Reliability and Energy Efficiency Enhancement for Emergency-Aware Wireless Body Area Networks (WBAN)

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Abstract

Medium Access Control (MAC) protocols based on Time Division Multiple Access (TDMA) can improve the reliability and efficiency of WBAN. However, traditional static TDMA techniques adopted by IEEE 802.15.4 and IEEE 802.15.6 do not sufficiently consider the channel status or the buffer requirements of the nodes within heterogeneous contexts. Although there are some solutions that have been proposed to alleviate the effect of the deep fade in WBAN channel by adopting dynamic slot allocation, these solutions still suffer from some reliability and energy efficiency issues and they do not avoid channel deep fading. This paper presents two novel and generic TDMA based techniques to improve WBAN reliability and energy efficiency. Both techniques synchronize nodes adaptively whilst tackling their channel and buffer status in normal and emergency contexts. Extensive simulation experiments using various traffic rates and time slot lengths demonstrate that the proposed techniques improve the reliability and the energy efficiency compared to IEEE 802.15.4 and IEEE 802.15.6 in both situations, the normal and emergency contexts. This improvement has been achieved in terms of packet loss, up to 90% and energy consumption, up to 13%, confirming the significant enhancements made by the developed scheduling techniques.

1 Introduction

Wireless Body Area Network (WBAN) is usually a small network composed of low-power and low-processing sensors that capture body physiological information and send it wirelessly to a central base station. WBAN replaces complex and wired healthcare equipments to perform continuous monitoring of vital information without limiting user's movements [1]. Nevertheless, the unreliability of this type of network might lead to life-threatening situations. Given that sensors are battery powered and resource-constrained devices, energy depletion can be a serious problem to overcome. In addition, the human body absorbs energy when it is exposed to Radio Frequency (RF) electromagnetic fields leading to a weak signal and continuous attenuation. Transmission paths are also affected by the uncontrolled, dynamic nature of the human body movement, because it causes frequent changes in the network topology, which deteriorates the stability of the transmission links. Consequently, the signal strength falls below receiver sensitivity and causes not only deep fading issue, but also long disconnectivity and unreachability of the sensor node from the main network [2, 3, 4]. According to an empirical study presented in [2] and conducted on a real WBAN worn by a person doing different daily-activities, it revealed that when a deep fade occurs in the WBAN channel, it lasts for at least 10 ms. However, if nodes are allowed to operate in a timely, scheduled manner, following contention free channel access, such as a TDMA approach, the fading becomes the primary source of unreliability. TDMA based channel access helps in both channel status prediction and energy saving because the scheduled duty cycles at the nodes avoid idle listening and overhearing.

The IEEE 802.15.4 and IEEE 802.15.6 standards are considered as the WBAN de-facto standards. IEEE 802.15.4 supports TDMA channel access by using Guaranteed Time Slots (GTS(s)) in the Contention Free Period (CFP) [5], while IEEE 802.15.6 provides TDMA mechanisms through the scheduled allocation slots in the contention free access periods [6]. However, TDMA mechanisms adopted by both standards are not able to provide a reliable and energy efficient channel access for WBAN as they provide static slot allocation. First, each node in the network has to use the channel in its time slots whether its link encounters deep fading or not. Second, each node is allocated the same number of slots in each TDMA round regardless of its needs. For those reasons, if a node loses data packets during its time slots due to deep fade, performing re-transmission will be useless because the deep fade of the links persists for a long period of time. Although there are some efforts proposed in literature to solve this issue by adopting dynamic slot allocation and considering the channel status, the majority of proposed techniques do not avoid the deep fade when it occurs.

To solve this problem, two novel TDMA based Medium Access Control (MAC) techniques are proposed in this paper. The first technique is called Dynamic Scheduling Based on Sleeping slots (DSBS), and the second technique is called Dynamic Scheduling Based on Buffer (DSBB). Both DSBS and DSBB avoid the deep fade in the channel by allowing the nodes to sleep dynamically whenever they detect a deep fade in their links. Besides, both DSBS and DSBB, allocate dynamically time slots to nodes, according to their needs. The need of the nodes is related to the size of the load in their buffer, the frequency at which the node needs to access the medium and whether it is an urgent access. In WBAN, the success of the medium access is correlated with the status of the links between nodes. If a node sleeps during its active session when the deep fade occurs, more packets will be saved in its buffer, and hence that node requires more slots in the next TDMA round than other nodes, so to cope with the increased load in its buffer. DSBS and DSBB mainly differ in the dynamic slot allocation to be adopted by the controller of the nodes in the subsequent TDMA round. In DSBS, the controller calculates the number of slots each node has slept during its active session due to deep fade, based on which it assigns that node extra slots in the next superframe. In DSBB however, the controller follows an opposite approach, and calculates the number of packets that are saved in each node's buffer, which reflects whether the node has slept during its active session due to deep fade or not. In DSBB the controller does not need to do any calculations related to the link status of the node, instead it will check the number of packets in the buffer of each node. The buffer information is encapsulated in the data packet sent by the node. Its highly likely that the node with more packets in its buffer than other nodes, has slept in the previous session due to its poor link status, and therefore requires extra slots in the next round so to reduce packets delay and avoid buffer overflow. Accordingly, in both DSBS or DSBB, nodes with more packets in their buffer get extra slots in the subsequent TDMA schedule. Compared to a previous work [7] where the performance of the proposed techniques is evaluated only in normal situations, this work addresses the emergence context and demonstrates how further energy consumption can be avoided.

The paper makes five-fold contributions: (1) it proposes a technique that avoids channel deep fade, which is explained in Section 3.1, (2) it proposes an adaptive scheduling technique that dynamically allocates the nodes time slots by analyzing their channel status, which is presented in Section 3.2, (3) it proposes another dynamic scheduling technique, which assigns time slots to nodes according to their buffer status as it reflects their links' status, this technique is presented in Section 3.3, (4) it evaluates the performance of the proposed techniques in both normal and emergency situations, which are discussed in Section 4 and Section 5 respectively, (5) it provides a hint on parametrizing the length of the TDMA schedule through choosing a suitable slot size. Experimental results revealed that the proposed techniques proved to have potential in improving WBAN reliability and energy efficiency in both normal and emergency situations.

The rest of the paper is structured as follows. Section 2 presents the weaknesses of existing techniques that adopt static TDMA based MAC in WBAN. Section 3 illustrates the proposed protocols in details. Section 4 presents the simulation setup and the performance evaluation of the proposed techniques in normal situations. Section 5 discusses emergency scenarios while Section 6 concludes the paper contribution and discusses future directions.

2 Related Work

There are several MAC schemes that attempt to tackle reliability in WBANs. The study in [8] surveys multiple contention and contention-free based MAC protocols from energy efficiency and TDMA perspectives [9, 10, 11, 12, 13, 14]. This section provides a brief summary on the channel access mechanisms adopted by IEEE 802.15.4 and IEEE 802.15.6 standards and discusses why their adopted TDMA based techniques fail to provide a reliable and energy efficient WBAN. Then, it presents the main TDMA based MAC solutions proposed in literature to overcome the limitations of the two standards.

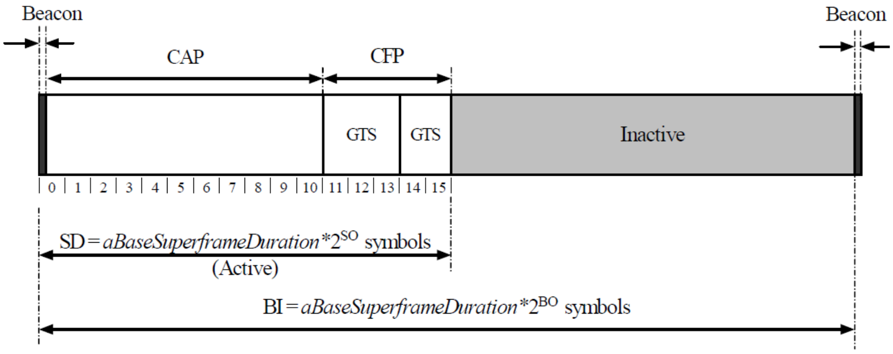

Figure 1: IEEE 802.15.4 MAC superframe structure [19].

2.1 WBAN De-facto Standards

2.1.1 IEEE 802.15.4

The IEEE 802.15 Task Group 4 (TG4) specified and recommended the IEEE 802.15.4 standard to be deployed in Wireless Personal Area Networks (WPANs) [5]. The IEEE 802.15.4 MAC layer operates in either beacon-enabled or beaconless modes. In the beacon-enabled mode, the Personal Area Network Coordinator (PANc) broadcasts regular beacon frames to synchronize nodes when they need to access the channel. The time between two successive beacons is referred to as the superframe or the Beacon Interval (BI), which is virtually divided into 16 equally sized slots [15]. Nodes can use the channel during the entire BI period or can sleep through some time portions. When a node needs to access the medium, it has to locate the beginning of the next time slot in order to compete for the channel based on the Carrier Sense Multiple Access/Collision Avoidance algorithm (CSMA/CA). This time portion is referred to as the Contention Access Period (CAP). Furthermore, the standard gives PANc the authority to assign a number of GTS slots (Guaranteed Time Slots) to some nodes exclusively. During these slots, these nodes are the sole users of the channel. This optional period, which includes seven GTS slots is called the Contention Free Period (CFP). The CFP along with GTS resembles a TDMA based MAC mechanism. The lengths of the periods discussed are specified through some parameters and the nodes in the network know the overall superframe specifications through the beacon frame, which is transmitted in the first time slot (slot 0) [15, 16, 17, 18, 19]. IEEE 802.15.4 superframe structure is depicted in Fig.1.

