Reliable and Energy Efficient Communications for Wireless Biomedical Implant Systems

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***Abstract*—Implant devices are used to measure biological parameters and transmit their results to remote off-body devices. As implants are characterized by strict requirements on size, reliability and power consumption, applying the concept of cooperative communications to wireless body area networks (WBANs) offers several benefits. In this paper, we aim to minimize the power consumption of the implant device by utilizing on-body wearable devices, while providing the necessary reliability in terms of outage probability and bit error rate (BER). Taking into account realistic power considerations and wireless propagation environments based on the IEEE P802.l5 channel model, an exact theoretical analysis is conducted for evaluating several communication scenarios with respect to the position of the wearable device and the motion of the human body. The derived closed-form expressions are employed towards minimizing the required transmission power, subject to a minimum quality-of-service requirement. 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.**

***Index Terms*—biomedical implants, IEEE P802.15 channel model, power consumption, reliability, wireless body area network (WBAN).**

I. Introduction

Implant devices are used in many biomedical and clinical applications where the continuous monitoring of a human body biological parameter is crucial [1]. 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 [2]. 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 reliability, low-power consumption and long-lifetime are vital characteristics that they should provide.

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. 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 [3], 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.

A. Motivation

Towards these goals, the concept of cooperative communications [4], [5] has been applied to WBANs in order to address the challenges related to energy efficiency and QoS requirements [2], [6], [7]. 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 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, taking into account the power transmission constraints and the required reliability in terms of the average bit error rate (ABER) and outage probability (OP).

B. Contribution and Related Works

The contribution of this paper is two fold. Firstly, we evaluate the performance of cooperative WBANs over realistic wireless propagation channels and derive specific closed-form expressions for the ABER and the OP of these channels. Several scenarios are investigated with respect to the location of the on-body wearable devices (e.g., wrist, chest). While the IEEE P802.15 channel model, which has been developed based on real field measurements [8], [9], [10], [11], has been widely used for evaluating the performance of WBANs via computer simulation [2], [6], [7], to the best of the authors' knowledge a complete study containing both simulations and a specific theoretical analysis extracting suitable equations has not been conducted yet, especially for scenarios involving both the "in-body to on-body" and "on-body to off-body" wireless propagation links. Although, the performance of wireless communication systems over well-known fading channels, such as the Nakagami-*m* and the Log-normal fading channels has been widely investigated (e.g., [12], [13], [14]), their relation to the IEEE P802.15 channel model and the corresponding power measurements is not always obvious and especially when considering specific set-ups with in-body, on-body and off-body wireless devices. Therefore, a complete theoretical

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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 DEM-II-MED, Implantable and Ingestible Medical Devices (IIMDs): Optimal-Performance-Oriented Design and Evaluation Methodology.

analysis was considered necessary in order to provide those ABER and OP expressions that are the most accurate when studying WBANs communication using IEEE P802.15 channel model. Closed-form expressions eliminate the need for time-consuming simulations and can be used for formulating practical optimization problems, that can be solved fast and accurately.

In [6] considering on-body scenarios and using a decode-and-forward strategy (DF), it was shown via simulations and experiments that the OP can be improved up to 15dB in typical IEEE 802.15.6 channels. In [7] the coexistence of multiple WBANs was investigated for the case where the WBAN-of-interest employs the DF strategy. In [15] an experimental investigation into the dynamic on-body channel with body movements was investigated, proposing a three-state Fritchman model to describe the burst characteristics of on-body fading. Several interference mitigation schemes, such as adaptive modulation as well as adaptive data rate and duty cycle for BANs, were presented in [16], while [17] provided theoretical analysis and Markov chain modeling of interference mitigation schemes, such as adaptive modulation and adaptive data rate for BANs.

Secondly, we employ the theoretical analysis in order to minimize the required transmission power (also constrained by the SAR limits), subject to a minimum QoS requirement, either expressed in terms of the ABER or the OP. This is an efficient approach since the complexity and power consumption are transferred from the in-body implants to the on-body relays, which can be easily replaced.

C. Outline

The paper is organized as follows. Section II and Section III illustrate the system and channel model respectively. The theoretical performance of the communication scheme under investigation is presented in Section IV, while Section V includes the optimization problem based on the theoretical results. Finally, Section VI presents the numerical results and some concluding remarks are highlighted in Section VII.

II. 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 to the access point (Fig. 1). Specifically, we define these devices as follows

1) Implant device (S): A device that is implanted inside the human body either exactly below the skin or deeper in the tissue. A deep tissue implant is located at a distance of about 90 mm or more from the body surface.
2) On-body or wearable device (R): This is considered to be a device that is located directly on the surface of the human skin or at most 20 mm away from it.
3) Off-body device (D): This device is an access point which has no contact with the human body and is at a distance between 10 cm to 5 m away from the human body.

