Allocation Slot Arrangement for Flexible Polling-based TDMA in Wireless Body Area Networks

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ABSTRACT

TDMA-based MAC schemes suit WBANs due to such networks' simple star topology and power limitations. In conventional ad hoc wireless networks, the specific arrangement of reservations within a TDMA frame is of minor importance as long as all nodes asking for a reservation are granted one within a frame interval. Yet emergency event preemptions or possible sensor-initiated and uncoordinated extensions of granted schedules, which seem inevitable for WBAN applications, make reservation arrangement an important problem. Here, such events could transgress an already scheduled reservation of maybe another node, jeopardizing the latter's transmission opportunity. This is more of an issue if we consider the power-limited nature of WBAN nodes, limiting the time they can keep awake looking forward for a maybe delayed transmission opportunity. In this paper we study the optimal arrangement of slave nodes' reservations which seeks to best fulfill the traffics' QoS requirements subject to a power consumption constraint. In that we account for nodes' reservation lengths, traffic QoS requirements, and the corresponding statistical characteristics of reservation extensions and emergencies. Our strategy protects the reservations of the more QoS-constrained of slaves' applications against the possible preemptions of others and also provides them with adequate bandwidth if they ever needed to extend their reservation on the fly.

Categories and Subject Descriptors

C.2.1 [**Computer-Communication Networks**]: Network Architecture and Design—*Wireless communication*

General Terms

Algorithms, Design

Keywords

Wireless Body Area Networks, QoS, power, slot arrangement

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1. INTRODUCTION

Wireless body area networks (WBANs) have gained attention through personalizing health device applications for every day users. Various consortia and standardization bodies have initiated efforts to lay the ground for an interoperable network of health devices. Among them, Continua Health Alliance [1], an open industry group of nearly 240 healthcare providers, communications, medical, and fitness device companies worldwide, is working toward establishing systems of interoperable telehealth devices and services in three major categories: disease management, independent aging, and health & fitness. The FCC has been promoting health applications by regulating the Medical Implant Communication Service (MICS), Medical Device Radiocommunications Service (MedRadio), and most recently Medical Micro-power Networks (MMNs). The IEEE is also playing its role by developing the ISO/IEEE 11073 Personal Health Device family of standards [4] for the application layer and the IEEE 802.15.6 [5] to address MAC and PHY layers for WBANS. Moreover, ZigBee and Bluetooth have recently each developed their own profiles for personal health devices.

WBANs typically have specific characteristics in terms of topology, application requirements, and power consumption. WBANs usually deal with body-worn or implantable medical sensors with a short communications range. Moreover, WBANs typically have a star topology in which a central hub node communicates with the slave nodes in a single hop to send or receive data.

Due to being medical-oriented, WBAN slave devices entail some unique requirements, the most important being that they should be ultra low power consuming. Implantable body sensors usually have very limited size, thus limited power supply. Changing batteries for these sensors is not pleasant for people carrying them. If a WBAN cannot achieve several months to years of life span, it would not be appealing, no matter how perfect its medical function is. The hub, on the other hand, is not usually faced with such strict power consumption constraints.

As for application requirements, pertinent data rates span a wide spectrum from low-rate intermittent transmissions of medical updates (such as body temperature reports once every few minutes) to high rate transmissions of video frames (such as from a capsule endoscope). Aside from the data rate, various traffic patterns each have their own QoS requirements such as reliability, delay, and priority. Typically an event-driven alarm message reporting a sudden drop in heart rate has a higher priority than traffic related to regular monitoring of a patient. Furthermore, real-time traffic from an ECG device is not as sensitive to few occasional packet drops as is a parameter reading application such as that of a patient's glucose level. Yet the former is notably more sensitive to delay than the latter.

Based on the above discussion, developing a Media Access Control (MAC) protocol that not only accounts for the power-limited nature of medical devices, but also one that seeks to address the QoS requirements of different traffic patterns affiliated with WBANs, seems inevitable.

It is commonly agreed that reservation-based MAC schemes can make WBAN systems consume less power compared to contention-based ones, such as CSMA, due to less contention, collisions, idle listening and overhearing [10]. Many efforts have been made on saving power by leveraging reservation-based MAC [9]. Yet reservation-based MAC schemes pose their own limitations for WBANs. Firstly, with reservation-based protocols, the handling of high priority emergency messages is not clear and should be appropriately addressed. Furthermore, the reservations are usually made for a single constant and stable traffic, which means other unscheduled traffic (from the same source node) need to use separate resources. This greatly limits the use of reservation mechanism. Also, existing reservation schemes cannot adapt to small fluctuation of traffic or channel conditions since the reservation is a negotiated agreement between two ends which requires signaling processes in case of ever needing to change. This rigid setting sometimes could impact the timely delivery of data packets in WBANs.

