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Abstract

IEEE 802.15.6 facilitates communication in the vicinity of or even inside a human body to serve heterogeneous medical, consumer electronics, and entertainment applications. This standard operates in beacon and non-beacon communication modes, and each mode employs different protocols, including CSMA/CA, for resource allocation on the channel. The CSMA/CA protocol presented in IEEE 802.15.6 allows quick and prioritized access to the channel by differentiating contention window bounds of nodes with different priorities. This paper provides a simple and accurate analytical model to estimate the throughput, energy consumption, and delay of this protocol for different priority classes, under the assumption of a finite number of nodes in saturated and lossy channel conditions. The accuracy of the proposed model is validated by simulations. The results obtained in this paper can be used to design standard priority parameters for medical and non-medical applications

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***Abstract*—IEEE 802.15.6 facilitates communication in the vicinity of or even inside a human body to serve heterogeneous medical, consumer electronics, and entertainment applications. This standard operates in beacon and non-beacon communication modes, and each mode employs different protocols, including CSMA/CA, for resource allocation on the channel. The CSMA/CA protocol presented in IEEE 802.15.6 allows quick and prioritized access to the channel by differentiating contention window bounds of nodes with different priorities. This paper provides a simple and accurate analytical model to estimate the throughput, energy consumption, and delay of this protocol for different priority classes, under the assumption of a finite number of nodes in saturated and lossy channel conditions. The accuracy of the proposed model is validated by simulations. The results obtained in this paper can be used to design standard priority parameters for medical and non-medical applications.**

***Index Terms*—IEEE 802.15.6, analytical, priority, CSMA/CA.**

I. Introduction

Research advances in miniaturized sensors, healthcare technologies, and wireless communications have allowed the realization of a standard model for ambulatory health monitoring. These advances have introduced the IEEE 802.15.6 standard for communication in the vicinity of or even inside a human body [1]. This standard can be used to serve a variety of medical and non-medical applications. For example, it may be used to effectively collect real-time patient information for diagnosis and treatment of many diseases, such as cardiovascular diseases, and may also assist in early detection of neurological disorders.

The IEEE 802.15.6 standard supports one-hop and two-hop star topologies. In a one-hop star topology, data exchange occurs directly between the hub (also called the coordinator) and the nodes. In a two-hop star topology, data exchange occurs indirectly, via a relay-capable node, between the hub and the nodes. The IEEE 802.15.6 supports two communication modes: 1) beacon communication mode, where the hub transmits beacons for resource allocation and synchronization, and 2) non-beacon communication mode, where scheduled allocations and polling are used. In the beacon communication mode, beacons are transmitted in the beginning of each superframe. The superframe is generally comprised of Exclusive Access Phases (EAP1 and EAP2), Random Access Phases (RAP1 and RAP2), a Managed Access Phase (MAP), and a Contention Access Phase (CAP), as shown in Fig. 1. The EAPs are used for life-critical traffic while the RAPs and CAP are used for regular traffic. Depending on the frequency band, the EAP, RAP and CAP periods may either employ a slotted-ALOHA or a Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) protocol. The MAP period employs polling for scheduled uplink, downlink, and bilink allocation intervals. It may also be used for unscheduled bilink allocation interval.

In this paper, we concentrate on the performance analysis of the IEEE 802.15.6 CSMA/CA protocol employed in the beacon communication mode. We present a simple and accurate analytical model that predicts throughput, energy consumption, and delay of this protocol for different priority classes. We assume a finite number of nodes in saturated and lossy channel conditions. The key approximation in our model is the assumption of independent busy channel and packet error probabilities. The performance analysis of the proposed model leads us to accurate results for different priority classes. These results can be used by the protocol designer to understand the tradeoff between different performance metrics that matter for quality of service.

The rest of the paper is organized as follows. Section II presents related work in this area. Section III presents a brief overview of the IEEE 802.15.6 CSMA/CA protocol. Sections IV and V present the analytical model and the performance results. The final section concludes our work.

