Design and Evaluation of a Receiver for Wired Nano-Communication Networks

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Abstract—In this paper, we propose a bio-inspired receiver, which detects the electrons transmitted through a nanowire, then, it converts the detected information to blue light using bioluminescence. We simulate the construction of the nanowire, present its electrical characteristics and calculate its maximum capacity for a better design of the receiver. The designed receiver contains two parts; a part that detects the transmitted electrons, which we model by using an equivalent circuit, and a part that converts the detected electrons to blue light. We derive the analytical expressions of the components of the equivalent circuit and give an approximation of their values. We calculate the probability of photons emission for each electrical pulse detected. We also determine the optimal threshold for Integrate Sample and Dump (ISD) receiver. We calculate the error probability of bits detection and present analytical and simulation results to evaluate the performance of the designed receiver. The results of this study show that the designed receiver can accurately detect the electrons sent through a conductive nanowire. Thus providing, to the best of our knowledge, the first technical solution that leads towards integrated wired electrical and optical nanonetworks.

Index Terms—Wired, nano-communication, bioluminescence, receiver, Aequorin, calcium, capacity, ISD receiver.

I. INTRODUCTION

ANOTECHNOLOGY has become a key area of research in multidisciplinary fields and its rapid and impressive advance has led to new applications, several of them associated with the biomedical and military industries. In order to achieve a common objective, nanomachines need to be able to implement a cooperative behavior to overcome their limited processing capacity forming a concept known as Internet of NanoThings (IoNT). These nanomachines can also create seamless connections with biological entities by applying emerging technologies such as Internet of Bio-NanoThings (IoBNT) and Internet of Medical Things (IoMT), which provides novel applications such as monitoring, diagnosis and local drug delivery [1]. Potential advantages coming from establishing communication between nanomachines triggered significant research towards developing effective communication capability at the nanoscale. Out of this research, three different directions were formed, as per the information available in the open literature: (i) use of wireless electromagnetic signals located in the THz band [2]–[5], (ii) bio-inspired wireless molecular communication using molecules [6]–[8] and (iii) wired based nano-communication using polymers [9].

Signals at the THz band suffer from very high path loss, mainly caused by water molecules absorption, which complicates their use inside the human body for medical applications [3]–[5]. In contrast, the biocompatibility of molecular communication makes it very promising for medical applications at nanoscale, such as monitoring, diagnosis and local drug delivery [6]. Several modulation techniques were proposed in the past for molecular communication systems and are available through the open literature. Depending on the properties of molecules, information can be modulated by using Concentration Shift Keying (CSK), which encodes the information in the number of released molecules. Molecular Shift Keying (MoSK) by using two types of molecules or Direction Shift Keying (DSK) that uses the direction of releasing molecules to convey information [10]. Nevertheless, the achievable throughput of molecular communication systems is very low and the delay is significantly high due to the random distribution of molecules in the medium [7], [8], [11], [12]. Moreover, molecular communication systems suffer from intersymbol interference, which still remains major deficiency despite the several techniques proposed in the literature to reduce it [13]–[17]. Wired nano-communication is a new method and uses the self-assembly ability of some polymers inside living cells to build an electrically conductive nanowire [9]. This method has the biocompatibility advantage as molecular communication does, but also, it has a very high achievable throughput, since fast moving electrons are the carriers of information. One of the main challenges of the wired nano-communication system is detecting the electrons at the receiver without losing its biocompatibility. The molecular communication receivers appearing in the open literature are designed to observe or absorb molecules in the medium [18]–[21], and thus, they cannot be used to detect electrons used in wired nano-communication.

In our recent works [9], [22], we proposed the idea of a receiver for a wired nano-communication system without studying or evaluating it. In this paper, we present the detailed system model of the proposed receiver, and we evaluate
its performance. The proposed receiver contains a Smooth Endoplasmic Reticulum (SER), which plays the role of Ca$^{2+}$ storage inside living cells [23]. The receiver also contains a recyclable concentration of the photo-protein Aequorin, which can be found in the jellyfish Aequorea Victoria that lives in the west coast of north America and the Pacific ocean [24]. Bioluminescence is a chemical reaction used by living organisms to generate light with enzymes and photoproteins. The designed receiver uses the transmitted electrons to stimulate the SER and trigger a chemical reaction involving the photo-protein Aequorin, which generates a bioluminescent light as shown in Fig. 1. Converting the transmitted electron pulses into light pulses at the receiver makes the extraction of information easier and can create a link between nanoscale and macroscale communication systems. Also, opens the way for the implementation of bio-inspired integrated electrical-optical nanonetworks. To study SER stimulation with the transmitted electrons, we simulate the conductive nanowire used in the wired nano-communication system, present its electrical characteristics and calculate its maximum capacity. The main contributions of the paper are summarized as follows:

1) To the best of our knowledge, we present the first design of a bio-inspired receiver that allows the detection of electrons at nano level for wired nano-communication systems.