In this paper we initially introduce a power saving MAC for WBANs which helps bring flexibility into the reservation-based MAC scheme with the help of polling from the hub. The core idea is that the reservation-based scheme lets the power limited slave nodes to sleep for extended periods of time when not communicating with the hub. Moreover using the polling scheme, the flexibility of letting a reservation spontaneously cross its predetermined boundary is built into the system. Such reservation extension is typically done on the fly and without prior coordination with the hub. PHY layer packet drops due to inadequate channel conditions can be a reason for a slave node needing to extend its reservation to allow for retransmissions. It can also be a result of it needing to fulfill its underachieved QoS requirements due to other reasons such as part of the reservation being used for in-band control signaling and not for actual data transfer, or to transmit unscheduled bursty packets which had not been previously foreseen into schedule.

Note that such a reservation extension mechanism is foreseen into the system solely to address the specific traffic patterns and QoS requirements of WBAN applications and are not typically seen in conventional reservation-based schemes such as in GSM networks. Furthermore, the reservation extension capability and also the possibility of already allocated reservations being preempted by emergency events, makes choosing an optimal *arrangement* of reservations within one frame an important problem. Again, the specific arrangement of reservations is not usually studied in conventional TDMA networks where various reservations are immune from interference and contention in their dedicated slots. The goal of this paper is to develop a mathematical framework to find the optimal reservation arrangement that seeks to best satisfy the WBAN traffic QoS requirements subject to a power consumption constraint, in the proposed flexible TDMA setting.

The rest of the paper is organized as follows; we start by some preliminary studies on the underlying MAC scheme and the traffic patterns and QoS requirements and power consumption modelling of the WBAN. We then formulate an optimization problem to address the reservation arrangement problem which accounts for the QoS and power consumption requirements. The paper is finally concluded after looking at some numerical results and discussions.

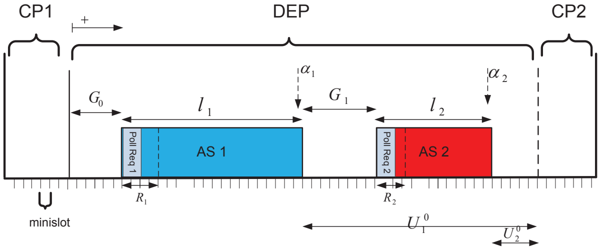

Figure 1: MAC frame format

2. PRELIMINARIES

2.1 Power-saving MAC Scheme

In what follows we briefly describe the parts of our WBAN MAC specifications that are pertinent to the scope of this paper. The time axis is divided into frames. Each frame consists of 3 periods (see Figure 1). Each period contains different number of mini slots.

A frame starts with the Control Period 1 (CP1). Three control tasks of the hub sending beacon and schedule messages (on the downlink) and slaves requesting emergency allocations (on the uplink) are performed here. The beacon message contains timing information for synchronization, WBAN information such as WBAN ID, channel information, and the length information of the frame. The schedule messages broadcasted by the hub indicates who is to transmit when and for what duration within the Data Exchange Period (DEP). Slave nodes can then go to sleep until their specified reservation start time, before which they should wake up and wait to be polled before starting their transmission. In case an emergency event comes up for a slave, it can solicit an emergency reservation through the Emergency Request message in CP1. Though the actual emergency message exchange happens in DEP. The location of this emergency allocation is determined by the hub and is usually the frontmost one available in DEP.

The next period is the Data Exchange Period (DEP), where the actual data exchange between the hub and the slave nodes happens. From the schedule message, each slave node knows the start time and length (in terms of number of minislots) of its reservation. The terms reservation and Allocation Slot (AS) are used interchangeably hereafter. Figure 1 shows the reservations of two nodes in the DEP. In each AS, polling requests always precede the real data exchanges. The polling requests contain the information about current position of the AS, allocation duration, and the destination body sensor's address. Furthermore, if not polled in time, a slave node can stay awake for a maximum duration of Reschedule Tolerance Threshold (R) to wait for a possibly delayed poll from the hub. Once received the poll, the addressed body sensor answers back after SIFS (short inter-frame spacing), with either a data packet or a polling response indicating no uplink data.

