Analysis of CSMA/CA mechanism of IEEE 802.15.6 under non-saturation regime

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Abstract—To evaluate the performance of the recently standardized IEEE 802.15.6 wireless body area network (WBAN) technology, we have developed an analytical model for an IEEE 802.15.6 network operating in non-saturation regime in an error-prone channel. We evaluate network performance for different User Priorities (UPs), under varying access phase length, UP differentiation, contention window size, and the use of RTS/CTS mechanism. Our results indicate that the most suitable vehicle for improving network performance is the choice of access phase lengths based on UP traffic loads. Moreover, we have found that the deployment of exclusive access phase (EAP) is not necessary in a typical WBAN; in fact, short exclusive and random access phases (EAP and RAP, respectively) lead to inefficient use of available bandwidth. We have also found that four out of available eight user priorities suffice to achieve even the most stringent requirements for WBAN performance, and that the use of RTS/CTS is counter-productive when the WBAN operates in non-saturated regime. All of these findings were verified through extensive simulations in OPNET.

Index Terms—wireless body area networks (WBANs); IEEE 802.15.6; probabilistic analysis; RTS/CTS handshake; access priorities

1 INTRODUCTION

Modern healthcare systems aim to provide timely, unobtrusive, and pervasive human well-being monitoring which has important use in case of both acute, health-threatening conditions and chronic conditions that necessitate continuous tracking of patient’s vital health variables. Recent technological advances have led to the development of low cost, low power sensing devices that can be worn on, or implanted in, the human body. These devices are then used to sense different healthcare signals such as electromyography (EMG), vital signs monitoring (heart rate, body temperature, respiratory monitoring, pulse oximetry, blood pressure), and others. Moreover, novel communication technologies have enabled the development of wireless body area networks (WBANs) that provide appropriate monitoring capabilities. Together, these advances enable healthcare providers to react appropriately when necessary and to collect a rich history of patient health data.

WBANs have attracted a lot of attention during the last few years, including the development of wearable materials, wireless sensors, actuators, and other related technologies [1], [2]. Proprietary MAC and PHY protocols have been introduced for WBANs [3], [4], while other projects used existing WLAN/WPAN standards such as IEEE 802.11, IEEE 802.15.4, ZigBee, and Bluetooth [5], [6]. Despite these developments, WBANs are difficult to implement due to stringent medical as well as regulatory requirements for healthcare application environments, but also on account of wide variation of bandwidth requirements for different health variables. Thus the IEEE 802.11e standard for wireless local area networks (WLANs) was found unsuitable due to its excessive processing, storage, and power requirements which body-worn sensor devices can’t satisfy; however, its prioritization mechanism would be extremely useful or healthcare signals. On the other hand, IEEE 802.15.4 low data rate wireless personal area network (LR-WPAN) standard provides low power capabilities and uses simplified carrier sense multiple access with collision avoidance (CSMA/CA) mechanism, both of which are well suited for WBAN use; but it has limited bandwidth, does not provide prioritization of device traffic and, in addition, suffers from excessive sensitivity to traffic volume. To address these shortcomings, IEEE has recently standardized IEEE 802.15.6 2012 [7], which has been specifically developed for WBANs to satisfy requirements for multi-priority medical data streams.

In the wide gamut of wireless communication protocols that use CSMA/CA as contention resolution mechanism, IEEE 802.15.6 CSMA/CA mechanism lies somewhere between IEEE 802.15.4 and IEEE 802.11e Enhanced Distributed Channel Access (EDCA). It contains considerable improvements over IEEE 802.15.4 with respect to medium sensing during backoff, and prioritization among the traffic classes. On the other hand, it differs from 802.11e EDCA due to interleaving of contention access period with the dedicated EAP and RAP phases. As such, the performance of IEEE 802.15.6 CSMA/CA mechanism warrants an in-depth analysis.