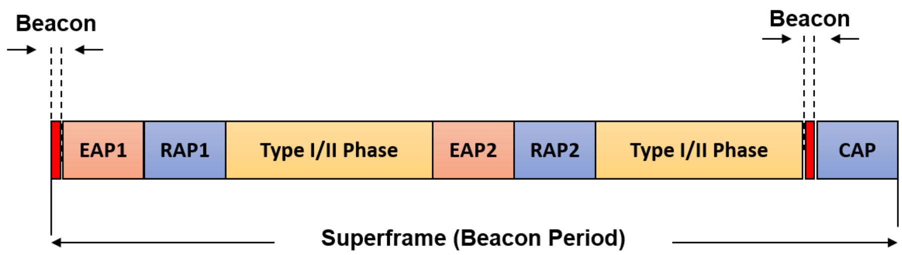

Figure 2: IEEE 802.15.6 beacon mode superframe structure.

2.1.2 IEEE 802.15.6

The IEEE 802.15 Task Group 6 (TG6) has proposed a new specific standard for WBAN, namely, the IEEE 802.15.6 [1]. Both IEEE 802.15.4 and IEEE 802.15.6 operate in beacon and beaconless modes. IEEE 802.15.6 adopts the superframe structure, which is bounded through beacon frames that are sent in fixed length beacon periods and combine both contention and contention-less access techniques to support the variety of data flaws [1, 6]. The superframe structure of the beacon mode is presented in Fig.2 and comprises the Exclusive Access Phase 1 (EAP1), a Random Access Phase 1 (RAP1), a Type I/II Phase, an Exclusive Access Phase 2 (EAP2), a Random Access Phase 2 (RAP2), a Type I/II Phase, and a CAP. The Type I/II Phase is sometimes referred to as Managed Access Period (MAP). The EAP is only used for emergency and offers the channel exclusively to the high priority data traffic, whereas RAP1, RAP2, and CAP are used for normal traffic. Type I/II Phase provides the capability of the TDMA channel access through the scheduled allocation slots during in the contention free access periods. Type I/II Phase schedules uplink, bi-link and downlink allocation intervals and for polling nodes for resource allocation. In CAP, RAPs and EAPs, nodes compete for the channel access following either the slotted Aloha or CSMA/CA. The coordinator (hub) can also deactivate those periods by setting the duration to zero [1, 6].

Similar to the IEEE 802.15.4, the coordinator uses the beacon frame to specify the duration of each access phase in the superframe structure according to the application requirement. Despite their similarities, there are various differences between the channel access mechanisms adopted by the two WBAN standards. A comparison between the MAC access techniques that are adopted by the standards is provided in [1]. Although the two standards support TDMA based channel access in the contention free period of their superframe, their mechanisms do not provide enough reliability and energy consumption efficiency. A number of efforts proposed in literature attempted therefore to solve the problem of static TDMA scheduling. Those solutions vary between tolerating the deep fade of the medium by reordering the nodes in the schedule, delaying the channel access period, or by exploiting both the contention and contention free access mechanisms in a hybrid manner. Some of the proposed techniques consider the heterogeneity of the traffic context in WBAN, while others do not. Those solutions are presented in the following subsections.

2.2 Dynamic TDMA based MAC scheduling techniques

2.2.1 Reordering nodes in the schedule

Tselishchev et al. in [20] proposed to change dynamically the order of nodes in the TDMA schedule according to the deep fading in the channel to minimize its effect. Liu et al. in [23] followed the same approach proposed by Tselishchev et al. in [20] and [21], and suggested to re-order the nodes in the next TDMA schedule when the deep fading occurs in the current one. However, changing the nodes order assures a slight reduction in packet loss rate over the static scheduling algorithm only. This is because the hub assumes that the deep fading of the links always occurs at the beginning of the active sessions of the node. In fact, the occurrence of the deep fade of the links is unpredictable. Deep fade might occur during the node's active period or at the end of the node's session as well, which means that the flipping technique might not contribute to any improvement and it might make things rather worse.

2.2.2 Delaying channel access

Tselishchev et al. in [21] tried to improve their solution in [20] by suggesting that packet re-transmission should be delayed to the subsequent superfames because direct packet re-transmission is useless. Rezvani and Ghorashi in [22] whose work is based on the IEEE 802.15.4, also adopted a similar strategy and suggested delaying the transmission of nodes in normal situations to the end of the superframe structure when deep fade occurs. However, this does not guarantee successful packets delivery, due to the unpredictability of the occurrences of the deep fade of the links.

2.2.3 Hybrid channel access

Other solutions suggested that the effect of the deep fade in the channel could be distributed by allowing nodes to contend in accessing the channel. Liu et al. in [24] suggested that the effect of the deep fade could be mitigated by adopting a hybrid superframe structure that involves both contention and contention free channel access techniques and estimates the channel status in the current TDMA round. Accordingly, if the channel suffers from deep fade, nodes are allowed to contend in accessing the medium in the next superframe structure, so that the deep fade of the channel is distributed between nodes. Although their solution considered the collision that could occur in the contention based period, they did not consider the energy consumption. Moreover, distributing the effect of the deep fade between the nodes does not offer a good solution as the node that transmits during the contention access period might have a poor link. Rezvani, and Ghorashi in [22] suggested adopting contention access approach for non-medical traffic and for medical data in emergencies. However, due to the availability of contention-random based access period, collision, idle listening and overhearing are likely to occur between nodes. This increases packet loss and dissipates energy. As a result, packets will not only be lost due to the deep fade in the channel, but also due to collisions.

2.2.4 Heterogeneous traffic consideration

In their proposed work in [22], Rezvani, and Ghorashi handled three types of traffic: the normal medical traffic, the emergency medical traffic, and the non-medical traffic. As mentioned previously, the proposed superframe structure comprises contention and contention free channel access mechanisms. Nodes with non-medical traffic contend in accessing the medium in CAP, whereas the nodes with normal medical traffic access the medium in the Normal TDMA period (NTDMA). Nodes in emergencies follow two mechanisms, they first try to compete in accessing the medium with the non-medical traffic in CAP, and if their transmission attempts fail, they are given extra slots to use the medium in the Emergency TDMA period (ETDMA). Although Rezvani, and Ghorashi considered that using CAP for emergencies is not reliable due to collision with the non-medical traffic, offering more time to the nodes in emergency will not solve the problem either and could be even worse. This is because, longer time in accessing medium exposes the nodes to longer deep fade duration, which lead to an increase loss of sensitive data and severely consumes energy. Moreover, the proposed technique requires a very sophisticated superframe structure while nodes in emergency might wait for multiple supeframes, which increases packets delay. The authors claimed a guarantee of less than 1 second for emergency transmission, however, as stated in [1] the delay requirements in emergencies should be less than 125 ms. Liu et al. considered emergencies in their two proposed works in [23] and [24]. In [23] Liu et al. proposed a constraint, which suggests that the transmitted information in emergency should be larger than the minimum throughput. Minimum throughput is correlated with the sampling rates that is decided by doctors according to medical scenario. This constraint is achieved by offering nodes in emergency more slots than other nodes. In their next work in [24], Liu et al. adopted a similar approach, but without providing a reliability constraint or slot allocation procedure. When the master node detects emergency, it offers those nodes that are related to the monitoring context more slots than other nodes. However, as WBAN is composed of a very vulnerable medium, offering emergencies nodes extra slots could not be beneficial at all. This is because if a node is in an emergency situation and has a poor link status, and has been allowed to access the valuable medium for longer time periods, then more sensitive information will be lost, which adversely reduces WBAN reliability. Moreover, according to their performance evaluation, accessing the channel for longer time in emergencies consumes more energy. In addition, the extra slots offered to the nodes in emergencies are taken from the rest of the nodes, and thus, in emergency situations, not all the nodes in the network will have the chance to use the medium.

To conclude, in normal situations, all previously discussed techniques allocate static number of time slots to nodes and do not justify the allocation criteria for the slots, or the slot length used for such allocation. In addition, their implementation requires complex amendments to IEEE 802.15.4 and IEEE 802.15.6 superframe structures. Moreover, nodes rely heavily on the controller to manage channel access schedule as these TDMA techniques are fully centralized. Indeed, the long duration of the deep fade could be harnessed in two ways: by adopting TDMA based MAC approach, a node has a sole use of the medium at a certain time slot. Accordingly, the node itself can realize that the reason behind losing its packets is the deep fade in the link between itself and the controller. In addition, when a node is in deep fading, it can realize that this phenomenon might last for long time and therefore performing re-transmission is useless.

```
Input: A number of nodes N, TDMA schedule of n slots, each Ni ∈ N is assigned equal number of slots S,
where S = n/N, and each Ni has a buffer Bi.
Output: Adaptive Sleep TDMA MAC
FOR each Ni ∈ N do the following
    WHILE TDMA round
        IF Ni(Si). start = true
            WHILE Ni(Si)
                IF node
                    Ni.set(state) ← Active;
                    IF Ni(Bi.numOfPkt) = 0
                        Ni.set (state) ← idle;
                    END IF
                    ELSE
                        Ni(Data_Packet.bufferField) ← Bi.numOfPkt;
                        Ni.send(Data_Packet);    Ni.wait (Ack);
                        IF Ack(Timer.timeout)
                            Ni.set(state) ← sleep;
                        END IF
                    END ELSE
                END IF
            END WHILE
        END IF
    END WHILE
END FOR
```

Figure 3: Adaptive Sleep TDMA MAC.