2) We model the stimulated part of the receiver as an equivalent circuit. We derive the analytical expressions of the equivalent circuit’s components, and we calculate the probability of photons emission for each electrical pulse sent.

3) We simulate the construction of the nanowire, present its electrical characteristics, calculate its maximum capacity and use it as an input to evaluate the designed receiver.

4) We also propose the optimal threshold for Integrate, sample and dump (ISD) receiver.

5) We calculate the bit error probability (i.e. Bit Error Rate-BER) of the proposed system as means of assessing its performance.

The rest of the paper is organized as follows. Section II gives an overview of the existing receiver models and summarizes the related works presented in the open literature. Section III highlights an in-depth description of the designed receiver by clarifying the SER role in electron detection, and by explaining the triggered chemical reaction responsible for the emission of light. In section IV, we present the 2 algorithms used in our framework to simulate the nanowire assembly in a stochastic 3D system. We also present the electrical characteristics of the nanowire and we calculate its maximum capacity. In section V we model the designed receiver by using an equivalent circuit, where SER and its membrane are represented by a capacitor and the sum of Ca$^{2+}$ channels represented by a resistor. We derive the analytical expression of the circuit components and we calculate the number of emitted photons for each electron pulse sent. We also simulate the proposed equivalent circuit and we calculate the error probability of photons emission for each electrical pulse sent. In section VI, We propose the optimal threshold for Integrate, sample and dump (ISD) receiver. We also calculate the bit error probability. Section VII discusses the numerical results of this study by presenting the receiver’s time response for different numbers of calcium channels and the bode diagram that shows the frequency response. It also provides the evaluation of the receiver in the form of the error probability as a function of SNR. We conclude the paper in section VIII.

II. RELATED WORKS

Several requirements must be considered when designing a Molecular Communication (MC) receiver. For instance, the size of the receiver must of nanoscale size, it must continuously be monitoring for the presence of molecules used to encode and transport information, it must be biocompatible and the information process must not rely on external macro-devices [25]. To receive the information through MC, the receiver needs two units; a unit for detecting molecularly conveyed signals and a processing unit for decoding the information [6]. Most of existing MC studies that are available through the open literature ignore the physical design of the receiver, by assuming that it can perfectly count the number of molecules [25]. Few other studies focused on the physical design, which can be categorized into two groups: biological-based receivers and nanomaterial-based receivers.

The biological-based design of a MC receiver uses synthetic biology to implement reception functionalities within living cells, thus producing tools that are useful to the design of bacteria-based receivers [26]. Synthetic biology can also be used to integrate genetic logical gates for complex computations and memory [27]. A transfer function of such system is derived in [28]; it provides a system-theoretic model for MC receivers. Nanomaterial-based MC receiver manifestations use the latest advances in nanotechnology and artificial materials, such as graphene, carbon nanotubes and organic polymers [29]–[32] to design nanoscale biological Field-Effect-Transistors (bioFETs) [33]. Depending on the type of biosensors integrated in these bioFETs, olfactory biosensors [34], protein [35] or single-stranded DNA [36], a wide range of targets can be detected.

Several MC receiver-techniques have been proposed. They can be grouped into three categories: passive receivers, absorbing receivers, and reactive receivers. The simplifying assumption concept that is widely made for passive MC receivers reported in the open literature, is that they are 3D spherical entities with transparent membranes and are used as perfect molecule observers (they count each molecule relevant to the communication process that reaches their surface) [14], [17], [37]–[40]. While observing, a passive receiver has no impact on the propagation movement of molecules in the medium, because the complicated relationship between molecular movement and sampling processes is ignored in the proposed models [25]. Absorbing provide a more realistic receiver design; they include the concept of molecular degradation to which all molecules that hit the receiver’s surface are subjected to [41]. A perfect absorbing receiver absorbs instantly all hitting molecules. For this to even be close to be realistic, it requires that there is a very high concentration of receptors with very high absorption rate in its surface. Both passive and
absorbing categories are far from being realistic. Nonetheless, they are widely used in literature, as they provide more computationally tractable models of the molecular detection process. The reactive receiver design is more realistic in a sense that it uses more specialized receptors or enzymes, having finite reaction rates [42], [43]. Contrary to passive and absorbing receivers, the reaction of receptor-ligand is not ignored in the reactive receivers. In this paper, the proposed receiver uses a combination of absorbing and reactive techniques.

