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A Novel WBAN MAC protocol with Improved Energy Consumption and Data Rate

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Abstract

Wireless Body Area Networks (WBANs) are introduced as an enabling technology in tele-health for patient monitoring. Designing an efficient Medium Access Control (MAC) protocol is the main challenge in WBANs because of their various applications and strict requirements such as low level of energy consumption, low transmission delay, the wide range of data rates and prioritizing emergency data. In this paper, we propose a new MAC protocol to provide different requirements of WBANs targeted for medical applications. The proposed MAC provides an efficient emergency response mechanism by considering the correlation between medical signals. It also reduces the power consumption of nodes by minimizing contention access, reducing the probability of the collision and using an efficient synchronization algorithm. In addition, the proposed MAC protocol increases the data rate of the nodes by allocating the resources according to the condition of the network. Analytical and simulation results show that the proposed MAC protocol outperforms IEEE 802.15.4 MAC protocol in terms of power consumption level as well as the average response delay. Also, the comparison results of the proposed MAC with IEEE 802.15.6 MAC protocol show a tradeoff between average response delay and medical data rate.

Keywords: Wireless Body Area Networks, Wireless Sensor Networks, Medium Access Control protocol, power efficiency, emergency response.

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1. Introduction

A Wireless Body Area Network (WBAN) usually consists of a number of miniature sensor nodes which have enough capabilities to process information and transmit it to a central node for diagnosis and monitoring purposes. These sensors can be located around or on the body surface, or even implanted inside the human body. WBAN supports a wide range of medical and non-medical applications from a simple data file transfer to remote health monitoring of a patient's state and helping the disabled [1][2]. This includes heterogeneous requirements with a wide dynamic range of parameters. For example, data rate can be from 10 kb/s to 1Mb/s [3]. Also, the transmission cycle of nodes may range from a few milliseconds to several hours. Some medical applications can be life-critical, which needs strict latency requirement and real-time transmission with the possibility of emergency situation occurrence [4]. Furthermore, low energy consumption and the life time of the nodes are other issues in the design of medical sensor nodes, especially in implanted ones. Due to these heterogeneous requirements, MAC protocol design becomes the main challenge of WBANs' design.

The main challenge of MAC protocol design in a WBAN is to provide efficient performance in terms of power consumption, latency and emergency response at the same time. As available MAC protocol standards could not fully provide these requirements of WBANs, at the end of 2007, IEEE established a new task group of IEEE 802.15.6 [5] known as WBAN to propose a new standard for physical and MAC layer of these networks. The current IEEE 802.15.6 standard defines three PHY layers; Narrowband (NB), Ultra wideband (UWB), and Human Body Communications (HBC) layers (in HBC, human body is the medium for short range transmission) [6]. According to IEEE 802.15.6, the emergency alarm must be notified in less than 1 sec, which means that emergency alarms have priority over all other signallings [5].

The main schemes for the MAC protocols of sensor networks can be divided into schedule-based (such as TDMA) and contention-based (such as CSMA/CA and ALOHA) protocols [7,8]. In schedule-based protocols, some slots are are allocated to each node to transmit or receive data without collision. Therefore, the nodes can sleep in other slots to save energy. In contention-based protocols, nodes have to contend in a shared channel in order to access the channel, hence collision is possible. On the other hand, these protocols are more flexible and scalable than schedule-based ones. However, in WBANs a single physiological abnormality may affect many sensors in different parts of the body [3] and this usually happens in emergency cases. Therefore, it is quite possible for a group of sensors to sense emergency signals at almost the same time. In this case, a CSMA/CA protocol faces heavy collisions and as a result extra energy consumption with a high latency [9].

Since collisions, overhearing, idle listening, control packet overhead and traffic fluctuations are the main resources of wasting energy in wireless sensor networks [7][8], TDMA-based protocols can be more proper for WBANs because of their strict requirements. Generally, TDMA-based protocols outperform contention-based ones in all aspects except adaptability to changes in network topology, because they need synchronization mechanism which is difficult to be implemented in dynamic networks. However, since WBANs have relatively constant network structures and fixed sensor functions, synchronization mechanism can be easier [9]. It should be mentioned that existing TDMA-based protocols which are proposed for other wireless sensor networks (such as [10][11][12][13]) can not satisfy WBANs requirements, such as low power consumption, low latency, emergency mechanism and so forth. Therefore specific MAC protocols have to be designed for WBANs.

In this paper, we propose a new TDMA-based MAC protocol to provide different requirements of WBAN targeted for medical applications. Our main contributions are as follows. A new synchronization algorithm is proposed to allow the nodes stay in sleep mode, when they don't want to send any packet. Also a proper mechanism for emergency transmission in less than 1 sec is proposed based on the correlation between medical signals in emergency conditions. However, we consider a tradeoff between the average emergency transmission delay and the data rate of the nodes. In addition, the contention-based access period is reduced and substituted by a contention-free period in order to save energy and decrease the transmission delay. Furthermore, resource allocation is done based on the traffic condition of the network to efficiently use the channel and increase the data rate of the nodes.

The rest of this paper is organized as follows: Section 2 reviews the related works. Section 3 describes the proposed MAC protocol in detail. In Section 4, the simulation results of the proposed MAC protocol are illustrated and finally we give concluding remarks in Section 5.

2. Related Work

Several MAC protocols have been developed for WBANs during past few years. The main improvements of WBAN MAC protocols in the literature can be divided into three main categories: system performance in terms of energy consumption and delay [14][15][16][17][18][19], emergency response [20][21][22] and security issues [23], which the first two classes are more important in medical applications. Also, there are some MAC protocols which improve the performance of the WBAN in both classes, such as [24][25][26] and our proposed protocol in this paper.

As IEEE 802.15.4 is a low-power communication protocol, it could be selected for WBAN applications [3]. However, there are some problems that make IEEE 802.15.4 impractical for WBANs. One of these problems is synchronization; nodes have to wake up periodically to receive the synchronization packets and this increases the level of energy consumption. Furthermore, there are maximum seven Guaranteed Time Slots (GTSs) which are not enough for WBANs because most of medical sensor nodes have periodic data which usually are transmitted in GTSs in IEEE 802.15.4 for collision-free transmission [15]. Also, the results show that in IEEE 802.15.4 the transmission delay increases as the data rate of the nodes increases. This means that a wide range of data rates cannot be supported in these systems [27]. The other problem is that there is no mechanism for emergency transmission. Therefore, many researchers have focused on improving IEEE 802.15.4 features.

As can be seen in **Fig. 1**, a superframe of IEEE 802.15.4 has an active and an inactive period. The active period consists of a beacon, a contention access period (CAP), and a contention free period (CFP). In the CAP part, the nodes access the channel with CSMA-CA mechanism and the CFP part is composed of guaranteed time slots (GTS) for collision-free transmission. If a node intends to get resources for its periodic traffic, it should first send a GTS request in the CAP part, and then the coordinator allocates a GTS to that node [28].

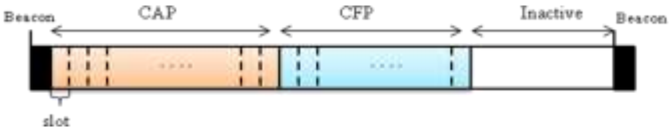


Fig. 1. Superframe structure in IEEE 802.15.4.