In other words, the node predicts its link status in the upcoming time-periods in the channel. Following this prediction, the node can take direct action whenever it detects that its link is poor during its time slots without relying on the controller. This idea is the entrance point to our proposed techniques, presented in Section 3.

3 The Proposed DSBS and DSBB Techniques

This section illustrates the proposed TDMA based MAC algorithms, which are generic enough to be adopted by any protocol, standard or communication technology that provides TDMA based capabilities. Both techniques are based on the proposed Adaptive Sleep TDMA algorithm presented in the following subsection.

3.1 Adaptive Sleep TDMA MAC

After successful association with the controller, nodes send TDMA slot request frames to ask the controller to assign them a number of TDMA slots. The initial number of TDMA slots to be requested is one of the configuration parameters of the network, and it should be parametrized once the network is established. In order to achieve the highest level of reliability, the TDMA schedule has to be configured in a way that all the slots in the TDMA are occupied by the nodes leaving no availability for extra free time slots. In addition, at the beginning of the network operations, the slots of the TDMA schedule should be distributed equally between the nodes. After receiving the TDMA slots request, the controller records the number of slots requested by each node in a control frame that specifies the TDMA schedule. This control frame manages the network and specifies the parameters values of the TDMA schedule. The control frame is similar to the beacon frame adopted by the IEEE 802.15.4 and the IEEE 802.15.6 standards. Using this frame, nodes are scheduled to access the channel when the controller receives the TDMA slot request. If the request has been accepted first, the associated node will use the channel before others. Besides, the controller offers each node a number of time slots equal to the number of requested slots. The controller advertises the schedule using the control frame. Therefore, a node will wake up during its allocated time slots and try to transmit its packets. The node should receive an acknowledgment from the controller after every successful packet transmission. If the node fails to receive an acknowledgment frame, then the node assumes that its link suffers from a deep fade, and thus will not perform packet re-transmission. In addition, the node will shut down its transceiver and continue sleeping until the TDMA current round finishes. Other nodes will continue to use the channel according to the schedule.

3.2 Dynamic Scheduling Based on Sleeping Slots (DSBS) MAC

Allowing the nodes to sleep during their active period leads to unfairness in utilizing the medium hence it will increase the number of packets in the node's buffer. At very high traffic rates, this will cause buffer overflow. As a result, if the packets are not lost due to deep fade, they are more likely going to be lost due to buffer overflow. Moreover, sleeping during active session increases packet delay. Therefore, optimized solutions are required to solve the delay, unfairness and buffer overflow issues without increasing the size of the buffer. Optimized solutions can be achieved by dynamically allocating the resources according to nodes' requirements. Consequently, the proposed DSBS technique is based on the sleeping duration of the nodes. For example, extra slots can be allocated to the nodes that have more packets in their buffers. Typically, nodes that have slept during their active period in the previous round would logically have more packets in their buffer compared to others (assuming nodes transmit identical amount of traffic rates).

```
Input: 1 controller CRL, a number of nodes N, TDMA schedule of n slots, each Ni ∈ N is assigned equal
number of slots S, where S = n/N, the minimum number of slots Ni can acquire is slotsMinValue and each Ni
has a buffer Bi.
Output: Dynamic slot allocation TDMA schedule
FOR each Ni ∈ N do the following
    WHILE TDMA round
        IF Ni(Si). start = true
            WHILE Ni(Si)
                IF controller
                    IF NOT (CRL. received(Ni(Data_Packet)))
                        CRL.creates(list);   CRL(list[item]) ← Ni(ID);
                        CRL(timer.start) ← local_time;
                    END IF
                END IF
            END WHILE
            CRL(timer.end)←local_time;   ti← timer.end - timer.start;
            E ← ti  / slotSize;   CRL(list[Ni(ID)]) ← E;
        END IF
    END WHILE
END FOR
IF controller
    IF NOT (list = NULL)
        Sort (N, Data_Packet.bufferField,list);
        NR ← N - list.length;
        FOR (i=1, i ≤ list.length; i++)
            IF Ni(E) < 1
                CRL.allocate(Ni) ← S;
            END IF
            ELSE
                Si ← S + E;
                WHILE (n − (Si*list.length) / NR ) < slotsMinValue
                    CRL.allocate(Ni) ← Si - 1;
                END WHILE
            END ELSE
        END FOR
        FOR (i=1; i ≤ NR; i++)
            WHILE (n/NR ≥ slotsMinValue) AND (n MOD NR) > 0)
                Si ← (n / NR) + 1;   CRL.allocate(Ni) ← Si ;   n ← n − Si;
            END WHILE
        END FOR
        Si ← n / NR;   CRL.allocate(Ni) ← Si;   n ← n - Si;
    END IF
    ELSE
        FOR(i=1; i ≤ N; i++)
            CRL.allocate(Ni) ← S;
        END FOR
    END ELSE
    CRL. send (Beacon);   CRL.delete(list);
END IF
```

Figure 4: Dynamic Scheduling Based on Sleeping Slots (DSBS).

At its basic level, in this step, we do not consider traffic prioritization. Since all the time slots in the TDMA schedule are occupied and as the number of time slots in any TDMA schedule is finite and limited, the only possible way to give nodes extra slots is to borrow these slots from other nodes whose links have not suffered from fading in the current round. This is to relax the constraint on their buffer and to meet at the same time the delay requirement, which is 250 ms at maximum for normal traffic [1]. Each node should be allocated a number of slots equal to the number of slots it slept during the previous round. By recording the time at which the node slept, and when the node's active session ends, the controller can decide for how long the node has slept during its active time slots and allocates a number of slots accordingly. The DSBS pseudocode is depicted in Fig.4. To have a better description of the DSBS, we state the following definitions.

Definition 1: Let N and n be the total number of nodes in the network and the total number of the TDMA schedule slots respectively, $\forall N_i \in N \rightarrow S$ slots is assigned to N_i once the network is established, where $S = n/N$.

Definition 2: Given a slot length L, the node's total channel access time is denoted as T_i, where $T_i = S_i * L$.

Definition 3: Let the time recorded by the timer for a node be t_i, then the number of slots the node has slept will be $E = t_i/L$, where $E \leq S$. Accordingly, as long as there are enough slots in the schedule, the controller (CRL) assigns N_i extra slots E. Therefore, in the next round, N_i will be assigned a total number of slots $S_i = S + E$ slots. Note that if $E \leq 1$ then there is no need for the controller to offer N_i any extra slots in the next round and there will be no change in the TDMA original schedule. Thus, at any round, $1 \leq E \leq S$, and more than one node could sleep during its active session due to the deep fade in the channel.

DSBS works as follows: during the TDMA round, the controller should expect to receive packets from the nodes according to the TDMA initial schedule. If the controller does not receive what it expects from a certain node at a certain time, it switches on directly a clock timer and keeps it activated until the end of the active time duration of that node. This timer will record for how long that node is sleeping. Therefore, during any TDMA round, if at least one node sleeps during its active period, the CRL creates a list and saves the IDs of nodes with bad links along with the calculated number of slots they slept. The nodes in the list can acquire extra number of slots E as long as there are enough slots to distribute. The group of nodes that are not included in the list is denoted as N_r.N_r refers to the remaining nodes, which had a good link status in the previous TDMA round, and therefore do not require extra slots for the next round. Accordingly, a minimum number of slots that each $N_i \in N_r$ can acquire should be defined. We denote this threshold value as **slotsMinValue**. If the number of the remaining slots in the schedule is not enough to be distributed over N_r, then the extra slots for the nodes in the list should be decremented until there are enough slots to distribute over the nodes that are not in the list. This is to avoid any $N_i \in N_r$ from acquiring a number of slots less than **slotsMinValue**. However, in some conditions, the opposite case might occur, i.e., after allocating the nodes in the list extra slots, and allocating **slotsMinValue** each node in the set N_r, a number of remaining slots in the schedule might still be available. In this case, those remaining slots will be allocated to the nodes that buffered more packets.

To achieve fairness between nodes, a new field is added to the node's data packet to carry its current buffer size. Besides calculating the sleeping time of the node in the current round, CRL sorts nodes according to value of their buffer field, which is added to the node's data packet. Accordingly, in the next round, after assigning extra slots to nodes with bad links, the remaining number of slots are assured to be distributed equally over the N_r, whereby each $N_i \in N_r$ is assigned **slotsMinValue**, then any extra slots will be granted to nodes according to the number of packets in their buffer. Using this approach, the slot allocation will consider node's communication requirements and avoids fading in the channel. It is worth mentioning here that this technique should take place just in case at least one node had a bad link during the previous TDMA round. Otherwise no change should take place on the next schedule and nodes should be re-allocated a number of time slots S equivalent to the number they requested when the WBAN was established. In the sequel, we will consider two examples implementing DSBS.

Example 1: Assume that the total number of nodes in the network is $N = 5$. If the total number of the TDMA schedule is $n = 15$ time slots, then each node in the network N_i should be assigned $S_i = 3$ slots. If the slot length $L = 3$ ms, then for each $N_i \in N$, the node's total channel access time $T_i = 9$ ms. Let's assume N_3 slept during its active session for $t_3 = 6$ ms, then the number of slots N_3 has slept is 2 slots, which also means that the number of extra slots the node should acquire is $E = 2$. Accordingly, the CRL creates a list $L = N_3, 2$. Therefore, in the next round, N_3 will be assigned a total number of slots $S_i = 5$ slots (3 original slots + 2 extra slots). The rest of the nodes in $Nr = N_1, N_2, N_4, N_5$ will be offered the **slotsMinValue**. If **slotsMinValue** is set to 2 for example, then the overall number of the allocated slots will be 13 slots. The remaining unassigned 2 slots will be offered to those nodes with highest number of packets in their buffer.