II. Related Work

Numerous research efforts are dedicated to the study of the IEEE 802.15.6 standard. Most of these efforts focus on the throughput analysis of the IEEE 802.15.6 contention-based protocols, including CSMA/CA and slotted-ALOHA protocol. The authors of [2] present an analytical model for the analysis of the IEEE 802.15.6 CSMA/CA protocol under saturated traffic and noisy channel conditions. Using a three-dimensional markov chain, they conclude that the medium is always accessed by high priority nodes due to short duration of backoff periods. In another similar study, the authors analyze the effects of access phase lengths on the network performance [3]. They conclude that small and larger access phase lengths considerably affect the utilization of network resources. They also conclude that the IEEE 802.15.6 CSMA/CA protocol is unable to utilize the medium effectively under high traffic loads. The authors of [4] study the maximum theoretical throughput and minimum delay limits of the IEEE

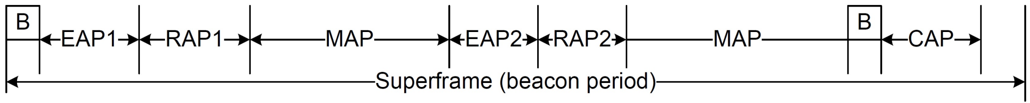


Fig. 1. Superframe structure in IEEE 802.15.6 beacon communication mode

802.15.6 CSMA/CA protocol for an ideal channel. This study can be used by protocol designers for packet optimization and determining theoretical bounds for different applications. In [5], an analytical model is presented for estimating the device lifetime for scheduled access modes. The saturation throughput of the IEEE 802.15.6 slotted-ALOHA protocol for heterogeneous network is studied in [6]-[7]. The authors of [8] also study the IEEE 802.15.6 slotted-ALOHA protocol and propose the use of different spreading code lengths. They conclude that spreading code lengths with contention probability greatly affect the network performance under different channel models. In [9], the authors improve the IEEE 802.15.6 slotted-ALOHA protocol by introducing a novel contention probability dynamism based on the queue length of the nodes. It is shown that the proposed dynamism outperforms the conventional IEEE 802.15.6 slotted-ALOHA protocol in terms of throughput, delay, and packet drop rate. The authors of [10] study the effects of different priority classes for different traffic. They conclude that, for high traffic scenarios, the performance of these priority classes is the same as that of a random backoff procedure. Conversely for low traffic scenarios, the use of priority classes shows high performance in terms of throughput and network lifetime. Other works such as [11]-[12] consider the IEEE 802.15.6 standard for energy harvesting body area networks.

III. Overview of IEEE 802.15.6 CSMA/CA Protocol

In this protocol, the node sets its Backoff Counter (BC) to a random integer uniformly distributed over the interval [1, CW] where $CW \in [CW_{min}, CW_{max}]$ is called the contention window, and it depends on the number of failed data transmissions. The values of CW_{min} and CW_{max} are selected according to the priority classes presented in Table I. These priority classes are assigned based on the type of data traffic, ranging from best-effort data traffic to the most critical emergency traffic. Initially, the CW is set to CW_{min} for each priority class and remains the same for each successful data transmission. The node decrements the BC by one for each idle CSMA/CA slot. Once the BC reaches zero, the data is transmitted. The node locks the BC because of the following reasons: 1) the channel is busy because of a frame transmission, 2) the current time is outside of EAP, RAP, or CAP phases, and 3) the current time left in the EAP, RAP, or CAP is not enough to complete the data transmission. The node unlocks the BC when the channel is sensed idle for Short InterFrame Space (pSIFS) duration or when the current time left in the EAP, RAP, or CAP is enough to complete the data transmission. If the contention fails, the node doubles the CW for even number of failures, and keeps it unchanged for odd number of failures. If doubling the CW exceeds the CW_{max}, the node sets the CW to CW_{max}. As illustrated in Fig. 2, the node selects a BC over $[1, CW]$ and decrements it. When the BC reaches zero, the node transmits the data, however, this transmission fails. The node retries in the following phase by selecting a new BC over previous $[1, CW]$, which fails again (the CW is unchanged for odd number of failures). Finally, the node doubles the CW and selects a BC over the new $[1, CW]$. Once the BC reaches zero, the data is transmitted. This transmission is successful and the CW is reset to CW_{min}.

