IEEE 802.15.6 Under Saturation: Some Problems to Be Expected

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Abstract: **Because currently available wireless technologies are not appropriate for wireless body area networks (WBANs), the IEEE 802.15.6 standard was introduced by the IEEE 802.15.6 Task Group to satisfy all the requirements for a monitoring system that operates on, in, or around the human body. In this work, we develop an analytical model for evaluating the performance of an IEEE 802.15.6-based WBAN under saturation condition and a noisy channel. We employ a three-dimensional Markov chain to model the backoff procedure as specified in the standard. Probability generating functions (PGFs) are used to compute the performance descriptors of the network. The results obtained from the analytical model are validated by simulation results. Our results indicate that under saturation condition, the medium is accessed by the highest user priority nodes at the vast majority of time while the other nodes are starving.**

Index Terms: **IEEE 802.15.6, normalized throughput, performance evaluation, saturation condition, wireless body area networks (WBANs), wireless healthcare systems.**

I. INTRODUCTION

A wireless network of sensors pervasively monitoring the human body increases the chance to predict, diagnose, and monitor the response of the body to treatments earlier in at-risk groups. The concept of ubiquitous and pervasive human well-being monitoring sensor system with regards to physical, physiological, and biomedical parameters in any environment and without activity restriction for all people (not only the at-risk groups) provides invaluable benefits which is becoming a reality with the important advances in sensors, miniaturised processors, wireless data transmission technologies, increased battery duration, reduced energy consumption, and power scavenging [1]. These technology developments have allowed the realization of small and intelligent medical sensors that can be worn or implanted in the human body.

Wireless body area networks (WBANs) were first introduced to fully exploit the benefits of wireless technologies in telemedicine and medical care [2], [3]. The human body environment is much smaller than usual wireless sensor network (WSN) environments and requires a different type and frequency of monitoring, with different challenges than those faced by WSNs.

Currently available wireless local area network (WLAN) and wireless personal area network (WPAN) technologies such as Bluetooth [4], Zigbee [5], and Wi-Fi (IEEE 802.11) [6] are not appropriate for WBANs [1] since they do not meet the medical (proximity to human tissue) and relevant communication regulations for some application environments. They also do not support the combination of reliability, quality of service (QoS), low power, data rate and non-interference required to broadly address the breadth of body area network applications [7]. Due to a lack of appropriate wireless technology that satisfies all of the requirements for WBANs the IEEE 802.15.6 Task Group (TG) developed a communication standard optimized for low-power devices and operation on, in, or around the human body (but not limited to humans) to serve a variety of applications including medical and personal entertainment [8]. Examples of the applications served by the proposed standard include: *Electroencephalogram (EEG)*, *electrocardiogram (ECG)*, *electromyography (EMG)*, monitoring of vital signals (e.g., temperature (wearable thermometer), respiration, heart rate, pulse oximeter, blood pressure, oxygen, pH value , glucose value, cardiac arrhythmia). A medical WBAN example is shown in Fig. 1. The depicted WBAN includes a few sensors to monitor the vital health information of the body.

In this work, we develop a three-dimensional Markov chain in order to model the backoff procedure of the CSMA/CA mechanism and the exclusive and random access phases of IEEE 802.15.6 under saturation condition and an error-prone channel. We model all eight user priorities ($\mathrm{UP}_k,\ k = 0, \cdots, 7$) as specified in the standard so that all the nodes are saturated. In other words, there is at least one data frame in the queue waiting to be served at all times. In our probabilistic approach, we assume that the collision probability of a frame transmitted by a node is constant and independent of the number of retransmissions. Using probability generating functions (PGFs), we compute the average time between two successive successful accesses to the medium and the normalized throughput for all UPs. Our approach also provides the ability to calculate the mean backoff time in every backoff stage. We validate the analytical results by using an accurate simulation model.

Though there are a few works in the literature introducing specific MAC protocols for WBANs [9]–[13] this is the first work to our best knowledge that evaluates the performance of the IEEE 802.15.6 CSMA/CA mechanism.

The remainder of this paper is organized as follows. Section II briefly introduces the IEEE 802.15.6 standard. In Section III the analytical model is developed. In Section IV the performance descriptors for the network are defined and computed using PGFs. Section V introduces the parameters used in the simulation and the analytical models and results are analyzed through the performance descriptors. Finally, Section VI concludes the paper and highlights some avenues for future research.