Example 2: Now, assume that there is another node recorded in the list L, which requires extra slots, $L = N_3, 2, N_4, 3$. This means that in the next round, N_3 should be assigned a total number of slots $S_3 = 5$ slots, N_4 should be assigned a total number of slots $S_4 = 6$ slots. As the total number of slots in the TDMA schedule $n = 15$, then obviously, there is no enough time slots to distribute over $N_r = N_1, N_3, N_5$. Because according to this calculation, the overall number of slots that should be allocated to the nodes in both lists L then N_r will be 17, whereas the total number of slots of the TDMA schedule is 15. In this case, the number of slots for N_4 should be decremented to 5, and N_3 should be allocated just 4 slots. Consequently, there will be enough time slots to distribute over $N_r = N_1, N_3, N_5$ as each $N_i \in N_r$ will be allocated the **slotsMinValue**.

3.3 Dynamic Scheduling Based on Buffer (DSBB) MAC

When the node sleeps during its active period, the packets during this time will be stored in its buffer. Assuming a basic scenario where nodes send packets at Constant Bit Rate (CBR) with the same packet arrival rate, then the number of packets in the node buffer could help to estimate the sleep duration. Therefore, in the second technique, we chose to offer the nodes extra time slots based only on the number of packets in their buffer. Nodes with the highest number of buffered packets will be allocated more slots in the next round. We again propose the following definitions, which help in the description of the proposed approach.

Definition 4: Let T be the time each packet takes from the moment it is transmitted by the node until it receives the acknowledgment frame and let L be the slot length, then the capacity of each time slot to hold packets is given by $C = L/T$. Accordingly, if one slot can occupy C packets, then 2 slots can occupy 2C packets, and 3 slots can occupy 3C packets, etc.

Definition 5: Let x be the number of packets in the buffer, and C is the capacity of the time slot, then the extra slots E allocated to nodes according to the number of packets carried in their buffer can be calculated as follows:

$$E = \begin{cases} 1 & \text{if } (1 \leq \ x \ \leq C) \\ \left\lfloor \frac{x}{C} \right\rfloor + 1 & \text{if } (x \ mod \ C > 0) \\ \frac{x}{C} & \text{otherwise} \end{cases} \tag{1}$$

The pseudocode of DSBB is depicted in Fig.5. Similar to DSBS technique, nodes can be allocated extra slots according to the number of packets in their buffer, as long as there are enough slots remaining to cover all nodes. When there are no enough slots in the schedule to offer nodes extra slots, then each $N_i \in N_r$ acquires **slotsMinValue**. However, if all the nodes have been allocated the required slots, the remaining slots in the schedule will be eventually granted to those nodes that carry more packets in their buffer. Example 3 depicts a scenario of DSBB.

Example 3: If we assume that $T = 1$ ms and the slot length $L = 3$ ms, then the capacity of each time slot to hold packets $C = 3/1 = 3$ packets. As each node is originally allocated $S = 3$

```
Input: 1 controller CRL, a number of nodes N, TDMA schedule of n slots of capacity C Data_Packets, each
Ni ∈ N is assigned equal number of slots S, where S = n/N, the minimum number of slots Ni can acquire is
slotsMinValue and each Ni has a buffer Bi.
Output: Dynamic slot allocation TDMA schedule
IF controller
        FOR each Ni ∈ N do the following
                IF NOT (list = NULL)
                        Sort (N, Data_Packet.bufferField.list);   i ← 1;
                        WHILE (n / N ≥ slotsMinValue) AND (i ≤ N)
                                IF  i ≤ list [Ni(Data_Packet.bufferField)] AND
                                                    list [Ni(Data_Packet.bufferField)] ≤ [i] * C
                                        Si ← S + i;
                                END IF
                                ELSE IF  [i]*C ≤ list[Ni(Data_Packet.bufferField) ] AND
                                                    list[Ni(Data_Packet.bufferField)] ≤ [++i] *C
                                        Si ← S + i;
                                END IF
                                CRL.allocate(Ni) ← Si ;   n ← n – Si;   N ← N - 1;
                        END WHILE
                        FOR (i = 1; i < NR; i++)
                                WHILE (n / NR ≥ slotsMinValue) AND (n MOD NR) > 0)
                                        Si ← (n / NR) +1;   CRL.allocate(Ni) ← Si;   n ← n – Si;
                                END WHILE
                                Si← n / NR;   CRL.allocate(Ni) ← Si;   n ← n - Si;
                        END FOR
                END IF
                ELSE
                        FOR(i = 1; i ≤  N; i++)
                                CRL.allocate(Ni) ← S;
                        END FOR
                END ELSE
        END FOR
        CRL.send(Beacon); CRL.delete(list);
END IF
```

Figure 5: Dynamic Scheduling Based on Buffer information (DSBB).

slots, then the 3 slots can hold 9 packets. Assume that in the current TDMA round, N_3 sends its data packet to the CRL and the buffer field of N_3 is $x_3 = 6$ packets, then the number of the extra slots that should be offered to N_3 for the next TDMA schedule, is $E = 2$ slots. So in total $S_3 = 5$ slots. The procedure of distributing the slots over the remaining nodes is identical to the one presented in Example 1 in Section 3.2.

4 Simulation Setup and Performance Evaluation

The reliability and energy performance of DSBS and DSBB are compared and evaluated against the performances of IEEE 802.15.4 and IEEE 802.15.6 standards. To carryout the simulation experiments, we used the latest version of Castalia open source simulator, Castalia-3.3 [26] and used the parameters described in Table.1. The WBAN topology is composed of 6 nodes: one controller at the right hip and five nodes (four at the four limbs and one in the middle of the chest). The study in [4] shows statistics about the duration of the deep fade for each node's link and how frequent the signal falls below receiver sensitivity for that link. The 5 nodes send 105 bytes data packet (including overhead) to the controller at a constant bit rate. It is worth mentioning that the IEEE 802.15 TG6 provides no specific mechanism or values for parameterising the IEEE 802.15.6 superframe [1][6], but IEEE 802.15 TG4 does [5][7, 8, 9, 10, 11]. As it is stated in [5][15, 16, 17, 18, 19], IEEE 802.15.4 slot size duration depends on the value of the Superframe Order (SO) parameter, which is responsible for calculating the active period duration of the IEEE 802.15.4 superframe. Moreover, the IEEE 802.15.4 superframe consists of 16 time slots, therefore each one of the 5 nodes can be allocated 3 slots at maximum once the network is established. All compared MAC protocols adopt 15 time slots TDMA schedule. The slots lengths are calculated according to the SO values of the IEEE 802.15.4. The slot that remains after excluding the 15 slots for CFP, will be used for CAP wherein nodes contend for accessing the channel. Indeed, both TG4 and TG6 working groups recommended that when configuring the IEEE 802.15.4 and IEEE 802.15.6 superframe structures there should be a minimum value for the contention based access before the contention free period starts. According to our intensive simulations for the IEEE 802.15.6, we found that for a successful IEEE 802.15.6 operations, RAP should be at least 2 slots. All the algorithms examined are allowed to operate within 100 % duty cycle. However, DSBS and DSBB allow the nodes to sleep further in their active period when their links encounter deep fade. Two scenarios were followed. In the first scenario the performance of the two protocols is evaluated with respect to various CBR values, whereas in the second scenario different slots lengths are considered instead. Those two scenarios are illustrated in details in Section 4.1 and Section 4.2 respectively.

4.1 Scenario 1: The Impact of Traffic Rate

In this scenario, the performances of DSBS, DSBB, IEEE 802.15.4, and IEEE 802.15.6 are examined over 11 different traffic rates, which vary from a very low traffic rate (5 p/s) up to very high traffic rate (100 p/s). All the protocols work through 100% duty cycle with 3.75 ms slot size (SO=5 for IEEE 802.15.4). Given that each packet takes around 1.208437 $\approx$ 1.21 ms from the moment it is transmitted until the node receives the acknowledgment frame, each slot can occupy up to three packets. The protocols are compared against their reliability, measured in terms of the packet loss rate as presented in Fig.6. The power consumption of all protocols is also measured to assess their energy efficiency as illustrated by Fig.7.

parameter	value
Simulator	Castalia 3.3
Simulation time (s)	500
Number of nodes	6 (1 controller and 5 nodes)
Total number of TDMA slots	15
slotsMinValue	2
Buffer size (byte)	32
Traffic model	CBR (normal traffic)
Traffic rate (p/s)	5, 10, 20, 30, 40, 50, 60, 70, 80, 90, 100
Slot sizes (ms)	1.875, 3.75, 7.5, 15
Duty cycle	100%
MAC packet length (byte)	142
IEEE 802.15.4 related configurations	
GTS(s)	3
SO values	4,5,6,7
IEEE 802.15.6 related configurations	
RAP	2 slots
Scheduled access	15 slots
MAC Packet length (byte)	1000

Table 1: Simulation Parameters.