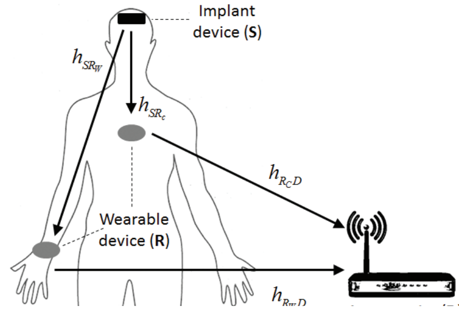

Fig. 1: System model overview.

The links between the implant device and the wearable ones are expressed as SR_i, where $i = \{c, w\}$ denotes the location of the wearable device on the human body (c and w stand for chest and wrist respectively). Similarly, the links between the wearable devices and the access point are denoted as $\mathrm{R}_i\mathrm{D}$, where $i = \{c, w\}$.

III. CHANNEL MODEL

The IEEE 802.15.6 is working on the RF signal propagation inside and near the human body and has developed realistic channel models for different scenarios and frequency bands which are used in biomedical applications [9]. In this paper, the communication links SR_i and $\mathrm{R}_i\mathrm{D}$ are modeled according to these recommendations, as it will be explained later.

The devices involved in biomedical applications must comply with the rules adopted by the FCC with respect to the frequency bands and power limitations [3]. The frequency bands that are used for medical applications are the Medical Implant Communication Service (MICS) band (402-405 MHz) and the Industrial, Scientific and Medical (ISM) band (2360-2400 MHz). The MICS standard, established by FCC, recommends that the transmission power should not exceed $25\,\mu$W in order to avoid electromagnetic (EM) emissions that could be harmful for the human health [18]. The main characteristics of the MICS and ISM frequency bands are summarized in Table I.

The channel amplitude of the SR_i and $\mathrm{R}_i\mathrm{D}$ links is denoted by h_{SR_i} and h_{R_iD} respectively, and consist the time domain representation of the channel, namely the output of the channel when its input is a delta function $\delta(t)$. If the transmission power of the implant and wearable devices are P_s and P_r respectively, then the instantaneous signal-to-noise ratio (*SNR*) of the SR_i and $\mathrm{R}_i\mathrm{D}$ links can be expressed as

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

where N_0 is the power spectral density of the zero mean complex additive white gaussian noise, which equals to

$$N_0 = k\,T_0\,B\,10^{\frac{NF}{10}}\ [W] \qquad (2)$$

TABLE I: Characteristics of MICS and ISM standards

	MICS	ISM
Frequency Band	402–405 MHz	2360–2400 MHz
Bandwidth	300 KHz	62.5 KHz
Transmitted Power	$25\,\mu$W (-16 dBm)	0.5 mW (-3 dBm)
Data Rate	$>$ 250 kbps	250 kbps
Operating Range	0–2 m	0–10 m

TABLE II: Implant to relay (SR_i) communication channel parameters

	Deep tissue implant	Near surface implant
$P_L(d_0)$	47.14	49.81
n	4.26	4.22
σ	7.85	6.81

where k is the Boltzmann constant, T_o is the body temperature in Kelvin, B is the bandwidth in Hz and NF is the noise figure at the receiver in dBm. Assuming $T_0 = 310°K = 37°C$ and $NF = 8$ dB, the total noise power is -110.92 dBm at MICS and -117.73 dBm at ISM [18]. In order to comply with the channel models developed in [9], where the channel amplitudes include both the path loss and the shadowing effects, the channel has not been normalized.

A. The In-body to On-body (SR_i) communication channel

The statistical path loss model characterizing the channel between an implant device and a wearable one at a distance d (MICS band), is expressed as

$$P_L(d) = P_L(d_0) + 10n\log_{10}\frac{d}{d_0} + s\ [dB] \quad (3)$$

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 (RV) that is normally distributed [8]. The values of these parameters, which depend on the kind of implant employed (near surface or deep implant), are given in Table II.

As a result, the squared absolute value of the channel gain, h_{SR_i}, will be given by

$$|h_{SR_i}|^2 = 10^{-\frac{P_L(d)\ [\mathrm{dB}]}{10}} \quad (4)$$

or after using (3)

$$|h_{SR_i}|^2 = 10^{-\frac{P_L(d_0)+10n\log_{10}\frac{d}{d_0}}{10}}10^{-\frac{s}{10}} = \mathrm{ct}\ 10^{-\frac{s}{10}} \quad (5)$$

where $\mathrm{ct} = 10^{-\frac{P_L(d_0)+10n\log_{10}\frac{d}{d_0}}{10}}$.

When the RV, s, is normally distributed with zero mean and standard deviation σ, the RV, $Z = 10^{-\frac{s}{10}}$, follows a Log-normal distribution with $\mu_{\log} = 0$, $\sigma_{\log} = \frac{\sigma\ln(10)}{10}$ and a probability density function (pdf) given by [19, ch.5]

$$f_Z(z) = \frac{1}{z\sigma_{\log}\sqrt{2\pi}}e^{-\frac{[\ln(z)-\mu_{\log}]^2}{2\sigma_{\log}^2}}. \quad (6)$$

Thus, using (1) the *SNR* of the link between the implant and the wearable device can be expressed as

$$\gamma_{SR_i} = \frac{\mathrm{ct}\ P_s}{N_0}10^{-\frac{s}{10}} \quad (7)$$

which follows the Log-normal distribution with $\mu_{\gamma_{\mathrm{SR}_i}} = \ln(\mathrm{ct}\ \frac{P_s}{N_0})$ and $\sigma_{\gamma_{\mathrm{SR}_i}} = \frac{\sigma\ln(10)}{10}$.