Each node, in the slotted CSMA-CA mechanism, has three parameters: the backoff exponent

(*BE*), the contention window (*CW*), and the maximum number of attempts for transmission of a packet (*NB*). When a node wants to transmit a packet, it first sets it's *BE* to the minimum *BE* parameter, *MinBE*, in first backoff stage and selects a random number within the interval of [0, 2^{BE-1}] to initialize the backoff counter. When the counter becomes zero, the node performs Clear Channel Assessment (CCA) process two consecutive times. If the channel is detected idle in both CCA slots, the node starts transmission in the next slot. Otherwise, it goes to next backoff stage and *BE* increases by 1 ($BE \leq maxBE$) to start another transmission attempt. The transmission attempt repeats until a successful transmission takes place or the backoff stage reaches NB_{max} [28]. Other MAC protocols such as Preamble-based TDMA [29], H-MAC [14], low-energy low-duty cycle [19], DTDMA [30] and DTDMA [31], are proposed based on the TDMA for WBANs in recent years. **Table 1** summarizes some of the recent proposed MAC protocols for WBAN with their advantages and shortages.

Table 1. Summary of some WBAN MAC protocols.

MAC	Innovation	Advantages	Shortages
H-MAC [11]	using heart beat rhythm for synchronization.	nodes do not have to wake up every SF.	Emergency is situation not considered.
DTDMA [27]	putting CAP after CFP, setting inactive period based on CFP.	improving energy consumption and data loss rate.	emergency is situation not considered.
Modified 802.15.4 [12]	setting the length of SF and active period based on requirements.	more than 7 slots in CFP, improvement on energy and delay.	Emergency is not considered, waking up every SF.
BATMAC [13]	using relay in each node.	reduction of fading effect.	correlation between medical signals is not considered, waking up every SF.
Energy efficient MAC [14]	using two beacons in each SF, setting a slot for alarms.	separation of implanted traffic and on-body ones, delay improvement.	correlation between medical signals is not considered, waking up every SF.
Enhanced 802.15.4[17]	proposing new synchronization, defining 2 modes for system.	improvement on delay, real time emergency transmission.	correlation between medical signals is not considered.
Minimizing energy [20]	defining feature vector for node and optimizing slot length for each node.	optimized length of slot, improvements on delay.	correlation between medical signals is not considered, waking up every SF.
CA- MAC [21]	adaptive mechanism based on the traffic type of the network.	collision omitted, improvement on delay and energy.	emergency is not considered, fixed application.

Fig. 2 shows the superframe structure of IEEE 802.15.6 standard which is recently released [5]. The superframe consists of beacon, exclusive access phase (EAP) for high priority data transmission, random access phase (RAP) for any type of packet, managed access phase (MAP), second beacon and contention access phase (CAP). CSMA/CA or slotted ALOHA mechanisms is used in EAP, RAP and CAP while polling/posting access or scheduled access is used in MAP. The length of each part of superframe is fixed and predetermined according to the application. Also, the length of RAP cannot be zero. The fixed duration of different parts of superframe affects the channel efficiency of the WBAN targeted for medical applications. The normal medical traffic is a periodic traffic which usually uses MAP part for scheduled

transmission, therefore channel is often idle during EAP and RAP. Also, the fixed duration of different parts of superframe can make the length of superframe longer compared to the case that the length of each part is set based on the traffic condition. When the length of superframe is longer, the data rate of the nodes which need to transmit in each superframe, is decreased.

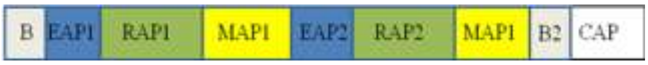


Fig. 2. Superframe structure of IEEE 802.15.6.

3. MAC protocol design

According to the special requirements of WBANs and the specific attributes of medical monitoring systems, the proposed MAC protocol in this paper is designed for a star topology network. The network is composed of a coordinator node and several sensor nodes which collect data continuously and send their data packets to the coordinator with specific transmission cycle. Here, the transmission cycle of the node is approximately equal to the Duty Cycle (DC) of the node, since the synchronization algorithm lets the node stay in sleep mode till next transmission. The transmission cycle of each sensor node is determined based on the desired life time of that node and physician's recognition according to patient's situation and the importance of sensed biological signal. In this study, transmission cycle of the sensor nodes remains fixed unless in special cases, such as emergency condition or physician recognition. To inform the nodes of changes on transmission cycle, the coordinator sets a bit (*change_field*) in ACK packet which is transmitted by the coordinator to the node after receiving data packet. The node checks the change_field bit in the received ACK. If the bit is set to one, the node wakes up in the next superframe to receive beacon which contains the information of new transmission cycle. The proposed protocol is explained in detail in the following subsections.

3.1 MAC structure

According to the specific requirements of WBANs, we choose a superframe structure including active and inactive periods, each of them consists of several time slots. The active period, as depicted in **Fig. 3(c)**, is composed of a beacon for synchronization and slot allocation information, CAP period, Emergency TDMA (ETDMA), Normal TDMA (NTDMA) and Emergency Slot (ES). The superframe is bounded with beacon packet which is transmitted by the coordinator to all sensor nodes at the first two slots of each SF. The length of superframe is determined based on the application and remains fixed. However, the length of each part of superframe, except ES, is variable in every superframe. Each part of superframe may have a zero length except ES and NTDMA which always exist. The coordinator set the length of each part according to the condition of the network. To be informed of the condition of the network, the coordinator performs CCA during ES slot. The emergency nodes (nodes with emergency packet) send alarm in ES slot. Therefore, busy channel in ES slot means that at least one node has emergency situation. It should be mentioned that the emergency nodes send their alarms in ES just to inform the coordinator that there is emergency condition in the network. When the coordinator recognizes an emergency condition, it sets the CAP part where the emergency nodes can contend through CSMA/CA mechanism to transmit their alarm packet to the coordinator. Also, ETDMA is the part where the emergency nodes can transmit their emergency data packet without collision. The exact process of transmission of the nodes in normal and emergency condition is explained below.

In the proposed protocol, we assume that each node can primarily process the sensed data and check if the signal is in its biological normal range or not. If all sensor nodes sense normal data, i.e. idle channel in ES, the coordinator sets the NTDMA after the beacon. In NTDMA, nodes send their normal data packets periodically without collision and receive an ACK packet after any transmission. To save energy, the node sleeps after receiving ACK until its next transmission. Slots of NTDMA are allocated to the sensor nodes based on their transmission cycle. Also, the number of allocated slots to the nodes in NTDMA is different and proportional to the data size and the data rate of the nodes, since the nodes have different data sizes. For instance, an endoscope sensor has a larger data size than an electrocardiogram (ECG) one. The coordinator has the data sizes and the transmission cycles of all nodes in a table, therefore it allocates the slots of the NTDMA of each superframe accordingly.