As we can see from Fig.6, DSBS and DSBB achieve less packet loss as opposed to the legacy IEEE 802.15.4 and IEEE 802.15.6 standards at all traffic rates. This is because, on one hand, the proposed techniques avoid the deep fade in the channel, which is the primary source of packet loss in WBAN, and on the other hand, they distribute the time slots between nodes according to nodes' requirements. The IEEE 802.15.6 MAC frame size implemented in Castalia-3.3 simulator is around 1000 bytes, which is very large compared to the 142 byte (including data packet overhead), adopted by DSBS and DSBB. Therefore, 3.75 ms slot length is not sufficient to transmit the long MAC IEEE 802.15.6 packet and the transmission will be differed constantly to the next superframe. As mentioned previously, at the beginning of each IEEE 802.15.6 superframe and before the nodes follow the 15 TDMA slots schedule, nodes follow contention based channel access in RAP of two slots. Consequently, during this period, nodes will transmit altogether, which causes collision, increases packet loss and therefore will deteriorate the performance of IEEE 802.15.6 standard.

Fig.7 shows that both DSBS and DSBB achieve less energy consumption compared to IEEE 802.15.4 and IEEE 802.15.6. This is because the proposed techniques allow the nodes to save energy while sleeping during their active time slots, and avoid useless packets re-transmissions. Moreover, nodes are given time slots according to their needs, which would avoid idle listening

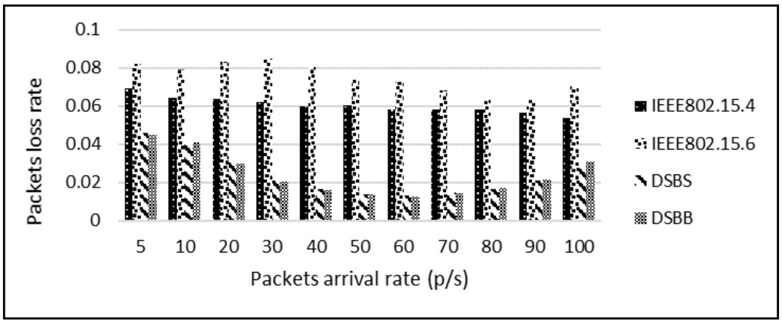

Figure 6: Packets loss rate for different and increasing CBR(s).

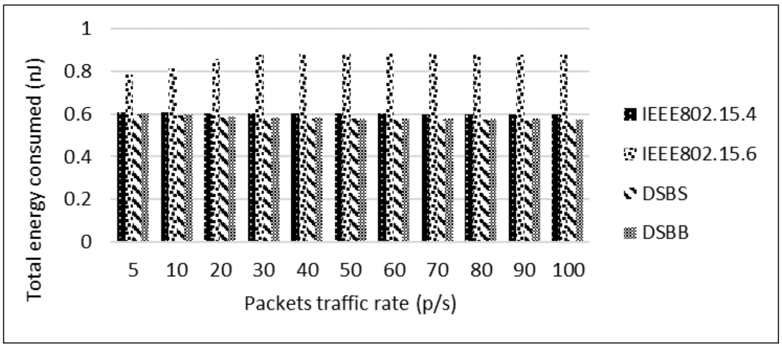

Figure 7: Total energy consumption for different and increasing CBR(s).

process that might occur if nodes are given more time than they actually need. Looking carefully at the results, it is noticed that DSBS achieves less energy consumption than DSBB as DSBB assigns slots based on the number of the packets in the node's buffer, which increases the probability of a node to get extra slots and use the channel for long time and consequently consume more energy. According to these experiments, IEEE 802.15.6 has the worst performance with respect to energy consumption. This is because nodes spend two slots in RAP during the contention based access period, which adversely increases energy consumption. Nodes need to stay idle while other transmit, which in return might lead to collision and consequent re-transmission.

4.2 Scenario 2: Changing the Slot Size

Results achieved in Section 4.1 call for analyzing the effect of the duration of accessing the channel on the performance of the proposed protocols. In essence, the performance of the proposed protocols should be investigated with longer slot durations and different slot lengths. For this purpose, four values of SO were chosen, wherein each value contributes to a different value for the slot time length. Those values are respectively: SO= 4 (1.875 ms slot length), SO= 5 (3.75 ms slot length), SO=6 (7.5 ms slot length) and SO= 7 (15 ms slot length).

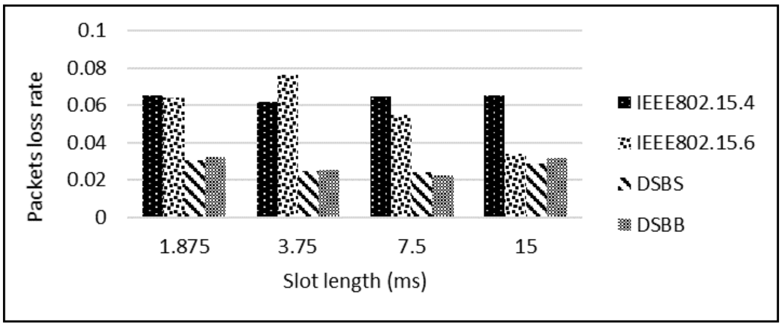

Figure 8: Packets loss rate for different slot sizes.

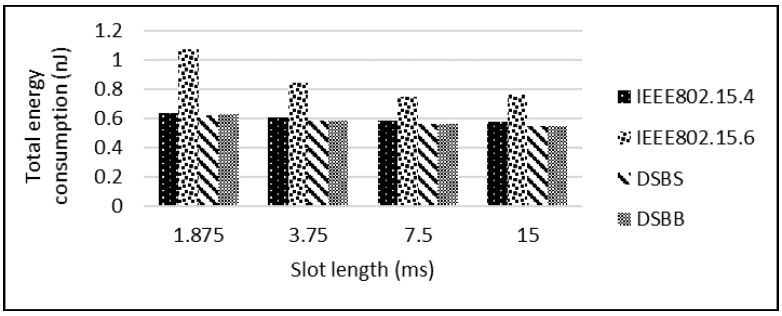

Figure 9: Total energy consumption for different slot sizes.

The performance of the proposed DSBS and DSBB, IEEE 802.15.4 and IEEE 802.15.6 is evaluated over those slot lengths and using the same performance metrics presented in Section 4.1. To reflect the heterogeneity of a WBAN network, different traffic rates are simulated: node 1 sends 5 p/s, node 2 sends 30 p/s, node 3 sends 40 p/s, node 4 sends 15 p/s and node 5 sends 1 p/s. The remaining experimental parameters are identical to those adopted in Scenario 1 and presented in Table.1. Fig.8 reveals that for all slot lengths, both DSBS and DSBB outperform IEEE 802.15.4 and IEEE 802.15.6. This means that the proposed protocols achieve more reliable WBAN than these standards regardless the slot size thanks to fair slot distribution mechanism. However, it can be noticed that apart from 7.5 ms slot duration, DSBB outperforms DSBS. This is because DSBB offers time slots to the nodes according to the number of packets in their buffer, which is more accurate than giving time slots to the nodes based on their sleep period durations during the previous round. For example, in some cases, nodes sleep at the end of their assigned time slots, and therefore will not be assigned extra time slot in the upcoming round. It can be noticed also that the gap between the performance of the proposed protocols and IEEE 802.15.6 diminishes at 15 ms slot size. This is because the 15 ms slot offers the IEEE 802.15.6 MAC frame enough time to be transmitted during the current superframe duration.

Fig.9 reveals that for all slot lengths, both DSBS and DSBB achieve less energy consumption regardless of the duration of the slot length. DSBS still outperforms DSBB. This is because DSBS offers the nodes some time slots based on the number of time slots they consumed while sleeping during the previous rounds. Thus, nodes will be given systematically long time opportunities to stay active, which avoids energy dissipation. Looking carefully at Fig.9, it is noticed that at 15 ms, nodes consume the least power due to the longer time periods the nodes might sleep when they face fading, which saves more energy. IEEE 802.15.6 consumes much more energy as opposed to the other protocols, due to the longer period in performing contention based access in the two slots RAP, as it is explained in Section 4.1.

5 Protocols' Performance in Emergencies

In order to evaluate the performance of DSBS and DSBB in emergencies, first we ought to define the emergency situation, and how it can be distinguished from the normal one, how it can be detected, and what happen when it occurs.

5.1 What is Emergency?

Emergency is a variation in the behavior of the current context in a way that could lead to life threatening situations [23]. Emergency could occur when a patient with a life threatening disease suddenly changed his/her activity, or his ambient environment encountered an unpredictable extreme high or low temperature, pressure, oxygenation, humidity, etc. In such circumstances, information related to the monitoring context should be transmitted with the highest possible quality of service (QoS), without packet loss, and at acceptable latency requirements while considering energy efficiency. For instance, if a patient with heart attack falls down, or performs an exercise, then the medical staff should focus on the heart rate data than other sensors data. Therefore, real-time transmission of the data from the ECG sensor device should be guaranteed, while other sensors' data such as EMG will become less important [22][24].

5.2 Emergency Detection

The controller detects the context variation in WBAN through data processing and analysis. In normal situations, sensor nodes operate within a standard data rate and duty cycle to sample and transmit data to the controller [18]. After collecting the data from all nodes, the controller processes and analyzes the received data, and can detect the change in the activity or the context by following one of the context recognition algorithms that are applied to the sensors data. Some of these algorithms can be found in [27]. Using such algorithms is independent from designing MAC protocols; thus, we will not go into details how those algorithms operate as this is beyond the scope of the study. After analyzing the data, if the controller detects abnormality in a physiological signal,it requests more data from the sensor to perform precise recognition. To achieve that, the controller orders the associated sensors to increase their sampling rate, which results in increasing their traffic rate [22, 23, 24].

