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PAPER

FOTA-MAC: A Novel Traffic Adaptive MAC Protocol for Wireless Body Area Networks

Nabila Azdad(✉), **Mohamed Elboukhari**

MATSI Laboratory, Mohammed First University, Oujda, Morocco

nabilaazdad5@gmail.com

ABSTRACT

Recently, Wireless Body Area Networks (WBANs) have emerged as a significant breakthrough in the healthcare sector due to their immense potential to revolutionize health outcomes. This type of network is able to support a diverse range of applications with traffic rates ranging from several bits per hour up to 10 megabits per second. The challenge lies in accommodating this wide range of applications and meeting their distinct requirements using a single suitably flexible medium access control protocol. In response to this challenge, our paper proposes a novel Traffic Adaptive MAC protocol designed specifically for the regular traffic of WBANs. This innovative protocol dynamically adapts its operation based on the observed traffic, leading to significant efficiency gains compared to the standardized MAC protocols IEEE 802.15.4 and IEEE 802.15.6. Our contribution aims to address the critical need for a tailored and adaptive MAC protocol that can seamlessly handle varying traffic loads within WBANs. By incorporating our protocol, we envision enhanced communication efficiency and improved performance, unlocking new possibilities for healthcare applications and ultimately revolutionizing the healthcare industry.

KEYWORDS

WBAN, MAC protocol, regular traffic

1 INTRODUCTION

Traditionally, health monitoring services have been limited to clinics and hospitals, where collecting information about health status necessitates the use of wire-based sensors and electrodes for several hours in the majority of cases, which is uncomfortable for body and mood. But now, thanks to a new type of network architecture, namely, Wireless Body Area Network (WBAN) [1] [2], it becomes possible to track health status in a comfortable way while engaged in routine life activities.

Using WBANs, health related data can be monitored online regardless of the user's location. Indeed, such networks incorporate different physiological devices, wearable or even implantable, able to sense significant physiological parameters

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from the human body and transmit them wirelessly to a nearby device that may display the according information on a user interface or forward them to off-site doctors for diagnostic and therapeutic purposes using long-range communications.

Based on the literature, we have noticed that the great majority of the MAC protocols proposed for intra-WBAN communications taking place between sensors and the central unit are derived from the beacon-enabled mode of IEEE 802.15.4, and aim to differentiate the channel access configuration of nodes based on their traffic category [3] [4] [5] [6]. However, to the best of our knowledge, all the existing works enhance the overall network performance at the expense of some specific nodes within the regular traffic category. Furthermore, although a single choice for the MAC parameter values does not achieve optimum performance for all the periodicity levels of regular traffic under WBANs [7], there is no solution that differentiates the access configuration of the different sensor profiles under periodic traffic. In the current paper, we propose a new traffic-aware MAC protocol for the regular traffic of WBANs, namely Fairness-Oriented Traffic Aware MAC Protocol (FOTA-MAC). Our proposal aims on one hand to optimize the performance of WBANs whatever the traffic loads, and on the other hand, to ensure an equitable channel access configuration between the different sensor profiles within the regular traffic category by configuring the access of each profile in a way that optimizes its performance. FOTA-MAC complements the existing solutions, and can be easily merged with them for better performance under wireless body area networks.

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

2 FOTA-MAC PROTOCOL OPERATION

FOTA-MAC protocol (Fairness-Oriented Traffic Aware Medium Access Control protocol) is developed for the regular traffic applications of WBANs, and operates in star topology WBANs using the beacon-enabled mode. The detailed operation of our protocol is discussed below.

2.1 Traffic patterns

In FOTA-MAC, three traffic pattern classes are distinguished: **Light-periodic traffic class, Heavy-periodic traffic class,** and **heterogeneous-periodic traffic class.** Based on the classification presented in [8], we have initialized the threshold that distinguishes light traffic from heavy traffic to 1000 bits/s.