B. The On-body to Off-body (R_iD) communication channel

The path loss of the link between the wearable relay and the access point, $P_{L_{R_iD}}$, at ISM frequency band depends on the distance and the orientation between the two devices, the part of the body where the relay is located and the motion of the human body. The best fitting distributions for these scenarios have been found to be the Log-normal, the Gamma or the Nakagami-*m* distributions [8].

Considering that $|h_{R_iD}|^2 = P_{L_{R_iD}}$ and using (1) where the second equation defines the *SNR* of the channel from the relay to the access point, the distribution that the *SNR*, γ_{R_iD}, has can be specified for each of the possible scenarios as follows.

1) The Log-normal distribution model: For the case that the path loss, $P_{L_{R_iD}}$, follows the Log-normal distribution with location parameter, μ, and scale parameter, σ, it can be inferred that the *SNR*, γ_{R_iD}, also follows the Log-normal distribution with $\mu_{\gamma_{\mathrm{R}_i\mathrm{D}}} = \mu + \ln(\frac{P_r}{N_0})$, $\sigma_{\gamma_{\mathrm{R}_i\mathrm{D}}} = \sigma$ [19] and a pdf given by

$$f_{\gamma_{\mathrm{R}_i\mathrm{D}}}(\gamma) = \frac{1}{\gamma\sigma\sqrt{2\pi}}e^{-\frac{\ln\gamma-(\mu+\ln(\frac{P_r}{N_0}))}{2\sigma^2}}. \quad (8)$$

2) The Gamma distribution model: The path loss of the channel, $P_{L_{R_iD}}$, may be Gamma distributed with shape parameter, k, and scale parameter, θ. This implies that the *SNR*, γ_{R_iD}, is also Gamma distributed with $k_{\gamma_{\mathrm{RD}}} = k$, $\theta_{\gamma_{\mathrm{RD}}} = \frac{P_r}{N_0}\theta$ and a pdf expressed as

$$f_{\gamma_{\mathrm{R}_i\mathrm{D}}}(\gamma) = \frac{1}{(\frac{P_r}{N_0}\theta)^k\Gamma(k)}\gamma^{k-1}e^{-\frac{\gamma}{\frac{P_r}{N_0}\theta}} \quad (9)$$

where $\Gamma(\bullet)$ is the Gamma function.

3) The Nakagami-m distribution model: Defining $x = P_{L_{R_iD}}$ and for the case that the path loss of the channel follows the Nakagami-*m* distribution, its pdf is expressed as

$$f(x; m, \Omega) = \frac{2m^m}{\Gamma(m)\Omega^m}x^{2m-1}e^{-\frac{m}{\Omega}x^2}. \quad (10)$$

Taking into account (1), it follows that the *SNR*, γ_{R_iD}, is Nakagami-*m* distributed with parameters $m_{\gamma_{\mathrm{R}_i\mathrm{D}}} = m$ and $\Omega_{\gamma_{\mathrm{RD}}} = \frac{P_r}{N_0}\Omega$ and a pdf given by

$$f_{\gamma_{\mathrm{R}_i\mathrm{D}}}(\gamma) = \frac{2m^m}{\Gamma(m)(\frac{P_r}{N_0}\Omega)^m}\gamma^{2m-1}e^{-\frac{m}{\frac{P_r}{N_0}\Omega}\gamma^2}. \quad (11)$$

IV. Theoretical Performance Analysis

In this Section, we derive analytical closed-form expressions for the ABER and the OP considering a variety of communications scenarios.

A. Average Bit Error Rate

Considering Binary phase-shift keying (BPSK) modulation the BER as a function of the instantaneous *SNR*, γ, is given by

$$P_e(\gamma) = Q(\sqrt{2\gamma}) = \frac{1}{2}\mathrm{Erfc}(\sqrt{\gamma}) \quad (12)$$

where $\mathrm{Erfc}(\bullet)$ denotes the Gaussian error function. The ABER is derived by averaging $P_e(\gamma)$ over the pdf of γ, i.e.,

$$P_e = \int_0^\infty P_e(\gamma)f_\gamma(\gamma)\mathrm{d}\gamma = \int_0^\infty \frac{1}{2}\mathrm{Erfc}(\sqrt{\gamma})f_\gamma(\gamma)\mathrm{d}\gamma. \quad (13)$$