5.3 Emergency in Our Experiments

In this section, we explain how we investigate emergency in our simulations. In normal situations, nodes send data packets at a constant bit rate (CBR). In emergency situations however, nodes' traffic rate increases and turns to random, and according to the literature, such as the work in [23, 24], their traffic rate follows the Poisson model in which packets inter-arrival time follows exponential distribution. Apart from the traffic rate, our simulation experiments parameters are identical to those presented in Section 4.1. At the beginning of the simulation, WBAN is set to operate in a normal situation during which nodes follow CBR traffic model. Each node chooses a traffic rate (R) randomly from the range [1-10] p/s, where the inter arrival time (T) is static, and $T = 1/R$. When emergency is detected, two consequences occur: (1) the traffic rate λ of those nodes related to the monitoring context increases (in accordance to the increase of their sampling rate), (2) nodes' traffic rate λ jumps abruptly from CBR with static inter-arrival time to Poisson traffic rate with inter-arrival time of exponential distribution. Emergency was applied at two different simulation periods: the first period lasted for 100s from 50-150s, during which the inter-arrival time follows exponential distribution of mean 0.02 and rate $\lambda = 50p/s$. The second period lasted for 150 s from 300-450s, during which the inter-arrival time follows

Link Status	The Node
Nodes with very good link status	N_2
Nodes with good link status	N_4
Nodes with bad link status	N_1 and N_5
Nodes with very bad link status	N_3

Table 2: Classification of the links' status of the nodes.

Scenario	The Involved Nodes
A node of a very good link with a node of good link	N_2 and N_4
A node of a very good link with a node of a bad link	N_2 and N_1, or N_2 and N_5
A node of a very good link with a node of a very bad link	N_2 and N_3
A node of a good link with a node of bad link	N_4 and N_1, or N_4 and N_5
A node of a good link with a node of very bad link	N_4 and N_3
A node of bad link with a node of bad link	N_1 and N_5
A node of bad link with a node of very bad link	N_1 and N_3, or N_5 and N_3

Table 3: Scenarios of the nodes in emergency.

exponential distribution of mean 0.01 and rate $\lambda = 100p/s$. In those periods, two nodes are chosen to have emergency. The nodes were chosen in a way that could enable us to evaluate the performance of DSBS, DSBB, IEEE 802.15.4 and IEEE 802.15.6 at all possible cases that might occur regarding the channel status. As different scenarios involve different nodes in emergency with different links status, the combinations of nodes in emergency vary according to the nodes general links status. Based on intensive simulation of parameters presented in Table.1, for five nodes positioned in a WBAN, whose links average path loss presented in [4], we were able to categorize node links status as it shown in Table.2.

Where N_1, N_2, N_3, N_4, N_5 refer to the five nodes. According to this categorization, there are five nodes with four different links' status. If we chose to apply emergency on two nodes, then we will have seven possible scenarios of two nodes in emergency with different links' status. The possible nodes combinations are presented in Table.3. The selected nodes are as follows: N_1 and N_2, N_1 and N_4, N_1 and N_5, N_2 and N_3, N_2 and N_4, N_3 and N_4, N_3 and N_5. We evaluated the performance of the protocols using those seven scenarios, which we applied on three slot sizes: 3.75 ms, 1.875 ms, 7.5 ms, and the experiments were repeated 20 times. It is worth mentioning here that this work does not consider prioritizing nodes based on the sensitivity of their data or their relation to the monitoring context. In other words, all nodes will have the chance to use the channel, even if they are not in emergency. The distribution of slots will run according to DSBS and DSBB techniques explained in Section 3.2 and Section 3.3 respectively. This is because the goal of this section is to evaluate whether increasing the channel access duration to nodes in emergency based only on their channel and buffer status could improve WBAN QoS and energy efficiency, and whether DSBS and DSBB can cope with both emergencies and normal situations. Considering nodes prioritization based on their traffic context is left for future work. We evaluated the protocols performance in terms of packets loss rate, latency and energy efficiency. The following subsections present the results of the protocols' performance at each slot length by applying the simulation parameters in Table.1. and triggering the emergency over the nodes in seven scenarios.

5.3.1 Results of 3.75 ms Slot Length

Fig.10 depicts the results for reliability performance in terms of packets loss. It is clear that our proposed protocols outperform the legacy IEEE 802.15.4 and IEEE 802.15.6 at all scenarios regardless of which nodes have been chosen for emergency. This is because nodes encountering emergency situation as all other nodes avoid the deep fade in the channel and therefore avoids losing their packets. Moreover, nodes are allocated extra slots based on their links status and buffer status, which is also beneficial for the node in emergency to cope with the increased traffic rate. It can be noticed also that even for the node with very good link, i.e. N_2, the proposed protocols still outperform the legacy standards, because they always avoid the deep fade in the channel, and thus their probability of losing packets is always less than the legacy standards. This means that avoiding the deep fade in the channel and re-allocating the nodes extra slots based on their channel status and buffer status can tolerate to both normal and emergency situations.

As for the end-to-end delay, Fig.11 shows that all algorithms outperform IEEE 802.15.6, due to the long length of the MAC frame size of the IEEE 802.15.6. However, the proposed algorithms perform worse than the IEEE 802.15.4 at all nodes apart from the nodes with very good links (i.e. N_2). This is rational, because nodes have to sleep whenever their links face fading in the channel, and therefore the data packets are scheduled for the next TDMA round, which increases the delay of the packets. On the other hand, N_2 faces fewer sleep opportunities due to its very good link status, which explains why its packets has less delay. It can be noticed from Fig.11 that at most cases DSBB outperforms DSBS. This is because in DSBB allocates

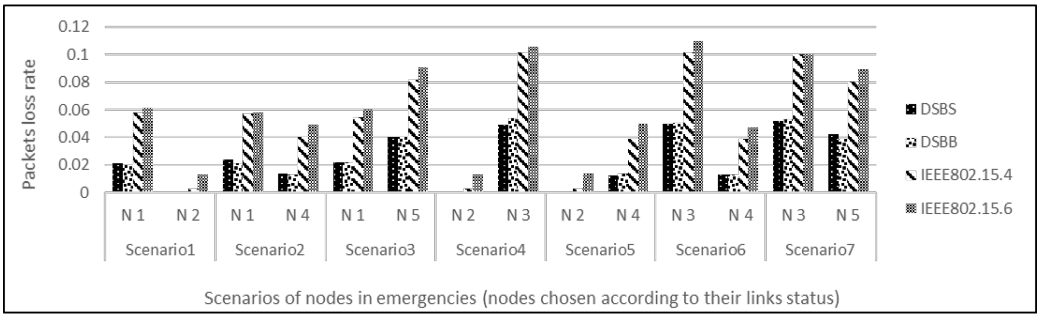

Figure 10: Packet loss rate with 3.75 ms slot length.

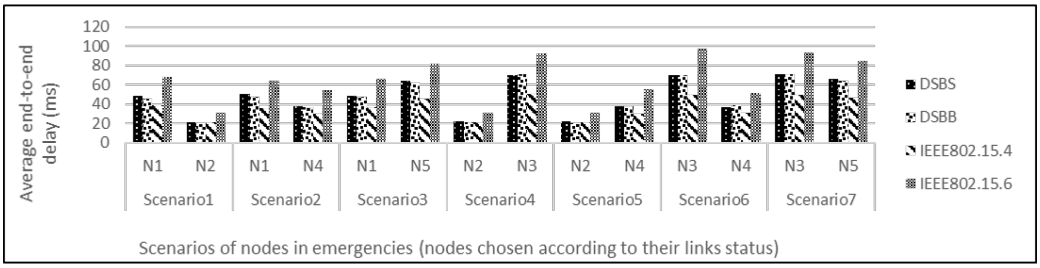

Figure 11: Latency for nodes in emergency with 3.75 ms slot length.

the nodes time slots based on the number of packets in their buffer. If the node that has to be allocated extra slots is also in emergency, then that node will have more opportunities to send its increased traffic load, which decreases the delay of its packets. Although the latency of the DSBS and DSBB is increased, the maximum rate of packets that are received after 125 ms is less than 20%. It can be noticed that the maximum rate is at N_3. This is because N_3 has a bad link status and therefore will have more sleep periods than the other nodes. The maximum rates at IEEE 802.15.4 and IEEE 802.15.6 are respectively 10% and over 25%. By comparing the results with the IEEE 802.15.4, results indicate that the increase in the delay in DSBS and DSBB is acceptable as the difference in the maximum rate is fewer than 10%. However, this slight increase in the delay is accompanied with a noticeable decrease in the packets loss.

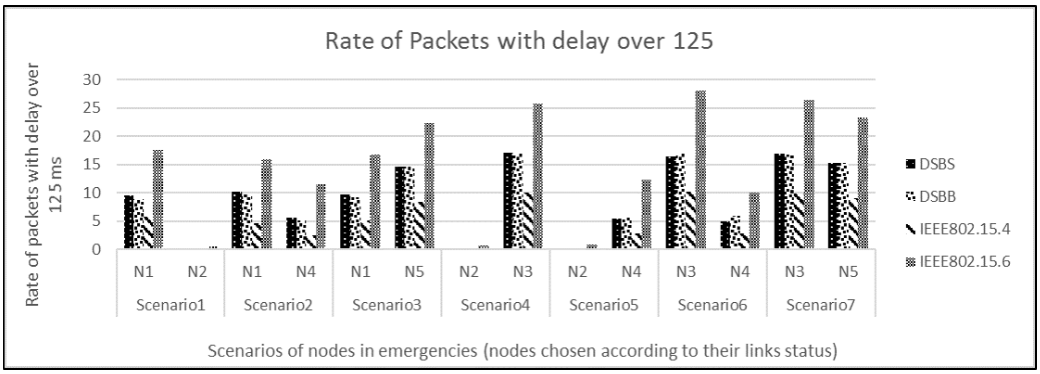

Figure 12: Rate of packets received with a delay over 125 ms with 3.75 ms slot length.

