation Study in Energy Consumption

Figure 8 shows the energy consumption with different queue management scheme.

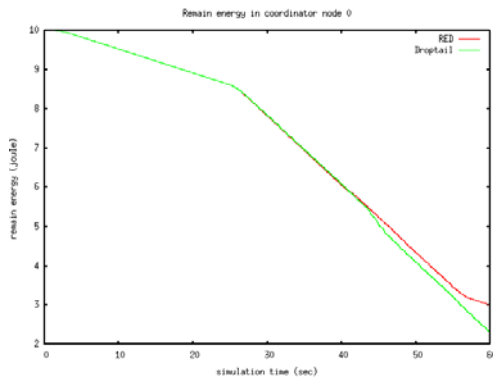


Figure 8. Comparing the energy consumption of RED with DropTail.

The traffic load is 100 packets/s, total simulation time is 60 seconds. When the traffic load is light (from 10s to 25s), the energy consumption of DropTail is the same as RED. Conversely, both two mechanisms consume energy rapidly when traffic load is getting heavier (from 25s to 40s). Then we can observe that residual energy of coordinator node 0 is higher than DropTail if using RED mechanism. This is because RED can lessen traffic congestion to decrease the

energy consumption. As simulation result shows, using RED can get better energy consumption than DropTail when traffic load is getting heavier.

V. CONCLUSIONS

In this paper a comprehensive performance evaluation of the IEEE 802.15.4 protocol in beacon-enabled and non-beacon-enabled mode is proposed. We evaluate the impact of the following parameters on the performance of slotted CSMA/CA: (1) the beacon order and the superframe order, (2) queuing management scheme such as RED and Droptail, (3) different traffic loads with dynamic adaptation scheme.

Simulation results show that RED queue management scheme accompanied with an appropriate setting of BO, SO can effectively achieve a better performance. Besides, the RED can decrease end-to-end delay and energy consumption compared to the DropTail (FIFO) scheme. Despite the vary kinds of experiments have done in this paper, how to correctly decide the RED parameters and BO, SO values according different kind of traffic loads is still an issue.

Future work we will observe mobile sink and sensor nodes as possible. How the nodes mobility model and velocity to affect the end-to-end delay, packet delivery ratio and better energy consumption in multimedia services over IEEE 802.15.4 wireless sensor networks is the direction of study.

REFERENCES

- [1] "PART 15.4: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low-Rate Wireless Personal Area Networks (LR-WPANs)," IEEE Std. P802.15.4a/D5, 2006.
- [2] Wikipedia, http://en.wikipedia.org/wiki/Random_early_detection.
- [3] S. Patel, P. Gupta and G. Singh, "Performance measure of Drop tail and RED algorithm", *International Conference on Electronic Computer Technology (ICECT)*, 2010, pp.35-38.
- [4] G. Epiphaniou, C. Maple, P. Sant and M. Reeve, "Affects of Queuing Mechanisms on RTP Traffic: Comparative Analysis of Jitter, End-to-End Delay and Packet Loss", *ARES '10 International Conference on Availability, Reliability, and Security*, 2010, pp.33-40.
- [5] N. T. Le, S. W. Choi and Y. M. Jang, "Approximate queuing analysis for IEEE 802.15.4 sensor network", *Second International Conference on Ubiquitous and Future Networks (ICUFN)*, 2010, pp.193-198.
- [6] J. Misic and V.B. Misic, "Access delay for nodes with finite buffers in IEEE 802.15.4 beacon enabled PAN with uplink transmissions", *Computer Communications (28) Journal*, pp.1152-1166, 2005.
- [7] C. Buratti, "Performance Analysis of IEEE 802.15.4 Beacon-Enabled Mode", *IEEE Trans. on Veh. Technol.*, vol.59, pp.2031-2045, May 2010.
- [8] Bo Gao, Chen He, "An individual beacon order adaptation algorithm for IEEE 802.15.4 networks," *Communication Systems, 2008. ICCS 2008. 11th IEEE Singapore International Conference on*, Nov. 2008, pp. 12-16.
- [9] J. Jeon, Jong Wook Lee, Jae Yeao Ha and Wook Hyun Kwon, "DCA: Duty-Cycle Adaptation Algorithm for IEEE 802.15.4 Beacon-Enabled Networks", *Vehicular Technology Conference, VTC2007-Spring*. IEEE 65th, pp.110-113.
- [10] A. Kouba, M. Alves and E. Tovar, "A Comprehensive Simulation Study of Slotted CSMA/CA for IEEE 802.15.4 Wireless Sensor Networks", in *Proc. of 6th IEEE International Workshop on Factory Communication Systems*, Jun, 2006.
- [11] "The Network Simulator - NS-2". <http://www.isi.edu/nsnam/ns/>.
- [12] J. Zheng and M. J. Lee, "Will IEEE 802.15.4 make ubiquitous networking a reality? A discussion on a potential low power, low bit rate standard," *IEEE Communication Magazine*, vol. 42, no. 6, pp.140-146, 2004.