1) ABER for the Gamma distribution model: For the case that the *SNR* is distributed as a Gamma RV, (13) can be solved in closed form by averaging (9) over (12). Thus, using [20, (1.5.3.1)] the ABER for the Gamma model, $P_{e,Gam}$, is given by

$$P_{e,Gam} = \frac{\Gamma(2k_\gamma)}{\Gamma(k_\gamma)}2^{-2k_\gamma}\vartheta_\gamma^{-k_\gamma}\frac{{}_2\mathrm{F}_1\left(k_\gamma, \frac{1}{2}+k_\gamma, 1+k_\gamma, -\frac{1}{\vartheta_\gamma}\right)}{\Gamma(1+k_\gamma)} \quad (14)$$

where

$${}_2\mathrm{F}_1(a, b; c; z) = \sum_{n=0}^{\infty}\frac{(a)_n(b)_n}{(c)_n}\frac{z^n}{n!} \quad (15)$$

is the Gauss hypergeometric function with $(q)_k = q\,(q{+}1)(q{+}k-1)$ and $(q)_0 = 1$ denoting the Pochhammer symbol.

$$P_{e,Nak} = \frac{1}{6\sqrt{\pi}\Gamma(m_\gamma)}\left(\frac{m_\gamma}{\Omega_\gamma}\right)^{-\frac{3}{4}}\left\{3\sqrt{\pi}\left(\frac{m_\gamma}{\Omega_\gamma}\right)^{\frac{3}{4}}\Gamma(m_\gamma) - 6\sqrt{\frac{m_\gamma}{\Omega_\gamma}}\,\Gamma\left(\frac{1}{4}+m_\gamma\right)\times\right.$$
$$\left.\times\,{}_p\mathrm{F}_q\left(\left[\frac{1}{4},\frac{1}{4}+m_\gamma\right];\left[\frac{1}{2},\frac{5}{4}\right];\frac{\Omega_\gamma}{4m_\gamma}\right) + 2\,\Gamma\left(\frac{3}{4}+m_\gamma\right){}_p\mathrm{F}_q\left(\left[\frac{3}{4},\frac{3}{4}+m_\gamma\right];\left[\frac{3}{2},\frac{7}{4}\right];\frac{\Omega_\gamma}{4m_\gamma}\right)\right\} \quad (16)$$

2) ABER for the Nakagami-m distribution model: Considering the Nakagami-m case, the ABER can be derived by averaging (10) over (12). After some mathematical manipulations, the ABER, $P_{e,Nak}$, is finally expressed as in (16), where ${}_p\mathrm{F}_q(N;V;z)$ is the generalized hypergeometric function, i.e.,

$$ {}_p\mathrm{F}_q(N;V;z) = \sum_{k=0}^{\infty}\frac{(N_1)_k(N_2)_k...(N_p)_k}{(V_1)_k(DV_2)_k...(V_q)_k}\frac{z^k}{k!} \quad (17)$$

with p being the length of vector N and q the length of vector V.

3) ABER for the Log-normal distribution model: On the other hand, the integral in (13) cannot be solved in closed form for the case that the *SNR* follows the Log-normal distribution and therefore calculating the ABER, $P_{e,Log}$, requires the approximation of the error function. Towards employing an approximation with satisfactory accuracy over the whole range of values $[0,\infty]$, the approximation proposed in [21] was used, i.e.,

$$\mathrm{Erfc}(x) = 2\left(0.168\,e^{-1.752x^2} + 0.144\,e^{-1.05x^2} + 0.002\,e^{-1.206x^2}\right) \quad (18)$$

as well as the upper bound [22]

$$\mathrm{Erfc}(x) \leq \frac{1}{3}e^{-4x^2} + \frac{1}{6}e^{-2x^2} + \frac{1}{2}e^{-x^2}. \quad (19)$$

After approximating the error function as a sum of exponentials and using the pdf of the Log-normal distribution (13), the integral that has to be calculated becomes a series of sums that have the following form

$$I = \int_0^{+\infty}\frac{1}{2}ae^{-bx}\frac{1}{x\sqrt{2\pi}\sigma}e^{-\frac{(\ln(x)-\mu)^2}{2\sigma^2}}dx. \quad (20)$$

Defining the Frustration function as [23]

$$\mathrm{Fr}(k,l) = \int_0^{+\infty}\frac{1}{x\sqrt{2\pi}l}e^{-kx^2}e^{-\frac{(\ln(x)+l^2)^2}{2l^2}}dx \quad (21)$$

the integral can be written as follows

$$I = \frac{a}{2}\mathrm{Fr}\left(be^{\mu+\frac{\sigma^2}{2}},\frac{\sigma}{2}\right). \quad (22)$$

Thus, the ABER for the Log-normal model, $P_{e,Log}$, using the best approximation (18) is expressed as in (23), while it can bounded by (24) after using the upper bound approximation (19) for the error function.

4) ABER for the In-body to Off-body (SD) communication channel: Assuming that the wearable device decodes and forwards the received signal from the implant device to the access point, the end-to-end ABER for BPSK modulation can be expressed as

$$P_{e,SD} = (1-P_{e,SR_i})P_{e,R_iD} + P_{e,SR_i}(1-P_{e,R_iD}) \quad (25)$$

where P_{e,SR_i} and P_{e,R_iD} are the ABER of the SR$_i$ and the R$_i$D links respectively. As already mentioned, the SR$_i$ communication link follows the Log-normal distribution whereas the R$_i$D link can be Log-normal, Gamma or Nakagami-m distributed, i.e., $P_{e,SR_i} = \{P_{e,Log-appr},\,P_{e,Log-bound}\}$ and $P_{e,R_iD} = \{P_{e,Gam},\,P_{e,Nak},\,P_{e,Log-appr},\,P_{e,Log-bound}\}$ depending on the location of the wearable device on the human body, its orientation to the access point, the motion of the human body and its distance from the access point.

