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On the Application of Slotted-ALOHA in Optical Wireless Body-Area Networks

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***Abstract*—In this work, we investigate the multiple access (MA) management in optical wireless body-area networks (WBANs) for medical applications. Here, given the limited battery lifetime and computational resources of medical sensor nodes, placed typically on the human body, efficient MA management can be done in the medium-access control (MAC) layer, e.g., via random access to the optical wireless channel. We propose the use of Slotted-ALOHA protocol, which has the potential advantages of simplicity and efficiency to reduce packet collisions and to enhance the overall throughput. We further optimize the network energy efficiency by taking into consideration a realistic channel model based on particle swarm optimization, given the high complexity of the optimization problem. This approach provides valuable insights into the efficient design of optical WBANs.**

***Index Terms*—Optical wireless body area network; Slotted-ALOHA; Optical wireless communications; Particle swarm optimization.**

I. Introduction

The ever-increasing need for early disease prevention and continuous remote health monitoring has accentuated the importance of wireless body area networks (WBANs) as a pivotal emerging technology. WBANs encompass a wide range of applications, categorized into medical and non-medical domains by the IEEE 802.15.6 standard [1]. In medical applications, typically, a few sensor nodes (SNs) are positioned on the human body to read and transmit the vital signs to a coordinator node (CN), also placed on the patient's body. The CN, in turn, forwards the collected data to an external network.

So far, most designed systems and prototypes have been based on radio-frequency (RF) communication links, mainly using ZigBee or Bluetooth technologies, which use the license-free ISM band and are subject to severe interference with other existing networks. Moreover, the utilization of RF waves raises concerns about the potential health impact on exposed individuals, prompting the IEEE 802.15.6 standard to impose restrictions on specific absorption rates (SARs) to mitigate risks [2]. These facts have motivated the use of optical wireless communications (OWC) for medical WBANs [3], [4], which offer a huge unlicensed spectrum, while ensuring data security due to the confinement of optical signals in indoor spaces. Note, OWC can also be used for transmitting data from implanted sensors over short distances, traversing the skin [5].

In terms of intra-WBAN connectivity, i.e., data transfer between medical SNs to the CN, one important consideration is to manage the multiple access (MA) requirement. Here, low complexity transmission scheduling schemes have been

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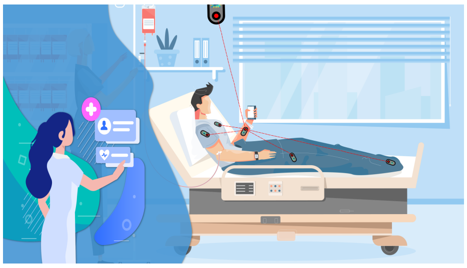

Fig. 1: Optical WBAN for patient monitoring in a hospital ward.

TABLE I: Typical medical SNs, with their placement on body, the corresponding bit rates, and the channel DC gain with respect to the CN, assumed to be placed on the hip [3].

Type	Bit-rate (kbps)	Position	SN #	H_0 (dB)
Pulse oximetry	32	Earlobe	1	-57.76
Heart rate	3	Lower arm	2	-56.87
Temperature	0.02	Shoulder	3	-53.34
Glucose level	2	Thigh	4	-56.17
Blood pressure	0.01	Upper arm	5	-57.83

designed to aid meeting the requirements of low power consumption and reliable transmissions [6]. The Slotted-ALOHA protocol, which is popular in wireless ad-hoc sensor networks, promises low number of collisions, low complexity, and low power consumption [7]. We consider in this work the use of this protocol for MA management between SNs and the CN. Although being considered for RF-based WBANs [8], [9], to the best of the authors' knowledge, its performance for optical WBANs has not been investigated so far.

A visual example of an optical WBAN can be seen in Fig. 1. Given the particularities of the optical channel, the formulation of resource allocation and transmission probabilities of each SN is inherently different from that in RF-based networks. Given the importance of energy consumption, we formulate a maximization problem of the network energy efficiency, accounting for transmission probabilities and data-rate under quality-of-service (QoS) and max-power constraints. We derive a solution to this highly complex optimization problem using particle swarm optimization (PSO), which is an iterative method based on the exploration and exploitation of the solution space. Through a set of numerical results, we demonstrate the relatively fast convergence of the algorithm and provide valuable insights into the operation of optical WBANs.