When a node senses an emergency data, it wakes up and waits for the beacon to be synchronized and informed of the location of the ES slot. By receiving the beacon, the node becomes synchronized with the coordinator and sends an alarm packet in ES slot (**Fig. 3(a)**). Alarm is a small packet which is transmitted in one slot by the sensor node to the coordinator in order to inform it of the emergency condition in the network. Since medical data are highly correlated, which means that if some part of the body does not work well, the probability that more than one sensor needs to send emergency data to the coordinator is high. Therefore, the probability of collision in ES slot is considerable. In the proposed protocol, in order to consider this correlation and possible collision in ES, the coordinator always performs CCA in ES slot and if it finds the channel busy, the coordinator sets a short CAP period after the beacon (**Fig. 3(b)**). The emergency nodes can send their alarms in CAP through a mechanism which is similar to slotted CSMA/CA. The coordinator sets NTDMA part after CAP period and the duration of inactive period decreases, consequently. According to the received alarms, the coordinator allocates slots of ETDMA to the emergency nodes which have sent their alarms in CAP period. Medium access in ETDMA is based on the TDMA access hence; the emergency nodes send their emergency data packets in their allocated slots without collision (**Fig. 3(c)**). The coordinator sets NTDMA part after ETDMA, for normal data transmission based on the transmission cycle of nodes.

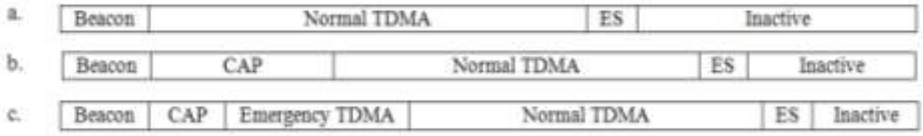


Fig. 3. a. Superframe in normal situation, b. Superframe in emergency situation when nodes are competing, c. Superframe when emergency nodes have sent their alarm in the previous superframe**.**

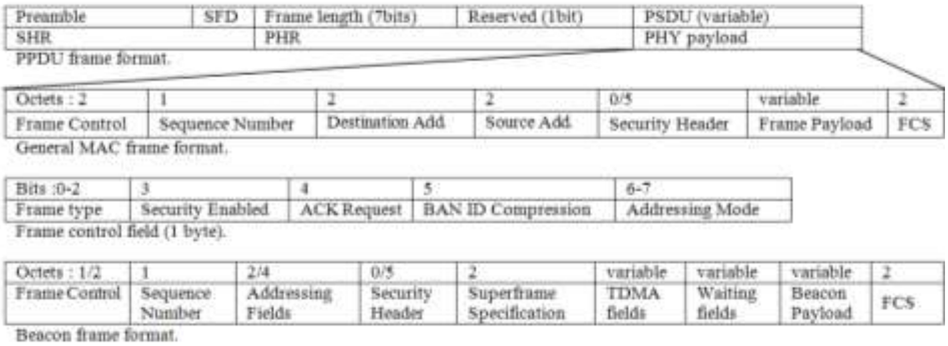
As aforementioned, to consider the correlation of medical signals in emergency situation which may cause collision in ES slot, the coordinator performs CCA in ES slot to set the CAP part in the case of emergency condition. By this method, the emergency nodes may transmit their alarms more reliably compared to the protocols which consider only one slot for alarm transmission, such as [20] and [22]. The other point is, although the alarm packets may face collision in CAP period, emergency data packet transmission in ETDMA is collision free. As the alarm packet is transmitted in contention access period, a small duration would be chosen for CAP and consequently, the length of superframe can be decreased. On the other hand, the data rate of some nodes is high, i.e. they need to transmit in each superframe. Therefore, smaller superframe can support more data rate as in this case the nodes obtain more allocated slots. Therefore, the separation between alarm transmission and emergency data transmission improves the system performance in terms of data rate.

In order to more precisely consider the correlation between medical signals, sensor nodes in a WBAN can be divided into uncorrelated groups, each of which contains the nodes that are correlated with each other. At each group, one node is possibly more important than other ones, therefore it should have priority in sending alarm signals to the coordinator. This classification is done based on the physician recognition and the health condition of the person who uses WBAN. For instance, ECG signal is more important than glucose signal for a person with cardiac disease, therefore, the ECG node should have priority over glucose node. In order to realize this prioritization, the range of backoff times for each node can be set, accordingly. This means that more important nodes use shorter backoff ranges compared to others and therefore, the probability of channel access is higher for important nodes.

As mentioned above, the contention algorithm in CAP in the proposed MAC protocol is similar to the slotted CSMA/CA, with some differences. First, nodes perform CCA only once before transmitting their alarm packet, because the duration of CAP is short and the number of emergency nodes are limited. The second difference is that there is no limitation for the number of attempts for transmitting alarm packets, i.e. the nodes contend in CAP till a successful transmission. It should be mentioned that nodes do not receive ACK in CAP so they must wait for beacon to find out about the success (or failure) of their transmitted alarm. If there is no allocated slot for them in the beacon, the node sends another alarm in ES slot.

The main advantage of this protocol compared to the other ones is considering the correlation between medical data in emergency situations. Neglecting this fact may yield to serious collisions in emergency conditions which makes the protocol impractical. The other advantage of the proposed protocol is that the traffic of emergency alarms is separated from others in the network to improve the emergency transmission latency. This happens by limiting contention access to emergency nodes. Also, by setting the length of different parts of the superframe according to the condition of the network, channel is used efficiently and the data rate of the nodes is increased.

The format of the frames in the proposed MAC, are almost identical to the IEEE 802.15.4 [32], and there are small differences. First, WBAN address is not necessary in the address field as we assume that the communication is limited inside a WBAN. Second, instead of *pending data*, we use *waiting data* in control frame, which refers to the case that an emergency node sends the alarm packet in previous superframe successfully, but there are not enough slots in current SF to be allocated. Hence, the node should wait for the next SF. Third, instead of GTS, TDMA is used as depicted in **Fig. 4**. Slot allocation and synchronization are explained in the following subsections.



Preamble	SFD	Frame length (7bits)	Reserved (1bit)	PSDU (variable)
SHR		PHR		PHY payload

PPDU frame format.

Octets : 2	1	2	2	0/5	variable	2
Frame Control	Sequence Number	Destination Add	Source Add	Security Header	Frame Payload	FCS

General MAC frame format.

Bits :0-2	3	4	5	6-7
Frame type	Security Enabled	ACK Request	BAN ID Compression	Addressing Mode

Frame control field (1 byte).

Octets : 1/2	1	2/4	0/5	2	variable	variable	variable	2
Frame Control	Sequence Number	Addressing Fields	Security Header	Superframe Specification	TDMA fields	Waiting fields	Beacon Payload	FCS

Beacon frame format.

Fig. 4. frame formats in the proposal protocol.

3.2 Slot allocation

In the proposed MAC protocol, slot allocation in NTDMA depends on data sizes and the transmission cycles of nodes. As the time resolution of the proposed MAC protocol is a time slot, data sizes and transmission cycles of a node are expressed in terms of the number of slots. Also, the sensor nodes that need to transmit their data in every superframe are called *permanent nodes*. These nodes occupy some fixed slots in every superframe and a time guard (T_g) is considered between these slots in order to avoid overlap between slots (**Fig. 5**). For slot allocation to the nodes with a transmission cycle larger than one superframe, which called *impermanent nodes,* the following process is performed:

B	S_1	t_g	S_2	t_g	…	S_k	t_g	ES	inactive

Fig. 5. Slot allocation in normal condition.

