Reliable and Energy Efficient Communications for Wireless Biomedical Implant Systems

G. D. Ntouni, A. S. Lioumpas, and K. S. Nikita
School of Electrical and Computer Engineering, National Technical University of Athens, Greece

Abstract— During the last years, the implant devices tend to comprise a complete wireless transceiver, enabling the remote control of the monitoring. In contrast to conventional wireless communication systems, medical implants are characterized by much stricter limitations on size, reliability and power consumption, with the latter being of critical importance, since the replacement of the implants usually requires an invasive procedure.

In this paper, taking into account a realistic wireless propagation environment based on the IEEE P802.15 channel model, we investigate the system's performance in terms of the Bit error Probability under various scenarios. The results of this work indicate that the placement of the wearable relays on the human body (e.g., hip, wrist, ankle) plays an important role for both the total power consumption and the wireless link quality. Several scenarios are investigated, which give insight into the system requirements and its behavior under realistic wireless environments and power considerations.

1. INTRODUCTION

Wireless body area networks (WBANs) comprise low-power devices in, on or around the human body and are used in order to monitor physiological signals for healthcare applications [1]. More recently implant devices are used in many biomedical and clinical applications where the continuous wireless monitoring of a human body biological parameter is crucial. Ubiquity, reduced risk of infection and early diagnosis of a health risk are among the advantages of the WBANs with implant devices. Nevertheless, they usually involve an invasive procedure and therefore their reliability, low-power consumption and long-lifetime are vital characteristics that they should be provided.

In healthcare applications reliable communication implies that the communication link does not suffer from outages and that the quality of service (QoS) will be preserved within a desirable range, while maintaining the maximum transmission power below a required level. Low power transmissions are important because the radio frequency (RF) emissions may be harmful for the patients and also battery lifetime should not be reduced. The specific absorption rate (SAR), defined as the rate at which the human body absorbs RF energy, should comply with the Federal Communications Commission (FCC) regulations [2], laying out its expectations for the development and approval of new Medical Body Area Networks (MBANs), i.e., short-range, low-energy wireless networks capable of connecting medical devices together. Thus, the trade-off between transmission power and QoS is a substantial research topic of critical importance especially for WBANs.

Towards these goals, the concept of cooperative communications [3, 4] has been applied to WBANs in order to address the challenges related to energy efficiency and QoS requirements [1, 5]. In this paper, following the same concept, we consider using implantable devices employed with biosensors that transmit their measurements to an off-body access point (AP) through wearable devices which act as relays. The assessment of the performance of these systems over realistic wireless propagation channel models, especially developed for WBANs [6–9] constitutes our major motivation. Moreover, our work is also motivated by the crucial trade-off between the transmission power and the QoS requirements for medical applications involving implants. We evaluate the performance of cooperative WBANs over realistic wireless propagation channels under several scenarios with respect to the placement of the on-body wearable devices (e.g., wrist, chest). In this way, the complexity and power consumption are transferred from the implant device to the on-body relay, which is an efficient approach since they can be easily replaced, in contrast to the in-body implants.

2. SYSTEM MODEL

We consider a system model where an implant device S (source) communicates with an off-body access point D (destination), via a number of on-body devices R_i (relays), which decode-and-forward the signal they receive from the implant providing multiple copies of the transmitted signal at the destination. Specifically, we define these devices as follows: 1) Implant device: A device that is implanted 50 mm to 90 mm under the skin. 2) Off-body device: An access point at a distance between 10 cm and 5 m away from the human body. 3) On-body or wearable device: A device on the surface of the human skin or at most 20 mm away from it.

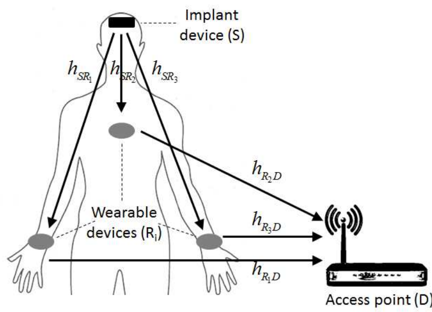

Figure 1: System model overview.