TABLE I
CW bounds for IEEE 802.15.6 CSMA/CA

Traffic type	Priority class	CW_{min}	CW_{max}
Background	0	16	64
Best effort	1	16	32
Excellent effort	2	8	32
Video	3	8	16
Voice	4	4	16
Medical data	5	4	8
High-priority data	6	2	8
Emergency event report	7	1	4

IV. Proposed Analytical Model

We assume a finite number of contending nodes n_i in the priority class $i = \{0, 1, ...7\}$. Each n_i always has a packet available for transmission. Let b_i be the probability that the channel is sensed busy (in an ideal channel condition) for a priority class i, and let p_r be the packet error probability. Since b_i and p_r increment the backoff stage of a tagged node, we consider the union of these events, assuming that they are independent [13]. Let p_i represent both events, we have

$$p_i = b_i + (1 - b_i)p_r. \tag{1}$$

The expression for p_r can be obtained as

$$p_r = 1 - (1 - p_e)^{H+E(P)+ACK}, \tag{2}$$

where H and $E(P)$ represent the header and payload information, respectively, ACK represents the acknowledgement packet, and p_e is the bit error probability and is equal to the average value of Bit Error Rate (BER)[1]. Let H_P and H_{PH} be the Physical Layer Convergence Protocol (PLCP) preamble

[1]Calculating p_e requires a thorough investigation of physical layer parameters including noise and interference, multipath fading, attenuation, etc, and is out of scope of this paper. For simplicity, we assume that p_e is constant throughout our analysis. The results are presented for different BER values.

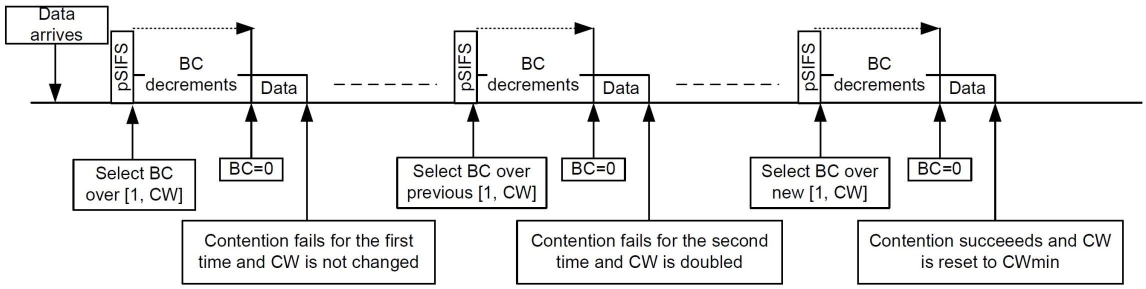


Fig. 2. IEEE 802.15.6 CSMA/CA protocol

and header, respectively, and let M_H be the MAC header (including MAC footer), we have

$$H = H_P + H_{PH} + M_H. \tag{3}$$

The expression for b_i can be obtained as [14]

$$b_i = 1 - (1-\tau_i)^{n_i - 1} \prod_{j=0, j\neq i}^{7} (1-\tau_j)^{n_j}, \tag{4}$$

where τ_i is the probability that a tagged node in the priority class i transmits a packet. Following [15] and the renewal reward theorem, the transmission probability τ_i can be derived as the average reward during the renewal cycle, and is given by

$$\tau_i = \frac{\overline{X_i}}{\overline{Y_i} + \overline{X_i}}, \tag{5}$$

where $\overline{X_i}$ is the average number of attempts by a tagged node in the priority class i and $\overline{Y_i}$ is the average backoff time experienced by the same node. The number of attempts X_i during Y_i can be modeled as a geometrical random variable [16]-[17], and its mean $\overline{X_i}$ is given by