Initial research work in this direction focused on obtaining throughput and delay bounds in saturation regime which is less complex to analyze. As the node buffer is never empty in saturation, frame arrival rate at the network node is equal to or exceeds its frame departure rate which results in buffer overflows and, under infinite buffer assumption, instability. From the viewpoint of modeling, saturation regime can be described with a discrete-time Markov chain (DTMC) only, without queuing analysis of the node buffer and the associated extension of DTMC to semi Markov chain with general distribution of time between state transitions. In [8], [9], a numerical
model was developed to evaluate the theoretical throughput and delay limits of IEEE 802.15.6-based networks, however the model does not consider user priorities and access phases of the standard, and assumes a collision-free network over an ideal channel. In [10], [11], authors studied the performance of the IEEE 802.15.6 MAC under saturation condition for all traffic classes, while the impact of access phases lengths was studied in [12].

However, stable operation of a WBAN necessitates that its nodes operate well below the saturation regime node is non-saturated, which prevents buffer overflows, excessive end-to-end delays, and the subsequent reduction in throughput. CSMA/CA performance under non-saturation regime in IEEE standards has been investigated in [13], [14] for IEEE 802.11, [15], [16], [17] for IEEE 802.11e, and [18] for IEEE 802.15.4. These models combined queuing and Markov chain analysis, with different level of detail and accuracy. However, they are not appropriate for the IEEE 802.15.6 modeling due to the differences in their respective implementations of the CSMA/CA mechanism, and the number of relevant works that consider different user priorities and the impact of access phases is still small. The authors in [19] have investigated the performance of IEEE 802.15.6-based networks using a simulation model only. In [21], the authors investigated the performance of IEEE 802.15.6-based networks under non-saturation condition based on results reported in [11]. However, this non-saturation model has been developed with the implicit simplifying assumption that the packets enter into and leave the queue based on their packet arrival rate (i.e., the impact of queuing on departure process was ignored).

Given that the saturation model involves only DTMC analysis, an analytical model of IEEE 802.15.6 which would involve non-saturation is significantly more complex since it must account for queuing analysis of node behavior, probabilistic analysis of medium access, and semi Markov process technique. The last one is necessary since periods between transitions in associated Markov chain are neither constant nor exponentially distributed. In [20] we focused on impact of fading in physical layer and interaction between physical and MAC layer using a simplified MAC model of IEEE 802.15.6 CSMA/CA. Our non-saturation model of IEEE 802.15.6 presents significant improvement over earlier models [10], [11] since it includes queuing analysis and probabilistic backoff duration sub-models integrated in semi Markov process framework. Furthermore, we note that modeling interactions of all these components is a tedious task; some very limited results were published in [22].

The major contributions of this work are summarized as follows:

- We have developed a detailed analytical model for investigating the performance of the IEEE 802.15.6-based WBANs. Due to random distribution of time between observation points we model the system as semi Markov process. The analytical model is composed of three interrelated sub-models that focus on the Markov chain, backoff duration, and queuing. In the Markov chain sub-model, we develop eight dependent 3-dimensional discrete time Markov chains (DTMCs) to compute the medium access probabilities of all UPs. In the backoff duration sub-model, we extend the DTMCs to 4-dimensional DTMCs to calculate the backoff durations of all UPs.
- We develop a Geo/G/1 queuing sub-model of node buffer in order to model the probability distribution of buffer occupancy as well as the distribution of duration of the idle period of the node and probability that the queue is empty after a data frame service completion.
- The developed analytical model addresses all eight UPs (UPk, k = 0 . . . 7) and the first exclusive and random access phases (EAP1 and RAP1) under finite load and an error prone channel.
- By iteratively solving all priority models we obtain performance metrics for all UPs under varying lengths of EAP1 and RAP1. We investigate how an increase of the length of the exclusive (random) access phase, whilst keeping the length of the random (exclusive) access phase constant, affects the performance of the network.
- We have developed a complete simulation model using OPNET Wireless Modeller [23] – which does not have any such module – to validate the analytical model.
- We also investigate the efficiency of the specifications of the IEEE 802.15.6 standard for WBANs. In particular, while the standard does not explicitly mention RTS/CTS handshake, it does not forbid it either; as this is a standard technique used in other implementations of the CSMA/CA mechanism, we thought it prudent to investigate whether its deployment can improve network performance.