II. System and Channel Model

We consider an optical WBAN, comprising of S SNs and one CN in a star topology. Considering the Slotted-ALOHA protocol, SNs contend for the access to the medium only in the beginning of each time-slot. This way, the CN has the double role of both data collection from all SNs and communication synchronization. In Table I, we present some typical medical SNs, their typical data rates and DC channel gains between SNs and the CN. These latter are based on the realistic simulations presented in [3], considering infrared communications at 850 nm for a user with *local mobility* (at a fixed global position while moving its parts) in the middle of an empty room of dimension $(5\times5\times3)\,\mathrm{m}^3$, using emitters at SNs of order-1 Lambertian pattern and a photodetector (PD) at the CN of 60° field-of-view (see [3] for more details).

Note, based on the observations in [3], for the cases of local and/or global mobility of the patient, the channel delay spread is practically negligible for data rates up to approximately 5 Mbps using the simple on-off keying (OOK) modulation.

For the statistical modeling of the channel DC gain, the approach in [3] has been to fit the histogram of the simulated channel gains to a given probability density function (PDF), using the Akaike information criterion (AIC). For the considered CN position, shown in Table I), the best fit model has been shown to be that of the Gamma distribution:

$$f_X(x) = \frac{1}{\beta^\alpha \Gamma(\alpha)} x^{\alpha-1} e^{-\frac{x}{\beta}}, \tag{1}$$

where α and β are the shape and rate parameters, and $\Gamma(\cdot)$ denotes the Gamma function. Here, $\alpha = 6.11$ and $\beta = 0.07$.

III. WBAN Energy Efficiency Analysis

Denoting the probability of accessing the channel for the kth SN by q_k, the average throughput $\bar{R}_k$ is obtained as the product of the average rate of the SN $\hat{R}_k$ (when the node successfully accesses the channel), and the probability of successful channel access:

$$\bar{R}_k = \hat{R}_k \; q_k \prod_{i\neq k}(1-q_i). \tag{2}$$

Proposition 1: Denoting the corresponding channel fading coefficient by h_k, the average rate of the SN when the node successfully accesses the channel, is given by:

$$\hat{R}_k = R_k \left(1 - \frac{\gamma(\alpha, X_k/\beta^2)}{\Gamma(\alpha)}\right), \tag{3}$$

where η is the PD responsivity, $\Pr\{\cdot\}$ denotes probability, $F_{|h_k|^2}(\cdot)$ is the cumulative distribution function (CDF) of $|h_k|^2$, and σ^2 is variance of the additive white Gaussian noise [10]. Moreover, α and β are the parameters for the Gamma distribution corresponding to $|h_k|$ (see (1)), $\gamma(\alpha, x)$ is the lower incomplete Gamma function, and,

$$X_k(R_k, P_k) = \left(\frac{2\pi\sigma^2(2^{R_k}-1)}{e|\eta H_{0,k} P_k|^2}\right)^{1/2}. \tag{4}$$

Proof: Assuming the k^{th} SN during the random access phase transmits at a fixed transmission rate R_k, the average rate $\hat{R}_k$ is determined by the product of R_k and the probability of a non-outage event, i.e.,

$$\begin{aligned}\hat{R}_k =& R_k \Pr\left\{\log_2\left(1+\frac{e}{2\pi}\frac{|\eta h_k H_{0,k} P_k|^2}{\sigma^2}\right) \geq R_k\right\} \\ =& R_k\left(1-F_{|h_k|^2}\left(\frac{2\pi\sigma^2(2^{R_k}-1)}{e|\eta H_{0,k}P_k|^2}\right)\right). \end{aligned} \quad (5)$$

Here, $H_{0,k}$ is the channel DC gain between the CN and the SN and P_k denotes its consumed power. With $|h_k|$ following the Gamma distribution with parameters α and β, $|h_k|^q$, $q > 0$ follows the generalized Gamma distribution with parameters α, β, p, d, and a [11]. For $q = 2$, we have $p = 1/q$, $d = \alpha/q$, and $a = \beta^q$ [11], and the CDF is given then as

$$F_X(x) = \frac{\gamma(d/p, (x/a)^p)}{\Gamma(d/p)}. \quad (6)$$

By plugging (6) to (5), we get the equation of (3). ■

Given the *Proposition 1*, the energy efficiency (EE) of each individual SN is defined as the ratio of its average throughput and its output power consumption:

$$\mathsf{EE}_\mathrm{k} = \bar{R}_k/P_k. \quad (7)$$

Assuming that the EE maximization of each SN is of equal importance, here, we maximize the sum of energy efficiencies of all SNs. Taking into account the QoS requirement of each SN, the maximum allowed output power and the constraint of the individual successful channel access probability, we formulate the optimization problem as follows.

