An Adaptive Energy Efficient Emergency Packet Transmission Scheme in Medical Implant Communication

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ABSTRACT

In order to find out current operating channel of the hub during emergency in implant communication, a node sequentially sends an empty frame in all the available channels until it receives an acknowledgement. This type of transmission technique, however, adds higher overhead if the correct channel selection probability is high and/or payload size to transmit is small. In such instance, the direct data transmission technique (i.e. without empty frame in advance) could exhibit better performance. In this paper, to save energy from inappropriate transmission attempt, we propose to use these two transmission schemes adaptively. Nodes will select the transmission mode by taking into account the probability of successful transmission and the payload size. We find payload threshold value that serves as switching criterion between two schemes during various network scenarios.

1. INTRODUCTION

Implant healthcare deals with monitoring and collection of diagnostic data from medical implant devices. The implant healthcare system coordinates communication between implant nodes and the hub. Monitoring and collection of performance data from self-contained heart pacemaker, monitoring of brain pacemaker for treatment of Parkinson's disease, and use of muscle stimulators to aid on rehabilitation of immobilized patients are some of the examples of implant healthcare system [4]. In case of emergency, implant nodes also send alert signals to the response team.

In implant healthcare system, implant nodes have limited power capacity. Recharging or using higher weight batteries in implant devices leads to complications. But then, lifetime of such implant devices should be maximized to avoid risk of failure and complications of replacement. Therefore, efficient low power hardware usage and efficient network setup have been two major concerns in implant healthcare.

To facilitate energy efficient implant healthcare services, a number of state-of-the-art medical devices and network protocol have been developed so far [2]. Recently, IEEE 802.15.6 Task Group (TG6) has also introduced a new standard called IEEE 802.15.6 Wireless Body Area Network (WBAN) standard including Physical (PHY) and Medium Access Control (MAC) layer specifications for implant communication [1]. IEEE 802.15.6 has provisioned Medical Implant Communication System (MICS) band for this purpose [5]. However, for enhanced performance, a number of system design issues are still to be resolved. We can notice one of such issues existing in IEEE 802.15.6 implant communication during emergency data transmission. In this paper, we highlight the issue and present a simple but effective solution.

The rest of the paper is organized as follows. Section 2 gives background information and problem statement in details. Section 3 discusses about proposed solution. Section 4 gives analytical model. Section 5 discusses about results. Finally, Section 6 concludes the paper.

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2. MICS BAND COMMUNICATION

MICS band is regulated and world wide allocated band specified between 402-405 MHz for implant communication. The main advantage of MICS band, in comparison to other bands, is its low signal attenuation when signal propagates through the human body.

In MICS band, a node and the hub have to go through mutual discovery process to connect with each other (as beacon mode transmission is not allowed). The hub first selects a channel among the available channels (10 channels in total unless restricted) and broadcasts a timed frame called T-Poll frame. The node sequentially scans each channel until it receives T-poll frame. On receiving T-poll frame, the node sends its management frame to the hub. On the reply, the hub provides connection information such as wake up schedule, allocation slots, and the channel order list[1] to the node. Then the node wakes up at its next scheduled time and sends its data. During emergency, however, the transmission mechanism is different. As emergency is critical, nodes are allowed to transmit instantly [3]. The node first selects a channel on which it had its last successful transmission. Then, the node sends an empty frame with Immediate Acknowledgement (I-ACK) request. If the node receives I-ACK frame, the node sends its data. Otherwise the node retries in the same channel for *pMICSNodeEmergencyRetries* (let say r) times. In case of further failures, the node

[1] List of channels that the hub intends to choose in decreasing likelihood when required to choose a new channel.

moves to the next channel and tries there. The process continues until I-ACK frame is received in the correct channel. Finally, on receiving I-ACK frame, the node sends its data.

2.1 Limitation of MICS Band Communication

As stated above, IEEE 802.15.6 has specified 402-405 MHz MICS band for implant communication. While each communication link uses 300 KHz carrier frequency, it creates 10 possible channels. Among 10 available channels, the hub operates in any one channel at a time. The hub may change the operating channel if required by regulations or due to channel conditions such as interference and others. When the hub changes a channel, nodes are provided with updated channel order list as soon as they are connected for their next scheduled transmission. During emergency, however, the node has to initiate the transmission without any kind of knowledge about the operating channel. Thus, the node starts to scan the channel by sending an empty frame. But, in energy consumption point of view, the channel scanning process is not always advantageous. As it adds significant amount of overhead, especially during following two cases the technique could be counterproductive: 1) when the probability of correct channel selection is high, 2) when the payload size is small. Nevertheless, in implant communication, both of these conditions can occur frequently. First, the payload size may vary depending upon the application. For instance, if the data type is only an alert signal, the payload size will be small (few bytes). On the other hand, if the data type is medical imaging, the payload size will be large (hundreds of bytes). Second, since the number of channels is fixed in the system and the node keeps on trying sequentially, the probability of successful transmission increases with each successive transmission attempt.