2.2 Superframe structure of FOTA-MAC

Initially, the structure of the first superframe is similar to that of IEEE 802.15.4 [7] and consists of two parts: a contention access period (CAP1) where nodes contend for channel access using Slotted CSMA/CA, and an inactive period. Then, at the beginning of each superframe, the coordinator node decides about its structure based on the traffic pattern(s) observed in the previous superframe. If the observed pattern is of the first or second class, the CAP1 period of the current superframe will be adapted according to the number of packets received and those queued during the previous superframe. However, if a heterogeneous-periodic traffic was detected during the previous superframe, the current superframe will be divided into two periods CAP1 and CAP2. CAP1 deals with light traffic, while CAP2 deals with heavy traffic. On one hand, this will allow to mitigate high channel contention and collisions in the deployed networks, and on the other hand, each traffic category will be treated appropriately. The period lengths of CAP1 and CAP2 are broadcasted in the beacon frames. To decide about the structure of each superframe, the coordinator node follows the following steps:

Step 1: Computing the number of nodes in the considered WBAN. At the reception of an association request from a sensor node, the coordinator node extracts its traffic class from the received frame and increments either N_L if the value of the class is 0 (the sensor generates light traffic), or N_H if the value of the class is 1 (the sensor generates heavy traffic). (cf. Algorithm 1).

Algorithm 1: Computing the Number of Nodes in Each Traffic Category
Inputs: Let ni ∊ **N denotes a node with association request, and ci traffic class of ni**
Outputs: N_L: Number of nodes with light traffic, N_H: Number of nodes with heavy traffic

N_L ← 0;
N_H ← 0;
while (! End of L_{CAP1}) do
  if(! isCoordinator)
    associationRequestPacket->setTrafficCategory(ci);
    sendAssociationRequest;
  end if
  if (isCoordinator)
    receiveAssociationRequest();
    c ← associationRequestPacket->getTrafficCategory();
   if c == 1
     N_H + +;
   else if c == 0
     N_L + +;
   end if
  end if
end while

Step 2: Adjusting the active period part(s). After computing the number of nodes in each traffic category, the coordinator node will be aware of the existing traffic-pattern(s), and adjusts the active period part(s) based on (cf. Algorithm 2):

- The ratio of number of nodes in each traffic category (N_L and N_H) to the total number of nodes (N_T) 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.

Algorithm 2: Adjusting the Active Period Part(s)
Inputs: L_{CAP1}: the length of the CAP1 period in the previous superframe, N_L: Number of nodes with light traffic, N_H: Number of nodes with heavy traffic, N_T: total number of nodes pendingPacketsTable[]:Table containing the number of packets buffered by each sensor rcvPktsPrev: The total number of packets received in the previous superframe
Outputs: Length of CAP1 in the current superframe Length of CAP2 in the current superframe

// Computing the total number of packets buffered during the previous superframe
PendingPktsPrev ← 0;
for (i←1; i < N_T; i++)
    pendingPktsPrev ← pendingPktsPrev + pendingPacketsTable[i];
End for
/*First situation: detection of heterogeneous traffic*/
if (N_L != 0 et N_H != 0)
        beaconPacket->setCAP1length(L_{CAP1} * N_L/N_T);
        beaconPacket->setCAP2length(L_{CAP1} * N_H/N_T);
else
/*Second situation: detection of homogeneous traffic*/
    if (rcvPktsPrev != 0)
        *beaconPacket->setCAP1length(L_{CAP1} * (pendingPktsPrev + rcvPktsPrev) / rcvPktsPrev);*
        beaconPacket->setCAP2length(0);
    else
        beaconPacket->setCAP1length(L_{CAP1});
        beaconPacket->setCAP2length(0);
    end if
end if

Step 3: Adjusting the superframe parameters. 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 (cf. Algorithm 3).

Algorithm 3: Adjusting SO and BO Parameters
Inputs: FO_0: initial value of FO N_L: Number of nodes with light traffic, N_H: Number of nodes with heavy traffic,
Outputs: FO and BO values

if (N_L != 0 et N_H != 0)
        FO ← FO_0
        BO ← FO_0
    else if (N_L == 0 et N_H != 0)
        FO ← FO_0
        BO ← FO_0 + 1
    else
        FO ← FO_0
        BO ← FO_0 + 2
end if

2.3 The adopted channel access schemes

According to the references [9] and [10], the contention-based access scheme used by the beacon-enabled mode of IEEE 802.15.4 (Slotted CSMA/CA) provides a high level of reliability under low loads WBANs. However, it faces limitations in supporting high traffic loads. After analyzing the findings presented in the references [7] and [11], and aiming to achieve more reliable communications in WBANs, we have opted to incorporate two versions of Slotted CSMA/CA in our proposal. For light traffic, we adopt the traditional profile of Slotted CSMA/CA. For heavy traffic, we introduce a new version named Fast Slotted CSMA/CA (FS-CSMA/CA). In this new version, contending nodes use a fixed value of BE (initialized to BEinit) throughout the algorithm without increasing it when the channel is sensed as busy. This modification ensures quick access to the communication medium, reducing buffer overflow probabilities and contention time.