### III. Receiver Design

From chlorophyll pigments in plants to the neural system in human brains, many biological systems use chemical means to detect and send electrons in the medium. Inspired by the muscle fiber contraction and relaxation process, we propose a receiver design for wired nano-communication networks, which uses SER to detect transmitted electrons, moving through a nanowire. To avoid the absorption of electrons by the receiver’s surface, the receiver can be constructed with a hybrid phospholipid/alkanethiol bilayers membrane as proposed in [44]. Because of its insulating nature, this hybrid will minimize the loss of electrons at the receiver. The nucleation of monomers that trigger the formation of the actin self-assembly can be tethered at the bio-engineered membrane of the receiver by using a polyethylene glycol (PEG) at one end and an electrode at the other end [45]. The insertion of the monomer can be spontaneous, electrochemical or with a proteoliposome insertion as explained in detail in [45]. When the assembled nanowire reaches the receiver, it binds to one of the monomers already anchored in the receiver’s membrane with electrodes, which creates the means to have passage of electrons through the insulating membrane. As shown in Fig. 1, the designed receiver contains SER that stocks Ca\(^{2+}\) ions and a photo-protein that emits blue light in the presence of Ca\(^{2+}\) ions. The emitted light can be detected by one or more other nanonodes by means of photo-detection, thus implementing use of optical communication in the nanonetwork.

#### A. Detection of Electrons

The Ca\(^{2+}\) ion distribution is used in one of the most important biological signaling mechanics between living cells, and is involved in performing critical biological functions such as hormone regulation, muscle contraction and neuronal excitation [46]. The concentration of Ca\(^{2+}\) ions inside the cells must be regulated all the time using a very complex system, where SER plays the role of Ca\(^{2+}\) ions storage facility. The smooth endoplasmic reticulum, also called sarcoplasmic reticulum in muscle cells, is a tubular structure organelle found in most living cells. The capacity of SER at stocking Ca\(^{2+}\) ions is considerably large because of a buffer called calsequestrin that can bind to around 50 Ca\(^{2+}\) cations, which decreases the amount of free Ca\(^{2+}\) inside the SER; therefore, more calcium can be stored [47]. When SER is stimulated electrically, the calcium channels open and Ca\(^{2+}\) ions are released fast inside the cells, as shown in Fig. 2. The Ca\(^{2+}\) concentration is considerably low inside the cells, thus a tiny increase in their concentration is detectable.

#### B. Light Emission

Photo-proteins are priceless biochemical tools in many fields, including drug discovery, protein dynamic studies and gene expression analysis. Aequorin is a very important photo-protein for biological studies because it helps researchers measure and study the Ca\(^{2+}\) distribution in vivo. Upon binding with Ca\(^{2+}\) ions, the oxidation of Aequorin
Aequorin bioluminescent reaction that generates blue light in the presence of Ca\(^{2+}\) ions.

molecule is triggered, resulting in the emission of a bioluminescent blue light (470 nm). There are other photo-proteins in nature with emission at different wavelengths, such as Luciferin (530 nm) and some chromophores (630 nm). However, unlike other bioluminescent reactions that involve the oxidation of an organic substrate such as Luciferin and chromophores, adding molecular oxygen is not required to generate Ca\(^{2+}\)-dependent light emissions, because Aequorin protein has oxygen bound to it [49]. Other advantages of using Aequorin are that it does not involve any diffusible organic factor, no direct participation of enzymes and that it can be recycled after use [50]. Aequorin is extracted from the jellyfish Aequorea Victoria that lives in the west coast of north America and the Pacific ocean [24], and then is purified in distilled water. This photo-protein is very sensitive to changes in the concentration of free Ca\(^{2+}\), which explains its extensive use as an indicator of the presence of Ca\(^{2+}\) ions in biological studies. When there is very low concentration of Ca\(^{2+}\), the light intensity emitted by Aequorin will be independent from Ca\(^{2+}\) concentration. The bioluminescent reaction becomes Ca\(^{2+}\) dependent only when the concentration exceeds 10\(^{-7}\) M.