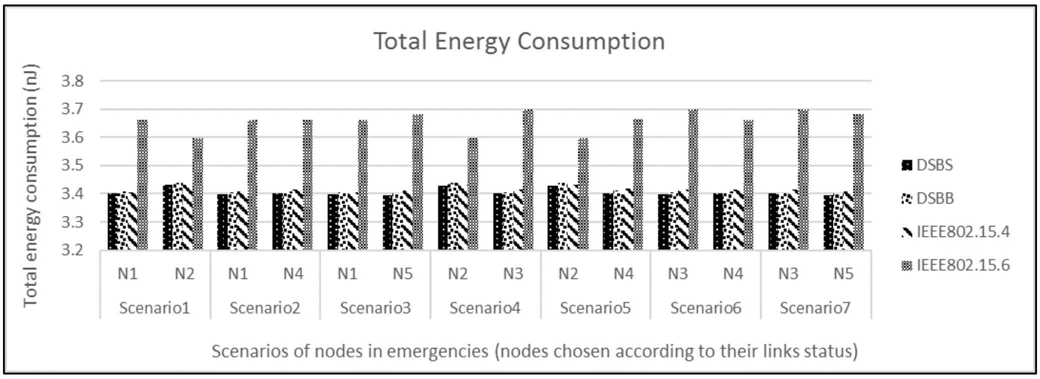

Figure 13: Total energy consumption with 3.75 ms slot length.

Fig.13 depicts the results of total energy consumption. It is clear that IEEE 802.15.6 performs worse than all other algorithms. DSBS incurs less energy consumption than the IEEE 802.15.4 at all nodes. DSBB outperforms IEEE 802.15.4 at all nodes apart from the nodes with very good links status (i.e. N_2) where DSBB consumes slightly more energy than IEEE 802.15.4 and DSBS. This is because DSBB allocates the nodes extra slots based on the current buffer size. Despite that N_2 presents a very good link status, its link could face fading at some point, and as it is in emergency, it will have high load of packets in its buffer based on which it will be acquired extra slots. Therefore, N_2 will have more opportunities to use the channel, which results in a slight increase in its energy consumption compared to other protocols. We notice that at all nodes DSBS outperforms both the DSBB and the legacy standards. This is because DSBS gives nodes in emergency fewer opportunities to use the channel than the DSBB. Following DSBS, the duration of the extra slots, which are allocated to nodes equals to the duration of the deep fade that the nodes faced during the previous TDMA round. This could not be enough time for nodes in emergency to send their data packets due to the increased traffic loads, which also explains why DSBS results in more delay and packets loss than the DSBB.

5.3.2 Results of 1.875 ms Slot Length

The achieved results for 1.875 ms slot length almost match those achieved for 3.75 ms slot size. Fig.14 reveals that the proposed protocols outperform the legacy standards in terms of packets loss in all scenarios, regardless of which node is in emergency. Fig.15 shows that there is a slight increase in the delay at DSBS and DSBB compared to the IEEE 802.15.4, but still both proposed protocols outperform the IEEE 802.15.6. Fig.16 shows that DSBS and DSBB result

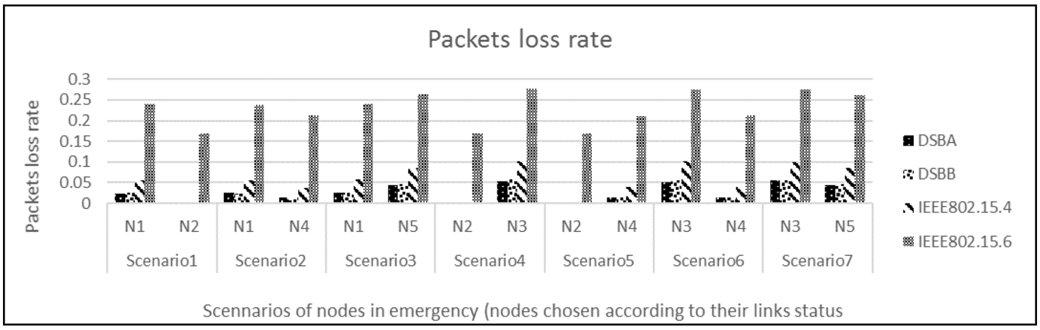

Figure 14: Packets loss rate for nodes in emergency applied in the seven scenarios at 1.875 ms slot length.

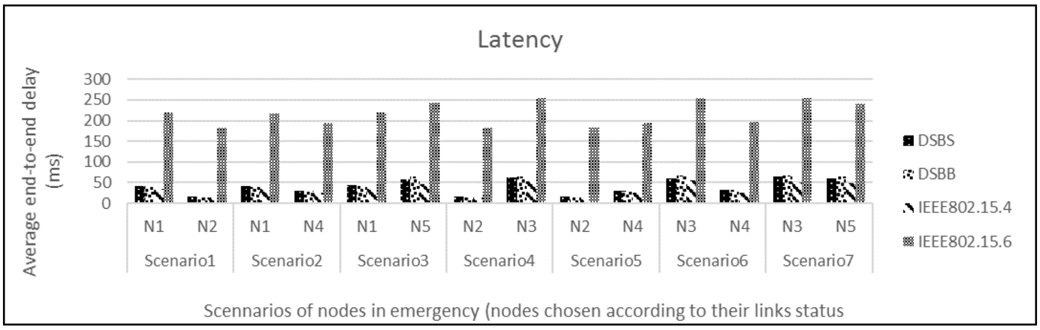

Figure 15: Latency for nodes in emergency applied in the seven applied scenarios at 1.875 ms slot length.

in around 5% more packets with delay over 125% compared to the IEEE 802.15.4. However, it is shown in Fig.17 the DSBS consumes less energy than both standards at all scenarios. DSBB outperforms IEEE 802.15.4 at all nodes apart from the nodes of very good link status, which is similar to the results of Fig.13 and due to the same reasons.

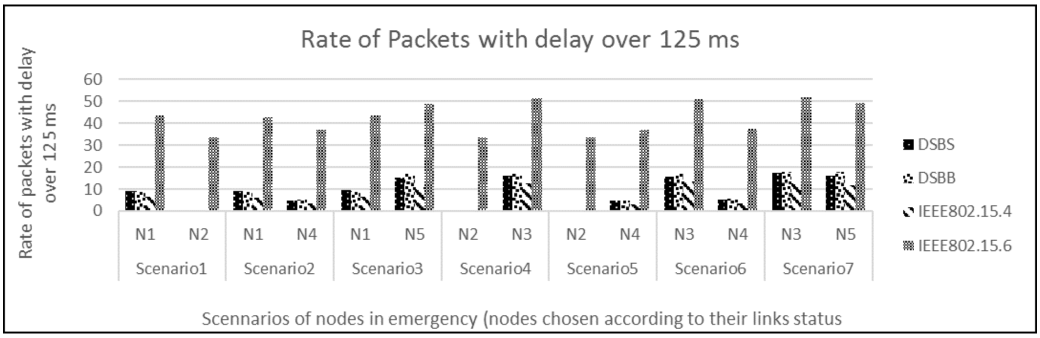

Figure 16: Rate of packets received with delay over 125 ms for nodes in emergency at 1.875 ms slot length.

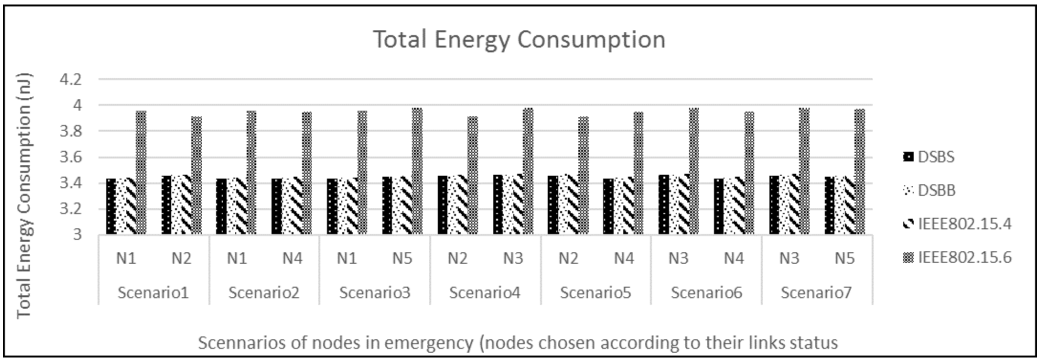

Figure 17: Total energy consumption for nodes in emergency at 1.875 ms slot length.