3 PERFORMANCE EVALUATION OF FOTA-MAC UNDER WBAN

In this section, the performance of FOTA-MAC is evaluated and compared with the IEEE norms 802.15.4 and 802.15.6. in terms of **Delivery reliability** (measured in terms of packet delivery ratio (PDR)) and **Timeliness** (measured in terms of the average transmissions delay (AD)).

3.1 Simulation environment and parameters

For evaluating the performance of our proposal using Castalia simulator, we considered a star topology where sensor nodes transmit their packets to the coordinator node (Node #0) at a constant rate. And for taking into consideration the rapidly changing environment of WBAN (body moving), we have used the temporal variation model provided by Castalia. Our simulations are carried out into two scenarios:

- In the first one, the performance of FOTA-MAC is evaluated under light (5 packets/node/s) and heavy (125 packets/node/s) homogeneous traffic models with respect to various node densities. The size of the data packets is fixed at 5 bytes.
- In the second one, we evaluate our solution under heterogeneous-periodic traffic. In this part, our simulations are carried out according to two parts of scenarios:
  - In scenario A, we set the number of nodes with heavy traffic to 10 and varied the number of nodes with light traffic from 5 to 50. Nodes with light traffic generate 120 bits/s (5 packets/s with a payload of 3 bytes), while heavy traffic ones generate 36000bits/s (50 packets/s with a payload of 90 bytes).
  - In scenario B, we set the number of nodes with light traffic to 10 and varied the number of nodes with heavy traffic from 5 to 50. Nodes with light traffic generate 80 bits/s (5 packets/s with a payload of 2 bytes), while heavy traffic ones generate 20,000bits/s (25 packets/s with a payload of 100 bytes).

The MAC parameters considered for FOTA-MAC are listed in Table 1.

Table 1. FOTA-MAC parameters

Parameter	Value	Parameter	Value	Parameter	Value
FO_0	4	macMaxCSMABackoffs	4	$L_{CAP1\text{-}init}$ (Slots)	16
BEinit	5	macMaxFrameRetries	2	macMaxBE	7

3.2 Simulation results and analysis

Scenario 1.

Delivery reliability. Figure 1 illustrate the delivery reliability results observed under the different configurations considered in the first scenario.

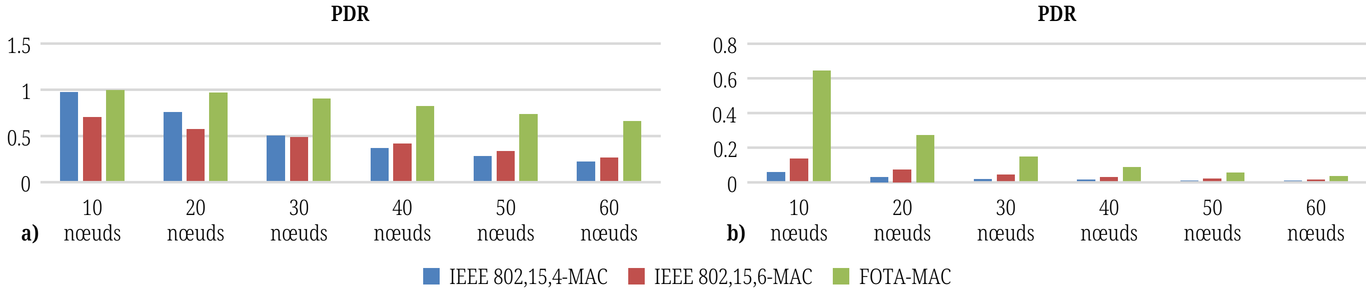

Fig. 1. Delivery reliability versus traffic density under (a) light traffic and (b) heavy traffic

The results indicate that our proposal ensures a very high level of delivery reliability under light traffic conditions, reaching up to 99.99%. Moreover, the protocol shows significant performance improvements under heavy traffic conditions, with a speedup of up to 1008% compared to IEEE 802.15.4 and 367% compared to IEEE 802.15.6.