B. Outage Probability

One important performance measure regarding the transmission rate and reliability of these systems is the OP. In what follows, the exact expressions for the OP will be derived for each type of the end-to-end communication channel.

1) Single Wearable Device: Transmitting data from the implant to the off-body access point through a relay requires two time-slots. In a slow fading communication channel with channel gain h, transmission power P_t and noise power N_0, the maximum mutual information, $\mathcal{R}$, is expressed as

$$\mathcal{R} = \frac{1}{2}\log_2\left(1+|h|^2\frac{P_t}{N_0}\right) \quad (26)$$

where the factor $1/2$ comes from the two time-slot requirement. Denoting the mutual information of the SR$_i$ and R$_i$D links as $\mathcal{R}_{SR_i}$ and $\mathcal{R}_{R_iD}$ respectively, the maximum mutual information of the SD link is given by

$$\mathcal{R}_{SD} = \min\{\mathcal{R}_{SR_i},\mathcal{R}_{R_iD}\}. \quad (27)$$

The OP of the in-body to off-body (SD) communication channel for a given rate $\mathcal{R}_o$ equals [24]

$$\begin{aligned} P_{\text{out}} =& P\left\{\min\{\mathcal{R}_{SR_i},\mathcal{R}_{R_iD}\} < \mathcal{R}_o\right\} \\ =& \left[1-\left(1-P\{\mathcal{R}_{SR_i}<\mathcal{R}_o\}\right)\left(1-P\{\mathcal{R}_{R_iD}<\mathcal{R}_o\}\right)\right]. \end{aligned} \quad (28)$$

Using (26) each of the two probabilities shown in (28) can be expressed as follows

$$\begin{aligned} P\{\mathcal{R}<\mathcal{R}_o\} =& P\left\{|h|^2 < \frac{(2^{2\mathcal{R}_o}-1)N_0}{P_t}\right\} \\ =& F_{|h|^2}\left(\frac{(2^{2\mathcal{R}_o}-1)N_0}{P_t}\right) \end{aligned} \quad (29)$$

where $F_{|h|^2}(x)$ is the cumulative distribution function (cdf) of the distribution that $|h|^2$ follows.

Assuming that $|h|^2$ follows a Log-normal distribution with parameters μ and σ, it can be shown that (29) equals

$$P_{Log}\{\mathcal{R}<\mathcal{R}_o\} = \frac{1}{2}\,\mathrm{Erfc}\left[-\frac{\ln\left(\frac{(2^{2\mathcal{R}_o}-1)N_0}{P_t}\right)-\mu}{\sigma\sqrt{2}}\right]. \quad (30)$$

$$P_{e,Log-appr} = 0.168\,\mathrm{Fr}\left(1.752\,e^{\mu_\gamma+\frac{\sigma_\gamma^2}{2}}, \frac{\sigma_\gamma}{2}\right) + 0.144\,\mathrm{Fr}\left(1.05\,e^{\mu_\gamma+\frac{\sigma_\gamma^2}{2}}, \frac{\sigma_\gamma}{2}\right) + 0.002\,\mathrm{Fr}\left(1.206\,e^{\mu_\gamma+\frac{\sigma_\gamma^2}{2}}, \frac{\sigma_\gamma}{2}\right) \tag{23}$$

$$P_{e,Log-bound} = \frac{1}{6}\mathrm{Fr}\left(4\,e^{\mu_\gamma+\frac{\sigma_\gamma^2}{2}}, \frac{\sigma_\gamma}{2}\right) + \frac{1}{12}\mathrm{Fr}\left(2\,e^{\mu_\gamma+\frac{\sigma_\gamma^2}{2}}, \frac{\sigma_\gamma}{2}\right) + \frac{1}{4}\mathrm{Fr}\left(e^{\mu_\gamma+\frac{\sigma_\gamma^2}{2}}, \frac{\sigma_\gamma}{2}\right) \tag{24}$$

For the case that $|h|^2$ has Gamma distribution with parameters k and θ, (29) is expressed as

$$P_{Gamma}\{\mathcal{R} < \mathcal{R}_o\} = \frac{\Gamma(k) - \Gamma\left(k, \frac{(2^{2\mathcal{R}_o}-1)N_0}{\theta P_t}\right)}{\Gamma(k)} \tag{31}$$

where $\Gamma(k,s)$ is the lower incomplete gamma function. Finally, when $|h|^2$ follows a Nakagami-m distribution with parameters m and Ω, (29) becomes

$$P_{Nak}\{\mathcal{R} < \mathcal{R}_o\} = \frac{\Gamma(m) - \Gamma\left(m, \frac{m}{\Omega}\left(\frac{(2^{2\mathcal{R}_o}-1)N_0}{P_t}\right)^2\right)}{\Gamma(m)}. \tag{32}$$