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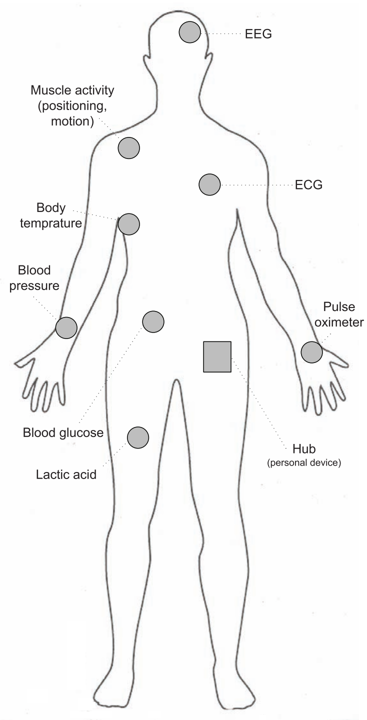

Fig. 1. A WBAN example with a few nodes and a hub.

II. IEEE 802.15.6 STANDARD

IEEE 802.15.6 [7] defines a standard for WBANs which is a short-range, low-power, and highly reliable wireless communication in the vicinity of or inside a human body. QoS, extremely low power and simultaneous compliance with strict non-interference guidelines are the main goals of the standard.

All the nodes and the *hub*s in the network are organized into logical sets referred to as body area networks (BANs) and coordinated by their respective hubs for medium access and power management. Every BAN has one hub, while there may be 0-64 nodes.

There are eight different access categories that indicate the user priorities for accessing the medium. The user priority values are determined based on the designation of frame payloads (traffic) contained in the frame according to Table 1.

A hub establishes a time base that divides the time axis into beacon periods (*superframes*) regardless of whether it is to transmit the beacon to provide or support time reference allocations in its BAN.

In this work, all the nodes are synchronized to support the contention-based mechanism of IEEE 802.15.6. We assume that the hub in the WBAN operates in beacon mode with superframe boundaries. The hub places the access phases—exclusive access phase 1 (EAP1), random access phase 1 (RAP1), type-I/II access phase, exclusive access phase 2 (EAP2), random access phase 2 (RAP2), type-I/II access phase, and contention access phase (CAP)—in the order stated and shown in Fig. 2. The length of any of these access phases may be set to 0 by the hub, but RAP1 does not have a length shorter than the guaranteed minimum length communicated in connection assignment frames. The hub transmits a preceding B2 frame to announce a non-zero length CAP.

Table 1. BAN user priority mapping.

UP	Traffic designation	$\mathrm{CW}_{\min}$	$\mathrm{CW}_{\max}$
0	Background (BK)	16	64
1	Best effort (BE)	16	32
2	Excellent effort (EE)	8	32
3	Controlled load (CL)	8	16
4	Video (VI)	4	16
5	Voice (VO)	4	8
6	Media data or network control	2	8
7	Emergency or medical event report	1	4

Type-I/II access phases are utilized by the hub for scheduling uplink, downlink, and bilink allocation intervals required for the polling mechanism. Because in this work we do not study the polling mechanism of IEEE 802.15.6, we assume that the lengths of type-I/II access phases are set to 0. Other phases are contention-based access phases.

The access method for obtaining the contended allocations is CSMA/CA for narrowband PHY and slotted aloha for UWB. In this work, we consider the CSMA/CA MAC mechanism running in narrowband PHY as described in the standard.

A hub or any node may obtain contended allocations in EAP1 and EAP2 if it requires the transmission of data frames of the highest UP (i.e., emergency or medical event report). The hub or a node with the highest UP frames may treat the combined EAP1 and RAP1 as a single EAP1, and the combined EAP2 and RAP2 as a single EAP2, to allow continual invocation of CSMA/CA and improve channel utilization.

The user priorities are differentiated by the values of the minimum and maximum contention windows. The predefined relationships between contention window (CW) bounds—$\mathrm{CW}_{\max}$ and $\mathrm{CW}_{\min}$—and UPs are depicted in Table 1.

Based on the CSMA/CA mechanism, a node shall maintain a backoff counter and contention window to determine when it obtains a new contended allocation. The node sets its backoff counter to a sample of an integer random variable uniformly distributed over the interval $[1, \mathrm{CW}]$. The node is allowed to transmit one frame of UP over the medium if the backoff counter reaches 0. CW is a contention window chosen as follows:

- If the node did not obtain any contended allocation previously, succeeded a data frame transmission, or requires no acknowledgement, it sets CW to $\mathrm{CW}_{\min}[\mathrm{UP}]$.
- If the node failed, i.e., if the node did not receive an expected acknowledgement to its last frame transmission in the last contended allocation it had obtained–it keeps the CW unchanged if this was the mth time the node had failed consecutively, where m is an odd number; otherwise, the CW is doubled.
- If doubling the CW makes the new CW exceed $\mathrm{CW}_{\max}[\mathrm{UP}]$, the node shall set the CW to $\mathrm{CW}_{\max}[\mathrm{UP}]$.