Denoting P_s and P_r as the transmitted power by the source and relay respectively, h_{SR} and h_{RD} as the channel coefficients between source-relay (S-R link) and relay-destination (R-D link) and N_0 as the power spectral density of the zero mean complex additive white gaussian noise introduced by the receiving device,

$$\gamma_{SR_i} = \frac{P_s \cdot |h_{SR_i}|^2}{N_0} \quad \text{and} \quad \gamma_{R_iD} = \frac{P_r \cdot |h_{R_iD}|^2}{N_0} \tag{1}$$

denote the instantaneous signal-to-noise ratio (SNR) of S-R_i and R_i-D links respectively.

3. CHANNEL MODEL

The IEEE P802.15.6 is working on understanding the RF signal propagation inside and around the human body and has already created realistic channel models for different scenarios and frequency bands which are used in biomedical applications [7]. In this paper, the communication channel from the implant to the off-body device (S-D link) is divided into two subchannels, the first one from the implant to the on-body device S-R_i and the second one from the on-body to the off-body device R_i-D, each of the which was modeled according to the IEEE P802.15.6 working group recommendations.

In order to serve biomedical applications the Federal Communication Commission (FCC) has adopted rules regarding the frequency bands and power limitations to support the development and use of medical Body Area Network devices [2]. The frequency bands used for communication in implant technology are the Medical Implant Communication Service (MICS) standing for the frequency band 402–405 MHz and the Industrial, Scientific and Medical (ISM) radio band between 2360 and 2400 MHz. Besides that, the MICS standard, established by FCC, recommends that the transmission power should be 25 μW in order to avoid the danger of EM emmisions for the human health [10], while the total noise power is −110.92 dBm at MICS and −117.73 dBm at ISM [10].

3.1. The S-R Communication Link

The statistical path loss model describing the power loss of the S-R link in MICS frequency band at a distance d between them, is expressed in dB as

$$P_L(d) = P_L(d_0) + 10n \log_{10} \frac{d}{d_0} + S \tag{2}$$

where $P_L(d_0)$ is the path loss in dB at a reference distance $d_0 = 50$ mm, n is the path loss exponent and $S \sim \mathcal{N}(0, \sigma^2)$ is a random variable that is normally distributed, the exact values of these parameters can be found in [6].

The squared absolute value of the channel gain h is connected with the path loss in dB as follows

$$|h_{SR}|^2 = 10^{-\frac{P_L(d)[\text{dB}]}{10}} \tag{3}$$

and using (2) and (3) it can be easily observed that

$$|h_{SR}|^2 = 10^{-\frac{P_L(d_0)+10n\log_{10}\frac{d}{d_0}}{10}} 10^{-\frac{S}{10}} = a10^{-\frac{S}{10}}, \tag{4}$$

It should be noted that the channel is not normalized, which means that when calculating the *SNR* of the channel, the path loss and shadowing effects are taken into account. This may make our comparisons a little bit more difficult, but offers accuracy as it deters the introduction of inconsistencies while comparing performances of systems in different environments.

When S is a normally distributed random variable with mean 0 and standard deviation σ, $Z = 10^{-\frac{S}{10}}$ has Log-normal distribution with $\mu_{\log} = 0$ and $\sigma_{\log} = \frac{\sigma \ln(10)}{10}$ [11, Ch. 5]. Thus, the *SNR* of the S-R link given by (1) can be expressed as

$$\gamma_{SR} = \frac{aP_s}{N_0} 10^{-\frac{S}{10}} \tag{5}$$

and has Log-normal distribution with $\mu_{\gamma_{SR}} = \ln(a\frac{P_s}{N_0})$ and $\sigma_{\gamma_{SR}} = \frac{\sigma \ln(10)}{10}$.

3.2. The R-D Communication Link

The path loss of the R-D link $P_{L_{RD}}$ at ISM frequency band depends on the distance and the orientation between the two devices, the wearable device location on body and the human subject motion. Thus, the best fitting distribution for these scenarios may be Log-normal, Gamma or Nakagami-m with appropriate parameters [6].