2) Multiple Wearable Devices: Considering a topology with K relays, each of which decodes and forwards the data it receives from the implant to the off-body access point, the maximum end-to-end mutual information is equal to

$$\mathcal{R}_{SD} = \max_{j\in K} \min\{\mathcal{R}_{SR_i^j}, \mathcal{R}_{R_i^j D}\} \tag{33}$$

where index j accounts for each of the K relays. In this case, the OP of the whole system is given by

$$P_{\text{out}} = \\ = \prod_{j=1}^{K}\left[1 - \left(1 - P\{\mathcal{R}_{SR_i^j} < \mathcal{R}_o\}\right)\left(1 - P\{\mathcal{R}_{R_i^j D} < \mathcal{R}_o\}\right)\right]. \tag{34}$$

V. Optimizing Energy Efficiency and Reliability

The closed-form expressions derived in Section IV regarding the ABER and the OP can be exploited towards the following dual optimization problems.

A. Optimization with ABER constraints

- Minimizing the required transmission power for achieving a predetermined QoS requirement in terms of the ABER, i.e.,

$$\begin{aligned} &\textit{Minimize} \quad P_s \le P_{th,1}\ \&\ P_r \le P_{th,2} \\ &\textit{subject to}\ P_{e,SD} \le P_{e,th} \end{aligned} \tag{35}$$

  where $P_{th,1}$ and $P_{th,2}$ are the thresholds applied to the implant and to the relay transmission power respectively and $P_{e,th}$ is the maximum value of the ABER that satisfies our requirements regarding the system reliability.
- Maximize the performance in terms of the ABER, given the maximum allowable implant and relay transmission power, i.e.,

$$\begin{aligned} &\textit{Minimize} \quad P_{e,SD} \\ &\textit{subject to}\ P_s \le P_{th,1}\ \&\ P_r \le P_{th,2} \end{aligned} \tag{36}$$

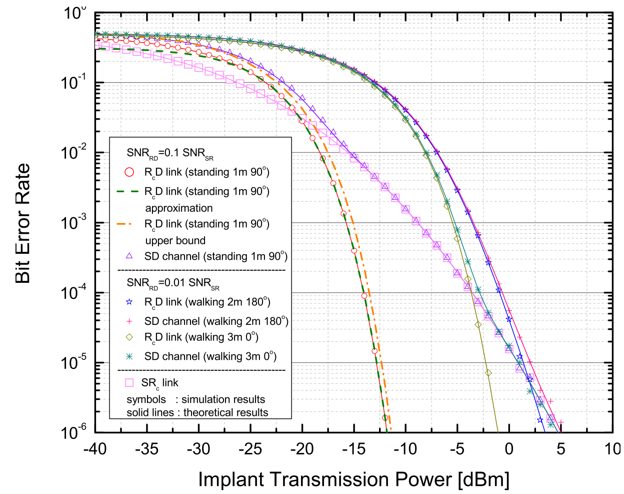

Fig. 2: Comparison between the theoretical and simulation results for scenarios representing the three different types of distributions that *SNR* may have. (Table III)

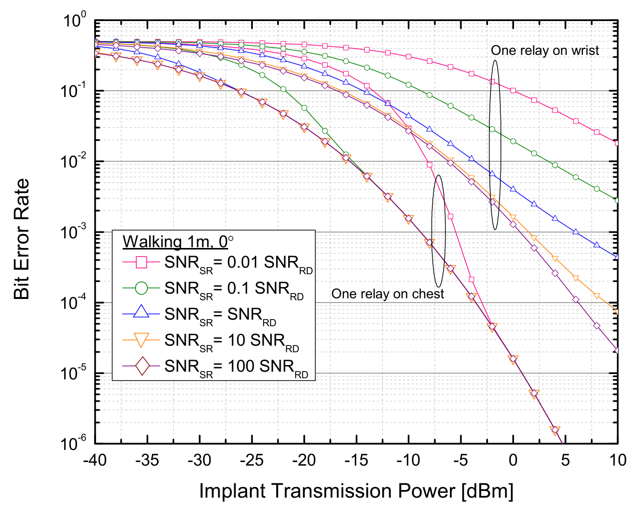

Fig. 3: ABER performance: One wearable device placed on a walking human body at about 1 m away from the AP with an orientation of 0° is employed for relaying the signal to the AP.

B. Optimization with OP constraints

- Minimizing the required transmission power for achieving a predetermined QoS requirement in terms of the OP, i.e.,

$$\begin{aligned} &\textit{Minimize} \quad P_s \le P_{th,1}\ \&\ P_r \le P_{th,2} \\ &\textit{subject to}\ P_{out,SD} \le P_{out,th}\ \text{for}\ \mathcal{R}_o \end{aligned} \tag{37}$$

  where $P_{out,th}$ is the threshold applied to the OP in order to satisfy the desired system reliability and $\mathcal{R}_o$ is a specified value of the system data rate.

