A new highly efficient MAC protocol for WBAN: exceptional performance in the face of selfish behaviors

Nabila Azdad, Mohamed Elboukhari
MATSI Laboratory ESTO, Mohammed First University, Oujda, Morocco

Article Info	ABSTRACT
	Over the last two decades, wireless body area networks (WBANs) have gained significant traction in healthcare applications. These networks facilitate connections among various sensors, which can be integrated into clothing, placed directly on the body, or implanted beneath the skin. While these sensors typically serve a single application, they generate traffic with diverse requirements. Managing this diversity necessitates tailored treatment to meet specific traffic needs while satisfying application requirements such as reliability and timeliness. In this paper, we propose a novel, flexible, and power-efficient medium access control (MAC) protocol designed to seamlessly complement existing solutions. Our protocol, available in two versions as an enhancement to the beacon-enabled mode of IEEE 802.15.4, aims to optimize quality of service (QoS) for periodic traffic applications within WBANs, irrespective of traffic and density conditions, without compromising energy efficiency. Our results demonstrate significant improvements compared to the standardized IEEE 802.15.4-MAC protocol across all test scenarios, even in the presence of selfish behaviors. These findings underscore the protocol's efficacy in enhancing reliability and efficiency in wireless healthcare systems.

Corresponding Author:

Nabila Azdad
MATSI Laboratory ESTO, Mohammed First University
Oujda, Morocco
Email: nabilaazdad5@gmail.com

1. INTRODUCTION

Traditionally, monitoring health status has been confined to medical facilities such as clinics and hospitals. In these settings, acquiring health information typically involves the use of wired sensors and electrodes for extended periods, causing discomfort to the individual both physically and emotionally [1], [2]. With the advent of a novel network structure known as wireless body area network (WBAN) [3]–[5], a more convenient approach to tracking health status during daily activities has emerged. Through the utilization of WBANs, health-related data can now be seamlessly monitored in real-time, irrespective of the individual's whereabouts. These networks integrate various physiological devices, whether wearable or implantable, designed to capture essential bodily parameters (such as heart rate, blood pressure, and temperature). Subsequently, this data is transmitted wirelessly to a nearby coordinating device (e.g., wristwatch, tablet, smartphone, and laptop), which can display the pertinent information on a user interface or relay it to remote medical professionals for diagnostic and therapeutic purposes through long-range communication channels. As illustrated in Figure 1, three levels of communications can be distinguished in WBANs: intra-ban communications where body sensors interact with each other and with personal devices [6]. Inter-BAN communications that entail interactions between personal devices and access points [7] and Beyond-BAN communications that connect body sensor networks with the external environment [8].
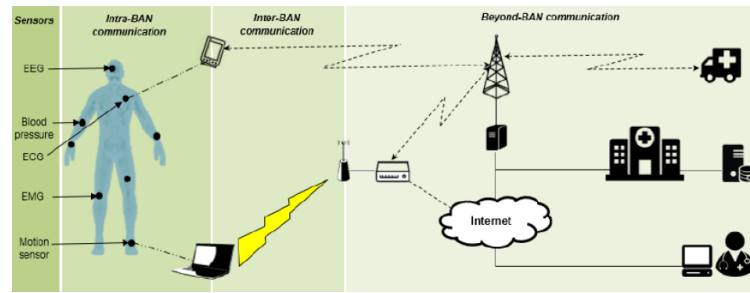
Figure 1. WBAN communication architecture [5]

Existing literature indicates that the great majority of the medium access control (MAC) protocols proposed for intra-WBAN communications draw inspiration from the beacon-enabled mode of IEEE 802.15.4. These protocols aim to adapt node channel access based on traffic categories [9]–[12]. However, prior efforts to enhance overall network performance have often disadvantaged nodes in the regular traffic category. Despite recognizing that a single set of MAC parameters cannot optimize performance across all traffic periodicity levels in WBANs [13], there is a lack of solutions to differentiate access configurations for the different sensor profiles under periodic traffic. In this context, our study introduces a novel MAC protocol for WBAN regular traffic, named fairness-oriented traffic aware MAC protocol (FOTA-MAC). Our approach aims to optimize WBAN performance under diverse traffic loads and ensure equitable channel access for the different sensor profiles within the regular traffic category. This is achieved by configuring access for each profile to align optimally with its performance characteristics.