The slave node can then go to sleep until the CP1 of the next frame when it should wake up to receive the new beacon and schedule messages from the hub.

Control Period 2 is for other unscheduled transmission requirements by body sensors such as new joining nodes associating and exchanging their connection requirements with the hub.

Note that due to the fixed length of CP1, its border with DEP is fixed. Yet as the length of the DEP depends on the connection requirements of the nodes and can vary, its boundary with CP2 can be dynamically adjusted by the hub (hence the dashed line in Figure 1). Note that for any connected sensor, it is required to keep awake during the beacon and schedule messages in CP1. For those nodes which have scheduled allocations can go back to sleep until their reservations come. As for the access mode, it is poll-aided contention-based in CP2 and for the emergency requests in CP1, yet as mentioned above, is contention-free reservation-based in DEP.

2.2 WBAN Traffic QoS Constraints

Different sources of traffic can be envisioned within a WBAN. Such traffic sources can differ both in occurrence pattern and QoS requirements. For example some traffic may be related to the constant monitoring of a patient's ECG. Such data is periodic in nature and should meet stringent delay constraints. On the other hand, transferring an X-ray image to a central computer is more about reliability than delay. Emergency messages, such as those reporting a heart failure or fall detection, although happen infrequently, but are the least delay tolerant of all. Our MAC protocol is designed to suit different traffic patterns and their QoS requirements, at the same time as having the power saving goal in mind.

Despite all the different traffic patterns, periodic data transfers of parameters (such as body temperature reading), waves (such as ECG readings), or images (such as from a capsule endoscope) consume the most bandwidth in WBANs. The transport of such periodic traffic first needs establishing a "connection" with the hub in CP2. This connection consists of reservations for a certain node inside the DEP of consecutive or intermittent frames. For such periodic traffic, we address the delay-induced drop (D) rate as the main QoS criterion. This measures the portion of data that could not be delivered within tolerable delay bounds. Similar notions of delay-bound reliability have previously been studied in [7, 8] but in different contexts. In our setting a packet is declared useless (and hence dropped) once not granted channel access before the tolerable delay deadline. As an example, for an ECG device which is supposed to send 800 bytes every 200 milliseconds, we have $D = 0.25$ in a $0.2s$ interval where it is only able to send 600 bytes of its information.

To accommodate different delay constraints affiliated with various periodic traffic sources, we choose the frame duration to be the maximum that can satisfy the strictest delay constraint among all traffic sources. Such a traffic source then needs a reservation in every frame to fulfil its delay requirement. Other traffics' connections, on the other hand, can be assigned a reservation every few frames based on their specific delay requirement.

Note that with this setting, a source's packets are assumed reliably transmitted once that is done anytime before the end of the DEP of the frame they are supposed to be transmitted in. Hence the actual position of the corresponding AS within the corresponding DEP is not important as long as it is not entirely taken over by or partially transmitted due to neighboring AS extensions or emergency events. On the other hand not being allocated all requested bandwidth within that frame renders the left out packets useless due to incurring more than the tolerable delay.

2.3 WBAN Device Power Constraints

We focus on the radio power consumption in body sensor nodes, as it is the most dominant source of energy consumption [6]. A radio device functioning based on the proposed MAC scheme can be in one of the following states: listen, transmit, receive and sleep, which have different power consumption levels. Hence, the average power consumption of radio device n, denoted as P_n, can be modeled by determining the fractional time it stays in each state per unit time. Let us denote the power consumption in each state as P^L ,P^T, P^R, and P^S for listen, transmit, receive and sleep states respectively. We can show that for uplink data transport[1]:

$$P_n = \frac{l_n^1 + l_n^2 + l_n^3}{l} P^R + \frac{l_n^4}{l} P^T + \frac{l_n^5}{l} P^L + \frac{l_n^6}{l} P^S < P_{avg} \quad (1)$$

Where l is the total frame duration, l_n^1, l_n^2, and l_n^3 represent time slaves n spends in each frame for receiving the beacon, schedule, and polling messages respectively. Also, l_n^4 represents the actual time it spends for transmission in DEP. l_n^5 is the maximum duration of time slave n can keep awake and listen for a maybe late polling packet. This is the time duration we referred to as Reschedule Tolerance Threshold (R) before. Finally $l_n^6 = l - \sum_{i=1}^{5} l_n^i$. Note that as the values of l_n^1, l_n^2, and l_n^3 are dictated by the protocol and l_n^4 depends on the traffic requirements, (1) can be used to find l_n^5 i.e. R, for each of the slave nodes.