- Maximize the performance in terms of the OP, given the maximum allowable implant and relay transmission power, i.e.,

$$\begin{aligned} &\textit{Minimize} \quad P_{out,SD} \text{ for } \mathcal{R}_o \\ &\textit{subject to } P_s \leq P_{th,1} \;\&\; P_r \leq P_{th,2} \end{aligned} \tag{38}$$

VI. Numerical Results

In this section, the theoretical analysis is employed for evaluating the performance of the biotelemetry scheme under investigation, considering various scenarios as regards the location of the wearable devices, the motion of the human body, its orientation to the access point and its distance from it. Table III summarizes the parameters of the R_iD communication links that relate the theoretical results in terms of the *SNR* distributions with these practical communication scenarios. In all simulations, the implanted device is considered to be embedded below the head skin at a depth 10 mm. The relays are placed either on the right wrist (50 cm away from the implant) or on the chest (30 cm away from the implant).

The strong agreement between theoretical results and simulations is illustrated in Fig. 2 for various scenarios. As regards the approximation of the Log-normal distribution, it can be observed that its accuracy improves for ABER $\leq 2 \cdot 10^{-1}$. Fig. 3 and 4 illustrate the ABER for the case of a single wearable device. It can be easily observed that increasing the implant transmission power leads to an accordingly decreasing ABER. On the other hand, increasing the relay transmission power improves the system performance until the ABER reaches a floor, indicating the criticality of the communication link between the implant and the relay, which determines the system performance that cannot become better than the performance of the SR_i link no matter how much the relay transmission power increases.

Furthermore, as depicted in Fig. 4, considering non-identical average SNRs at the SR_i and R_iD links, 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, whereas it is important adding a chest relay when a wrist relay is in use.

In addition to this, the performance in terms of the OP is depicted in Fig. 5 and Fig. 6, illustrating the data rate limitations under the existing maximum implant transmission power restrictions, i.e., 25 μW (-16 dBm). Employing two relays on the chest maximizes the probability to achieve a 250 kbps data rate. It should be noted, that in our analysis we have not used error correction coding or other techniques that could enhance the achievable data rate besides the increase in the transmission power.

Afterwards, utilizing the optimization problems (Section V) and the closed-form expression for the ABER and the OP, we examine the minimum transmission power at both the implant and the wearable devices, while satisfying a required ABER or OP and taking into account the FCC power limitations (Fig. 7). As shown in Table I, in order to avoid dangers of EM emissions for the human health the transmission power of the implant (P_s) should be less than 25 μW (-16 dBm) and that of the relay (P_r) less than 0.5 mW (-3 dBm). Once again, the criticality of the link between the implant and the relay is highlighted. Besides that, as shown in Fig. 8, for the data rate used in our simulations, an acceptable OP can be achieved using transmission power both to the implant and to the relay that are lower than the limits stated above.

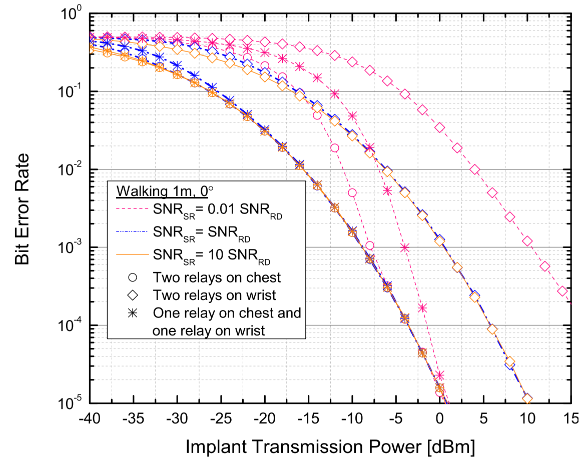

Fig. 4: ABER performance: Two wearable devices placed on a walking human body at about 1 m away from the AP with an orientation of 0° are employed for relaying the signal to the AP.

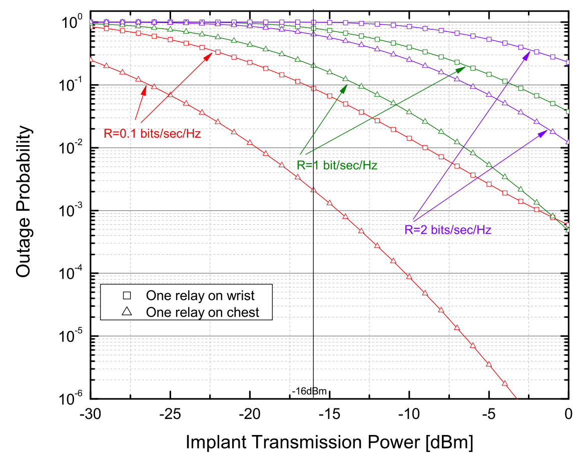

Fig. 5: OP performance: One wearable device placed on a walking human body at about 2 m away from the AP with an orientation of 0° is employed for relaying the signal to the AP, assuming $\overline{SNR}_{SR_i} = \overline{SNR}_{R_iD}$.