Assume that there are N_{ip} *impermanent nodes* with different Transmission Cycles (*TC*) in a WBAN and TC_{GCF} is the GCF (Greatest Common Factor) of their *TC*s, as presented in (1).

$$TC_{GCF} = \underset{i}{GCF}\,(TC_i) \tag{1}$$

where TC_i is the TC of the i^{th} impermanent node. Also assume that TC_{GCF} is a multiple (M) of the length of a superframe (T_{SF}), i.e.

$$TC_{GCF} = M \times T_{SF} \tag{2}$$

We divide the sequence of superframes to groups each of which contains M superframes (SF), i.e. $SF_1, \ldots, SF_M$ compose a group. From equations (1) and (2), we can write:

$$TC_i = m_i \times M \times T_{SF} \tag{3}$$

which means that the i^{th} impermanent node sends once in each m_i groups. Suppose that all of the impermanent nodes must transmit their data packets in the first group. If we allocate the NTDMA parts of superframes of the first group to the impermanent nodes regularly, i.e. the first node sends in the SF_1, the second one sends in the SF_2 and so forth, then two situations are possible. First, when $M > N_{ip}$; in this case, the slots of NTDMA period of each superframe of a group may be allocated to just one of the impermanent nodes, i.e. in each superframe at most one impermanent node sends its packet. Second, when $M < N_{ip}$; in this case, allocating the slots of NTDMA of each superframe of a group to just one of the impermanent nodes is not possible, hence some superframes may contain more than one impermanent node's transmission in their NTDMA part. Therefore, depends on the value of M and N_{ip}, there are maximum $\left\lceil \frac{N_{ip}}{M} \right\rceil$ impermanent nodes transmission in each superframe of a group, i.e. coordinator allocates slots to at most $\left\lceil \frac{N_{ip}}{M} \right\rceil$ impermanent nodes in NTDMA part of each superframe of a group, where $\lceil . \rceil$ is the ceil function which maps a real number to the largest next integer. As a numerical example, assume a network with 3 nodes A, B, and C with transmission cycles of 10, 30 and 40 superframes, respectively. Here for simplicity, the transmission cycles of the nodes are expressed in terms of superframe. In this case, M = 10, therefore, the sequence of the superframes are divided to groups each of which contains 10 superframes. Node A sends its normal data packets once in each group. Node B sends once in every three groups and node C sends once in every four groups. Hence, the duration of NTDMA period can vary in each superframe, and it is necessary to choose the length of superframe proportional to the number of nodes, their data sizes and transmission cycles.

To describe the slot allocation process of CAP and ETDMA, which are for emergency traffic, the emergency transmission steps must be considered. Suppose that all sensor nodes are in normal situation till the k^{th} superframe where the emergency condition occurs. First, nodes with emergency data send their alarms in ES slot of the superframe. The coordinator performs CCA in ES and finds channel busy in ES of the k^{th} superframe, so it puts a CAP period with its maximum length in the $(k+1)^{th}$ superframe. The coordinator allocates slots in ETDMA part to the emergency nodes which could transmit their alarms in CAP period of the $(k+1)^{th}$ superframe. The emergency nodes which could not access the channel in CAP period of the $(k+1)^{th}$ superframe, send another alarm in ES of $(k+1)^{th}$ superframe. Hence, the coordinator finds out that there is at least one node with emergency condition and sets CAP period in the $(k+2)^{th}$ superframe. The length of CAP in the $(k+2)^{th}$ superframe should be chosen properly from the range of [min_CAP_Duration, max_CAP_Duration] to make sure that there are enough slots to be allocated in ETDMA to the nodes that have sent their alarms in the $(k+1)^{th}$ superframe.

The coordinator allocates the slots of ETDMA part of the $(k+2)^{th}$ superframe according to the received alarms in the CAP of the $(k+1)^{th}$ superframe and the length of the inactive period of the $(k+2)^{th}$ superframe. If there are enough slots in the $(k+2)^{th}$ superframe, the coordinator allocates the required slots to all nodes which have sent alarm in the $(k+1)^{th}$ superframe. Otherwise, the coordinator chooses an optimum combination for transmitting emergency data in ETDMA of the $(k+2)^{th}$ superframe and informs other nodes to wait and send their emergency data in the ETDMA of the $(k+3)^{th}$ superframe. This process is called *set waiting field* in **Fig. 6**. These waited nodes have priority over the nodes that sent their alarm in current CAP. The optimum combination is chosen based on the prioritization which is described in subsection 3.1 for considering correlation between medical signals. This means that the nodes with higher priority must transmit their emergency data sooner. Also, in the case of equal priority for two nodes which transmit their alarm in previous superframe, the coordinator allocates slots in ETDMA to the node that maximizes the usage of slots of superframe. As an example, assume that three equal-priority nodes, with data size of 2, 3 and 4, have transmitted their alarms in CAP of previous superframe, and we have six slots available to ETDMA part of current superframe. Therefore, the coordinator allocates slots to two nodes which has data size of 2 and 4 because these two nodes can maximize usage of slots of the superframe.

Generally, slot allocation depends on the number of nodes intending to send data packet (either normal or emergency one), data sizes and transmission cycles of nodes, the length of superframe and channel state in ES slot. One of the advantages of the proposed protocol is that normal data transmission always continues in any condition, because inactive period is used to send the emergency data. The block diagram of slot allocation process is depicted in Fig. 6. In this figure, list_alarm denotes the list of nodes that have sent their alarms successfully in previous superframe.

According to the slot allocation process, the length of superframe (expressed in the number of slots) should be computed in a way that provides the requirements of network as follows:

$$T_{SF} > T_{always} + max\_CAP\_Duration + Beacon\_period + max_i(DS_{ip}+1)\times f \quad , T_{min} \leq T_{SF} \leq T_{max} \tag{4}$$

where $f=\left\lceil \frac{N_{ip}}{M} \right\rceil + 1$, $M=\left\lceil \frac{TC_{GFC}}{T_{SF}} \right\rceil$ and T_{always} is the number of slots which are occupied by the permanent nodes and DS_{ip} is the data size of the i^{th} impermanent node. The integer 1 in calculating f shows that both ETDMA and CAP may exist in one superframe. As can be seen, right side of the inequilibrium is dependent of T_{SF}. Hence, inequilibrium (4) can be rewritten as follows and be solved by numerical methods:

$$T_{SF} + max_i(DS_{ip}+1) \times \left\lceil \frac{T_{SF} \times N_{ip}}{TC_{GFC}} \right\rceil > T_{always} + max\_CAP\_Duration + Beacon\_period + max_i(DS_{ip}+1). \quad (5)$$