In what follows we propose an AS arrangement scheme that seeks to minimize the delay-induced drop rate of various traffics' packets subject to a power consumption constraint exhibited in the slave nodes' R values.

3. ALLOCATION SLOT ARRANGEMENT

3.1 Problem statement

As stated in the previous section, the heart of the proposed MAC scheme is a connection-oriented data exchange phase in the DEP. As stated there, slave nodes initially negotiate their connection parameters with the Hub in CP2. Then, the hub after collecting everyone's connection requests, broadcasts the schedule messages indicating everyone's allocated reservations. Slave nodes can then go to sleep until their specified Allocation Slot (AS) start time, before which they should wake up and wait to be polled before starting their transmission.

An important question in the above setting that needs to be answered by the hub is: "What is the best arrangement e.g. permutation of AS's within the DEP?". Assuming that the total allocation does not exceed the maximum duration of the DEP, at first sight it might seem that the specific arrangement of ASs is not important since each slave

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[1] Note that in (1) we have considered transactions that happen on a regular basis in periodic traffic monitoring and not sporadic or one-time events such as emergency reports or initial association and connection establishment in CP2.

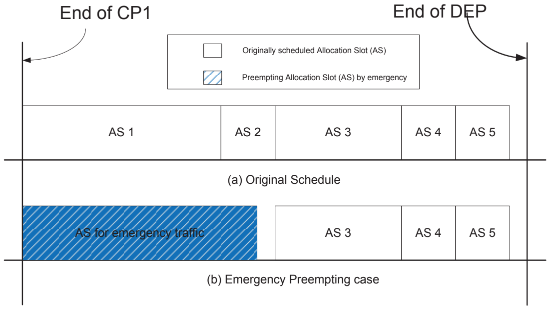

Figure 2: AS preemption by emergency events

Table 1: Input parameters

DEP max. length	L	
Emergency	probability	p_0
	distribution	$f_{X_0}(x_0)$
slave n	weight factor	w_n
	AS length	l_n
	Resched. Tolerance Thld.	R_n
	AS extension probability	p_n
	AS extension distribution	$f_{X_n}(x_n)$

has its dedicated AS which is immune from contention and interference. However as we shall see, emergency message handling and spontaneous AS extensions in a WBAN make AS arrangement an important problem.

Consider for example the case in Figure 2. As can be seen, emergency traffic (which as mentioned before takes the frontmost AS) has preempted AS1 and AS2. If the latter ASs happened to be that of higher priority traffic (than that of AS3, AS4, and AS5), then clearly the arrangement in Figure 2 (a) was not the best option to start with (since as evident in Figure 2 (b) the highest priority traffic gets preempted by emergency traffic whereas the lower priority ones get to keep their assignments). Also, extending an AS duration beyond what initially granted by the hub, could affect the subsequent ASs, causing them to lose their transmission opportunities. One can now see one of the tradeoffs involved in choosing an efficient AS arrangement in this example: dedicating an earlier AS to a node makes it vulnerable to emergency preemptions, while leaving its schedule towards the end not only leaves it with less room to extend its schedule, but also leaves it with the higher risk of being affected by proceeding ASs' possible grant extensions. Hence the search becomes on to find the optimal arrangement, in which ASs suffer the least in case of possible preemptions by emergency events or spontaneous extensions of neighboring ASs at the same time as leaving them enough space for their own probable spontaneous AS extensions.

In our proposed MAC scheme each node starts transmission/reception from the scheduled starting time of the reservations (ASs). As stated above, if one reservation is extended without adjusting the schedule in advance, the reservation next to it will be affected. With the polling mechanism proposed previously, the affected body sensors can regain the assigned allocation slots by simply keeping awake for a determined amount of time (maximum of R) if not polled in time. Hence the flexibility of extending the reservations becomes feasible. However, even when the extension does not exceed the channel limit, the delay and the extra awakening time are not desirable for the body sensors. As discussed before, in our setting the delay within one frame will not deteriorate the QoS criterion. The delay crossing the frame boundaries can undermine the QoS greatly, rendering such packets obsolete. Additionally, the consequential longer awakening time is against the objective of power saving in WBANs.