The remainder of the paper is organized as follows: Section 2 briefly introduces the IEEE 802.15.6 standard. In Section 3, we describe the major features of the analytical model, the details of which can be found in the Online Supplement. In Section 4, we analyze the performance of an IEEE 802.15.6-based WBAN for all UPs. Section 5 summarizes our findings and concludes the paper.

### 2 IEEE 802.15.6 Standard

This section includes a brief description of the IEEE 802.15.6 standard. Eight user priorities (UPs) are defined in the standard; they are differentiated based on the minimum and maximum contention windows, (CW_{min}, CW_{max}), as shown in Table 1. Priority values are determined based on the designation of frame payloads (traffic) contained in the frame.

<table>
<thead>
<tr>
<th>UP</th>
<th>Traffic designation</th>
<th>CW_{min}</th>
<th>CW_{max}</th>
</tr>
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<tbody>
<tr>
<td>0</td>
<td>Background (BK)</td>
<td>16</td>
<td>64</td>
</tr>
<tr>
<td>1</td>
<td>Best effort (BE)</td>
<td>16</td>
<td>32</td>
</tr>
<tr>
<td>2</td>
<td>Excellent effort (EE)</td>
<td>8</td>
<td>32</td>
</tr>
<tr>
<td>3</td>
<td>Controlled load (CL)</td>
<td>8</td>
<td>16</td>
</tr>
<tr>
<td>4</td>
<td>Video (VI)</td>
<td>4</td>
<td>16</td>
</tr>
<tr>
<td>5</td>
<td>Voice (VO)</td>
<td>4</td>
<td>8</td>
</tr>
<tr>
<td>6</td>
<td>Media data or network control</td>
<td>2</td>
<td>8</td>
</tr>
<tr>
<td>7</td>
<td>Emergency or medical event report</td>
<td>1</td>
<td>4</td>
</tr>
</tbody>
</table>
The time axis is divided into beacon periods (superframes) by the hub operating in beacon mode as the coordinator of the network. A superframe may include exclusive access phases (EAP1 and EAP2), random access phases (RAP1 and RAP2), type-I/II access phases, and contention access phase (CAP) - in the order shown in Fig. 1. All phases except RAP1 may have a zero length. The EAP periods can be only accessed for transmitting the UP frames while all UPs are allowed to access the medium during either RAP or the CAP. The hub or a node with UP 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 and improve channel utilization. Type-I/II access phases are utilized by the hub for the polling mechanism; other phases are contention-based access phases. In this work, we focus on EAP1 and RAP1 phases, and set the lengths of all the access phases to zero.

At the beginning of every backoff phase a random integer number is uniformly drawn from the contention window (CW), \( [1, CW_{k,i}] \), as the backoff count for a node of UP, where \( CW_{k,i} = W_{k,i} \) for \( i = 0 \ldots R \). The data frame is dropped if the number of retransmissions during a backoff process exceeds the maximum retry limit \( R \). The contention window for a node of UP during the \( i \)-th backoff phase is obtained as follows:

- \( W_{k,0} = W_{k,min} = CW_{k,min} \);
- \( W_{k,i} = \min\{2W_{k,i-1} - 1, CW_{k,max}\} \) for \( 2 \leq i \leq R \), if \( i \) is an even number; and
- \( W_{k,i} = W_{k,i-1} - 1 \) for \( 1 \leq i \leq R \), if \( i \) is an odd number;

where \( CW_{k,min} = W_{k,0} \) and \( CW_{k,max} = W_{k,m} \) indicate the maximum and minimum contention window sizes for a node of UP.

The node must lock its backoff counter when any of the following events occurs:

- The backoff counter is reset upon decrementing to 0.
- The channel is busy due to a transmission on the medium.
- The current time is outside an access phase where the node can transmit, that is, any RAP or CAP if UP does not have the highest value, or outside any EAP, RAP, or CAP, if UP has the highest value.
- 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 corresponding access phase is too short to complete the frame transaction.

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

- The channel has been idle for SIFS within an access phase in which the node can access the medium.
- 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.

Upon unlocking the backoff counter, the node decreases its backoff counter by one for each idle CSMA slot that follows. Upon reaching zero, the node has obtained a contended allocation and transmits data; we assume that the node transmits a single data frame during one access to the medium.