Timeliness. The average network delay results observed under the different considered configurations are illustrated in Figure 2.

The obtained results show that FOTA-MAC is capable of achieving faster communications than both standards. As shown in the figures, the use of FOTA-MAC under light traffic conditions reduces the average delay by up to 99.588% compared to IEEE 802.15.4 and 99.472% compared to IEEE 802.15.6. Under heavy traffic conditions, the reduction is up to 97.393% over IEEE 802.15.4 and 95.747% over IEEE 802.15.6.

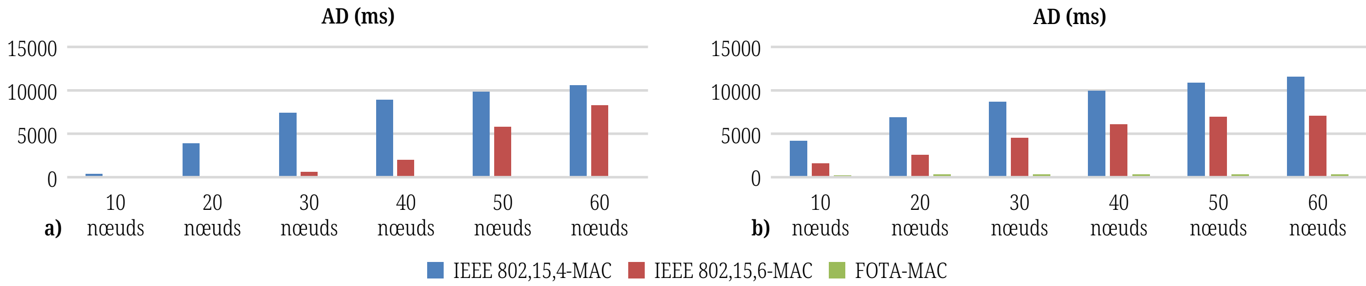

Fig. 2. Timeliness versus traffic density under (a) light traffic and (b) heavy traffic

Scenario 2. Figures 3 and 4 show the performance results in terms of reliability and timeliness.

Delivery reliability. We can notice that our protocol provides significant performance accelerations as compared to the two IEEE standards: almost up to 434.52%

compared to IEEE 802.15.4, and up to 323.51% compared to IEEE 802.15.6. For example, for a WBAN consisting of 50 nodes with low traffic and 10 nodes with heavy traffic, FOTA-MAC achieves a PDR of 81%, while the two standards do not exceed 15.3%.

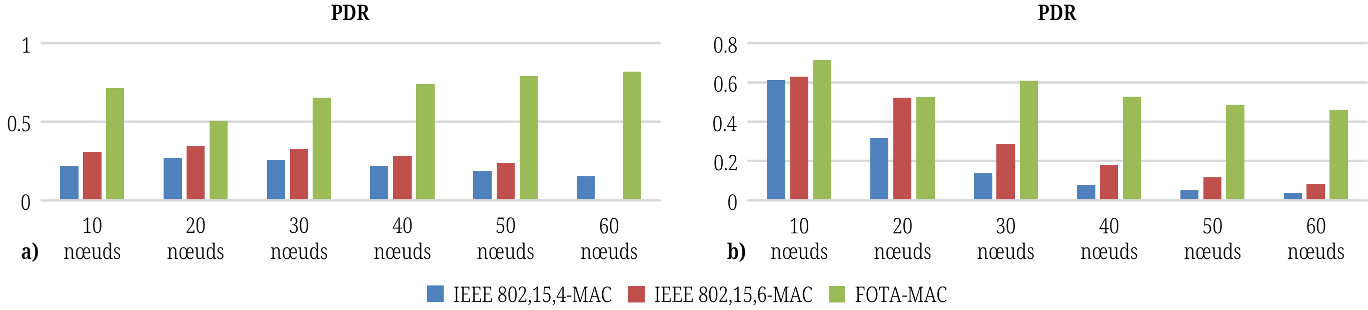

Fig. 3. PDR results under a heterogeneous traffic model for different network densities: (a) 10 nodes require high data rates, and (b) 10 nodes require low data rates