With the above introduction, our goal is to develop a mathematical framework to find the optimal AS arrangement that the hub needs to advertise in the schedule messages. The optimal arrangement is the one minimizing the weighted sum of traffic sources' delay-induced drop rates subject to a constraint on the devices' power consumptions.

3.2 Problem formulation

Typically, the inputs to our problem are the maximum length of the DEP, emergency event parameters, and slave nodes' traffic pattern and QoS requirements (see Table 1). Note that in Table 1, $l_n = l_n^3 + l_n^4$ (see Eq. (1)). We also assume the emergency and AS extension lengths to be exponentially distributed i.e. $f_{X_0}(x_0) \sim \exp(\lambda_0)$ and $f_{X_n}(x_n) \sim \exp(\lambda_n)$. Based on this information the hub now seeks to find the optimal arrangement of ASs within the DEP. Hence, the output is the optimal arrangement of ASs, that is AS end times of all slave nodes[2] i.e. $\alpha_n, n \in \Psi$ (see Figure 1 and Table 2). Note that in this framework an AS does not need to start right after the end of a previous AS. Moreover there could be arbitrary gaps between adjacent ASs.

Here we brief the outline of our strategy before going into mathematical details. The hub initially calculates the delay-induced drop (D_n) rate for AS n in a given arrangement of ASs[3]. As discussed before D_n is the expected proportion of data that does not get transmitted within the tolerable delay window[4]. Hence any node which manages to send all required packets in the supposed frame's DEP (despite possibly being polled later than expected) has $D_n = 0$. This extra awakening, however, shall incur a power consumption cost on the sensor. The hub then forms a weighted sum of all slaves' D_n's. The weights (w_n's) represent the corresponding traffic's intolerance to packets being dropped due to not meeting the delay constraint. For example packets containing ECG waveform data are more tolerant to occasional drops than those carrying a patient's body parameter (such as temperature) reading. Finally the arrangement which attains the minimum weighted sum is chosen as optimal and the corresponding schedule message broadcasted to all slave nodes. We shall now elaborate on the mathematical details.

Based on the above discussion and parameters in Table

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[2] We could interchangeably use AS start times. Here we have chosen end times for notational convenience.

[3] We assume that each AS corresponds to a single slave node and vice versa.

[4] Note that in a conventional TDMA scheme such as that used in GSM systems $D_n = 0$ but here due to previously mentioned factors such as the preemption by other AS's or occurrence of emergency events, slaves might actually get less time for transmission than initially granted by the hub.

Table 2: Summary of notations

Ψ	Set of slave nodes
Γ	Set of all arrangements of ASs
α_n	AS end time of node n
U_n^x	Residual time from x-shifted α_n to no-pass zone

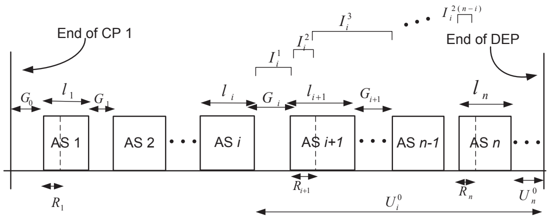


Figure 3: Demonstrating AS i extension intervals $I_i^1, \cdots, I_i^{2(n-i)}$.

2, the goal is to choose the AS end times such that:

$$\{\alpha_n | n \in \Psi\} = \underset{\gamma \in \Gamma}{\operatorname{argmin}} \quad D \tag{2}$$

where

$$D = \sum_{n \in \Psi} w_n D_n^\gamma \tag{3}$$

subject to satisfying

$$R_n, \quad \forall n \in \Psi \tag{4}$$

In rigorous terms, a specific arrangement $\gamma \in \Gamma$ consists of both a specific permutation of AS's along with continuous valued gaps between them and that of the DEP boundaries.

Before proceeding any further we need to state the set of rules that WBAN slave nodes in this paper follow:

1. Each slave node can wake up only once during a DEP.
2. In case an awakened slave n is not polled at the predetermined time by the hub, it can keep awake for a maximum of R_n.
3. $R_n < l_n$.
4. If slave n is polled within time $x < R_n$ of its awakening, it is granted an AS length of $\min{(l_n, l_n + U_n^x)}$.

Note that $U_n^0 = L - \alpha_n$ and $U_n^x = U_n^0 - x$ (see Figure 1 and Table 2). That is, U_n^x denotes the distance of slave n's AS end time from the no pass-zone when its start time is delayed by x seconds. For this initial version the no-pass zone is the end of DEP.