3 Analytical Model

In this section, we outline the analytical model for investigating the performance of the CSMA mechanism of IEEE 802.15.6; a detailed discussion of the model can be found in the Online Supplement. The analytical model consists of three inter-related sub-models, as follows.

- Markov chain sub-model: In the analytical model, we observe the system at moments of beginning of EAPs and RAPs, backoff decrements, and packet departures. In these points the random process under study has a Markov property. These points are called Markov points. The time between two successive Markov points is a random variable which affects the steady state probabilities. Therefore, the process under consideration is a semi Markov process [24]. For evaluating the semi Markov process we need DTMCs and the time distributions between the Markov points. The Markov chain sub-model is composed of a set of eight 3-dimensional DTMCs to compute the access probabilities of the UPs. The DTMCs are developed based on the backoff procedure of the IEEE 802.15.6 CSMA mechanism. This sub-model also needs the probability that the queue is empty after a data frame service completion, which is calculated in the queuing sub-model.

- Sub-model of backoff durations: The probability distributions of all the backoff phases and the total backoff duration before a successful access to the medium or a data frame drop for all UPs are formulated by the backoff duration sub-model. The probability generating functions (PGFs) of the backoff durations are computed based on the access probabilities of the UPs which are introduced in the Markov chain sub-model. The computed time distributions are used in the queueing and the Markov sub-models to calculate the transition probabilities in the semi Markov chains.

- Queuing sub-model: To calculate durations of idle periods and access probabilities of all UPs we need to know the queuing status of every UP in every CSMA slot.
The backoff probability distributions of all UPs, acquired by the backoff duration sub-model, are deployed to formulate the empty queue probability, duration of an idle period, and the queue size of every UP.

Detailed presentation of the model can be found in the Online Supplement. The three sub-models are inter-related yet extremely complex, which is why the solution is obtained in an iterative way.

4 PERFORMANCE EVALUATION

We used Maple 13 [27] to solve the analytical model outlined above and to calculate the performance descriptors of the network. Moreover, we have developed a simulation model of the IEEE 802.15.6 in OPNET [23]; this model implements the complete functionality of IEEE 802.15.6 as stipulated by the standard.

The wireless healthcare network which is used for performance evaluation of the IEEE 802.15.6 standard under non-saturation regime consists of a hub and 28 nodes. The nodes include ten channels for Electroencephalogram (EEG), eight channels for Electrocardiogram (ECG), one blood pressure sensor, one glucose monitoring node, one blood oxygen saturation monitoring sensor (pulse oximeter), four physical activity monitoring sensors, one channel for Electromyogram (EMG), one body temperature sensor, and one respiration rate monitoring node.

The nodes are categorized into eight UPs, as shown in Table 3 which uses the parameter values from [28]. We assume that all the nodes in a given UP have equal traffic load and payload size.

While this setup may be somewhat arbitrary from the perspective of a healthcare worker, it is fairly representative of a real scenario in which an IEEE 802.15.6 WBAN might be employed.

We set the differentiation parameters of $CW_{k,\text{min}}$ and $CW_{k,\text{max}}$ for all the nodes according to the standard, as shown in Table 1. The retry limit is set to $R = 7$ for all the UPs.

The network performance is investigated with and without the RTS/CTS mechanism for accessing the medium; as noted above, this is a common approach which deserves scrutiny, even though the IEEE 802.15.6 standard does not mention it. (However, it does not prohibit it either.)

4.1 Medium access with RTS/CTS

The simulation and analytical results for the mean waiting time of data frames for all user priorities where the RAP1 length varies while the length of EAP1 is constant are shown in Fig. 2. For clarity, we have not shown the results for all user priorities; the priorities shown are labeled in the diagrams. Lines denote analytical results, while crosses denote simulation results.
As can be seen, increasing the length of RAP1 while EAP1 is kept constant improves (i.e., reduces) the frame delay for all UPs, since longer RAP periods lead to decrease of collision probability after an EAP period. In addition, having short EAP and RAP periods increases the number of CSMA slots in which the medium cannot be accessed by the nodes because there is not enough time to complete a data frame transaction during the current access phase.