Taking into account that $|h_{RD}|^2 = P_{L_{RD}}$ and defining the signal-to-noise ratio (*SNR*) of the R-D link as

$$\gamma_{RD} = \frac{P_r |h_{RD}|^2}{N_0}, \tag{6}$$

the distribution that the *SNR* of this link has can be specified for each of the possible scenarios.

3.2.1. The Gamma Model

The path loss of the link $P_{L_{RD}}$ may also have Gamma distribution with shape parameter k and scale parameter θ. This implies that γ_{RD} (6) has Gamma distribution with $k_{\gamma_{RD}} = k$, scale parameter $\theta_{\gamma_{RD}} = \frac{P_r}{N_0}\theta$.

3.2.2. The Log-normal Model

For the case that the path loss $P_{L_{RD}}$ is log-normally distributed with location parameter μ and scale parameter σ, it can be inferred that γ_{RD} (6) has Log-normal distribution with $\mu_{\gamma_{RD}} = \mu + \ln(\frac{P_r}{N_0})$ and $\sigma_{\gamma_{RD}} = \sigma$ [11].

3.2.3. The Nakagami-m Model

For the case that the path loss of the R-D link has Nakagami-m distribution with parameters m and Ω, it can be inferred that γ_{RD} has also Nakagami-m distribution with parameters $m_{\gamma_{RD}} = m$ and $\Omega_{\gamma_{RD}} = \frac{P_r}{N_0}\Omega$.

4. PERFORMANCE ANALYSIS AND NUMERICAL RESULTS

4.1. Simulations

In the following we examine and compare the performance of the presented scheme in terms of the BER and the power transmission. The in-body device is implanted below the head skin at a depth of 60 mm monitoring brain edema for example, while the average horizontal distance between the walking human subject and the off-body access point is 2 m, with an orientation of 0 rads. Moreover, the relays may be placed either on the chest at a distance of about 30 cm from the implant or on the right wrist at a distance of about 50 cm away from the implant. We examine four different scenarios, depending on the position and the number of utilized relays: i) One relay on the chest ii) One relay on the wrist iii) One relay on the chest and one relay on the wrist iv) Two relays on the wrist.

The frequency of 402 MHz is employed for the transmission from the implant to the relays (S-R) and the frequency of 2.36 GHz from the relays to the off-body access point (R-D). The transmission power allocated to the relays may differ from that allocated to the implant device (P_{t_i}) as it can be easily observed by the values of the *SNR* in the boxes of all the following figures, where indices *i-c* and *i-w* stand for the implant to chest or wrist relay (S-R) link respectively and *c-o* and *w-o* for the chest or wrist relay to access point (R-D) link respectively. At this point, it should be noted that there is a constant difference between the average $\overline{SNR}$ of the implant-to-chest relay channel and the implant-to-wrist relay channel, i.e., $\overline{SNR}_{i\text{-}w} = \overline{SNR}_{i\text{-}c} - 9.36\,\text{dB}$.

4.2. Results

Figures 2(a) and 2(b) illustrate the BER of the communication link between an implant and an off-body device through a relay placed on the chest and the wrist respectively. The first observation that can be made concerns the impact of the relay transmission power. It can be easily observed that increasing the relay power improves the system performance until the BER reaches a ceiling. This occurs because the BER of the overall S-D communication link is determined by the worst link (S-R or R-D). This fact indicates the criticality of the communication link between the implant and the wearable device. Moreover, the importance of the relay position on the human body becomes evident by comparing the performance when either the chest or the wrist relay is employed. More specifically, placing the relay on the chest provides a better performance than placing it on the wrist.