3. ADAPTIVE TRANSMISSION SCHEME

As stated above, the default transmission scheme could be counterproductive if the probability of successful transmission is high and/or payload size is small during emergency data packet transmission in MICS band. To address this issue, we propose to use the following two transmission schemes, let say S_1 and S_2, adaptively.
S_1: Data transmission with empty frame in advance (default data transmission scheme).
S_2: Data transmission without empty frame in advance (direct data transmission scheme).

Let us suppose that there are n number of channels available in the system at any arbitrary transmission time, $n \in (1, 10)$. To develop a selection criterion between S_1 and S_2, we first analyze the average energy that the node has to spend in order to successfully transmit its data or drop at the end. We consider variable payload size. Then we find out the payload threshold value at which the energy consumption of both the schemes equals to each other. Then we select a transmission scheme on such a way that:

```
while number of available channel is n do
    if payload size ≤ payload threshold value then
        use S2
    else
        use S1
    end if
end while.
```

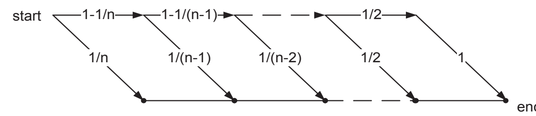


Figure 1: Channel transition in error free channels

Note that here the value of n decreases by 1 in every new channel. In the following Section, we present analysis to determine the payload threshold value.

4. ANALYSIS

Energy consumption due to transmission or reception of any packet can be related to power used for the duration of transmission or reception, respectively. In MICS band communication, the Physical Protocol Data Unit (PPDU) contains a Physical Layer Convergence Protocol (PLCP) preamble, a PLCP header, and a PHY Service Data Unit (PSDU). PLCP preamble is used for packet detection, timing synchronization, and carrier-offset recovery. PLCP preamble is transmitted at a specific symbol rate. PLCP header carries information necessary for decoding a packet, e.g. rate, length, parity, etc. PLCP header is transmitted at a specific header rate. PSDU consists of a MAC header, MAC Service Data Unit (MSDU) (i.e. payload), and Frame Check Sequence (FCS). PSDU is transmitted in any one of the assigned data rates. Therefore, if P_{tx} is transmit power, energy consumption due to empty frame transmission, E_{mty}, can be expressed as

$$E_{mty} = (T_{preamble} + T_{PLCPhdr} + T_{MAChdr}) * P_{tx}. \quad (1)$$

Where, $T_{(\cdot)}$ indicates time required to transmit respective frame and hdr stands for header. Here we have considered MAC header and FCS as a single entity. Similarly, if P_{rx} is receive power, energy consumption due to I-ACK frame reception, E_{i-ack}, can be expressed as

$$E_{i-ack} = (T_{preamble} + T_{PLCPhdr} + T_{MAChdr}) * P_{rx}. \quad (2)$$

As in (1) and (2), we can find energy consumption due to data transmission, E_{data}, as well.

$$E_{data} = (T_{preamble} + T_{PLCPhdr} + T_{MAChdr} + T_{data}) * P_{tx}. \quad (3)$$

Using (1), (2), (3), and some probabilistic analysis, we can easily find average energy that is required to send emergency packet using either S_1 or S_2. For calculation, we make an assumption that transmission can fail only because of two reasons: 1) wrong channel selection, 2) erroneous channel (bit error). In what follows, we analyze average energy consumption due to S_1 and S_2 for error free and erroneous channels, respectively.

