Real-time dynamic traffic scheduling for medical applications on IEEE 802.15.6

Guilherme Gil*†, Paulo Pedreiras*†, Luis Moutinho*†
*Department of Electronics, Telecommunications and Informatics, University of Aveiro, Aveiro, Portugal
†Instituto de Telecomunicações, Aveiro, Portugal

***Abstract*—The evolution and actual capabilities of sensor-based technologies concerning miniaturization, processing power and energy efficiency, together with advances in wireless communications, enabled the development and wide dissemination of the so-called wireless body area networks (WBANs) for health applications. The IEEE 802.15.6 standard, although purposely designed for these applications, prompts some issues regarding the schedulability of dynamic traffic as its scheduling services rely on allocation slots assigned statically and that are hard to modify at run time. This paper proposes a novel scheduling approach for this standard, in which the allocation slots are dynamically scheduled in each beacon period, according to the nodes' requirements, including response to erroneous transmissions of critical traffic, while allowing co-existence with legacy nodes.**

***Index Terms*—Wireless Body Area Networks, Real-time Systems, Dynamic Scheduling, Medical Applications**

I. Introduction and Related Work Overview

Wireless Sensor Networks (WSNs), commonly used in industrial environments to reduce labor costs, limit human errors and diminish possible manufacturing downtime, have started to transgress to the healthcare domain as they provide a safe and efficient method of obtaining medical data in real-time. These specialized WSNs, used in medical applications, are designated Wireless Body Area Networks (WBANs) and must comply with strict requirements [1], particularly concerning service latency and reliability. Communication protocols and standards for WBAN architectures have been thoroughly studied in the literature [2], with IEEE 802.15.6 being one of the most relevant [3]. IEEE 802.15.6 [4] organizes communications in sequential periods (superframes) comprising a series of access phases in which nodes can either communicate asynchronously, using CSMA/CA, or synchronously, using pre-assigned time slots. Nodes can request new slots, or change existing ones, by sending a request to the hub with the desired slot when first joining the network or when requiring more resources while operating. The hub then replies with the acceptance, refusal, or proposal of a different slot. Communications between the nodes and the hub are usually made through unicast schemes, including the assignment of the scheduled allocation slots. Consequently, modifications to an existing schedule are hard and inefficient as the hub must transmit control frames to each one of the nodes affected by a schedule change, making this approach unfit for networks with highly dynamic behavior. Several proposals in the literature attempt to address the aforementioned limitations and increase the scheduling flexibility and dynamic behavior of IEEE 802.15.6.

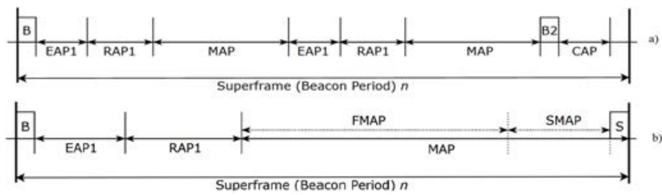

Fig. 1. a) IEEE 802.15.6 Beacon mode with beacon period superframe. b) Proposed superframe structure with MAP partition.

Some schedule the traffic according to the channel conditions [5] while others prioritize nodes requirements baudrate [6]. While their strategies provide more dynamism to the protocol, they all rely on modified control frames to transmit schedules, breaking compatibility with nodes following the standard. Similarly, other existing strategies break compatibility with standard IEEE 802.15.6 nodes by making modifications to the existing superframe or the standard MAC frames [7]. In this work, we propose a novel dynamic scheduling scheme for IEEE 802.15.6 that provides extended services for handling dynamic systems while allowing coexistence with standard nodes, with the following features:

- Allocation of dynamic slots performed on a per superframe basis, improving scheduling flexibility and bandwidth usage efficiency;
- Bandwidth efficient reactive fault-tolerance mechanism, in which message re-transmissions are dynamically scheduled by the hub only when required, i.e. upon the occurrence of errors.
- Faster and more reactive scheduling as nodes can join/disconnect from the network or adjust their communication requirements at run-time without requiring a sequence of potentially long unicast exchanges with the hub.