$$\begin{aligned} \max_{\mathbf{q},\mathbf{P},\mathbf{R}} \quad & \textstyle\sum_{k=1}^{S} \mathsf{EE}_\mathrm{k} \\ \text{subject to:} \quad & \mathrm{C}_1: P_k \leq P_{\max}, \forall k \in \mathcal{K} \\ & \mathrm{C}_2: \bar{R}_k \geq R_{\mathrm{thr}}, \forall k \in \mathcal{K} \\ & \mathrm{C}_3: 0 \leq q_k \leq 1, \forall k \in \mathcal{K}, \end{aligned} \quad (8)$$

where C_1, C_2 ensure the maximum energy consumption and QoS requirements, respectively, while C_3 is the probability limitation. Also, $\mathbf{q}$, $\mathbf{P}$, and $\mathbf{R}$ are the vectors containing the q_k, P_k, and R_k, $k = 1, ..., S$, respectively, $P_{\max}$ refers to the maximum allowed transmission optical power from the SNs, and R_{thr} is the data rate threshold related to QoS requirement, assumed to be the same for all SNs, without loss of generality.

IV. Particle Swarm Optimization

In order to find the optimum specifications for the SNs (i.e., probability of channel access, transmitted power, and data rate), we use the PSO computational method that optimizes a problem by iteratively trying to improve a candidate solution with regard to a given measure of quality [12], [13]. Given the objective function in (8), the optimization is achieved by having a population of candidate solutions (particles), and moving them around in the search-space (three dimensional here) over the particle's position and velocity. A detailed presentation of the algorithm is provided in Algorithm 1.

Algorithm 1 PSO to solve (8).

Initialization
Initialize all the needed variables
x_i ▷ Particle's i position
p_i ▷ Particle's i best position
g ▷ Swarm's best position
The rest of the variables are shown in Table II
Set Max (b_{up}) & Min (b_{lo}) limits for $\mathbf{q}, \mathbf{P}, \mathbf{R}$
for $i = 1$:Number of particles **do**
  $x_i \leftarrow U(b_{\mathrm{lo}}, b_{\mathrm{up}})$
  $p_i \leftarrow x_i$
  if $\mathsf{EE}_\mathrm{k}(p_i) > \mathsf{EE}_\mathrm{k}(g)$ **then**
    $g \leftarrow p_i$
  end if
  $v_i \leftarrow U(-|b_{\mathrm{up}} - b_{\mathrm{lo}}|, |b_{\mathrm{up}} - b_{\mathrm{lo}}|)$
end for

PSO method
for $i = 1$:Number of iterations **do**
  for $j = 1$:Number of particles **do**
    for $d = 1$:Number of dimensions **do**
      $r_p, r_g \leftarrow U(0, 1)$
      $v_{j,d} \leftarrow wv_{j,d} + \phi_p r_p(p_{j,d} - x_{j,d}) + \phi_g r_g(g_d - x_{j,d})$
    end for
    $x_j \leftarrow x_j + v_j$
    if $\mathsf{EE}_\mathrm{k}(x_j) > \mathsf{EE}_\mathrm{k}(p_j)$ **then**
      $p_j \leftarrow x_j$
      if $\mathsf{EE}_\mathrm{k}(p_j) > \mathsf{EE}_\mathrm{k}(g)$ **then**
        $g \leftarrow p_j$
      end if
    end if
  end for
end for

In Table II, we present the parameters for implementation of PSO in MATLAB®. Here, b_{lo} and b_{up} are tables that contain the lower and the upper limits for the 3 dimensional space of the problem, ϕ_p, ϕ_g and w are the cognitive parameter, the social parameter and the inertia weight for the particles' speed calculation, respectively. Also, in Algorithm 1, x_i is the position of particle i, p_i is the best known position for particle i during the iterations, g is the best position of all the particles, v_i is the velocity with which particle i moves around the 3 dimensional space, r_p, r_g are randomly generated numbers in every iteration, and $U(x_1, x_2)$ is a random number that follows the uniform distribution in $[x_1, x_2]$.