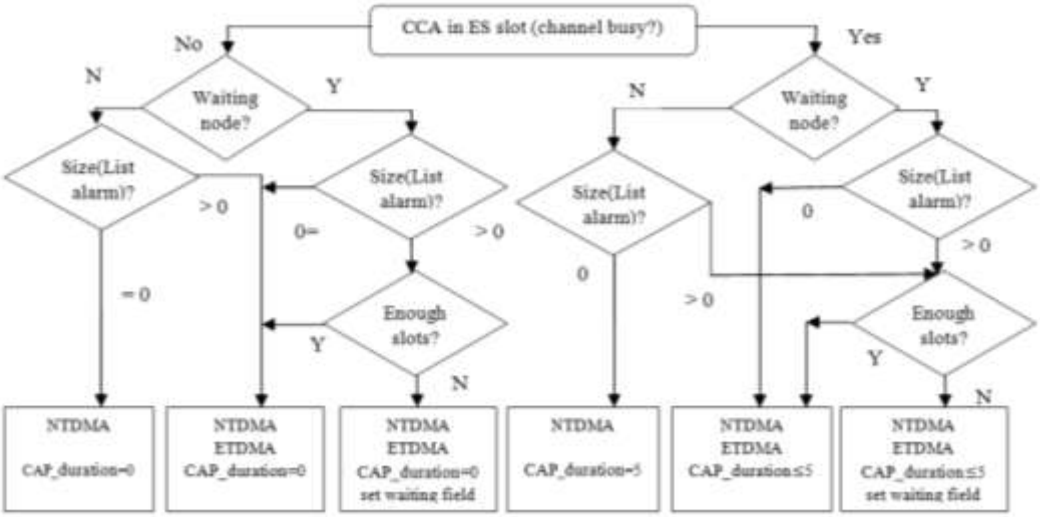


Fig. 6. Block diagram of slot allocation process in the proposed protocol.

3.3 Synchronization

In order to save energy and consequently increase the life time of nodes, nodes should be mostly in sleep mode. One of the resources of wasting energy is synchronization process in which nodes have to wake up regularly to be synchronized with coordinator through the beacon. In this section, we propose a method to reduce the number of slots in which the nodes have to wake up for synchronization. By using this method, when a node does not want to transmit packet, it can continue sleeping without losing its predetermined time for next transmission. However, the node is not always synchronized with coordinator during its sleep time.

We use the basic rule in synchronization which is widely used in different protocols, such as [33]. This rule states that if a node wants to wake up after T seconds to receive a packet from the coordinator, it must wake up $2\theta T$ seconds sooner to surly receive the packet, where θ is the frequency tolerance of crystals of the node and the coordinator. Assuming that $T = DC_i$ (duty cycle of i^{th} node), then the node must wake up $T_s=2\theta DC_i$ seconds sooner. In medical applications DC might take even more than one hour, therefore T_s can be very large. In the proposed synchronization algorithm, the beacon packet is transmitted at the beginning of each SF. Therefore, if the node wakes up too soon, it receives the beacon after at most T_{SF} slots. As a result, the node becomes synchronized with the coordinator and computes the remainder time to its next transmission (T_R). Therefore, it goes back to sleep mode for T_R - $2\theta T_R$, i.e. the node may wake up again $2\theta T_R$ seconds sooner and check the beacon for synchronization. As $T_R << T_s$, in this way the node can reduce the number of its waking ups for the sake of synchronization, considerably, without losing its predetermined time for next transmission.

As a numerical example, assume a node with DC=1 hour, Θ = 50 ppm and T_{SF} = 22 slots. Based on the IEEE802.15.4 protocol, each slot is equal to 0.32ms [28]. Therefore, the node should wake up $\frac{3600}{22\times 0.32}\approx 522$ times in IEEE 802.15.4 MAC protocol. Whereas in the proposed algorithm, the node should wake up $2\Theta DC$ = 0.36s sooner and wait for at most 22 slots to receive a beacon, in the worst case. By receiving the beacon, the node computes the T_R and goes to sleep again. T_R is almost 0.36s in the worst case. Then the node wakes up 36μs sooner which is less than one slot. Therefore, the node would be awake for at most 23 slots that are remarkably smaller than 511 slots. The whole algorithm for a node in a WBAN is depicted in **Fig. 7** where T_{cn} and T_{Nn} are clocks of the coordinator and the node, respectively, in a specific time.

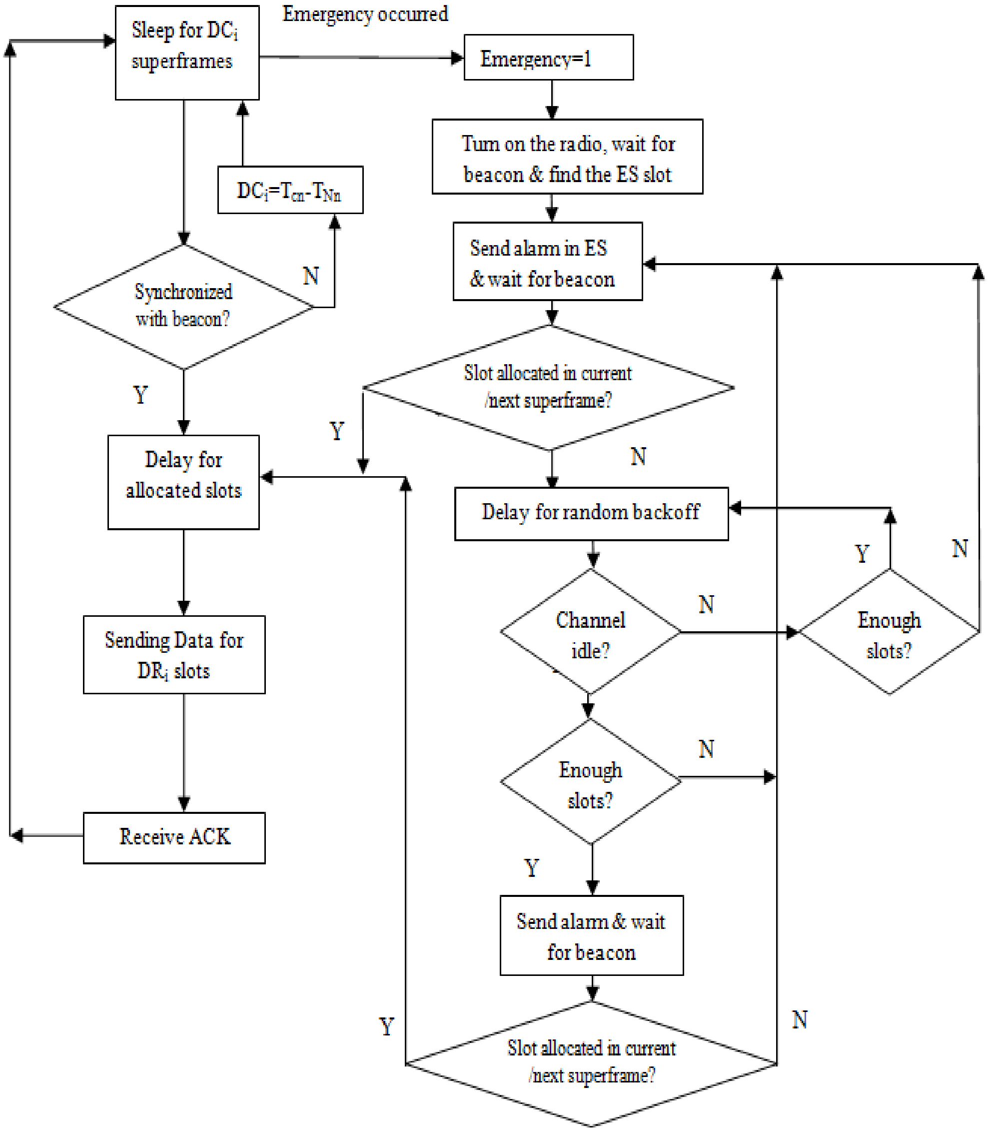


Fig. 7. Block diagram of the proposed algorithm for a node.