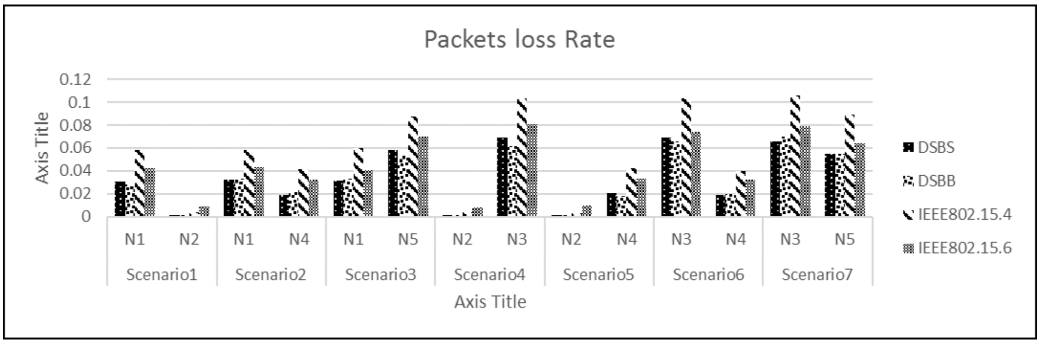

Figure 18: Packets loss rate for nodes in emergency applied in the seven applied scenarios at 7.5 ms slot length.

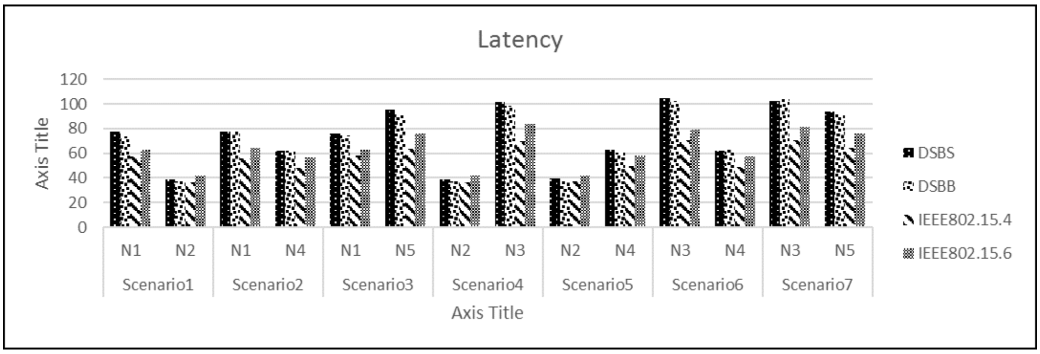

Figure 19: Latency for nodes in emergency applied in the seven applied scenarios at 7.5 ms slot length.

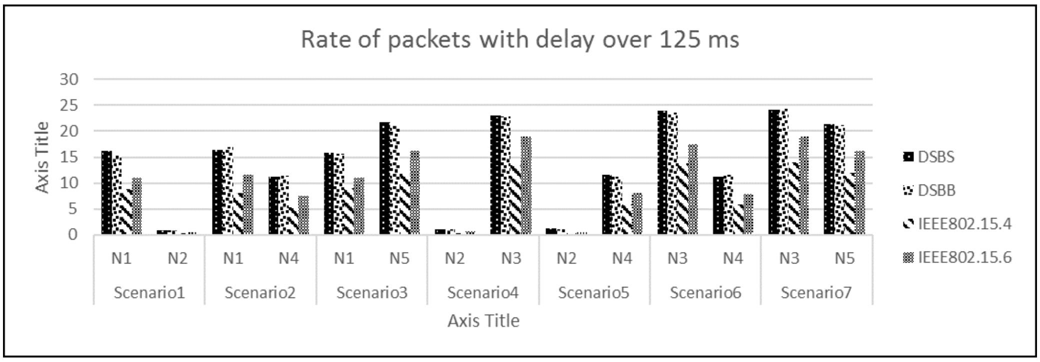

Figure 20: Rate of packets received with delay over 125 ms for nodes in emergency at 7.5 ms slot length.

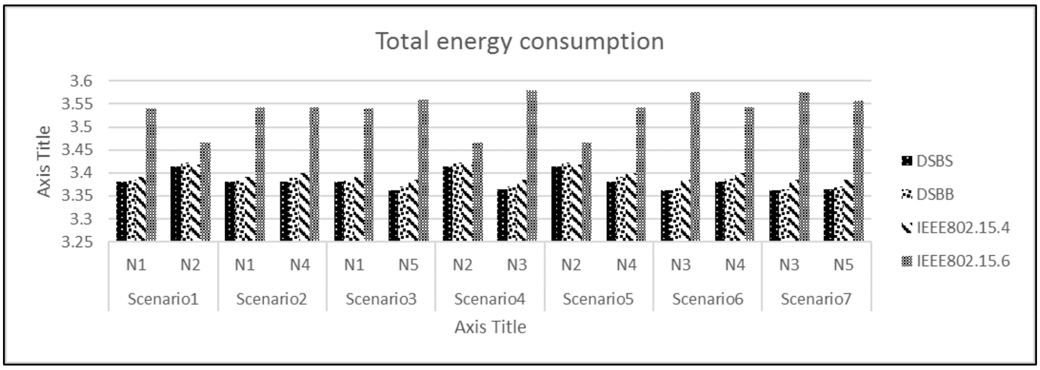

Figure 21: Total energy consumption for nodes in emergency at 7.5 ms slot length.

5.3.3 Results of 7.5 ms Slot Length

Figs.18-21 reveal that at the longer slot size, i.e. at 7.5 ms, the proposed algorithms still outperform the legacy standards. The only change that we notice is in the performance of the IEEE 802.15.6, which now outperforms the IEEE 802.15.4, because this slot size of 7.5 ms suits its packet length as it is explained in Section 4.2. The maximum rate of packets with delay over 125 ms is fewer than 15% at IEEE 802.15.4, and it is fewer than 20% at IEEE 802.15.6 whilst DSBS and DSBB has 10% more packets with delay over 125 ms compared to the IEEE 802.15.4. When it comes to energy consumption, the results are similar to those achieved in Fig.13 and Fig.17. DSBS consumes less energy than all other protocols and at all scenarios. Only at nodes with very good links, the DSBB consumes slightly more energy than IEEE 802.15.4.

5.3.4 Discussion

While it is common that the increased transmission opportunities increases throughput, at the expense of an increased energy consumption, our proposed algorithms proved a guarantee of the QoS in WBAN while decreasing energy consumption in both normal and emergency situations. Both DSBS and DSBB achieve less packets loss and energy consumption than IEEE 802.15.4 and IEEE 802.15.6, and allow all nodes to access the channel in both normal and emergency situations. In normal situations, the two proposed techniques reduce packet loss up to 61% and 68% compared to the IEEE 802.15.4 and IEEE 802.15.6 respectively. They also reduce energy consumption up to 0.62% and 7.3% compared to the IEEE 802.15.4 and IEEE 802.15.6. In emergencies however, the two proposed techniques reduce packets loss up to 63.4% and 90% with respect to their counterparts in IEEE 802.15.4 and 802.15.6 with an energy reduction up to 13% compared to the IEEE 802.15.6. Regarding the end-to-end delay, both DSBS and DSBB outperform IEEE 802.15.6, but have a slight increase in the delay over the IEEE 802.15.4 at all nodes, apart from nodes with very links status where their performances are close to IEEE 802.15.4. However, the increase in the delay is acceptable and meets the delay requirements, as the percentage of packets received with delay over 125 ms increased only 10% at maximum over the IEEE 802.15.4. We can tell from the achieved results, that 3.75-slot length contributes in the best performance amongst the other two slot sizes. Actually, longer slot sizes expose the nodes with poor links to more chances to face deep fade and longer durations in the vulnerable medium. Using our proposed protocols, the nodes are going to sleep in order to avoid losing packets, which increases the delay of their packets. On the other hand, very short slot sizes, such as the 1.875 will not give nodes enough time to access the medium, and it is very likely that if the node faces fading during this short period, it continues facing it in the next TDMA schedule, because the fading lasts for at least 10 ms. Other efforts in literature, tended to adopt a longer slot size, such as Liu et al. in [23] who adopted 10 ms slot length. This explains why in order to avoid continuous packet loss due to the longtime of deep fade, they thought about reordering the nodes in the TDMA schedule, which still does not reduce the effect of the deep fade as it is explained earlier. However, adopting shorter slot size, such as the 3.75 ms hinders the node from occupying the channel for long time, while at the same time offers the node enough time to access the channel, which also results in a TDMA with a shorter schedule length. Consequently, there will be no need for re-ordering nodes in the TDMA schedule, as a node will not occupy the channel for long time, and the rest of the nodes will get a faster chance to use the channel, which looks as if the order of the nodes is changed in the schedule.

6 Conclusions and Future Work

In this study, two new TDMA based scheduling algorithms have been proposed to improve the reliability and energy efficiency of WBAN. The proposed algorithms exploit the deep fade of the links in WBAN and use it as a criterion to dynamically allocate slots to nodes. In addition to improving WBAN reliability and energy efficiency in normal situations, the proposed protocols guarantee better QoS in emergencies situations while minimizing energy consumption. The two proposed techniques do not require substantial amendments to the superframe structures of IEEE 802.15.4 and IEEE 802.15.6. Only one extra buffer field is added to the data packet format. Moreover, the experimental results reveal that short slot lengths contribute to better performance. This is because a short slot gives nodes enough time to access the channel, while it reduces the probability that their links will experience deep fade in the channel. Consequently, other nodes with better links status will quickly use the channel. This study revealed that careful parametrization of the slot size of TDMA is highly recommended when deploying WBAN MAC protocols. As a future work, nodes prioritization will be considered in nodes' slots allocation. In other words, we will be investigating whether considering nodes' traffic context in addition to channel and buffer status improves the performance of both DSBS and DSBB algorithms. This includes considering different types of applications, emergency and normal, downlink and uplink, proactive and reactive.

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