The rest of this paper is structured as follows. In section 2, we situate FOTA-MAC among the protocols proposed in the literature. In section 3 presents the detailed operation of our proposal FOTA-MAC. The performance evaluation results of FOTA-MAC are presented and analyzed in section 4. Finally, we conclude the paper in section 5.

2. THE PROPOSED METHOD

According to our review of the literature, the great majority of the approaches proposed in the last seven years as improvements for the beacon-enabled mode of IEEE 802.15.4, have focused on differentiating the access of nodes according to the type of their traffic (as is the case for TA-MAC [14], traffic- adaptive priority-based MAC TAP-MAC [15] and energy consumption traffic prioritization MAC (ECTP-MAC) [16]), or based on their priority (as is the case for energy efficient traffic prioritization for MAC (EETP-MAC) [17] and TraPy-MAC [18]). However, although a single access configuration does not achieve optimal performances for all the periodic traffic conditions [13], so far there is no solution that differentiates the access of the different sensor profiles within periodic traffic category if they are of the same priority. The solutions presented in this paper are designed for periodic traffic and primarily concentrate on tailoring access configurations according to sensor throughput requirements. Thus, FOTA-MAC complements existing solutions and can be easily integrated with them for enhanced efficiency.

3. METHOD

FOTA-MAC protocol is proposed for the regular traffic applications of WBANs under two versions, and aims to achieve an optimal performance whatever the traffic conditions. It is based on an adaptable approach that adjusts its operation according to the observed traffic.

3.1. Traffic patterns

Both versions of FOTA-MAC categorize sensors into two profiles: i) sensors with light traffic and ii) sensors with heavy traffic. The network deployment unveils three distinct traffic patterns: a light homogeneous pattern, characterized by low-rate traffic generation; a heavy homogeneous pattern, where traffic rates range from medium to high; and a heterogeneous pattern, wherein sensor nodes generate varied traffic patterns. Utilizing the classification outlined in [19], we've set the threshold distinguishing light from heavy traffic profiles at 1,000 bits/s. This threshold can be adjusted based on the application's traffic.

3.2. The first version: FOTA-MAC-V1

In the first version of FOTA-MAC, the channel time is divided into superframe structures. These superframes begin with a beacon frame, signaling the start of an active phase during which nodes transmit data to the coordinator. The structure of the initial superframe mirrors that of IEEE 802.15.4, consisting of

two segments: a contention access period (CAP1) for nodes to contend for channel access, and an inactive phase for energy conservation. Subsequently, the duration of CAP1 in each superframe is adjusted based on the number of received packets and buffered packets from the preceding superframe:

$$\text{CAP1length} = L_{CAP1} \frac{(\text{PendingPktsPrev} + \text{RcvPktsPrev})}{\text{RcvPktsPrev}} \qquad (1)$$

where:
− L_{CAP1}: is the length of the CAP1 period in the previous superframe.
− pendingPacketsPrev: is the total number of packets buffered during the previous superframe.
− RcvPktsPrev: is the total number of packets received in the previous superframe.
the network coordinator defines the superframe structure based on two key parameters [20]:
− Beacon interval (BI): that determines the time interval between two consecutive beacons.
− Superframe duration (SD): that sets the duration of the active portion of the superframe.
The optional inactive period is defined when BI > SD, and its duration is given by [20]:

$$Inactive\ Period\ =\ BI\ -\ SD \qquad (2)$$

the duty cycle (DC), representing the percentage of time power is present, is calculated as follows [20].

$$DC\ =\ SD\ /\ BI \qquad (3)$$

BI and SD are determined by two superframe parameters, namely the beacon order (BO) and the superframe order (SO), according to the following equations [20], [21]:

$$BI\ =\ aBaseSuperframeDuration\ *\ 2^{BO} \qquad (4)$$

$$SD\ =\ aBaseSuperframeDuration\ *\ 2^{SO} \qquad (5)$$

for the values of FO and BO parameters, they are determined by choosing a higher duty cycle for heavy traffic scenarios.