3.4 Mathematical Analysis

In this section, power consumption and the average transmission delay are computed and compared to those in IEEE 802.15.4 MAC protocol. **Table 2** contains the average power consumption of different states of a transceiver during one slot.

Table 2. Typical power consumption of different states [28]

State :	Receiving	transmitting	CCA	Idle	sleep
Power state	40mw	30mw	40mw	0.8mw	0.16μw

The proposed MAC protocol is based on the superframe structure which consists of several slots. According to the IEEE 802.15.4 MAC, maximum data size in one slot is theoretically 10 bytes [28]. Therefore, data size of the nodes can be expressed in number of slots which for the given data size is necessary. For instance, a packet with data size of 15 bytes needs two slots for transmission. Also, the transmission cycles of the nodes are expressed in number of superframes for simplicity, i.e. we can say that a node sends its packet each A superframes instead of each T slots, where $T=A\times T_{SF}$.

Equations (6 – 10) show the average power consumption of a node in transmitting (P_tx), receiving (P_rx), CCA (P_CCA), idle (P_idle) and sleep (P_sleep) states, respectively. Obviously, the average power consumption in a specific state (P_State) is proportional to the number of slots of that state (T_state) as well as the average power of that state during one slot.

$$P\_tx = 30\ (\text{mw}) \times T\_tx \tag{6}$$

$$P\_rx = 40\ (\text{mw}) \times T\_rx \tag{7}$$

$$P\_CCA = 40\ (\text{mw}) \times n\_CCA \tag{8}$$

$$P\_idle = 0.8(\text{mw}) \times T\_idle \tag{9}$$

$$P\_sleep = 0.16(\mu\text{w}) \times T\_sleep \tag{10}$$

where in (6):

$$T\_tx = n\_trans \times (DS) + n\_request + n\_alarm \tag{11}$$

n_trans is the total number of transmitted data packets by a node, which is calculated as follows:

$$n\_trans = n\_normal + n\_emergency \tag{12}$$

where $n\_emergency$ is the number of transmitted data packets in ETDMA, $n\_request$ is the number of transmitted alarms by a node in CAP, n_alarm is the number of transmitted alarms by a node in ES and n_normal is the number of normal data packets which is equal to $\frac{n\_SF}{TC}$ where n_SF is the number of superframes. Since the data size of nodes can be more than one slot, the total number of transmitting slots is n_trans times of the data size of the node. The number of receiving slots (T_rx) is equal to the summation of the number of received beacon packets (n_beacon), the number of received ACK packets ($n\_ACK = n\_trans$) and total slots that an emergency node waits from sensing emergency data till receiving the first beacon (n_slot_rx).

$$T\_rx = n\_trans + n\_Beacon + slot\_rx \tag{13}$$

In IEEE 802.15.4, power consumption calculations are almost the same with small differences as follow:

$$T\_tx = n\_trans \times (DS) + n\_request \quad (14)$$

$$T\_rx = n\_trans + n\_Beacon \quad (15)$$

Since contention access period is limited to emergency nodes in the proposed MAC, it is obvious that the number of transmitted packets in CAP (*n_request*) in IEEE 802.15.4 is much larger than the total number of transmitted packets in CAP in the proposed MAC. For the same reason and also because the number of CCA performing before each transmission is half of those in IEEE 802.15.4, the number of CCA slots (*n_CCA*) in IEEE 802.15.4 MAC protocol is much larger than those in the proposed MAC. Therefore, power consumption in transmitting and CCA state in the proposed MAC would be less than that in IEEE 802.15.4 MAC. Since *P_idle* is related to the backoff period in contention mechanism, this power is reduced in the proposed MAC, too. As mentioned before, in IEEE 802.15.4 MAC a node has to wake up regularly for synchronization, but this problem is solved in the proposed synchronization algorithm. As a result, *n_beacon* and *P_rx* decrease considerably in the proposed MAC. Obviously, sleep duration is increased in the proposed MAC protocol because of the proposed synchronization algorithm.

Table 3. Definition of variables.

s	slot number	$P\{c^j\}$	probability of being in CCA state at slot j
T_e	interval arrival time of emergency packet	$P\{S_k^j\}$	probability of being in CCA at slot j and level k
w_k	maximum value of backoff range in level k	n_c^j	number of contending nodes at slot j
b^j	probability of busy channel in slot j	f^j	probability of free channel in slot j
$P\{z^j\}$	probability that a successful transmission ends in slot j	P_s	probability of a successful transmission

Since emergency transmission mechanism is CSMA-CA with one CCA (similar to unslotted CSMA/CA), we use the same formula of average transmission delay of IEEE 802.15.4 to compute the average emergency transmission delay (D_{mean}) [32]. The definitions of the variables are listed in **Table 3**.

$$D_{mean} = \sum_{s=0}^{Te/slot} (s+1)\frac{P\{z^s\}}{P_s} \quad (16)$$

$$P_s = \sum_{j=0}^{t_{\max}} P\{z^j\} \quad (17)$$

$$t_{max} = \sum_{k=0}^{NB_{\max}} w_k \quad (18)$$

where (s +1) represents the delay backoff before each transmission in (16) [32]. t_{max} is the latest possible slot in which a transmission can start and is proportional to NB_{max} and w_k (18).

$$P\{z^j\}=(1-b^{j-1})\, P\{c^{j-1}\} \prod_{k=0}^{NB_{\max}} (1-P\{S_k^{j-1}\})^{n_c^{j-1}-1} \quad (19)$$

(19) represents that if only one node, over n_c^{j-1} nodes, senses the channel in slot j-1 and finds the channel free, then the transmission would end successfully in slot j.
It can be seen that the average delay in the CSMA/CA mechanism is proportional to the number of the contending nodes (n_c^{j-1}). Therefore D_{mean} in the proposed MAC is less than what in the IEEE 802.15.4 MAC protocol, because the number of the contending nodes in the proposed MAC is much less than the ones in the IEEE 802.15.4 MAC. In order to compare, we assume that NB_{max} in the proposed MAC is the same as that in IEEE 802.15.4. However, there is no constraint on NB_{max} in the proposed MAC.