4.1 Without Channel Error

When there is no error in the channel, transmission fails only because of wrong channel selection. In error less channels, we assume that a node does not retransmit in the same channel. Instead, a node moves to the next channel and tries. Figure 1 shows channel transition diagram of this process. From Fig. 1, average energy consumption can be derived from summation of probability of energy consumption of every path that ends after successful transmission. Thus,

Table 1: Energy consumption during E_{fail} and E_{succ}

	S_1	S_2
E_{fail}	E_{mty}	E_{data}
E_{succ}	$E_{mty} + E_{data} + E_{i-ack}$	E_{data}

average energy consumption in the error less channel, E_{el}, can be expressed as

$$E_{el} = \sum_{i=2}^{n} \prod_{k=i}^{n} \left(1 - \frac{1}{k}\right) \left(\frac{1}{i-1}\right) \Big(\; (n-(i-1))\, E_{fail} + E_{succ} \; \Big) + \frac{1}{n} \left(E_{succ}\right). \tag{4}$$

Where, E_{fail} and E_{succ} stand for energy consumption during transmission failure and successful transmission, respectively. Table 1 shows values of E_{fail} and E_{succ} both for S_1 and S_2. Substituting these values in (4), we can calculate E_{el} for S_1 and S_2.

4.2 With Channel Error

When there is error in the channel, transmission fails either because of wrong channel selection or because of error. In erroneous channel, we assume that the node retransmits in the same channel for r times. If the node fails for r times in the same channel, it then moves into the new channel and tries there. The process continues until a packet is successfully sent or dropped at the end. Figure 2 shows channel transition diagram of this process. If we assume the probability of error is P_e, average energy consumption in the erroneous channel, E_{er}, can be expressed as

$$\begin{aligned} E_{er} = & \sum_{j=0}^{r} \left(\left(1 - \frac{1}{n}\right) + \frac{1}{n} P_e \right)^{j} \left(\frac{1}{n} \left(1 - P_e\right) \right) \Big(\; jE_{fail} + E_{succ} \Big) \\ & + \sum_{i=1}^{n-1} \sum_{j=0}^{r} \prod_{k=i}^{n-1} \left(\left(1 - \frac{1}{k+1}\right) + \frac{1}{k+1} P_e \right)^{(r+1)} \left(\left(1 - \frac{1}{i}\right) + \frac{1}{i} P_e \right)^{j} \left(\frac{1}{i} \right) \left(1 - P_e\right) \\ & \Big(\; \left((r+1)\left(n-i\right) + j \right) E_{fail} + E_{succ} \Big) \\ & + \prod_{k=1}^{n} \left(\left(1 - \frac{1}{k}\right) + \frac{1}{k} P_e \right)^{(r+1)} \left(n \left(r+1\right) E_{fail}\right). \end{aligned} \tag{5}$$

Substituting values of E_{fail} and E_{succ} in (5), we can calculate E_{er} for S_1 and S_2.

5. DISCUSSION

We analyze the performance of S_1 and S_2 numerically based on the above presented mathematical expressions and taking into account the parameters presented in Table 2. From the analysis, we obtain the payload threshold value. Then we use that value to analyze the performance of adaptive transmission scheme via simulation.

Figures 3 (a), (b), and (c) show energy consumption and payload threshold value for error free channels. Figure 3 (a) shows energy consumption due to S_1 and S_2 when only one channel is available in the system. This type of situation can occur at the last of the channel selection process or if we assume node is aware of the channel. Energy consumption of S_2 is less than that of S_1 for all range of payload size. As there exists no probability of failure, the presented result clearly shows that S_1 suffers more due to overhead associated with empty frame transmission. In this type of scenario, there exists no payload threshold value. Moreover, S_2 always outperforms S_1. But when the number of available channels increases, the correct channel selection probability decreases. As a result, energy consumption due to retransmission increases. However, if the payload size is small enough to counterbalance the effect of direct data transmission, energy consumption of S_2 will be less than that of S_1. In Fig. 3 (b), when number of available channel is 3, average energy consumption of S_2 is less than that of S_1 for payload size below 92 bytes. Whereas, for payload size above 92 bytes, the energy consumption of S_2 is more. We refer this payload size as the payload threshold value. In Fig. 3 (b), it can also be observed that the payload threshold value also changes with number of available channels. For instance, when number of available channel is 10, the threshold value is 22 bytes only. Figure 3 (c) shows the payload threshold value for different number of available channels during variable data rate. In Fig. 3 (c), the result also depicts that the payload threshold value decreases with data rate (as increase in data rate decreases the transmission time). Similarly, we can find the payload threshold value for erroneous channel, as shown in Fig. 4. But the noteworthy point is that the payload threshold values have been decreased in erroneous channels in comparison to the error free channels. It is because the effect of retransmission in the same channel (due to unknown and erroneous channel) is added in the erroneous channel environment.