$$\overline{X_i} = \sum_{x=0}^{m-1} p_i^x (1-p_i)(x+1) + p_i^m (m+1). \tag{6}$$

Similary, the backoff procedure of IEEE 802.15.6 CSMA/CA can be modeled as a geometrical random variable [16]-[18], where the CW is doubled for even number of failures only. For a minimum $CW = W_{i,0}$ in the priority class i and maximum backoff stage m, the average backoff time $\overline{Y_i}$ can be obtained as

$$\begin{aligned} \overline{Y_i} = &\sum_{x=0}^{m-1} p_i^x (1-p_i) \sum_{j=0}^{x} \frac{2^{\lfloor \frac{j}{2} \rfloor} W_{i,0} - 1}{2} \\ &+ p_i^m \sum_{j=0}^{m} \frac{2^{\lfloor \frac{j}{2} \rfloor} W_{i,0} - 1}{2}, \end{aligned} \tag{7}$$

where the first term in (7) indicates that the packet is successfully transmitted, while the second term indicates that packet is dropped after maximum attempts. The term $(2^{\lfloor \frac{j}{2} \rfloor} W_{i,0} - 1)/2$ represents the average CW of a node in the priority class i. It is worth noting that our p_i is different from the conditional collision probability used in the backoff expressions in [16]-[17]. We assume that the backoff is triggered by collision and error on the channel. By substituting (6) and (7) in (5), the unique value of τ_i can be obtained. Once τ_i is known, we can derive the value of p_i from (1).

Let p_I be the probability that the channel is idle in a slot time, and let s_i be the probability that exactly one node in the priority class i transmits on the channel. We have

$$p_I = \prod_{i=0}^{7} (1-\tau_i)^{n_i} \tag{8}$$

and

$$s_i = n_i \tau_i (1-\tau_i)^{n_i - 1} \prod_{j=0, j\neq i}^{7} (1-\tau_j)^{n_j}. \tag{9}$$

A. Throughput

Following [19] and [20], the normalized throughput T_i for the priority class i is given by the fraction of the payload transmission time to the total length of the slot time. Since our throughput model considers a lossy channel condition, the effects of p_r on the throughput must be considered. Let σ represent the backoff slot time. Let T_s be the average time that the channel is busy because of a successful transmission, T_c be the average time that the channel is busy because of a collision, and T_e be the average time that the channel is busy because of error on the channel. We have

$$T_i = \frac{s_i E(P)(1-p_r)}{p_I \sigma + p_s(1-p_r)T_s + p_s p_r T_e + (1-p_I-p_s)T_c}, \tag{10}$$

where $p_s = \sum_{i=0}^{7} s_i$ is the probability of a successful transmission in a slot time. The valules of T_s, T_c, and T_e can be obtained as (all values are expressed with the same unit)

$$T_s = H + E(P) + 2pSIFS + ACK + 2\pi \tag{11}$$

and

$$T_c = T_e = H + E(P) + pSIFS + \pi, \tag{12}$$

where π is the propagation time.

B. Energy Consumption

The average energy consumption of a tagged node depends on how long it stays in the backoff, channel sensing, and transmission, collision, and error stages. For the priority class i, let $E[B_i]$ and $E[CCA_i]$ be the average energy consumed by a tagged node due to backoff and Clear Channel Assessment (CCA) procedures, respectively, and $E[S_i]$ be the average energy consumed by a tagged node to a successful transmission. Moreover, let $E[C_i]$ be the average energy consumed by a tagged node to listen the ongoing transmission initiated by other nodes in the priority class i, and $E[R_i]$ be the average energy consumed due to error on the channel. The total energy consumption for the priority class i is given by

$$\overline{E_i} = E[B_i] + E[CCA_i] + E[S_i] + E[C_i] + E[R_i]. \quad (13)$$

Let P_{TX}, P_{RX}, and P_{IDLE} be the power consumed in transmit, receive, and idle states, respectively. We have

$$E[B_i] = P_{IDLE}(\overline{Y_i}\sigma) \quad (14)$$

and

$$E[CCA_i] = P_{RX}(\Phi\overline{X_i}), \quad (15)$$

where Φ is the CCA slot time and $\overline{X_i}$ is the average number of CCAs or attempts on the channel. Stated otherwise, whenever a node has a packet to send, it performs CCA (after backoff) before sending this packet, and therefore the average number of attempts is equivalent to the average number of CCAs on the channel.