4. Simulation Results

To evaluate the performance of the proposed MAC protocol, we develop a vector-based simulator in MATLAB [28]. Since the proposed MAC, IEEE 802.15.6 and IEEE 802.15.4 can be captured with a fixed duration backoff slot, it is possible to consider each simulator step as a new slot. The system state during each slot is tracked by using the state vectors of dimension N, which is the number of nodes. We consider a star-topology network composed of 6 nodes and one coordinator. To take account of all features of WBAN, we choose sensor nodes with wide range of data sizes and transmission cycles as depicted in **Table 4**. Based on IEEE 802.15.4 standard, the length of a slot is 0.32ms in which 10 bytes are transmitted. Hence, maximum data rate would be 250kb/s theoretically, although it is less in reality [27]. Therefore, we consider two slots for ECG with a data rate of 250kb/s. The transmission cycle of medical signals may be several hours, but because of simplicity, we consider at most 100 superframes for transmission cycle. Also, we assume that min_CAP_duration = 3 slots and max_CAP_duration = 5 slots in this network. Therefore, T_{SF} is 22 slots, using (4). In equation (4), T_{always} is 8 slots because each node occupies one slot more than its data size for ACK. Also, we assume that nodes transmit normal data packet periodically based on their transmission cycles and the emergency arrival distribution is Poisson with parameter λ which is the average arrival rate of emergency packets which is expressed in packets/slot.

Table 4. Data size & duty cycle of different nodes.

Node	Data size (slot)	Transmission cycle (superframe)
A. Endoscope	5	1
B. heart beat	1	1
C. ECG	2	10
D. insulin	1	20
E. temperature	1	50
F. Blood Pressure	1	100

Fig. 8 and **Fig. 9** show the average power consumption in emergency and normal conditions, respectively, for the proposed MAC protocol compared to IEEE 802.15.6 and IEEE 802.15.4 MAC. It is found that our proposed protocol consumes less power compared to IEEE 802.15.4 for all type of nodes, especially for *impermanent nodes*. Therefore this protocol can support a wide range of data sizes and DCs in terms of power consumption. As can be seen, the proposed MAC and IEEE 802.15.6 are similar in terms of power consumption of permanent nodes (A and B), since both of them use TDMA-based access for normal traffic. While, the proposed MAC protocol outperforms IEEE 802.15.6 MAC in terms of the power consumption of

impermanent nodes. This improvement is achieved through the proposed synchronization algorithm.

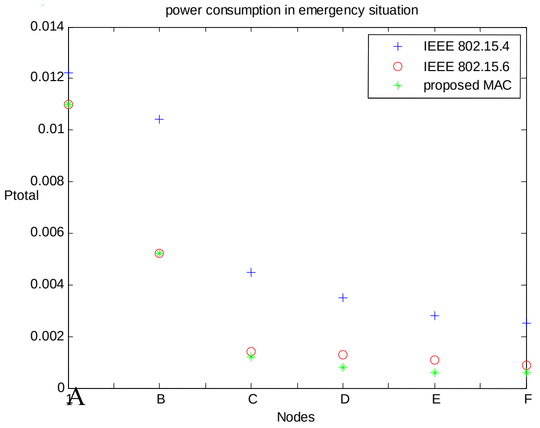


Fig. 8. Average power consumption when λ=1/700 packets/slot.

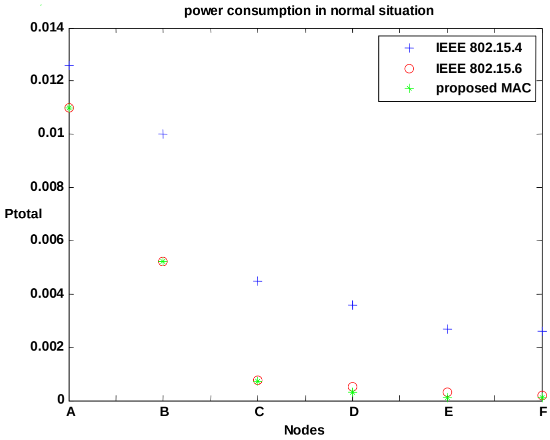


Fig. 9. Average power consumption in normal condition.

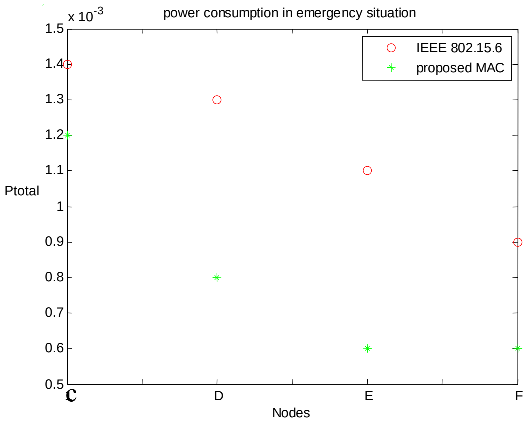


Fig. 10. Average power consumption of impermanent nodes in emergency condition.

For better comparison between IEEE 802.15.6 and proposed MAC protocol, we separate the average power consumption of these two protocols for impermanent nodes in **Fig 10**.

Fig. 11 shows the number of successful transmission data packets of nodes in different MAC protocols. It can be seen that nodes transmitted much more in the proposed MAC compared to the IEEE 802.15.6 and IEEE 802.15.4 MAC protocols. This curve proves that the proposed MAC can improve not only the power consumption, but also the number of successful transmission. In fact, in the proposed MAC our expectation of transmitted packet is guaranteed whereas in IEEE 802.15.4 MAC protocol this is not. On the other hand, the length of superframe for a given WBAN is less in our proposed MAC compared to IEEE 802.15.6 since the length of each part of superframe is set based on the traffic condition in the proposed scheme, while the length of each part of superframe is fixed in IEEE 802.15.6. Therefore, permanent nodes obtain more slots in the proposed MAC for transmission and their data rates is increased compared to the IEEE 802.15.6 MAC, as depicted in **Fig. 12**. Here, we assume that each permanent node occupies three slots in a superframe for transmission.

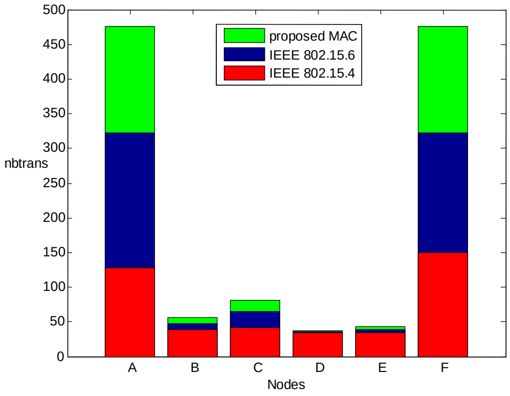


Fig. 11. Number of successful transmissions during 10^4 slots.

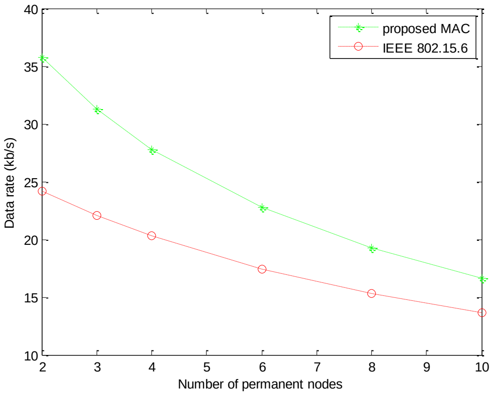


Fig. 12. Data rate of permanent nodes when there are five impermanent nodes in network.