The remainder of this document is structured as follows. Section II summarizes the main concepts of the IEEE 802.15.6 MAC layer. Section III provides a detailed description of the proposed protocol extensions. A preliminary and qualitative evaluation, illustrating the potential gains that can be attained by the use of the extensions, is presented in Section IV. Lastly, Section V draws some conclusions.

II. IEEE 802.15.6 MAC Brief Overview

The MAC layer of IEEE 802.15.6 [4] defines all the relevant aspects, including frame types, frame addressing and processing, medium access mechanisms, synchronism, security, Body

Area Network (BAN) creation, node connection/disconnection procedures, amongst others. In IEEE 802.15.6, both the nodes and the hub use an established time-based reference, where the controller partitions the time-axis into successive superframes or beacon periods of equal length. Each BAN may operate according to one of three possible modes, set and managed by the hub, however, the extensions proposed in this paper aim only at *Beacon mode with beacon periods* [4]. In this mode, the hub structures the superframes into a series of access phases, each with specific lengths (Fig 1 a)). At the start of the beacon periods, the hub broadcasts a beacon frame (B), setting the boundaries of the current superframe and synchronizing all the nodes. Each superframe can have a maximum of seven distinct access phases: two Exclusive Access Phases (EAP1 & EAP2), two Random Access Phases (RAP1 & RAP2), two Managed Access Phases (MAPs), and a Contention Access Phase (CAP). Nodes may transmit and receive frames in the EAPs, RAPs, and CAP using either CSMA/CA or Slotted Aloha. Regular asynchronous/event-based traffic is transmitted in both the RAP and CAP phases, while the EAP is reserved for emergency data (highest user priority (UP) frames). Lastly, the MAP phase conveys traffic allocated by the hub.

III. IEEE 802.15.6 Extensions

This section details the extensions to the IEEE 802.15.6 protocol proposed in this paper. It should be recalled that one of the target requirements is allowing the coexistence of extended and legacy nodes. To that end, we designed the new services as an overlay to the standard and made the following design decisions: (i) For sake of flexibility, it is used the IEEE 802.15.6 Beacon mode with beacon period superframe boundaries channel access with only three phases: EAP1, RAP1 and MAP. (ii) All of the original control and management frames from the standard are maintained and used when appropriate. (iii) All nodes (legacy and extended) respect the connection/disconnection scheme of the IEEE 802.15.6, and (iv) all frames associated with the protocol extensions are encapsulated as IEEE 802.15.6 data frames. The overall superframe structure, depicted in Fig 1 b), is kept as defined in the standard. However, the MAP is now split into two sub-windows: Flexible MAP (FMAP) and Standard MAP (SMAP). The SMAP window is managed by the standard IEEE 802.15.6 scheduled access mechanisms, while the FMAP window is managed by the extended scheduling services. It should be noted that the hub manages the allocations for both the SMAP and FMAP windows, although using different strategies for each. The length of SMAP and FMAP is adjusted dynamically, according to the actual bandwidth demand of nodes.

A. MAP Scheduling

Throughout the managed access phase, the traffic transmitted in the SMAP is scheduled as in the IEEE 802.15.6 standard, therefore this is the bandwidth portion allocated to legacy nodes. On the other hand, traffic in the FMAP is scheduled by the hub on a superframe-by-superframe basis. The hub's scheduling decisions are broadcast to the nodes via a specific downlink allocation (S), reserved at the end of the MAP (Fig 1 b)). This hub-to-node control channel is made via the IEEE 802.15.6 connection mechanism.

It is important to remark that a single control message, sent in slot S, defines the full schedule for the following FMAP, and that the schedule is built according with the system state, including current traffic requirements and events such as errors. This means that e.g. if a message sent by a node in a given FMAP is affected by an error, the hub can reschedule its re-transmission for the following FMAP, if there is room for it. Another observation is that nodes only need to listen to the channel for a single allocation (S) to determine if they are involved in a traffic exchange in the following FMAP.