The node locks the backoff counter when any of the following events occurs:

- The backoff counter is reset upon decreasing to 0.
- The channel is busy. If the channel is busy because the node detected a frame transmission, the channel remains busy until

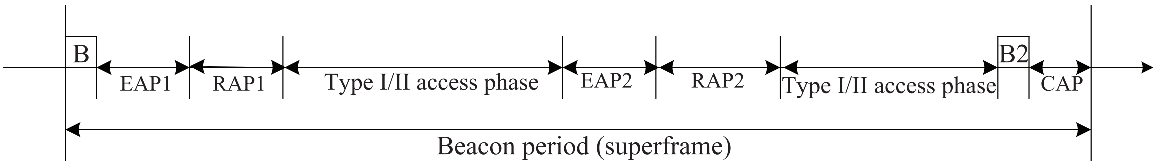

Fig. 2. Layout of access phases in a beacon period (superframe) for beacon mode.

at least the end of the frame transmission without the node having to re-sense the channel.

- The current time is outside the access phases where the node can transmit; any RAP or CAP for a UP without the highest priority (i.e., not for an emergency or medical event report) or is outside any EAP, RAP, or CAP for the highest user priority (i.e., for an emergency or medical event report).
- The current time is at the start of a CSMA slot within an EAP, RAP, or CAP, but the time between the end of the slot and the end of the EAP, RAP, or CAP is not long enough to complete a frame transaction and setting aside a nominal guard time mGT-Nominal.

The node unlocks the backoff counter when both of the following conditions are met:

- The channel has been idle for SIFS within an RAP or CAP if UP does not have the highest value or within an EAP, RAP, or CAP if UP has the highest value.
- The time duration between the current time plus a CSMA slot and the end of the EAP, RAP, or CAP is long enough to complete a frame transaction plus the nominal guard time mGT-Nominal.

Upon unlocking the backoff counter, the node decreases its backoff counter by one for each idle CSMA slot that follows. Upon having a backoff counter of 0, the node obtains a contended allocation.

III. ANALYTICAL MODEL

In this work, all eight UPs are considered, and each node has one UP. A node belongs to UP_k if it has a queue of user priority k. We consider a single hop WBAN with n_k nodes of UP_k and lengths of EAP2, RAP2, and CAP are set to 0.

All of the nodes in the network deploy an RTS/CTS mechanism for accessing the medium. The size of the data frames is set to $l_{d,b}$ bits. We assume an error-prone channel with a bit error rate (BER) of ber. The probability that neither RTS nor CTS is corrupted due to the channel noise is defined as $\delta = (1-ber)^{rts_b+cts_b}$, where rts_b and cts_b are the lengths of RTS and CTS, respectively, in bits. $\sigma = (1-ber)^{l_{d,b}+ack_b}$ is defined as the probability that the data frame and the corresponding acknowledgement are transmitted without getting corrupted by the noise, where ack_b is the length of the ACK frame in bits.

The backoff count for a node of UP_k is an integer uniformly drawn over the interval $[1, \mathrm{CW}_k]$, where $\mathrm{CW}_k = W_{k,i}$ for $i = 0, \cdots, R$; R is the transmission retry limit and has minimum value of $\mathrm{CW}_{k,\min} = W_{k,0}$ and maximum value of $\mathrm{CW}_{k,\max} = W_{k,m_k}$. CW_k is set to $\mathrm{CW}_{k,\min}$ when the backoff procedure is started. The contention window size during the ith backoff stage for a node of UP_k, $\mathrm{CW}_k = W_{k,i}$, is calculated as follows:

- $W_{k,0} = W_{k,\min} = \mathrm{CW}_{k,\min}$.
- $W_{k,i} = \min\{2W_{k,i-1}, \mathrm{CW}_{k,\max}\}$ for $2 \le i \le R$ if i is an even number.
- $W_{k,i} = W_{k,i-1}$ for $1 \le i \le R$ if i is an odd number.

Every node maintains a retry count with an initial value of zero. The retry count is increased by one when an unsuccessful medium access occurs.