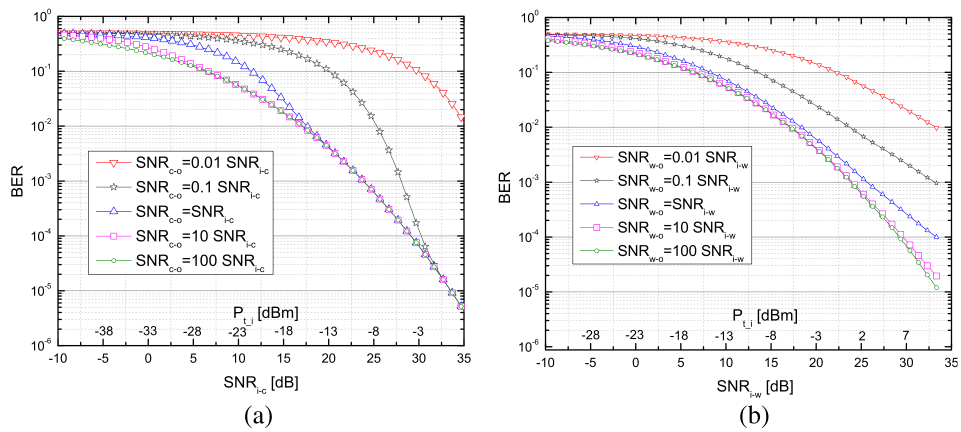

Figure 2: BER of the communication link between an implant and an off-body device through a relay placed (a) on the chest or (b) on the wrist.

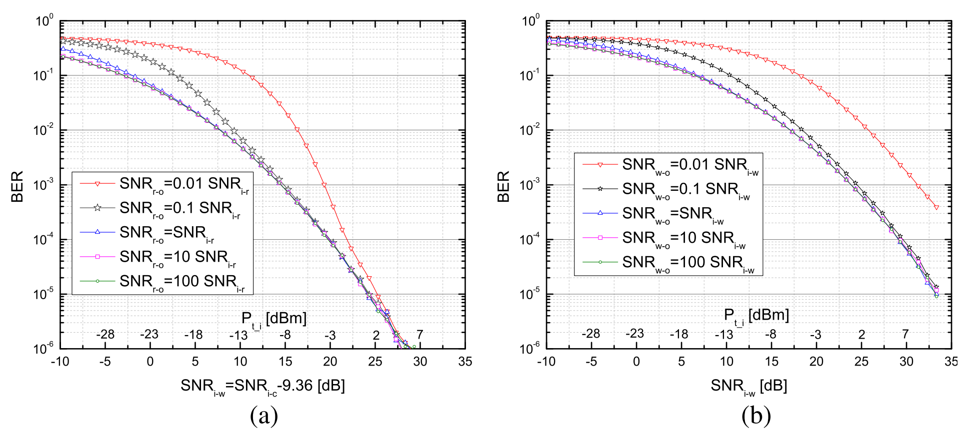

Figure 3: BER of the communication link between an implant and an off-body device through two relays placed (a) on the chest and the right wrist or (b) two relays both placed on the right wrist.

The performance of the system when two relays are employed simultaneously is illustrated in Fig. 3(a), where $\frac{SNR_{r\text{-}o}}{SNR_{i\text{-}r}} = \frac{SNR_{c\text{-}o}}{SNR_{i\text{-}c}} = \frac{SNR_{w\text{-}o}}{SNR_{i\text{-}w}}$. As depicted, depending on the channel conditions, employing two relays may not always result in sufficiently improved performance compared with the single relay case. For example, it can be seen that the performance gain that stems from adding a wrist relay is negligible, when a chest relay is already in use.

On the other hand, when the two relays that we used simultaneously are placed in the same part of the body, the system performance improves. This can be observed in Fig. 3(b) where two relays placed on the right wrist are used simultaneously. It is obvious that the system performance improves until it becomes replete and its performance is determined only by the S-R link efficiency from then on. Concerning the amount of power required, it was observed that the device consuming the greater amount of power is the implant placed inside the human body. Besides that, the performance of the S-R link is much worse than that of the R-D link, although it requires more power. For instance, the amount of power transmitted by the right wrist relay should be 10^5 times lower than that of the implant in order for the mean *SNR* of the two links to be equal.