3.3. The second version: FOTA-MAC-V2

In the second version of our protocol, we adopt a structure similar to that of IEEE 802.15.4 for the first superframe, which consists of a contention access period (CAP1) and an inactive period. Subsequently, the coordinator node dynamically adjusts the structure of each superframe based on the observed traffic patterns: homogeneous models operate similarly to the first version. For heterogeneous traffic, the superframe is divided into CAP1 for light traffic nodes and CAP2 for heavy traffic nodes. This segregation optimizes performance and minimizes conflicts, enhancing both quality of service (QoS) and energy efficiency. By activating sensor nodes only during relevant traffic periods, FOTA-MAC-V2 achieves greater energy efficiency [22]. The active period part(s) of each superframe are adjusted based on:
− The ratio of the number of nodes in each traffic category, to the total number of nodes in the considered WBAN model, if different traffic categories are detected.
− The total number of packets received during the previous superframe, if only one traffic category is detected.
− The Number of packets queued during the previous superframe, if only one category of traffic is detected. After adjusting the lengths of CAP1 and CAP2 by the coordinator node, it stills to adapt the superframe parameters that will be broadcasted in the beacon frame. The values of the FO and BO parameters are determined by choosing a higher duty cycle for heavy traffic scenarios.

3.4. The considered MAC frame format

To implement our new protocol using the same frames as the IEEE 802.15.4 standard [21], [23], [24] without the need to add new ones, we have exploited the three reserved bits of "the frame control field" of:
− Association requests for transmitting the traffic class of each sensor. Indeed, to allow the computation of the number of nodes in each traffic category by the coordinator node, each sensor node transmits its traffic class in the reserved field of the association request. The value of this field is set to 0 if the traffic rate of the node is inferior to the predefined threshold (1,000 bits/second), and 1 if the sensor node has a packet rate superior to the predefined threshold.

− Data frames for transmitting information about the buffer status of each node. Indeed, to estimate the number of pending packets for each traffic category by the coordinator, each node has to transmit the number of its buffered packets using the three reserved bits of data frames. At the reception of each data frame, the coordinator stores this information in an array, and updates it at each data frame reception from the same sensor. However, the three bits of the reserved field allow nodes to inform the coordinator about a maximum of seven pending packets, while they may store more packets in their buffers. Due to this constraint, we have considered the following equation to transmit the buffer status information in the reserved field [25].

$$\text{bufferStatus} = \frac{\text{numBufferedPkts}}{\frac{\text{bufferSize}}{7}} \tag{6}$$

Where numBufferedPkts is the number of queued packets, and buffer size specifies the maximum number of packets that can be stored in the queue. For the beacon frame of IEEE 802.15.4, we reused the "Final CAP Slot" subfield to identify the CAP1 period length instead of the CAP length. And we added a "CAP2 length" subfield to identify the length of CAP2.

3.5. The adopted channel access schemes

Based on the analyses presented in [7], [9], [10], [12], [26], [27], and in order to achieve more reliable communications, we have decided to adopt two versions of Slotted CSMA/CA [20], [21] in our proposal: the traditional profile of Slotted CSMA/CA [28] for light traffic, and for heavy-traffic, we have proposed a new version of slotted CSMA/CA namely, fast slotted CSMA/CA (FS-CSMA/CA) where the contending nodes use the same value of BE (initialized to BE_{init}) during all the steps of the algorithm without increasing it if the channel is sensed busy [29]. This new version will ensure a quick access to the communication medium, which decreases buffer overflow probabilities as well as contention time. Figure 2 presents the flow chart of the considered access schemes:
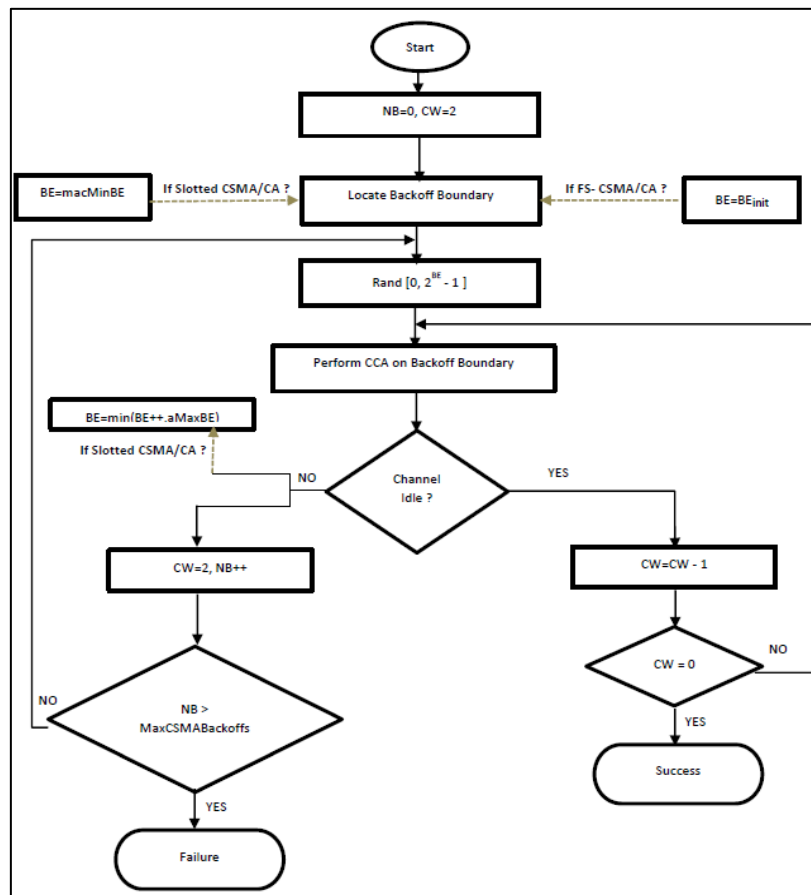