As can be seen in **Fig. 13**, when the number of impermanent nodes increases, the number of successful transmissions is relatively constant in our MAC protocol, while the number of successful transmissions decreases in IEEE 802.15.4 MAC because of contention access mechanism. In **Fig. 13** slow and medium nodes refer to impermanent nodes with large and average transmission cycles, respectively.

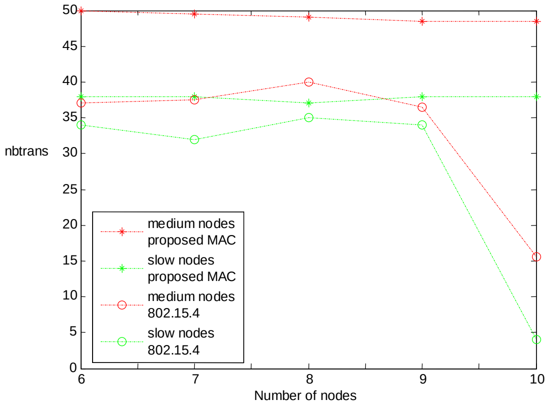


Fig.13. Number of successful transmission vs. number of nodes.

In **Fig. 14**, the system performance is evaluated to examine the effect of synchronization algorithm on power consumption improvement. To do this, the average power consumption of impermanent nodes under three protocols was simulated: IEEE 802.15.4, the proposed MAC with and without utilizing the proposed synchronization algorithm. It is found that the proposed synchronization algorithm is effective when the average arrival rate of emergency packet is large enough. As can be seen in **Fig. 14**, when $\lambda^{-1} = 300$, there is not much difference in power consumption of the nodes in a case that proposed synchronization algorithm is used, compared to the case that proposed synchronization algorithm is not used. In fact, the power consumption improvement in $\lambda=\frac{1}{300}$ packets/slot is because of using TDMA protocol instead of contention access protocol for normal data transmissions. Also, it is found that when λ^{-1} increases, the effect of synchronization algorithm increases, as well.

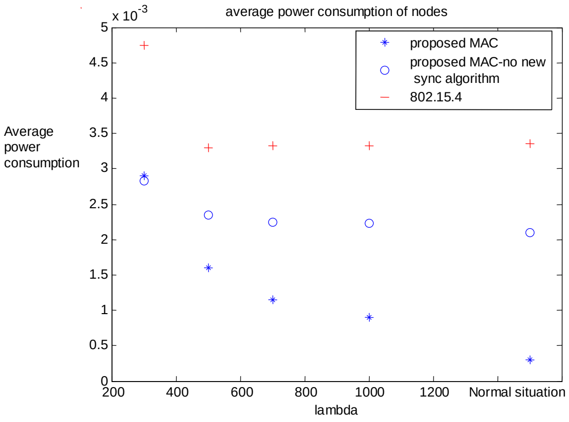


Fig.14. Average power consumption vs. λ^{-1}.

To evaluate the performance of the proposed MAC in terms of the average transmission delay, comparing emergency transmission delay in the MAC protocols would be enough, because predetermined TDMA protocol is used for normal data packets and it is obvious that TDMA protocol is faster than contention access protocol. **Fig. 15** shows the average transmission delay of emergency packets when the number of impermanent nodes varies. As can be seen in this figure, the average delay in the proposed MAC protocol is less than what is in IEEE 802.15.4 MAC. However, the latency of emergency packet in the proposed MAC is more than what is in IEEE 802.15.6 since there is always an exclusive contention access phase in superframe of IEEE 802.15.6. As aforementioned, the fixed duration of EAP and RAP decreases the data rate of the nodes and channel utilization, since the channel often is idle during these periods. In fact, there is a tradeoff between latency and data rate in our proposed MAC protocol subject to the necessity of emergency transmission in less than one second.

In delay evaluation, we assume the worst case which all impermanent nodes sense emergency signals with the same λ. In real cases however, when a biological signal goes out of its normal range, it may affect on only some of the other nodes, not all of them. We can say that the reason of delay improvement in the proposed MAC refers to the fact that an emergency node does not have to contend with all other normal nodes, whereas in the IEEE 802.15.4, an emergency node have to contend with all other nodes in the network. In other words, separation between emergency traffic and normal traffic decreases the emergency transmission delay.

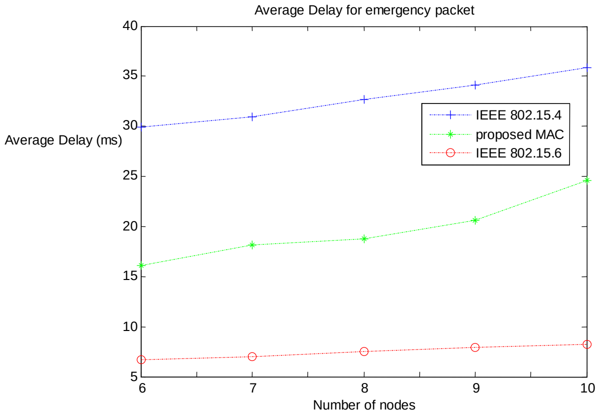


Fig. 15. Average emergency transmission delay.

To show the importance of correlation factor in designing a MAC protocol, we compare the number of successful transmitted alarms in two cases, when we consider and do not consider the correlation between medical signals. If this correlation is not considered, only one ES slot would be enough for emergency transmission, without emergency CAP period, as studied in [20] and [22]. **Fig. 16** shows that emergency mechanism such as what proposed in [20] and [22] is impractical because of neglecting correlation between signals, i.e. the nodes with emergency data could not send their alarms because of high collision in ES slot.

5. Conclusion

For wireless body area networks (WBANs) targeted for medical applications, we proposed a MAC protocol which reduces power consumption by minimizing contention access, reducing collision and using efficient synchronization algorithm. Also, by taking account of correlation between medical signals, an efficient emergency response mechanism is presented. In addition, the proposed MAC protocol increases the data rate of the nodes by allocating the resources according to the condition of the network. Mathematical and simulation results show that the proposed MAC protocol has the ability to reduce power consumption and emergency transmission delay, in comparison with 802.15.4 MAC. Also, it was illustrated that the proposed synchronization algorithm is effective in a case that arrival rate of emergency packet is not too high ($\lambda^{-1} > 300$). Also, by comparing the results of the proposed MAC with IEEE 802.15.6 MAC protocol, we see a tradeoff between the average response delay and medical data rate.

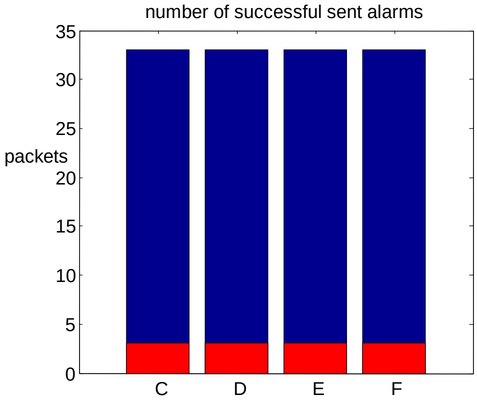


Fig. 16. Effect of correlated medical signals on number of successful transmitted alarms (blue ones are related to the proposed MAC and red ones are related to the MAC that does not consider the correlation)

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