TABLE III: Relay to Destination (R_iD) communication channel Distribution and Parameters of $|h|^2$

Scenario	Distribution	Parameters		Path Loss
Relay on the chest				
Standing 1m 90°	Log-normal	μ=-0.39	σ=0.23	63.24 dBm
Walking 2m 180°	Gamma	k=5.46	θ=0.073	61.67 dBm
Walking 3m 0°	Nakagami-*m*	m=7.17	Ω=0.43	47.64 dBm
Walking 2m 0°	Log-normal	μ=-0.41	σ=0.19	48.19 dBm
Walking 1m 0°	Log-normal	μ=-0.31	σ=0.12	41.91 dBm
Relay on the wrist				
Walking 2m 0°	Gamma	k=1.03	θ=0.13	34.67 dBm
Walking 1m 0°	Gamma	k=0.82	θ=0.26	30.97 dBm

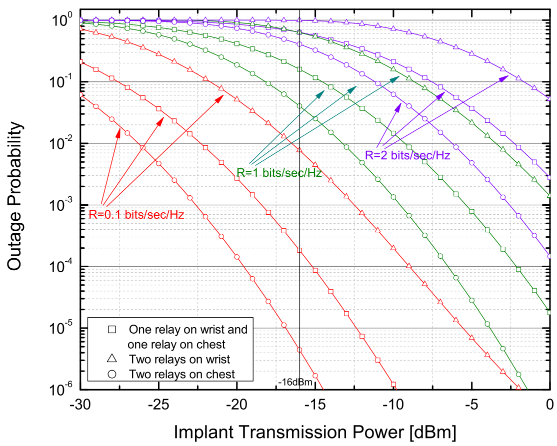

Fig. 6: OP performance: Two wearable devices placed on a walking human body at about 2 m away from the AP with an orientation of 0° are employed for relaying the signal to the AP, assuming $\overline{SNR}_{\mathrm{SR}_i} = \overline{SNR}_{\mathrm{R}_i\mathrm{D}}$.

VII. Conclusion

In this paper, a biotelemetry communication scheme was considered, consisting of an implant device and wearable on-body devices for relaying the information to an off-body access point. The performance of this scheme was assessed theoretically in terms of the ABER and OP, taking into account the realistic channel model proposed by the IEEE P802.15 group. Exact closed-form expressions were derived, considering a variety of practical communication scenarios as regards the number and position of the wearable devices and the motion of the human body, demonstrating the important benefits from employing wearable devices in specific body locations. The closed-form expressions were exploited towards optimizing the trade-off between energy consumption and performance and providing insight into the design of biotelemetry systems regarding the type of the wearable devices, their location and the required transmission power. Due to the strict power limitations of the implanted device, the utilization of a wearable device is necessary for forwarding the sensed information to an off-body access point several centimeters away from the human body. Finally, the severe propagation conditions within the human body critically affect the communication link between the implanted device and the wearable relays, which determines the performance of the overall communication link to the access point, while the location of the wearable relays on the human body (e.g., chest or wrist) plays an important role for the provided QoS and the power consumption of the implant device.

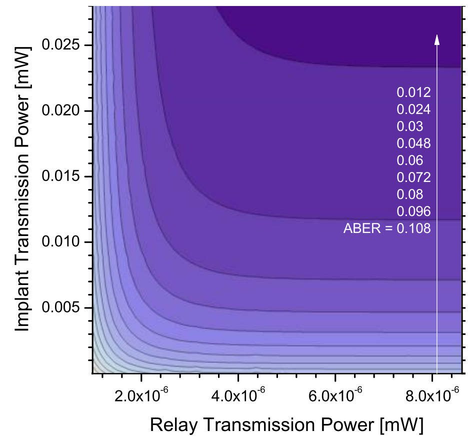

Fig. 7: Optimization problem for ABER: A chest relay placed on a human subject walking at about 1 m away from the AP with an orientation of 0° is employed for relaying the signal to the AP.

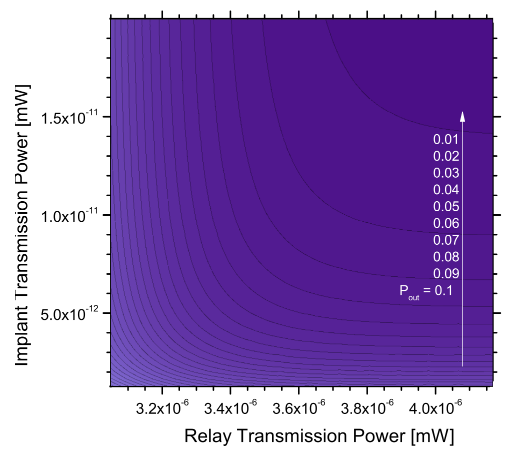

Fig. 8: Optimization problem for OP ($\mathcal{R}_o$=1 bits/sec/Hz): A chest relay placed on a human subject walking at about 1 m away from the AP with an orientation of 0° is employed for relaying the signal to the AP.

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