Figure 2. Flow chart of the considered access schemes

− Backoff exponent (BE): it facilitates the computation of the duration for which a node must wait before attempting a frame transmission. (BE is initialized to a variable known as macMinBE in slotted CSMA/CA algorithm).
− Contenion window (CW): it determines the number of backoff periods that must be idle before the start of transmissions.
− Number of backoff attempts (NB): it indicates the number of channel access attempts for the current transmission.
− macMaxFrameRetries: this parameter sets the maximum number of retransmissions a node can perform before dropping a frame in the absence of an acknowledgment.
− macMaxCSMABackoffs: it defines the maximum number of times a node will test the channel's activity before dropping a frame.

4.   RESULTS AND DISCUSSION

Occasionally, a node may exhibit selfish behavior at the MAC sub-layer, leading to a reduction in the waiting time (backoff period) to elevate its transmission priority. This self-serving conduct results in enhanced transmission capacity for the particular node at the expense of others. To assess our protocol's performance using Castalia simulator, we compared the effects of selfish behaviors on FOTA-MAC and the original IEEE 802.15.4 standard under two scenarios. Firstly, we examined homogeneous traffic scenarios, where we deployed a network of 9 sensors with the coordinator in a star topology. We considered two traffic patterns: a light traffic pattern where each sensor generates 80 bits/second and a heavy traffic pattern where sensors generate 2,000 bits/second. Sensor #1 acted as the selfish node in these scenarios. Additionally, we explored a heterogeneous traffic scenario with a network of 5 sensors and the coordinator in a star topology. Nodes #1, #2, and #3 generate 2,000 bits/second, while nodes #4 and #5 generate 400 bits/second. In this scenario, we considered two selfish nodes: sensors #1 and #5.