The above rules are by no means limiting of the framework. Any other set of rules could easily be incorporated into the framework. Ultimately, an optimization over the set of rules, as well as arrangements renders the optimal solution. The framework has been designed general enough such that if we were to add a rule such as "a lower priority AS cannot preempt a higher priority AS", the no-pass zone would be the predetermined start time of the closest higher priority AS.

In order to calculate D_n^γ, i.e. the expected delay-induced drop rate of AS n in arrangement γ, we first need to address A_n^x, the expected delay-induced drop rate of AS n when its start time is delayed by x seconds. We can show that:

$$A_n^x = \begin{cases} p_n \frac{\frac{1}{\lambda_n} + U_n^x}{\frac{1}{\lambda_n} + l_n} e^{-\lambda_n U_n^x} & U_n^x \geq 0 \\ p_n \frac{\frac{1}{\lambda_n} - U_n^x}{\frac{1}{\lambda_n} + l_n} - (1 - p_n) \frac{U_n^x}{l_n} & U_n^x < 0 \end{cases} \tag{5}$$

Note how (5) is derived: $U_n^x \geq 0$ means slave n's initially negotiated reservation can still be fully fulfilled despite its start time being delayed for x seconds. Hence slave n has nonzero drop rate ($A_n^x \neq 0$) only when it has an extension, which happens with probability p_n. In this case the expected duration needed to send all required packets is $l_n + \frac{1}{\lambda_n}$ of which only $l_n + \int_0^{U_n^x} x_n f_{X_n}(x_n) dx_n$ can be fulfilled and the rest is dropped (due to reaching the end of DEP). On the other hand for $U_n^x < 0$, if there is no AS extension (with probability $1 - p_n$) then even the initially negotiated AS of size l_n cannot be fulfilled and $-U_n^x$ of it gets dropped. Moreover if it did also need an extension (with probability p_n), $\frac{1}{\lambda_n} - U_n^x$ of total packets needing transmission would get dropped.

Note that based on definition we have $U_n^0 \geq 0$ and hence A_n^0 takes the form of upper expression in (5). We can now show that

$$D_n^\gamma = \prod_{j=0}^{n-1} (1 - p_j) A_n^0 + \sum_{i=0}^{n-1} \prod_{j=0}^{i-1} (1 - p_j) p_i A_n(x_i, \cdots, x_{n-1}) \tag{6}$$

The first summand in (6) accounts for the case where none of the ASs before AS n have spontaneous extensions and also there is no emergency event happening. Clearly in this case we have $D_n^\gamma = A_n^0$ as AS n's start time is not delayed. The terms inside the summation account for cases where there is either an emergency happening or when AS i, $1 \leq i < n$ (and none of the ASs before AS i) is having an extension. Moreover the notation $A_n(x_i, \cdots, x_{n-1})$ denotes the expected drop rate of AS n upon slave i's spontaneous extension, where AS n's start time could potentially be affected by $x_i, \cdots, x_{n-1}$. Hence addressing D_n^γ comes down to finding $A_n(x_i, \cdots, x_{n-1}), 1 \leq i < n$.

Let us define the intervals (see Figure 3) :

$$\begin{aligned} I_i^1 &= [0 \qquad G_i] \\ I_i^2 &= [G_i \qquad G_i + R_{i+1}] \\ I_i^3 &= [G_i + R_{i+1} \qquad G_i + l_{i+1} + G_{i+1}] \\ &\vdots \\ I_i^{2(n-i)} &= [G_i + \sum_{j=i+1}^{n-1} G_j + l_j \qquad R_n + G_i + \sum_{j=i+1}^{n-1} G_j + l_j] \end{aligned} \tag{7}$$

Using the law of total probability we can show that:

$$A_n(x_i, \cdots, x_{n-1}) = \sum_{k=1}^{2(n-i)} \int_{I_i^k} f_{X_i}(x_i) A_n(X_i = x_i, \cdots, x_{n-1}) dx_i \tag{8}$$