We denote τ_k as the probability of transmission by a node of UP_k assuming the medium is not busy. The slots in which the nodes pause their backoff counter because of a transmission on the medium or inaccessible access phases are not taken into account when τ_k is calculated. Thus, the probability that medium is idle during RAP1, which is where all UPs are allowed to transmit, is equal to

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

For a node of UP_k, $k = 0, \cdots, 6$, the probability that the medium is idle during the backoff countdown (in RAP1) is equal to

$$f_k = \frac{\prod_{i=0}^{7} (1-\tau_i)^{n_i}}{(1-\tau_k)}. \tag{2}$$

For UP_7, the probability that the medium is idle during the backoff countdown (in EAP1 and RAP1) is approximated as

$$f_7 = \frac{X_R \prod_{i=0}^{7} (1-\tau_i)^{n_i}}{(X_E+X_R)(1-\tau_7)} + \frac{X_E(1-\tau_7)^{n_7-1}}{X_E+X_R} \tag{3}$$

where X_E and X_R are the mean numbers of the CSMA slots in EAP1 and RAP1, respectively, which are considered in the Markov chain. In order to have more accurate access probabilities, we use an iterative approach for solving the Markov chain. The initial values are set to $X_E = eap1$ and $X_R = rap1$, where $eap1$ and $rap1$ are the lengths of EAP1 and RAP1 in slots, respectively. The values of X_E and X_R for the next iterations are calculated as follows:

$$X_E = \frac{eap1}{\phi + n_7\tau_7\psi\delta L_s + (1-\phi-n_7\tau_7\psi\delta)L_c}, \tag{4}$$
$$X_R = \frac{rap1 - L_s}{f + \sum_{t=0}^{7} n_t\tau_t f_t \delta L_s + \left(1 - f - \sum_{t=0}^{7} n_t\tau_t f_t\delta\right) L_c}$$

where $\phi = (1-\tau_7)^{n_7}$ and $\psi = (1-\tau_7)^{n_7-1}$.

As previously described, if the remaining time during the current access phase (RAP1 if UP does not have the highest value

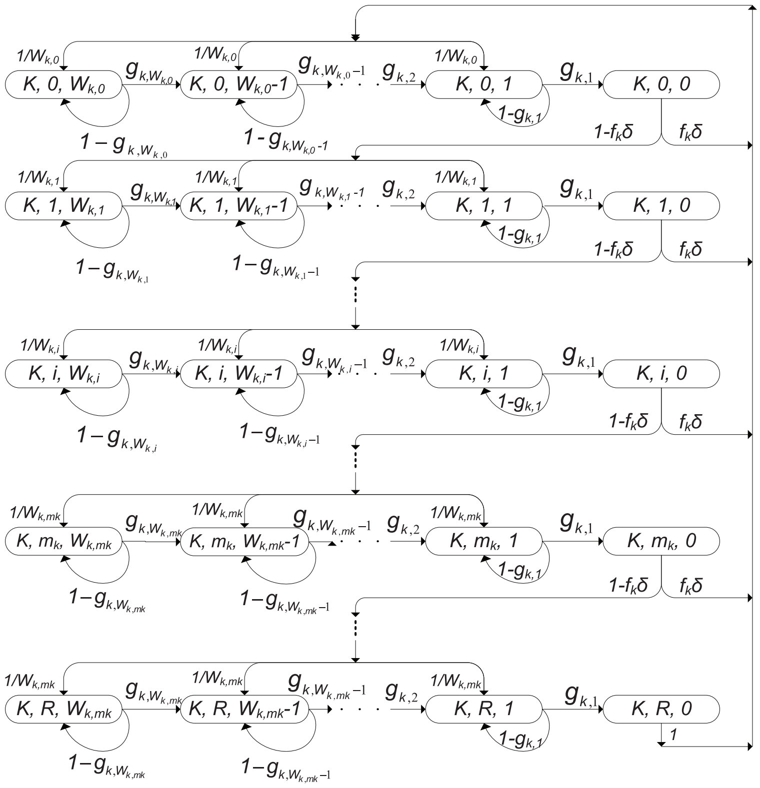

Fig. 3. Markov chain for UP_k.

or RAP1 and EAP1 if UP has the highest value) is not long enough for completing a frame transaction (RTS−CTS−data frame−ACK), the backoff counter is locked. In addition, nodes that do not have the highest priority must lock their backoff counter during EAP1. We introduce p_k as follows to address the probability that in a given CSMA slot, there is not enough time during the current access period. At the moment, the backoff counter is locked until beginning of the next access period (RAP1 for $\mathrm{UP}_k,\ k=0,\cdots,6$ or EAP1 for UP_7). We approximate the p_k values as follows:

$$p_k = \frac{3}{2(rap1 - L_s - C_k)},\ k=0,\cdots,6,$$
$$p_7 = \frac{3}{2(rap1 + eap1 - L_s - C_7)} \tag{5}$$

where $L_s = (rts + cts + l_d + ack + 3sifs)_s$ indicates the successful transmission time in slots, $L_c = (rts + cts + sifs)_s$ is the unsuccessful transmission time in slots in case of failure access to the medium or corrupted frame due to noisy channel, and $C_k = \mathrm{CW}_{k,\min} + \mathrm{CW}_{k,\max}/4,\ k=0,\cdots,7$ approximates the mean backoff counter.