4.1. Scenarios 1: evaluation under homogeneous traffic models

Figures 3-5 illustrate the results obtained for the first part of our test scenarios in terms of packet delivery ratio (PDR), average delays, and energy efficiency, respectively. The findings reveal that node #1, exhibiting selfish behavior in an IEEE 802.15.4 network under heavy homogeneous traffic, notably enhanced its own performance in terms of PDR, timeliness, and energy efficiency, at the expense of other nodes. Which highlights the capacity of selfish nodes to diminish the transmission capacity of others in such networks. Contrastingly, in networks employing our protocol, the selfish behavior of nodes merely diminishes their PDR and energy efficiency. In light homogeneous traffic scenarios, the selfish node improved its average delay but experienced declines in PDR and energy efficiency without major repercussions on other nodes' performance.
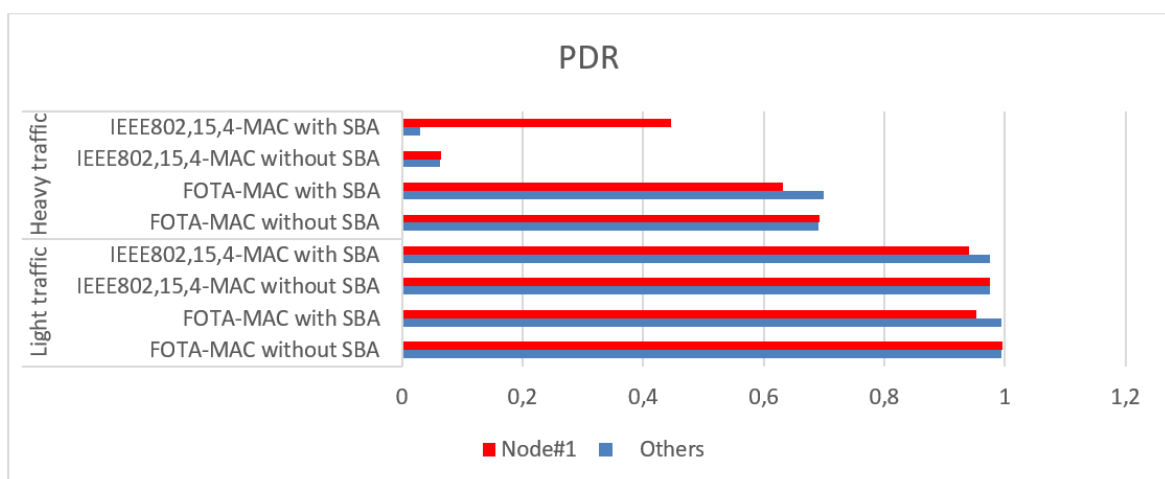

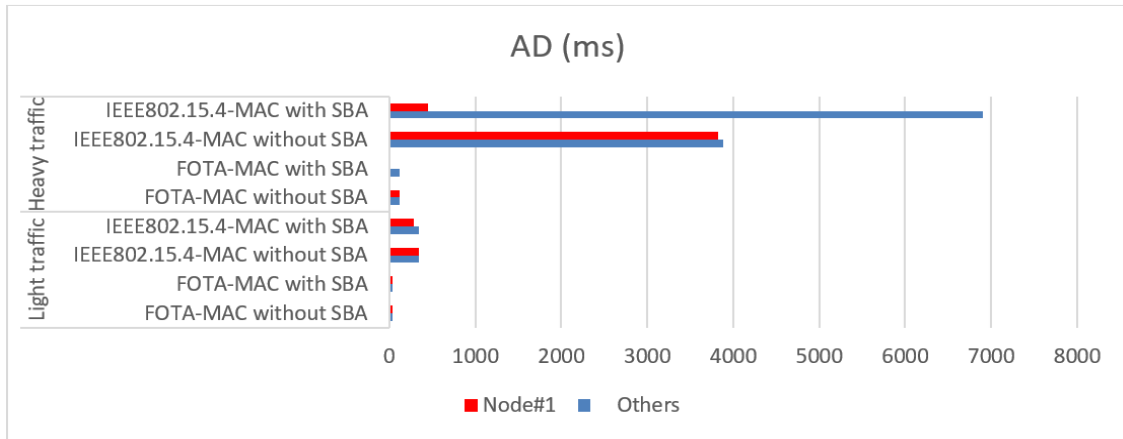Figure 3. The impact of selfish behaviors on homogeneous traffic in terms of PDR