$A_n(X_i = x_i, \cdots, x_{n-1})$ is $A_n(x_i, \cdots, x_{n-1})$ conditional on the event $\{X_i = x_i\}$. Finding $A_n(X_i = x_i, \cdots, x_{n-1})$ over each of the predefined intervals leads to the answer. Here we address one example. Other regions follow along

$$A_n(X_{n-2}=x_{n-2},x_{n-1}) = (1-p_{n-1})A_n^0 + p_{n-1}\Bigg(A_n^0 \int\limits_{0}^{G_{n-1}+G_{n-2}-x_{n-2}} f_{X_{n-1}}(x_{n-1})dx_{n-1} + \int\limits_{G_{n-1}+G_{n-2}-x_{n-2}}^{R_n+G_{n-1}+G_{n-2}-x_{n-2}} A_n(X_{n-2}=x_{n-2},X_{n-1}=x_{n-1}) f_{X_{n-1}}(x_{n-1})dx_{n-1} \int\limits_{R_n+G_{n-1}+G_{n-2}-x_{n-2}}^{\infty} f_{X_{n-1}}(x_{n-1})dx_{n-1}\Bigg) \qquad (9)$$

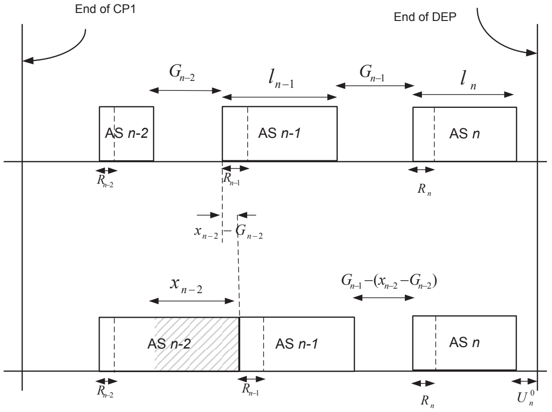


Figure 4: Figure used to derive $A_n(X_i = x_i, \cdots, x_{n-1})$

the same principles. As an example assume $i = n-2$,and $x_i \in I_i^2$ i.e. $G_{n-2} \leq x_{n-2} < G_{n-2}+R_{n-1}$. Figure 4 depicts this scenario. The dashed region for AS $n-2$ shows the grant extension length. As evident this grant extension causes the start time of AS $n-1$ to be shifted by $x_{n-2} - G_{n-2}$. Note that for $R_{n-1} \leq G_{n-1}$ we have $G_{n-1}-(x_{n-2}-G_{n-2}) \geq 0$. Hence (9) follows. Note that in (9) $A_n(X_{n-2} = x_{n-2}, X_{n-1} = x_{n-1})$ takes the form of the upper expression in (5) for $R_n \leq U_n^0$, but with (10) replaced for U_n^x.

$$U_n^{x_{n-2},x_{n-1}} = U_n^0 + G_{n-2} + G_{n-1} - x_{n-2} - x_{n-1} \qquad (10)$$

$A_n(x_i, \cdots, x_{n-1})$ for other values of $1 \leq i < n$ can be found similarly and replaced in (6) to yield the result for D_n^γ which are then used in our optimization framework (2). Note that due to the use of exponential distributions for emergency events and AS extensions, (9) and (6) all lead to closed form solutions, though the expressions do get more involved as the number of ASs increases.

4. NUMERICAL RESULTS

In this section we elaborate on a WBAN consisting of two slaves and a hub and study some numerical results on the optimal AS arrangement in a frame. We assume that the delay requirement for both traffic patterns is such that they should be transmitted in the frame under consideration. Clearly for a given arrangement $\gamma \in \Gamma$ and neglecting emergency events, we have $D_1^\gamma = A_1^0$ and:

$$D_2^\gamma = (1-p_1 e^{-\lambda_1 G_1})A_2^0 + p_1 e^{-\lambda_1 (G_1+R_2)} + p_1 \int_{G_1}^{G_1+R_2} f_{X_1}(x_1) A_2(x_1) dx_1$$

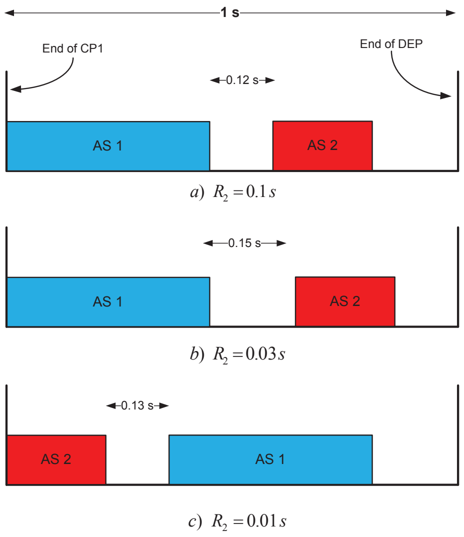
In order to evaluate the integral, based on the specific $\gamma \in \Gamma$ chosen, two cases can happen:

- $R_2 \leq U_2^0$: in which case $A_2(x_1) = A_2^{x_1-G_1}$ as in (5) noting that always $U_2^{x_1-G_1} \geq 0$.
- $R_2 > U_2^0$: again $A_2(x_1) = A_2^{x_1-G_1}$ as in (5) but this time $U_2^{x_1-G_1} \geq 0$ for $G_1 \leq x_1 < G_1 + U_2^0$ and $U_2^{x_1-G_1} < 0$ for $G_1 + U_2^0 \leq x_1 < G_1 + R_2$.