The value of $E[S_i]$ can be obtained as

$$\begin{aligned} E[S_i] = (1-p_i^{m+1})[&P_{TX}(T_H + T_{E(P)}) \\ &+ P_{RX}(2pSIFS + T_{ACK})], \end{aligned} \quad (16)$$

where T_H, $T_{E(P)}$, and T_{ACK} represent the packet header, payload, and acknowledgement transmission time, and $(1-p_i^{m+1})$ represents the successful tranmission of a packet after $m+1$ attempts [18]. The value of T_H can be obtained as

$$T_H = T_{H_P} + T_{H_{PH}} + T_{M_H}. \quad (17)$$

Let $\overline{F_i}$ be the average time that the tagged node locks the BC. As discussed above, the BC is locked due to three reasons, however in this analysis, we consider that the BC is locked due to a busy channel only. Following [21], the average number of busy slots is given by

$$\overline{F_i} = \frac{\overline{Y_i}}{1-b_i} b_i. \quad (18)$$

In order to calculate $E[C_i]$, we need to understand that the ongoing transmission listened by the tagged node may either be successful or else may result in a collsion. Since both cases consume energy of the tagged node, they are considered in our analysis [18]. The value of $E[C_i]$ can be obtained as

TABLE II
IEEE 802.15.6 PARAMETERS (2360 MHz TO 2400 MHz)

H_P	90 bits	R_S	600ksps
H_{PH}	31 bits	R_H	91.9 kbps
M_H	56 bits + 16 bits	π	$1\mu s$
T_{H_P}	H_P/R_S	$T_{H_{PH}}$	H_{PH}/R_H
T_{M_H}	M_H/R_D	$T_{E(P)}$	$E(P)/R_D$
pSIFS	$75\mu s$	$E(P)$	1920 bits
Φ	$63/R_S$	σ	$\Phi + 40\mu s$
ACK	193 bits	P_{IDLE}	$5\mu W$
P_{TX}	$27mW$	P_{RX}	$1.8mW$
R_D	485.7kbps	R_D	485.7kbps

$$E[C_i] = P_{RX}\left[\frac{p_s(1-p_r)}{1-p_I}T_s + (1 - \frac{p_s(1-p_r)}{1-p_I})T_c\right]\overline{F_i}, \quad (19)$$

where $\frac{p_s(1-p_r)}{1-p_I}$ and $(1 - \frac{p_s(1-p_r)}{1-p_I})$ represent that the tagged node listens a successful transmission and a collision, respectively. The term $1 - p_I$ represents that there is at least one transmission in a slot time.

Finally, the value of $E[R_i]$ can be obtained as

$$E[R_i] = P_{RX}\frac{p_s p_r}{1-p_I}T_e. \quad (20)$$

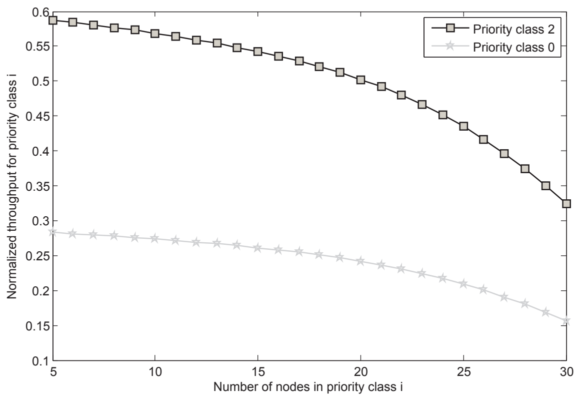
C. Delay

The average delay in saturated and lossy channel conditions includes the backoff delay, the delay when the BC is locked due to a busy channel, and the total transmission delay. We follow a similar approach used in [21] to caculate the average delay $\overline{D_i}$ for the priority class i,