We define $g_{k,j},\ k=0,\cdots,7,\ j=1,\cdots,W_{k,m_k}$ as the probability that the backoff counter of a node with UP_k decreases when the counter is equal to j. In fact, $g_{k,j}$ is defined to consider the slots in which the backoff counter is locked but the slots must be considered when calculating the access probability.

$$g_{k,j} = f_k\left(1 - p_k\frac{1-f_k^j}{1-f_k}\right). \tag{6}$$

We define $L_k = eap1 + (rts + cts + 3sifs + l_d + ack)_s,\ k=0,\cdots,6$ as the number of slots in which the backoff counter for a node of UP_k must be locked. During EAP1, just the nodes of the highest user priority are allowed to transmit or decrease their backoff counters. During RAP1, all of the nodes in the network have to lock their backoff counter where there is not enough time for completing a transmission. However, a node of UP_7 is not required to lock its backoff counter during EAP1 unless the medium is busy. Hence, we have $L_7 = (rts + cts + 3sifs + l_d + ack)_s$. If the backoff counter of a node of UP_k is equal to j and the node detects that there is not enough time for completing a data frame transmission, it has to lock the counter for $L_k + j$ slots.

The Markov chain for a node of $\mathrm{UP}_k,\ k=0,\cdots,7$ is shown in Fig. 3. The Markov chain represents a random process with stationary distribution $b_{k,i,j}$, where $k=0,\cdots,7$ indicates the user priority that the node belongs to, $i=0,\cdots,m_k,\cdots,R$ denotes the backoff phase in the backoff procedure invoked by the node, and $j=0,\cdots,W_{k,i}$ indicates the value of the backoff counter. The Markov chain includes only the time slots where the medium is accessible by the node. By solving the Markov chain, we compute the access probability τ_k. The access probability of a node of UP_k is calculated as following

$$\tau_k = \sum_{i=0}^{R} b_{k,i,0}. \tag{7}$$

We define $Y_k,\ k=0,\cdots,7$, as the input probability to the zero-th backoff phase. Hence, we have

$$Y_k = \tau_k f_k\delta + b_{k,R,0}(1 - f_k\delta). \tag{8}$$

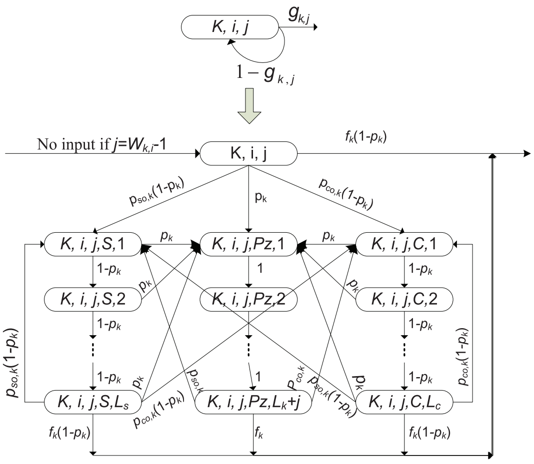

Fig. 4. Extended Markov chain for UP_k: We replace the component on top with the new component in Fig. 3 to compose the extended Markov chain.

It can be generally shown that for $k = 0,\cdots,7,\ i = 0,\cdots,R,\ j = 1,\cdots,W_{k,i}$, we have

$$b_{k,i,j} = \frac{(1-f_k\delta)^i Y_k (W_{k,i}-j+1)}{W_{k,i} g_{k,j}}. \tag{9}$$

For $k = 0,\cdots,7,\ i = 1,\cdots,R$, we have

$$b_{k,i,0} = (1-f_k\delta)^i Y_k. \tag{10}$$

Using equations (8) and (10) we calculate the value of Y_k as follows:

$$Y_k = \frac{f_k \delta \tau_k}{1-(1-f_k\delta)^{R+1}},\ k = 0,\cdots,7. \tag{11}$$

We can now compute the summation of all the stationary distributions $b_{k,i,j}$ at the ith backoff phase for $i = 0,\cdots,R$ as follows:

$$\sum_{i=0}^{R}\sum_{j=0}^{W_{k,i}} b_{k,i,j} = Y_k \sum_{i=0}^{R}(1-f_k\delta)^i\Big(1+\frac{1}{W_{k,i}}\sum_{j=1}^{W_{k,i}}\frac{W_{k,i}-j+1}{g_{k,j}}\Big). \tag{12}$$