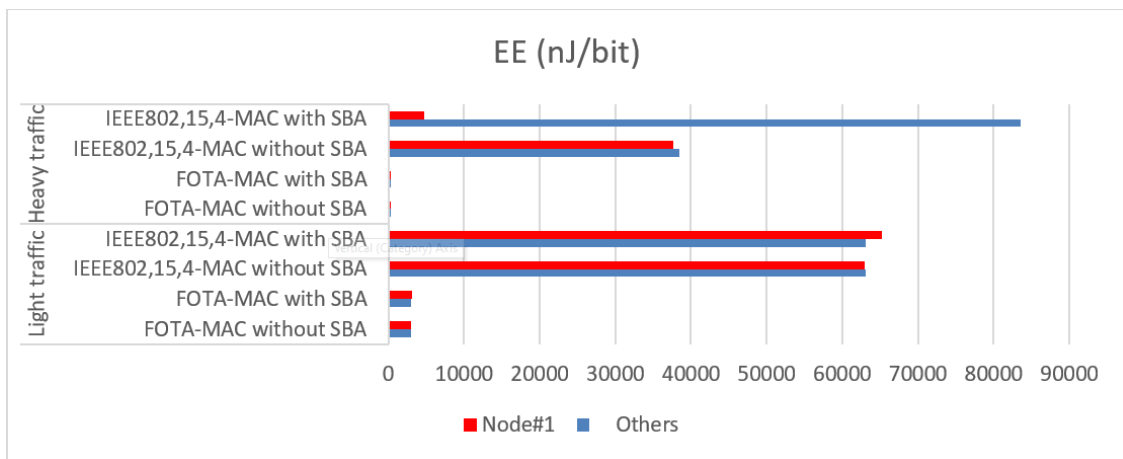Figure 4. The impact of selfish behaviors on homogeneous traffic in terms of the average delay

Figure 5. The impact of selfish behaviors on homogeneous traffic in terms of energy efficiency

4.2. Scenarios 2: evaluation under a heterogeneous traffic model

Figures 6-8 illustrate the performance results obtained for each sensor node under the second part of our test scenarios, in terms of PDR, average delays, and energy efficiency, respectively. Based on our findings, within the IEEE 802.15.4 standard, selfish nodes (#1 and #5) markedly enhance their performance at the expense of others, affecting PDR, transmission speed, and power efficiency. For the first version of our protocol, selfish behavior exhibited by nodes #1 and #5 leads solely to their performance degradation.
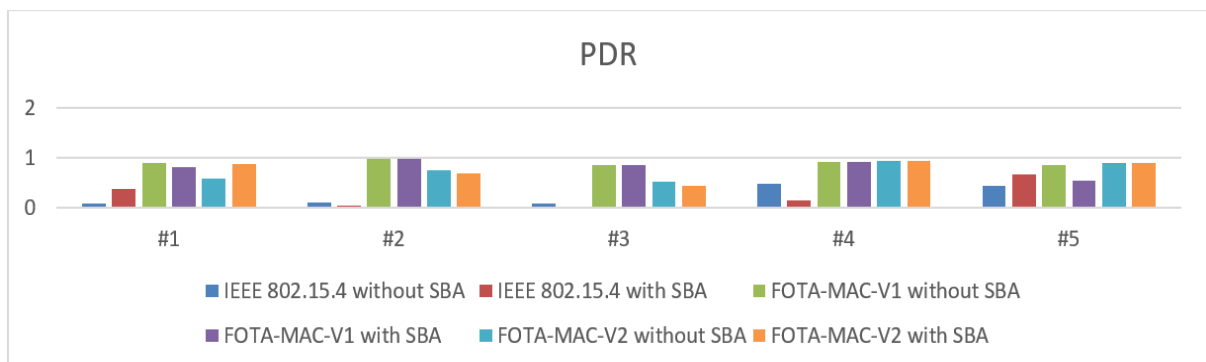

Figure 6. The impact of selfish behaviors on heterogeneous traffic in terms of PDR

In the second version of FOTA-MAC, node #1's selfish actions bolster its performance while detrimentally affecting competitors. Conversely, node #5's selfish conduct only diminishes its PDR, with negligible repercussions for competitors. However, despite the potential for performance degradation under this version due to selfish behavior, it remains more advantageous than IEEE 802.15.4. Moreover, FOTA-MAC-V2's superframe structure under heterogeneous traffic restricts selfish node activity to affect only nodes of the same category.
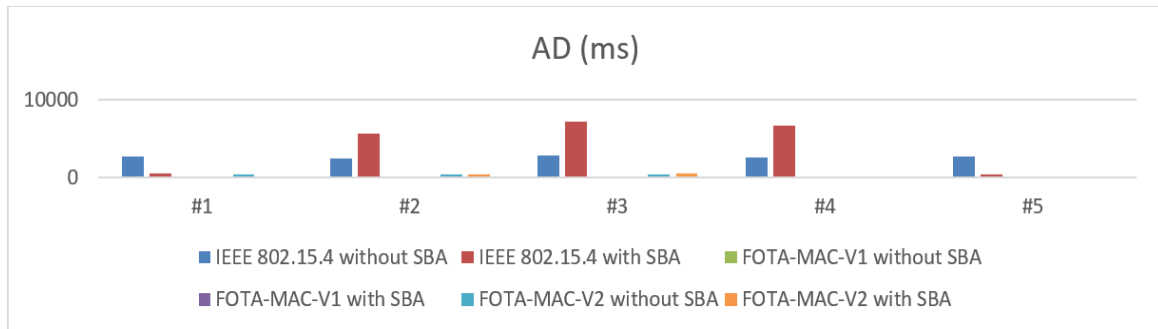