B. FMAP Management

As stated above, the hub has a centralized scheduler and transmits the FMAP schedule once in each beacon period. This schedule is sent to the nodes through the S allocation control channel, created during the connection phase, and encapsulated in a data frame that was designed from the perspective of an extended beacon. This control message, designated as B^{FMAP}, includes a command byte, for frame classification, followed by the set of abbreviate node addresses NID, and finally the number of allocation slots assigned to each one and control information. It should be highlighted that while this scheme uses one or more allocation slots for broadcasting the B^{FMAP} frame (depending on the amount of traffic) in the MAP, it allows for the hub to adapt the schedule dynamically and to employ bandwidth-efficient reactive error recovery mechanism, which are features that are lacking in the literature as well as in the standard.

C. Node Connection and Bandwidth Management

Nodes connect to the network using the standard mechanisms defined in the IEEE 802.15.6 protocol [4]. Standard nodes that need MAP scheduled allocations use the Downlink/Uplink or Bilink Request IEs (Information Elements) in Connection Request Frames, requesting specific allocation slots within the MAP. Upon receiving one such requests, the hub can take one of the following procedures:

- If the requested allocation falls within the FMAP, the hub assigns a different slot, in the the SMAP, if one is available. Otherwise the request fails.
- Conversely, if the requested allocation falls within the SMAP, the hub follows the standard procedure, i.e., assigns that slot, if available, or a closer one. If no slots are available the request fails.

On the other hand, when connecting to the network, extended nodes use the Application IE of the Connection Request frame so that the hub can distinguish them from the standard ones. In the Application IE, the nodes transmit the size of their messages, transmission periodicity and deadline, in order for the hub to construct the schedule. Nodes are able to change their requirements at run time by sending a new Connection Request frame. The hub receives the data (responds with a

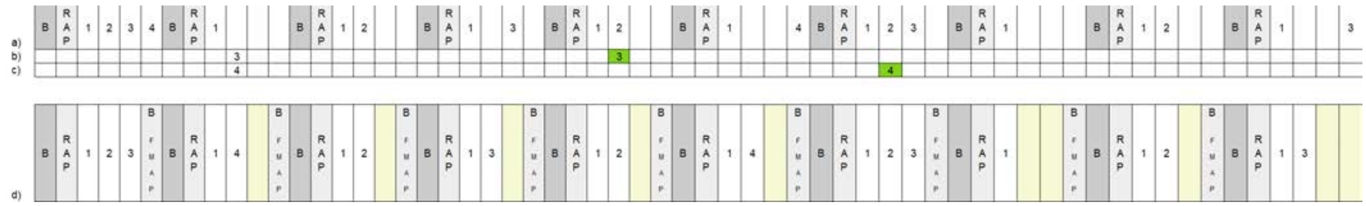

Fig. 2. Node schedulink example a) Standard b) Node 3 with initial phase c) Node 4 with initial phase d) Using FMAP

Connection Assignment) and dynamically updates the schedule for the following superframe.

IV. Preliminary Evaluation

Follows a simple example that aims at illustrating the potential advantages of the flexible scheduling scheme herein proposed. It is considered a superframe with RAP1 and MAP set to one and four slots, respectively, and the beacon B being transmitted at the start of each beacon period. Four nodes, each sending one message that uses a single allocation slot, join the network. The corresponding periods, expressed as integer multiples of the superframe duration, are $T_n = \{1, 2, 3, 5\}$. It is desirable to use scheduled uplinks, in order to minimize energy consumption. One possible allocation in such scenario is granting node 1 with the first MAP slot, node 2 the second, node 3 the third and node 4 the fourth, as shown in Figure 2 a). Note that despite not transmitting data in all superframes, nodes 2, 3 and 4 are not allowed to share allocation slots, because its periods are relative primes so independently of the initial phasing a collision would occur, as illustrated in Figure 2 b) and c). Consequently, despite using a relatively low bandwidth share ($approx.$ 51% of the MAP), no further scheduled messages can be admitted. By following the standard, one solution would be to use instead polled services. However, these services use more bandwidth, due to the poll message issued for each transaction, and implies that nodes have to be awake for the full MAP time, as the hub poll message instants cannot be predicted by the nodes, resulting in a significant increase in energy consumption.