In conclusion, taking into account that the transmission power of the implant device should be 25 μW (−16 dBm) in order to avoid dangers of EM emissions for the human health, it can be inferred by the figures that increasing the transmission power of the relay is vital for our achieving a satisfactory error probability.

5. CONCLUSION

In this paper, we have evaluated the performance of the communication links between an implant and an off-body access point which communicate through relays. It was shown that the communication link that consumes the greatest amount of power and in most cases determines the performance of the whole system is the S-R link from the implant to the relay. This comes from the fact that the link influencing the total BER is that with the worst performance. Placing relays at the human body improves the system's reliability and proves to be energy efficient. However, there is a threshold in the amount of the relay transmission power above which the system becomes replete and then its performance is totally determined by the S-R link. Moreover, the part of the human body where the relay will be placed is an important parameter and the most advantageous location among those examined was proved to be the chest. Finally, using multiple relays is not always considered to be efficient, as the location where they will be placed and the way they will be combined strongly influences their performance.

ACKNOWLEDGMENT

The project is co-financed by the European Union (European Social Fund — ESF) and Greek national funds through the Operational Program "Education and Lifelong Learning" of the National Strategic Reference Framework (NSRF) — Research Funding Program: ARISTEIA, project 68/1142 DEMII-MED, Implantable and Ingestible MEdical Devices (IIMDs): Optimal-Performance-Oriented Design and Evaluation Methodology.

REFERENCES

1. Arrobo, G. E. and R. D. Gitlin, "Improving the reliability of wireless body area networks," *Proceedings of the Annual International Conference of the IEEE Engineering in Medicine and Biology Society, EMBC, 2011*, 2192–2195, Boston, USA, Aug. 2011.
2. Federal Communications Commission, "Rules and regulations: Medical area body network," *Federal Register*, Vol. 77, No. 176, 55715–55735, Sep. 2009.
3. Hong, Y.-W., W.-J. Huang, F.-H. Chiu, and C.-C. J. Kuo, "Cooperative communications resource constrained wireless networks," *IEEE Signal Process. Mag.*, Vol. 24, No. 3, 47–57, May 2007.
4. Michalopoulos, D. S., A. S. Lioumpas, G. K. Karagiannidis, and R. Schober, "Selective cooperative relaying over time-varying channels," *IEEE Transactions on Communications*, Vol. 58, No. 8, 2402–2412, 2010.
5. Smith, D. B. and D. Miniutti, "Cooperative body-area-communications: First and second-order statistics with decode-and-forward," *Proceedings of the IEEE Wireless Communications and Networking Conference (WCNC)*, 689–693, Paris, Apr. 2012.
6. Yazdandoost, K. Y. and K. Sayrafian-Pour, "Channel model for body area network (BAN)," *IEEE802.15.6 Technical Contribution*, Document ID: 15-08-0780-09-0006, 41–56, 2009.
7. Miniutti, D., L. Hanlen, D. Smith, A. Zhang, D. Lewis, D. Rodda, and B. Gilbert, "Narrowband on-body to off-body channel characterization for body area networks," *IEEE802.15.6 Technical Contribution*, Document ID: 15-08-0780-09-0006, Aug. 2008.
8. Oh, J. Y., J. H. Kim, H. S. Lee, and J. Y. Kim, "PSSK modulation scheme for high-data rate implantable medical devices," *IEEE Transactions on Information Technology in Biomedicine*, Vol. 14, No. 3, 634-640, May 2010.
9. Kim, M. and J. I. Takada, "Characterization of wireless on-body channel under specific action scenarios at sub-GHz bands," *IEEE Transactions on Antennas and Propagation*, Vol. 60, No. 11, 5364–5372, Nov. 2012.
10. Abouei, J., J. D. Brown, K. N. Plataniotis, and S. Pasupathy, "Energy efficiency and reliability in wireless biomedical implant systems," *IEEE Transactions on Information Technology in Biomedicine*, Vol. 15, No. 3, 456–466, May 2011.
11. Papoulis, A., *Probability, Random Variables and Stochastic Processes*, 3rd Edition, McGraw-Hill Kogakusha, 1991.