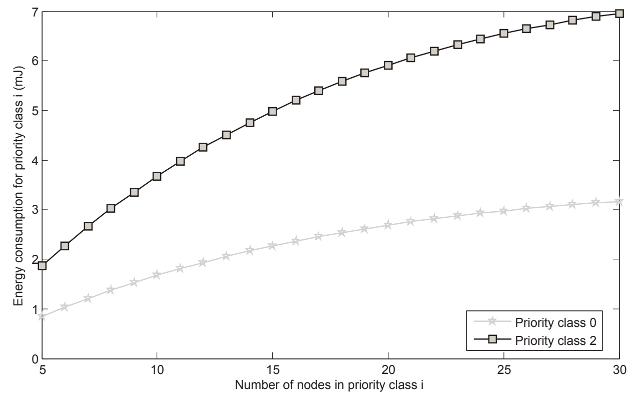
$$\overline{D_i} = \overline{Y_i}\sigma + \left[\frac{p_s(1-p_r)}{1-p_I}T_s + (1 - \frac{p_s(1-p_r)}{1-p_I})T_c\right]\overline{F_i} + T_s. \quad (21)$$

V. PERFORMANCE RESULTS

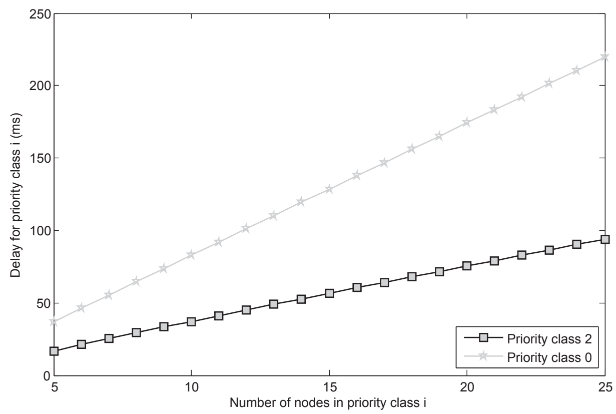
We study the proposed analytical model in terms of throughput, energy consumption, and delay using a discrete event simulator. For simplicity, we consider two priority classes (class 0 and class 2) only. However, the proposed model can easily be extended to other priority levels. Each priority class has equal number of nodes. These nodes are connected to the hub in a single-hop star topology, where each node always has a packet to send to the hub. The results are obtained for a lossy channel with different BER values (BER = 10^{-6} and BER = 10^{-4}). All other parameters used in our analysis are summarized in Table II. These parameters are specified for the narrowband physical layer (2360 MHz to 2400 MHz). According to this physical layer, the H_P and H_{PH} are transmitted at symbol (R_S) and header (R_H) rates, respectively, and the remaining packet is transmitted at the information data rate (R_D). Since the values of Φ and σ are different for each physical layer, they are calculated for the considered physical layer using the parameters given in Table II.



(a) Normalized throughput



(b) Energy consumption



(c) Delay

Fig. 3. Performance results in saturated and lossy chnnel conditions with BER=10^{-6}