In contrast, by using the extensions presented in this paper, additional messages can be scheduled, allowing in this case using up to 75% of the bandwidth, as illustrated in Figure 2 d), where lime colored slots are available. Note that this is an unfavourable scenario, as usually superframes comprehend a much higher number of slots, so the relative overhead due to the transmission of B^{FMAP} is expected to be much smaller than the 25% of this simple case. Nodes have to awake once in each superframe for listening for the B^{FMAP} message, but again the penalization in terms of energy consumption is expected to be, in general, relatively small, as B^{FMAP} immediately precedes the beacon message, so nodes still need to wake up just once. Therefore, in practical terms, nodes need to extend the listening period, once per superframe.

V. Closure

Advances in sensor-based technologies, particularly in what concerns size, energy, processing power and wireless communications, are enabling the development of increasingly complex and powerful Wireless BAN-based healthcare monitoring systems. This paper presents ongoing work towards the development of a novel scheduling scheme for such architectures, which extends the services provided by the IEEE 802.15.6 standard, allowing dynamic traffic scheduling. The proposed scheme permits changing the allocations in a per-superframe basis, with low overhead, and supports bandwidth-efficient reactive error handling, while preserving coexistence with legacy nodes, which are unique features with respect to the state-of-the-art approaches. A simple and preliminary example, illustrating the potential benefits that can be attained, is included. Future work includes carrying out an extensive performance comparison with state-of-the art approaches, as well as evolve the scheduling and error recovery mechanisms.

Acknowledgement

This work has been supported by the European Union's Horizon 2020 Research and Innovation Programme (H2020-FETOPEN-2018-2020, NeuroStimSpinal Project, Grant Agreement No. 829060). G.G. acknowledges the European Union's Horizon 2020 Research and Innovation Programme for her PhD grant under the NeuroStimSpinal Project (No. 829060). This work is funded by FCT/MCTES through national funds and when applicable co-funded EU funds under the project UIDB/50008/2020-UIDP/50008/2020

References

[1] S. Movassaghi, M. Abolhasan, J. Lipman, D. Smith, and A. Jamalipour, "Wireless body area networks: A survey," *IEEE Communications Surveys and Tutorials*, vol. 16, no. 3, pp. 1658–1686, 2014.

[2] R. Negra, I. Jemili, and A. Belghith, "Wireless Body Area Networks: Applications and Technologies," *Procedia Computer Science*, vol. 83, pp. 1274–1281, 2016.

[3] K. S. Kwak, S. Ullah, and N. Ullah, "An overview of IEEE 802.15.6 standard," in *2010 3rd International Symposium on Applied Sciences in Biomedical and Communication Technologies, ISABEL 2010*, 2010.

[4] R. Heile, A. Rick, K. Patrick, G. James, and Chaplin Clint, *IEEE Standard for Local and metropolitan area networks — Part 15 . 4 : Low-Rate Wireless Personal Area Networks (LR-WPANs) Amendment 1 : MAC sublayer IEEE Computer Society*, vol. 2012. 2012.

[5] M. E. Azhar, I. Rashid, S. K. F. Bashir, and Y. Zia, "IEEE 802.15.6 superframe adjustment by using drop packet estimation technique," *2016 6th International Conference on Innovative Computing Technology, INTECH 2016*, pp. 413–417, feb 2017.

[6] A. Muthulakshmi and K. Shyamala, "Efficient Patient Care Through Wireless Body Area Networks—Enhanced Technique for Handling Emergency Situations with Better Quality of Service," *Wireless Personal Communications*, vol. 95, pp. 3755–3769, aug 2017.

[7] B. Liu, Z. Yan, and C. W. Chen, "Medium Access Control for Wireless Body Area Networks with QoS Provisioning and Energy Efficient Design," *IEEE Transactions on Mobile Computing*, vol. 16, no. 2, pp. 422–434, 2017.