The designed receiver uses the short-time presence of the released Ca\(^{2+}\) ions to trigger the oxidation of Aequorin, which emits a photon for every 3 Ca\(^{2+}\) ions bounded, as shown in Fig. 3. This light emission mechanism of light emission triggers the release of over 70 kcal of energy as a visible radiation for every single chemical reaction [50]. In the next section, we model the electron detector as an RC circuit, and we calculate the radiant energy emitted from the bioluminescent reaction at each symbol interval.

### IV. SIMULATION FRAMEWORK

GlowScript VPython [51] is an easy and efficient way to create 3D environments for real time simulations. Our framework applies GlowScript as a browser-based implementation that runs a VPython program by using RapydScript, which is a Python-to-JavaScript compiler. In this study, we simulate the self-assembly of a polymer called “actin” to create a nanowire in real time, by using sphere molecules that diffuse randomly in a 3D cube as shown in Fig. 4. By using this framework, we can follow the position of the last assembled molecule in real time to study the speed of the nanowire’s construction, as the graph in Fig. 5 exhibits. In the next subsections, we present and explain the two algorithms we used in our framework.

#### A. Collision Between Actin Molecules

Algorithm 1 is a combination of two strategies; Periodic Interference Test (PIT) and Predicted Instant of Collision (PIC). The (PIT) consists of checking to detect if any collision has occurred between two molecules at every frame in the simulation. It tests if the molecules are approaching each other and whether they interfere spatially. When a collision is detected, the algorithm computes the new velocities after the collision using the momentum and energy conservation equations, and then attributes the new velocity to the moving molecules. If the simulation detects no collision during that frame, it continues to the next one. PIC, on the other hand, pre-calculates the exact time of collisions before spatial interactions between the molecules. The difference between PIT and PIC approaches is that the later models perfectly the collisions, at the cost of some extra computation, compared to the PIT approach, which is a lazy collision detection strategy. In algorithm 1, we use a combination of the two approaches to detect and model the collisions in real time.
Algorithm 1 Periodic Interference Test
1: procedure PITC(MOLECULE A, MOLECULE B):
2: At every frame instant \( t \):
3: Test if the two molecules are approaching each other.
4: if YES then
5: Test if they overlap (interfere) spatially.
6: if YES then
7: Collision detected.
8: Compute New Velocities.
9: \( T := \text{time of collision between A and B.} \)
10: if \( T < \text{next frame instant:} \) then
11: Move frame to intermediate instant \( T \).
12: Calculate velocities after collision.
13: end if
14: else
15: No collision detected.
16: end if
17: Goto next frame instant.
18: end if
19: end procedure

Algorithm 2 Nanowire Formation
1: molecule_array = [Transmitter]
2: if collision.detected = True then
3: if collision occurs with last(molecule_array) && last(molecule_array) \(!= \text{Receiver} \) then
4: \( M \leftarrow \text{molecule hitting the wire} \)
5: if Magnetic Field = 0 then
6: Randomly attach \( M \) to last(molecule_array)
7: molecule_array.append(M)
8: end if
9: if Magnetic Field \(!= 0 \) then
10: if \( M . \text{center.X} > \text{max(last(molecule_array).position)} \) then
11: \( Z = \text{function(magnetic field)} \)
12: if \( M . \text{center.Z} < \text{max(Z)} \) then
13: \( M . \text{momentum} = 0 \) % Stick the two molecules together
14: molecule_array.append(M)
15: end if
16: end if
17: end if
18: end if
19: end if

B. Nanowire Formation

If a random molecule in the environment strikes the last molecule of the constructed nanowire, it will attach to it, increasing the length of the nanowire. Several conditions are necessary for the molecules to stick in the nanowire, namely:

- One of the molecules having a collision is already sticking in the nanowire.
- The center of the striking molecule lies within a specified angle range from the center of the last attached molecule.
- The center of the next molecule being attached should be farther away from the transmitter and closer to the receiver, so that the nanowire is moving towards the receiver and not towards any random path.