Finally, we use the normalization condition of the Markov chain, which indicates that the summation of all the probabilities is equal to 1 for $k = 0,\cdots,7$, to obtain

$$1 = Y_k \sum_{i=0}^{R}(1-f_k\delta)^i\Big(1+\frac{1}{W_{k,i}}\sum_{j=1}^{W_{k,i}}\frac{W_{k,i}-j+1}{g_{k,j}}\Big). \tag{13}$$

By solving the equations, we compute $\tau_k,\ k = 0,\cdots,7$.

IV. PERFORMANCE DESCRIPTORS

In this section, we calculate the performance descriptors of the network to study the behavior of the system. The average time between two successive successful accesses to the medium is defined as the time interval between the instant when the backoff procedure is started for transmitting a data frame and the time when the frame is successfully transmitted. Normalized throughput for UP_k is defined as the fraction of time in which the channel is used to successfully transmit frames payload of UP_k.

In order to compute the performance descriptors, we needed to extend our Markov chain to include all the slots in which the backoff counter is locked. To compose the extended Markov chain we replace the component shown on top of Fig. 4 with the component shown below that in the first Markov chain (Fig. 3) for $k = 0,\cdots,7,\ i = 0,\cdots,R$, and $j = 0,\cdots,W_{k,i}$. Stationary distributions of $b_{k,i,j,S,t},\ t = 1,\cdots,L_s$ and $b_{k,i,j,C,t},\ t = 1,\cdots,L_c$ correspond to slots during the times when the data frame is successfully transmitted and when the RTS frame collides, respectively. The stationary distribution of $b_{k,i,j,Pz,t}$ for $t = 1,\cdots,L_k+j$ corresponds to a slot during the time when the node has to lock its backoff counter because there is not enough time to complete a frame transmission.

The probabilities that the backoff counter for a node of UP_k will be locked due to a successful transmission by the other nodes, $p_{so,k}$, or due to an unsuccessful transmission by the other nodes, $p_{co,k}$, are computed as follows:

$$\begin{aligned} p_{so,k} &= \delta\sum_{i=0}^{7}\frac{n_i\tau_i f_k}{1-\tau_i} - \frac{\delta\tau_k f_k}{1-\tau_k}, \\ p_{co,k} &= 1 - f_k - p_{so,k}. \end{aligned} \tag{14}$$

The PGF for data frame transmission time is defined as $St(z) = z^{rts+cts+l_d+ack+3sifs}$. The failed transmission time due to an RTS collision has the PGF of $Ct(z) = z^{rts+cts+sifs}$.

We define $BfS_{k,j}(z)$ as the PGF of the time from the moment when the backoff counter is locked due to a successful transmission by another node until the moment when the backoff counter is unlocked. $BfC_{k,j}(z)$ is defined as the PGF of the time interval between the instant when the backoff counter is locked due to an unsuccessful medium access by the other nodes and the instant when the backoff counter is unlocked. We introduce $Bfpz_{k,j}(z)$ as the PGF of the time from the moment when the backoff counter is locked because there is not enough time for completing a frame transmission until the moment when the backoff counter is unlocked. Based on the extended Markov chain, the PGFs are computed as follows:

$$\begin{aligned} Bfpz_{k,j}(z) &= z^{L_k+j}(f_k z + \Theta_{k,j}(z)), \\ BfS_{k,j}(z) &= p_k Bfpz_{k,j}(z)\frac{1-(1-p_k)^{L_s}z^{L_s}}{1-(1-p_k)z} \\ &\quad + (1-p_k)^{L_s} f_k z^{L_s} + (1-p_k)^{L_s}\Theta_{k,j}(z), \\ BfC_{k,j}(z) &= p_k Bfpz_{k,j}(z)\frac{1-(1-p_k)^{L_c}z^{L_c}}{1-(1-p_k)z} \\ &\quad + (1-p_k)^{L_c} f_k z^{L_c} + (1-p_k)^{L_c}\Theta_{k,j}(z) \end{aligned} \tag{15}$$

where $\Theta_{k,j}(z) = p_{so,k}BfS_{k,j}(z) + p_{co,k}BfC_{k,j}(z)$. $BfS_{k,j}(z)$, $BfC_{k,j}(z)$, and $Bfpz_{k,j}(z)$ can be analytically written based on the known parameters. We do not present the formulae here because they are large and the reader can simply derive them. The PGF of the time to decrease the backoff counter by one, which is the time interval between the moment when the backoff counter value of a node of $\mathrm{UP}_k,\ k = 0,\cdots,7$ is $j,\ j =$