Fig. 3 shows the normalized throughput, energy consumption, and delay in saturated and lossy channel conditions with BER=10^{-6}. Fig. 3 (a) shows the normalized throughput for the equal number of nodes in each priority class. Generally in saturated traffic conditions, the throughput degrades as a function of number of nodes in the network due to heavy collisions. As can be seen, high priority nodes (in class 2) utilize the channel effectively due to small CW. This eventually prevents low priority nodes (in class 0) to get access to the channel, thus affecting their throughput performance. A similar trend can be observed in the energy consumption of the high and low priority nodes as shown in Fig. 3(b). In general, the energy trend is exponential with the number of nodes. However, the energy consumption of low priority nodes is low since they stay in backoff or idle stage most of the time. For fifteen nodes, the highest normalized throughput for priority class 2 and class 0 is 0.54 and 0.26, respectively, while the energy consumed to achieve this throughput is 4.9mJ and 2.2mJ. It is worth noting that the larger CW increases the average waiting time of a packet to be served. This is further justified by the trend in Fig. 3(c). Since high priority nodes have small CWs, they dont have to wait longer and therefore get quick access to the channel. Fig. 4 shows the effects of BER on the network performance for priority class 2. As can be observed, error on the channel considerably affect the normalized throughput and energy consumption. For fifteen nodes, the normalized throughput for BER=10^{-6} and BER=10^{-4} is 0.54 and 0.18, respectively; the difference between the two values is more than a half. However, the energy consumption for BER=10^{-4} is slightly more than that of BER=10^{-6} as shown in Fig. 3(b) and Fig. 4. This kind of energy trend depends strongly on the BER values and the number of retransmission caused by error on the channel.

VI. Conclusion

In this paper, we presented a simple and accurate analytical model to compute the normalized throughput, energy consumption, and delay of the IEEE 802.15.6 CSMA/CA protocol. Our model assumed saturated and lossy channel conditions. By analyzing two priority classes (class 0 and class 2), we concluded that the performance largely depends on few parameters, such as CW, number of nodes in priority class

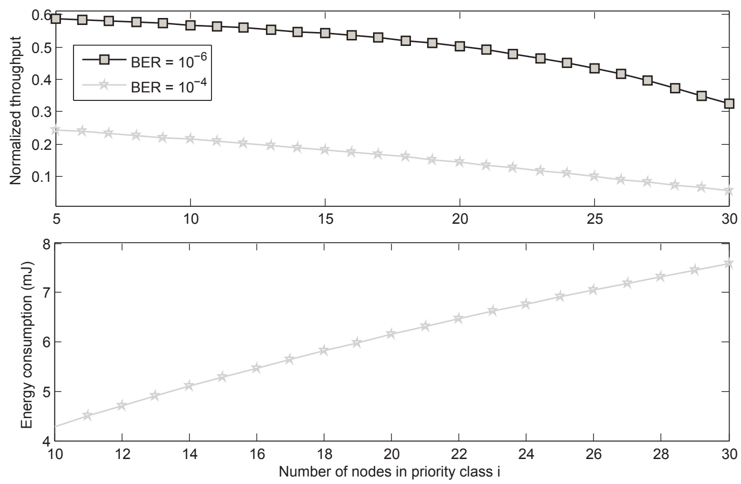


Fig. 4. Normalized throughput and energy consumption for priority class 2 with BER=10^{-6} and BER=10^{-4}

i, and BER values. We also noticed that high priority nodes achieved higher throughput, higher energy consumption, and lower delay due to small CW. We believe that this analysis would assist protocol designers in designing standard priority parameters while maintaining the desired quality of service.