The graphs show reasonably good match between the simulation and analytical results for the case where all the nodes deploy RTS/CTS mechanism. The difference is more pronounced in the area where the network approaches saturation and waiting times exhibit large variations due to potential instability. We also note that slot boundaries are synchronized for all the nodes in the analytical model, which may not be the case in the simulation model, esp. under low to moderate loads which, in turn, leads to higher collision probability in the simulation model since the collision may happen during two successive CSMA slots upon the start of a transmission.

In the second scenario, the length of EAP1 varies from 0.05 second to 0.12 second while the length of RAP1 is set to 0.3 second; the results are shown in Fig. 3. For clarity, we omit the simulation results as the match is reasonably good for this case too.

As can be seen, mean waiting time and transmission success probability of data frames increase for all UPs when the length of EAP1 increases. Namely, having a long EAP period essentially wastes network resources because the traffic load of the highest priority traffic category, UP7, is low. However, during the RAP periods the traffic congestion increases because other nodes have shorter time periods for transmission. The conclusion is that judicious choice of RAP and EAP periods according to the traffic loads of the UPs should lead to noticeable performance improvements.

4.2 Medium access without RTS/CTS

In case RTS/CTS is not used, a node will immediately send its data frame upon reaching the backoff counter of zero. Fig. 4
Fig. 5. Performance for the network with all UPs, no RTS/CTS; length of RAP1 is 0.3 sec.

Fig. 4. Mean waiting time for the network with all UPs, no RTS/CTS; length of EAP1 is 0.05 sec.

show mean waiting time for select UPs in the scenario RAP1 length varies while the EAP1 length is constant. As before, some UPs are omitted for clarity, and analytical and simulation results are shown with lines and crosses, respectively.

Comparing the graph in Fig. 4 with that in Fig. 2, we can see that the performance of the WBAN improves dramatically when the RTS/CTS mechanism is not used. We may conclude that the use of RTS/CTS is counterproductive in the scenario shown, where small to moderate data frame sizes of up to the maximum payload size of 600 B are used. This setup was selected for use in environments where signal to noise ratio (SNR) is low, in which case larger payloads are more likely to result in frequent frame errors and retransmissions.

However, for a WBAN in an environment with sufficiently high SNR, larger frame sizes may be used. In this case, using the RTS/CTS mechanism improves the performance of the network because the RTS/CTS avoids many of the errors, and its transmission time is considerably smaller than the transmission time of the data frame itself.

Results for the scenario in which the length of EAP1 varies from 0.05 second to 0.12 second while the length of RAP1 is fixed at 0.3 second are shown in Fig. 5 (as before, simulation results are omitted for clarity). The results confirm that increasing the length of EAP1, under non-saturation condition, increases the mean waiting time of the data frames, specifically the data frames that do not belong to the highest priority traffic class UP

4.3 Effectiveness of User Priorities

We have also investigated the effectiveness of user priorities provided by the IEEE 802.15.6 standard. We consider a network with medium load, consisting of a number of nodes with identical traffic loads of two packets per second with the packet payload of 150B, and vary the number of nodes whilst keeping other parameters unchanged. In line with the conclusions made by the experiments described in previous subsection, we don’t use RTS/CTS.

In the first scenario, we consider a WBAN including four nodes in each of the eight UPs. Fig. 6 show the mean waiting
time for select UPS. As can be seen, the difference between all categories except UP\textsuperscript{7} (the highest one) is rather small, despite different contention window size.

This conclusion is confirmed by a slightly different experiment that uses a WBAN with only four UPS, with each UP consisting of eight nodes. Comparing the results in Fig. 6 and Fig. 7, we may conclude that four priorities are more than enough, and that merging together priorities 0 and 1, 2 and 3, and 4 and 5, respectively, would not change the results in any noticeable way.

We also note that assigning some nodes to UP\textsuperscript{7}, as shown in Fig. 7(a), actually improves performance for all UPS, as high priority traffic decreases the frame transmission collision in the network, not to mention the fact that high priority traffic in UP\textsuperscript{7} is guaranteed very high performance compared to the other nodes.