V. Numerical Results

In this section, we present a set of simulation results for $S = 5$ to investigate the performance of the proposed method for maximizing the energy efficiency in an optical WBAN

TABLE II: PSO MATLAB code parameters

Parameter	Value	Parameter	Value
Particles	50	Iterations	1500
S	5	Variables	3
$b_{\text{lo}}(1)$	0.3	$b_{\text{lo}}(2)$	0.0001 (W)
$b_{\text{lo}}(3)$	0.001 (bps/Hz)	$b_{\text{up}}(1)$	0.9
$b_{\text{up}}(2)$	0.05 (W)	$b_{\text{up}}(3)$	2.5 (bps/Hz)
ϕ_p	1.1	ϕ_g	1.1
w	0.7	η	0.6 (A/W)

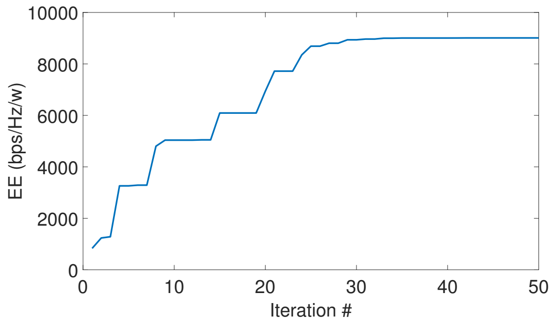

Fig. 2: Convergence of the objective function in (8) versus the number of iterations of Algorithm 1.

using the Slotted ALOHA protocol. After testing various configurations for the PSO method, the final considered simulation parameters are provided in Table II.

In Fig. 2, the convergence of the objective function is presented versus the number of the PSO algorithm iterations. We have observed that the PSO algorithm needs approximately 50 iterations to reach a near-to-optimal solution, with the selected configuration of the algorithm parameters, such as the cognitive and social parameters, as well as the inertia weight of the particles. Slight improvements are achieved until 250 iterations. Overall, these results confirm the optimization of the energy efficiency EE_k and the convergence of the algorithm.

We have further investigated the impact of the noise level in the system in Fig. 3. In fact, the energy efficiency of such a network can be adversely affected by high values of the noise variance, as lower data rates could be achieved with the same power consumption.

As an illustrative example, we have presented in Table III the results of the optimization, i.e., the position of the "particle" in the 3-parameters-by-5-nodes space, or in other words, the values of $\mathbf{q}, \mathbf{P}, \mathbf{R}$ for each of the five SNs. The output of the optimization algorithm in this case, with noise as in Table II, is given for every SN. By considering that the starting positions of the particles are random each time, we can assume that the position we reach after the execution is probably the best. Based on the obtained results, one may assign appropriate sensor types to the different SNs. Given the typical data provided in Table I, if possible, it would make sense to assign sensors with lower data generation rates to the

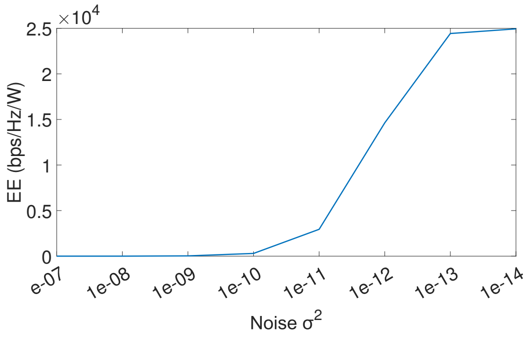

Fig. 3: Impact of the noise variance σ^2 on the objective function.

TABLE III: PSO results

	$\mathbf{q}$	$\mathbf{P}$ (mW)	$\mathbf{R}$ (bps/Hz)	Average $\mathbf{R}$ (bps/Hz)
SN1	0.84796	0.0001	1.4013	0.0287
SN2	0.42902	0.0001	1.6973	0.0047
SN3	0.70971	0.0001	0.79434	0.0071
SN4	0.60467	0.0001	2.0032	0.0112
SN5	0.63187	0.048688	2.2524	0.0142

locations with the worst channel conditions, while reserving the best channel condition positions for sensors with higher data generation rates.

VI. Conclusions

In this study, the energy efficiency of a Slotted-ALOHA-based optical WBAN was investigated and optimized, using realistic simulated data from a previous work. In order to solve the high complexity optimization problem, the PSO algorithm was employed, to determine the optimal power consumption, data-rate, and channel access probability for every node of the network. Insightful simulation results for the convergence and the impact of the noise power were provided and discussed, showing the suitability of PSO for the task of optimization of WBAN performance. Future work will consider the implementation of the Slotted-ALOHA protocol on an experimental setup in order to validate the presented theoretical results.

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