$1, \cdots, W_{k,i}$ at the ith, $i = 0, \cdots, R$, backoff phase and the moment when the backoff counter value becomes equal to $j-1$, $Bf_{k,i,j}$, is calculated as

$$Bf_{k,i,j} = p_k Bfpz_{k,j} + (1-p_k)(f_k z + \Theta_{k,j}(z)). \tag{16}$$

Now, we write the PGF of the ith backoff phase duration for UP_k as follows:

$$BfR_{k,i} = \sum_{j=1}^{W_{k,i}} \prod_{t=1}^{j} Bf_{k,i,t}\Big(f_k\delta(L_s p_k z^{L_k} + 1 - L_s p_k) + (1-f_k\delta)(L_c p_k z^{L_k} + 1 - L_c p_k)\Big)/W_{k,i}. \tag{17}$$

The PGF for the total time spent during the backoff procedure for a successful access to the medium for user priority $k, k = 0, \cdots, 7$ is computed as follows:

$$\begin{aligned} BfT_k(z) = & \sum_{i=0}^{m_k}(\prod_{u=0}^{i} BfR_{k,u})(1-f_k\delta)^i (z^{L_c})^i f_k\delta \\ & + \sum_{i=m_k+1}^{R}(\prod_{u=0}^{m_k} BfR_{k,u}) BfR_{k,m_k}^{i-m_k}(1-f_k\delta)^i (z^{L_c})^i f_k\delta \\ & + \Big(\prod_{u=0}^{m_k} BfR_{k,u}\Big) BfR_{k,m_k}^{R-m_k}(1-f_k\delta)^{R+1}(z^{L_c})^{R+1}. \end{aligned} \tag{18}$$

We define $AT_k(z), k = 0, \cdots, 7$ as the PGF of the time between two successive successful accesses to the medium by a node of UP_k, which is calculated as follows:

$$At_k(z) = \frac{BfT_k(z)St(z)\big(L_s p_k z^{L_k} + (1 - L_s p_k)\big)}{h_k}. \tag{19}$$

$L_s p_k z^{L_k} + (1 - L_s p_k)$ corresponds to the time when the node has successfully transmitted a data frame, and it checks if there is enough time to complete transmission of the next data frame. The probability that a data frame is successfully transmitted on the medium, h_k, is equal to

$$h_k = \sigma(1 - (1 - f_k\delta)^{R+1}). \tag{20}$$

The average time between two successive successful accesses to the medium by a node of $\mathrm{UP}_k, k = 0, \cdots, 7$ is computed as follows:

$$A_k = \left(\frac{d}{dz}At_k(z)\right)_{z=1} \text{slot} \tag{21}$$

where the first component is the average time between two successive accesses in slots and slot is the length of one CSMA slot in seconds.

Now, we compute the normalized throughput of a node of UP_k, $\tau_{N,k}$ as follows

$$\tau_{N,k} = \frac{\sigma h_k (l_p)_s}{(\frac{d}{dz}At_k(z))_{z=1}} \tag{22}$$

where $(l_p)_s$ is the payload size of a data frame in slots.

Table 2. Simulation (sim) and analytical (ana) results for average time between two successive accesses of a node of UP_k.

	Eap 1 Rap 1	0.05 sec 0.1 sec	0.1 sec 0.1 sec	0.05 sec 0.2 sec	0.1 sec 0.2 sec	0.2 sec 0.2 sec
0	Sim	3.2918918	5.4184615	1.9401950	2.8670325	4.0370242
	Ana	2.9665328	5.2261654	1.5269595	2.5073460	4.2404037
1	Sim	2.3732673	3.9873831	1.4504651	2.1131147	3.1304347
	Ana	2.1632912	3.8202375	1.1442045	1.8755653	3.1667681
2	Sim	1.6183419	2.5992779	1.0198412	1.4231315	2.1135029
	Ana	1.4373452	2.5573183	0.7615869	1.2551400	2.1332325
3	Sim	1.2950533	2.0151948	0.7898412	1.0659479	1.6181818
	Ana	1.0892373	1.9307160	0.5891145	0.9641621	1.6294785
4	Sim	0.9822432	1.3689637	0.5383955	0.7153416	1.0671937
	Ana	0.7398378	1.3169131	0.4014294	0.6579313	1.1166644
5	Sim	0.7251474	1.0713360	0.4169291	0.5746153	0.8451068
	Ana	0.5804816	1.0252315	0.3208524	0.5202644	0.8757485
6	Sim	0.5150013	0.7337906	0.2502111	0.3717088	0.5697828
	Ana	0.4052587	0.7167392	0.2253345	0.3645641	0.6151017
7	Sim	0.0335346	0.0288974	0.04033733	0.0350706	0.0298034
	Ana	0.0315762	0.0275581	0.03788309	0.0335599	0.0288227

Table 3. Simulation (sim) and analytical (ana) results for normalized throughput of a node of UP_k.