Thus, it seems safe to conclude that having four priorities instead of the original eight would give very similar results in terms of performance, while simplifying considerably the design of the firmware and software, as well as reducing the complexity of the hardware.

We have also analyzed network performance in the case where the network has only two UPS with 16 nodes each: one group with UP\textsuperscript{0}, and another with either UP\textsuperscript{6} or UP\textsuperscript{7}; the results are shown in Fig. 8. As can be seen, assigning traffic to the highest priority traffic class in case of non-zero EAP access phase, leads to better performance results for all nodes.

5 SUMMARY AND CONCLUSION

In this paper we have investigated the performance of wireless body area networks using the recent IEEE 802.15.6 WBAN standard. To this end, we have developed a detailed analytical model of the CSMA/CA mechanism utilized in IEEE 802.15.6 under non-saturation regime. Our analytical model captures not only medium access probabilities but also user priorities stipulated by the 802.15.6 standard as well as the interaction between exclusive and random access phases of varying length; moreover, it accurately models the behavior of individual node buffers under non-saturation regime. As a validation check, we have also developed a complete simulation model using OPNET Wireless Modeler suite. In this manner, we have been able to obtain a comprehensive evaluation of the performance of IEEE 802.15.6 networks operating with an error-prone channel.

The following observations regarding the behavior of IEEE 802.15.6-compliant WBANs can be made.

1) The presence of EAP phases is largely unnecessary for a typical WBAN, as they provide little improvement in terms of prioritization for UP\textsuperscript{7} nodes which are already highly prioritized by the small contention window sizes. At the same time, non-zero EAP phases considerably decrease the performance for all other UPS and, thus, impair total WBAN performance, unless the network traffic is high which is not a typical WBAN scenario.

2) Short EAP and RAP phases lead to inefficient use of WBAN bandwidth. According to our study, the CSMA slots at the end of EAP phases are wasted since there is not enough time for completing a frame transaction. In addition, frame collision probability noticeably increases at the beginning of an RAP phase because the nodes at priorities below UP\textsuperscript{7} have just unlocked their backoff counter and are, thus, highly likely to transmit a data frame. Since these nodes had to pause their backoff counter form the previous RAP and phase, and given the small contention window sizes of WBAN UPS, the number of such nodes is high, and degradation of performance is very likely.

3) Based on the current contention window sizes for different priority classes, deployment of eight UPS is unnecessary. Our study shows that traffic classes pairs of \{UP\textsuperscript{0} & UP\textsuperscript{1}\}, \{UP\textsuperscript{2} & UP\textsuperscript{3}\}, and \{UP\textsuperscript{4} & UP\textsuperscript{5}\} have almost equal performance measures. We came to conclusion that deployment of UP\textsuperscript{1}, UP\textsuperscript{3}, and UP\textsuperscript{5} is not required and does not provide considerable performance differentiation. We suggest deployment of only four priority classes, namely UP\textsuperscript{0}, UP\textsuperscript{2}, UP\textsuperscript{4}, and UP\textsuperscript{7} for WBANs. These UPS are able to provide sufficient performance differentiation at a lower cost for manufacturers of IEEE 802.15.6-compliant hardware and software.

4) The IEEE 802.15.6 CSMA/CA mechanism is not very efficient in utilizing the medium. In particular, small contention window sizes for all UPS lead to early saturation by increasing the collision probability under medium to high network traffic volume. For improving the WBAN performance we suggest increasing the CW sizes so as to decrease the collision probability; however, we should note that large CW sizes result in higher energy consumption.
5) For an unsaturated WBAN with a small to moderate data frame sizes, deploying the RTS/CTS mechanism degrades the network performance compared to the case where the nodes immediately transmit their data frames upon a successful medium access. Since the control frames are not so much smaller in size compared to the data frames in WBANs deployment of RTS/CTS degrades the network performance. We suggest immediate transmission of WBAN data frames for having better performance for all UPs.

It remains to be seen whether these problem areas will preclude wider utilization of the IEEE 802.15.6 standard for...
the development of WBANs.

REFERENCES


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