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References

[1] IEEE SA - 802.15.6 - *IEEE Standard for Local and metropolitan area networks - Part 15.6: Wireless Body Area Networks*, 2012.
[2] S. Rashwand, J.V. Misic, H. Khazaei, IEEE 802.15.6 under saturation: Some problems to be expected, *Journal of Communications and Networks*, vol.13, no.2, pp.142-148, 2011.
[3] S. Rashwand, J.V. Misic, Misic, Effects of access phases lengths on performance of IEEE 802.15.6 CSMA/CA, *Computer Networks*, vol.56, no.12, pp. 2832-2846, 2012.
[4] S. Ullah, M. Chen, K.S. Kwak, Throughput and Delay Analysis of IEEE 802.15.6-based CSMA/CA Protocol, *Journal of Medical Systems*, vo.36, no.6, pp. 3875-3891, 2012.
[5] C. Tachtatzis, F.D. Franco, D.C. Tracey, N.F. Timmons, J. Morrison, An Energy Analysis of IEEE 802.15.6 Scheduled Access Modes for Medical Applications, *LNCS Ad-hoc Networks*, vol. 89, pp. 209-222, 2012.
[6] M.S. Chowdhury, K. Ashrafuzzaman, K.S. Kwak, Modelling IEEE 802.15.6 slotted Aloha in heterogeneous condition, *IET Electronics Letters*, vol.50, no.5, pp.415,416, 2014.
[7] M.S. Chowdhury, K. Ashrafuzzaman, K.S. Kwak, Saturation Throughput Analysis of IEEE 802.15.6 Slotted Aloha in Heterogeneous Conditions, *IEEE Wireless Communications Letters*, vol.3, no.3, pp.257-260, 2014.
[8] M. Fatehy, R. Kohno, Variable Spread Slotted Aloha Simulation Analysis over IEEE 802.15.6 Using IR-UWB for Wireless Body Area Networks,*European Modelling Symposium (EMS)*, pp.572,577, 2013.
[9] M. Fatehy, R. Kohno, A novel contention probability dynamism for IEEE 802.15.6 standard, *EURASIP Journal on Wireless Communications and Networking*, vol. 92, 2014.
[10] L.Z. Kahsay, T. Paso, J. Iinatti, Evaluation of IEEE 802.15.6 MAC user priorities with UWB PHY for medical applications, *ISMICT*, pp.18-22, 2013.
[11] E.Kartsakli, A. Antonopoulos, L.Alonso and C.Verikoukis, A Cloud-assisted Random Linear Network Coding Medium Access Control Protocol for Healthcare Applications, *Sensors*, vol.14, no.3, pp.4806-4830, 2014.
[12] E.Ibarra, E.Kartsakli, A.Antonopoulos, J. Rodrigues and C.Verikoukis, Joint Power-QoS Control Scheme for Energy Harvesting Body Sensor Nodes, *IEEE ICC*, 2014.
[13] X.J. Dong, P. Varaiya, Saturation throughput analysis of IEEE 802.11 wireless LANs for a lossy channel, IEEE Communications Letters, vol.9, no.2, pp. 100,102, 2005.
[14] B. Li and R. Battiti, Performance analysis of an enhanced IEEE 802.11 distributed coordination function supporting service differentiation. Quality for all, pp. 152161, 2003.
[15] K. Liu, X. Ling, Y. Cheng, X. Shen, and J. Mark. A novel performance model for distributed prioritized MAC protocols, *IEEE GLOBECOM*, 2007.
[16] L.X. Cai, K.H. Liu, H. Rutagemwa, X.S. Shen, and J.W. Mark, Performance Analysis of Hybrid Medium Access Protocol in IEEE 802.15.3 WPAN, *IEEE CCNC*, pp. 445449, 2007.
[17] L.X. Cai, X.S. Shen, J.W. Mark, L. Cai, Y. Xiao,Voice capacity analysis of WLAN with unbalanced traffic, *IEEE Transactions on Vehicular Technology*, vol.55, no.3, pp.752,761, 2006.
[18] A. Maskooki, C. Soh, E. Gunawan, K .Low, Adaptive Routing for Dynamic On-Body Wireless Sensor Networks, IEEE Journal of Biomedical and Health Informatics, published online, 2014.
[19] G. Bianchi, Performance analysis of the IEEE 802.11 distributed coordination function, *IEEE journal on Selected Areas in Communications*, vol.18, no.3, pp.535,547, 2000.
[20] B. Li and R. Battiti, Performance analysis of an enhanced IEEE 802.11 distributed coordination function supporting service differentiation, *in Workshop on Quality of Future Internet Services*, pp. 152161, 2003.
[21] Y. Xiao, Performance analysis of priority schemes for IEEE 802.11 and IEEE 802.11e wireless LANs, *IEEE Transactions on Wireless Communications*, vol.4, no.4, pp.1506,1515, 2005.