Timeliness. The obtained results show that our protocol is capable of achieving much faster communications than the two IEEE standards in the great majority of the considered configurations. Indeed, we can note that the use of FOTA-MAC ensures significant reductions in the average times, going up to 99.94% compared to the IEEE 802.15.4, and up to 99.86% compared to IEEE 802.15.6. However, the degradation observed in the topology consisting of 10 sensors in each category shows that the inefficient use of the bandwidth may negatively affect the speed of transmissions if CAP2 traffic is more important than that of CAP1. For example, under this topology, the number of nodes in the two traffic categories is equal. Therefore, the two periods CAP1 and CAP2 are equal although the traffic of CAP2 is more important than that of CAP1, which increases the waiting time of the packets of CAP2 in the buffers while the traffic of CAP1 is not important enough, and degrades the speed of transmissions in the deployed network.

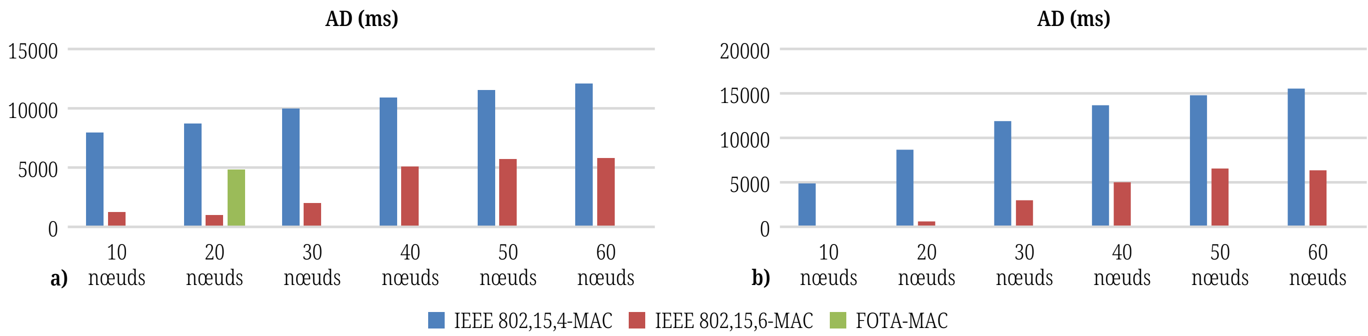

Fig. 4. Timeliness results under a heterogeneous traffic model for different network densities: (a) 10 nodes require high data rates, and (b) 10 nodes require low data rates

4 FOTA-MAC AND OTHER APPROACHES

After conducting an extensive literature review, we discovered that the majority of the approaches proposed in the past five years as enhancements for the beacon-enabled mode of IEEE 802.15.4 have mainly concentrated on two aspects. Some approaches, like TA-MAC [12], TAP-MAC [13], and ECTP-MAC [14], aim to differentiate node access based on their traffic type, while others, such as EETP-MAC [15] and TraPy-MAC [16], prioritize access based on node priority.

Interestingly, we observed that none of the existing solutions have addressed the differentiation of access for the different sensor profiles within the periodic traffic category if they share the same priority. In light of this gap, our proposed solution presented in this paper targets periodic traffic and primarily centers around differentiating access configurations based on sensor throughput requirements.

Consequently, FOTA-MAC is introduced as a complementary approach to existing solutions, offering the ability to easily adapt and merge with them to enhance the overall network efficiency. With our novel protocol, we strive to address the limitations identified in previous approaches and contribute to the advancement of the beacon-enabled mode of IEEE 802.15.4 in Wireless Body Area Networks (WBANs).

5 CONCLUSION

In this research, we have introduced a novel traffic adaptive MAC protocol for WBANs, 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 by configuring the access of each profile using the way that optimizes 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 versions of IEEE 802.15.4 and IEEE 802.15.6 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 over the two IEEE standards in terms of reliability and timeliness. For our future work, we plan to evaluate the energy efficiency of our protocol and assess its performance under selfish behaviors.

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7 AUTHORS

Nabila Azdad, MATSI Laboratory, Mohammed First University, 60000 Oujda, Morocco (E-mail: nabilaazdad5@gmail.com).

Mohamed Elboukhari, MATSI Laboratory, Mohammed First University, 60000 Oujda, Morocco.