Figure 5 shows the simulation results when using S_1 and S_2 independently as well as adaptively. Simulation model is

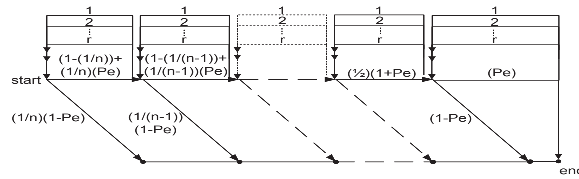
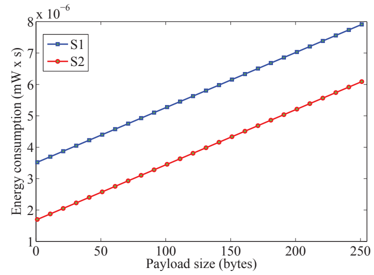


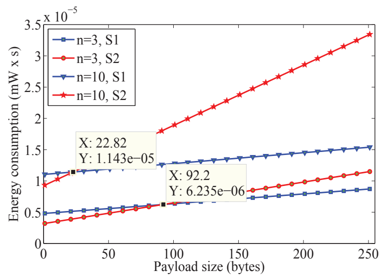
Figure 2: Channel transition in erroneous channels

Table 2: System parameters

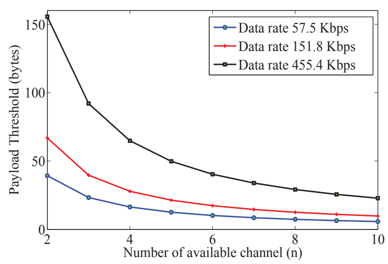
Parameters	Value
Preamble	90 bits
PHY header	31 bits
MAC header	56 bits
Payload size	0∼255 bytes
P_{tx}	-30 dBm
P_{rx}	-40 dBm
P_e	1e-06
Available channels (n)	1∼10
pMICSNodeEmergencyRetries (r)	2
Header rate	57.5 Kbps
Symbol rate	187.5 Ksps
Data rate	(57.5,151.8,455.4) Kbps



(a) Energy consumption when n=1 and data rate is 455.4 Kbps



(b) Energy consumption when n=3 and n=10 with data rate 455.4 Kbps



(c) Payload threshold value for variable data rate and available channel

Figure 3: Performance and payload threshold value in error free channel

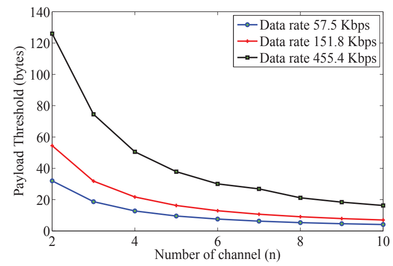


Figure 4: Payload threshold value in erroneous channel

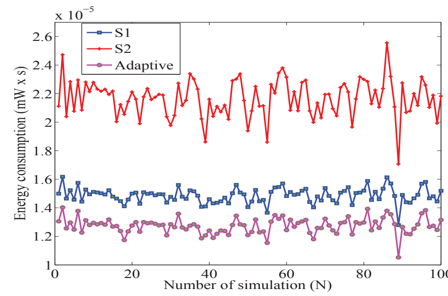


Figure 5: Average energy consumption with and without adaptive scheme

developed using Matlab. Taking into account the number of available channels and the payload threshold value, as derived above, the model is designed to select the appropriate transmission scheme in different random scenarios. Figure 5 shows simulation results for error free channel when data rate is 455.4 Kbps (average of 100 simulations). In Fig. 5, it can be observed that if only S_2 is used in the system, the performance will degrade further. However, if S_1 and S_2 are used adaptively, the performance will enhance significantly.

From the above observations it can be remarked that since a node knows about payload size and the number of available channels at the time of transmission, a node can adaptively select the transmission mode so that it can save energy from inappropriate transmission.

6. CONCLUSIONS

A scheme to support adaptive transmission, between direct and with empty frame in advance schemes, in implant communication during emergency is presented. The scheme is simple and can be realized only with subtle modification in the default scheme. The presented scheme can save energy from inappropriate transmission mechanism associated with default scheme; especially when the number of available channels is less and/or payload size to be sent is small. Through analytical modeling, the payload threshold values that serves as switching criterion between two schemes are also presented for various network scenarios.

7. ACKNOWLEDGMENTS

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