Figure 7. The impact of selfish behaviors on heterogeneous traffic in terms of the average delay
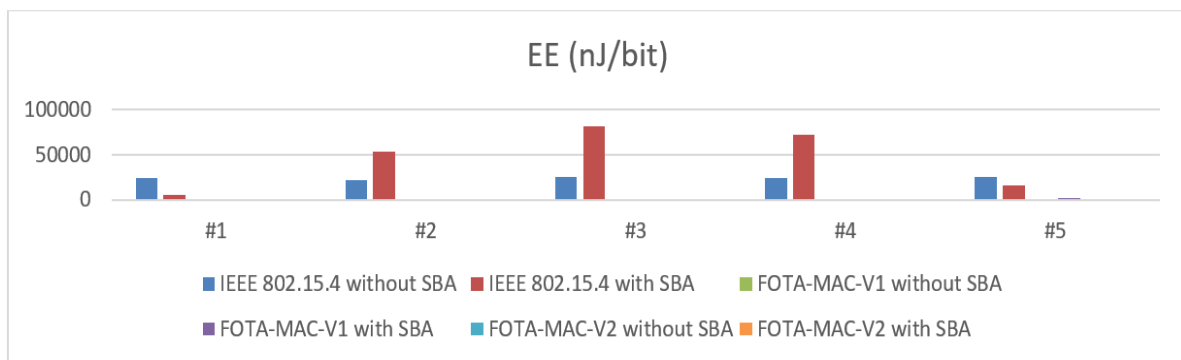

Figure 8. The impact of selfish behaviors on heterogeneous traffic in terms energy efficiency

5. CONCLUSION

In this research, we have introduced a novel traffic-aware energy efficient MAC protocol for WBAN-based health monitoring systems, namely, FOTA-MAC. This protocol replaces the static operation of IEEE 802.15.4 by a dynamic one that takes into consideration the traffic conditions to maximize the performance of the deployed networks. Furthermore, FOTA-MAC uses a fairness-oriented approach that aims on one hand to ensure a fair access configuration between the different sensor profiles through configuring the access of each profile using the way that optimize its performance, and on the other hand to optimize the performance of WBANs whatever the traffic loads. To evaluate the performance of FOTA-MAC, we have compared it with the original version of IEEE 802.15.4 under different traffic patterns using the latest version of Castalia simulator (3.3). Overall, the simulation results show that, FOTA-MAC performs more efficiently and achieves important gains even in the presence of selfish attacks. For our future works, we aim to improve FOTA-MAC-V2 by integrating detection and reaction processes against selfish behaviors. Then, after validating our improvements from a theoretical point of view, it would be highly useful to validate the final versions of our protocol using wireless sensor platforms.

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BIOGRAPHIES OF AUTHORS

Nabila Azdad 🆔 ⊞ SC ↻ received an M.Sc. degree in "Intelligent Systems and Networks" from the Faculty of Sciences and Technologies, Fez, Morocco, in 2016. She is currently a Ph.D. in MATSI Laboratory at Mohammed First University, Oujda, Morocco. Her research interests include wireless sensor networks, algorithms, and mobile healthcare. She can be contacted at email: nabilaazdad5@gmail.com.

Mohamed Elboukhari 🆔 ⊞ SC ↻ received an M.Sc. degree in computer science in 2005 from the Mohammed First University, Oujda, Morocco. He is currently a professor at the Higher School of Technology (ESTO), Mohammed First University, Oujda, Morocco. His research interests include web tracking and wireless network security. He can be contacted at email: elboukharimohamed@gmail.com.