To choose the weights, we use the specification for health applications QoS requirements as outlined in [3]. There, 5 levels have been anticipated for the reliability of transmissions for various traffic patterns, allowing the use of weights 0.2 to 1 in 0.2 increments. Figure 5 depicts the optimal AS arrangement for the two ASs when the power budget for slave 2 decreases over plots (a) to (c). Initially as AS 1 has a higher weight it is scheduled first where there is no danger of it being preempted (note that here we have neglected the occurrence of an emergency event). This is still the case in Figure 5 (b) although the gap with AS 2 has increased due to sensor 2 being able to keep awake for less time, hence protecting it more from AS 1's possible grant extension. Finally as the R_2 is substantially decreased, it is given the frontmost reservation.

5. DISCUSSION

We end the paper with some discussion on the complexity of finding the optimal arrangement. Note that the minimization in (2) is carried out over the set of possible arrangements i.e. AS permutations along with possible gaps between themselves and with that of DEP boundaries. Some points should be considered with respect to this. First, the minimization is done at the hub which has a considerably higher processing capability than the slave nodes. Second, the number of slave nodes in a WBAN is very limited in practical settings (hence a very limited number of ASs within a DEP). Lastly typical gap values between adjacent ASs is also chosen from a small discrete set. For a similar system such as the IEEE 802.15.4, a maximum of 7 ASs can share a maximum of 15 minisolts among themselves [2]. Nevertheless, we shall elaborate more on complexity-reducing algorithms for AS arrangement in a future study.



a) $R_2 = 0.1\,s$

b) $R_2 = 0.03\,s$

c) $R_2 = 0.01\,s$

Figure 5: Optimal Allocation Slot arrangement in DEP. For all cases $w_1 = 0.4$, $w_2 = 0.8$, and $l_1 = 0.5$ s, $l_2 = 0.2$ s. Also $R_1 = 0.05$ s, $p_1 = 0.05$, $p_2 = 0.1$, $\lambda_1 = \lambda_2 = 30$ $\frac{1}{s}$.

6. REFERENCES

[1] http://www.continuaalliance.org/.

[2] Wireless medium access control (mac) and physical layer (phy) specifications for low-rate wireless personal area networks. *IEEE Std.15.4*, 2006.

[3] Health informatics - PoC medical device communication - part 00101: Guide–guidelines for the use of RF wireless technology. *IEEE Std 11073-00101-2008*, pages 1–99, 2008.

[4] IEEE std 11073-00103-2012 - health informatics - personal health device communication part 00103: Overview, 2012.

[5] IEEE std 802.15.6-2012 - IEEE standard for local and metropolitan area networks - part 15.6: Wireless body area networks, 2012.

[6] G. Anastasi, M. Conti, M. D. Francesco, and A. Passarella. Energy conservation in wireless sensor networks: A survey.

[7] V. C. Gungor and O. B. Akan. Delay aware reliable transport in wireless sensor networks: Research articles. *Int. J. Commun. Syst.*, 20(10):1155–1177, Oct. 2007.

[8] E.-H. Ngai, Y. Zhou, M. Lyu, and J. Liu. Reliable reporting of delay-sensitive events in wireless sensor-actuator networks. In *Mobile Adhoc and Sensor Systems (MASS), 2006 IEEE International Conference on*, pages 101–108, 2006.

[9] H. Su and X. Zhang. Battery-dynamics driven TDMA MAC protocols for wireless body-area monitoring networks in healthcare applications. *IEEE Journal on Selected Areas in Communications*, 27(4):424–434, 2009.

[10] S. Ullah, H. Higgins, B. Braem, B. Latre, C. Blondia, I. Moerman, S. Saleem, Z. Rahman, and K. S. Kwak. A comprehensive survey of wireless body area networks. *J. Med. Syst.*, 36(3):1065–1094, June 2012.