	Eap 1 Rap 1	0.05 sce 0.1 sce	0.1 sec 0.1 sec	0.05 sec 0.2 sec	0.1 sec 0.2 sec	0.2 sec 0.2 sec
0	Sim	0.0002475	0.0001498	0.0004256	0.0002896	0.0002199
	Ana	0.0002714	0.0001540	0.0005273	0.0003211	0.0001898
1	Sim	0.0003419	0.0002051	0.0005747	0.0003905	0.0002627
	Ana	0.0003721	0.0002107	0.0007036	0.0004292	0.0002542
2	Sim	0.0005115	0.0003117	0.0008097	0.0005734	0.0003896
	Ana	0.0005601	0.0003148	0.0010572	0.0006414	0.0003774
3	Sim	0.0006487	0.0004021	0.0010394	0.0007618	0.0004808
	Ana	0.0007392	0.0004170	0.0013667	0.0008350	0.0004941
4	Sim	0.0008367	0.0005919	0.0015454	0.0011526	0.0008035
	Ana	0.0010883	0.0006114	0.0020057	0.0012237	0.0007210
5	Sim	0.0012303	0.0007557	0.0020811	0.0014341	0.0009827
	Ana	0.0013870	0.0007853	0.0025094	0.0015476	0.0009194
6	Sim	0.0015934	0.0011098	0.0032495	0.0021783	0.0016299
	Ana	0.0019867	0.0011233	0.0035732	0.0022085	0.0013089
7	Sim	0.0244259	0.0279726	0.0202608	0.0229639	0.0283014
	Ana	0.0254991	0.0292169	0.0212539	0.0239919	0.0279351

V. PERFORMANCE EVALUATION

In order to investigate the performance of an IEEE 802.15.6-based wireless network under saturation condition and an error-prone channel, we have conducted a set of experiments. We examine the developed analytical model for accuracy. We used Maple 13 [14] to solve the Markov chain to acquire the access probabilities and compute the performance descriptors. We simulated the IEEE 802.15.6 standard using Opnet simulator [15] to validate analytical results.

In the experiments, we consider all eight UPs in the network, which operates in the 2.4 GHz ISM band. The data transmission rate is set to 971.4 kbps, while the headers and control frames are transmitted in 91.6 kbps. The payload size of a data frame is set to 100 B. We set the differentiation parameters of $\mathrm{CW}_{k,\min}$ and $\mathrm{CW}_{k,\max}$ for all nodes according to the standard (Table 1). We set the retry limit to $R = 7$ for all of the UPs. ber is set to 2×10^{-5} for all of the nodes.

The simulation and analytical results for average time between two successive successful accesses and normalized throughput of all the UPs where $(eap1, rap1)$ are equal to $(0.05, 0.1)$, $(0.1, 0.1)$, $(0.05, 0.2)$, $(0.1, 0.2)$, and $(0.2, 0.2)$ in seconds are shown in Tables 2 and 3, respectively. The simulation and analytical results showed an acceptable match. The main point from the results is that under saturation condition, all of the nodes without the highest UP are in starvation mode. The vast majority of the time, the medium is accessed by the highest UP nodes. The results also indicate that IEEE 802.15.6 utilizes the medium poorly. The results show that increasing the length of the exclusive access phase while the length of random access phase is fixed decreases the chance of medium access by nodes without the highest priority.

VI. CONCLUSION

In this study, we developed a Markov chain for modelling the backoff procedure of IEEE 802.15.6 and exclusive and random access phases under saturation condition and and error-prone channel. We extended the Markov chain to compute the performance descriptors of the network. We computed the normalized throughput and average time between two successive successful accesses by a node using PGFs. The analytical results were validated by an accurate simulation model. Our results indicate that under saturation condition, the nodes without the highest UP suffer from the very little access to the medium inasmuch they severely starve. The UP_7 nodes have unfair access to the medium even though the medium is utilized less than 7% of the time for transmitting the frame payloads under saturation condition. In our future work, we will extend the developed models to model the standard under non-saturation condition. Tuning the lengths of the access phases and designing admission control mechanisms to improve the performance of the network are other future works.

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