To make the molecules stick, we give their momentum a zero value, and we do not update their position with time. Algorithm 2 also regulates the direction of nanowire formation. The direction is controlled by the magnetic field. If magnetic field is not applied (intensity is zero), there is no guidance for the direction of the actin self assembly, and the nanowire forms randomly. When magnetic field is applied, this changes, and as its strength increases, the nanowire’s growth becomes more aligned, following closer the straight-line connecting transmitter and receiver, as was confirmed by the experimental results reported in [52].

C. Actin Nanowire’s Maximum Current Intensity

The charge capacity of each actin monomer is \( \sim 4e \) [53], and by assuming 370 monomers/\( \mu m^1 \) of an actin filament, we can deduce that the charge volume of an actin filament that is 1 \( \mu m \) long is approximately 1480e. Thus, the maximum current intensity that can be sent through the nanowire is calculated by multiplying the total charge capacity of 1\( \mu m \) actin nanowire with the speed of the charges propagation through it, which produces the following expression [55]:

\[
I(t) = v(t) \times \psi_{tot}, \tag{1}
\]

where \( I(t) \) represents the nanowire’s current intensity, \( v(t) \) is the charge’s propagation speed (calculated in [56]) and \( \psi_{tot} \) is the charge volume of 1 \( \mu s \) actin nanowire. The proposed actin nanowire is more like a battery than a wire, which can be modeled with a series capacitor-resistor as we did in our recent work [55]. As electrons reach the positive side of the actin nanowire, the voltage differential drops, and the force of

\[\text{1Since the length of a monomer is around 5.4 nm and each monomer adds 2.7 nm to the filament, thus, 1 \( \mu m \) of actin filament have in average 370 monomers [54].}\]
attraction of the remaining charges reduces. This reduction in the force of attraction can explain the decrease of the current’s volume as the time progresses, as shown in Fig. 6.

D. Actin Nanowire’s Spectral Behaviour

The authors in [56] and [53] studied the electrical impulses and ionic waves propagating along actin filaments in both intracellular and in vitro environments, by modeling the actin filament as an RLC equivalent circuit. The effective resistance, inductance and capacitance for a 1 μm actin filament are [53]:

\[ C_{eq} = 0.02 \times 10^{-12} \text{F} \]
\[ L_{eq} = 340 \times 10^{-12} \text{H} \]
\[ R_{eq} = 1.2 \times 10^9 \Omega \]

Fig. 7 presents actin simulated nanowire’s spectral behaviour, provided in our recent work [55]. It displays the nanowire’s attenuation and phase as function of frequency and distance between transmitter and receiver. We can see that the attenuation of actin filaments is very high because of its resistance. The experimental study reported in [56] showed that despite the actin filaments attenuation, the velocity of the charges passing through it can reach 30,000 μm/s and then slows down rapidly in the first 60 μs. Moreover, the authors of [57] proved experimentally that adding gold nanoparticles to the actin monomers drastically decreases its attenuation.

V. RECEIVER MODEL

Cell membranes are biological structures that surround cells and separate their interior from the exterior environment. Ionic exchange occurs through the membrane, implementing complex processes. The membrane is constructed with phospholipid molecules, where the lipid end is hydrophobic, and the phosphate end is hydrophilic. When lipid ends connect to form a double-layered sheet, they create a spherical surface that perfectly separates the two volumes of liquid. However, a pure phospholipid bilayer is a perfect insulator, which does not allow even ion exchange. Thus, pores penetrating the membrane are needed to allow ions to bilaterally move through the membrane of the cell. These pores are called ion channels and by controlling their opening and closing, the cell controls the ionic flow. Cell membranes have specific channels for specific ion type. Closing them creates a difference between the ionic concentration inside versus outside the cell, which produces a voltage differential that is dependent on the ions’ type.

We represent by \( V_i \) the reversal potential generated by ions of type \( i \), which is the value of the membrane potential for which the flux of type \( i \) ions is zero, and represent by \( R_i \) the channel resistance, which is the inverse of channel’s conductance. According to Ohm’s law, the ionic flow across the channel is proportional to the reversal potential, and the proportionality factor is the channel conductance \( g_i \). It can be expressed as follows:

\[ I_i = \frac{V_i}{R_i} = g_i V_i, \quad (2) \]

where \( I_i \) is the current generated by the flow of \( i \) type ions occurring across the membrane. The current flows until \( V_i \) reaches an equilibrium called resting potential \( V_0 \), which equals:

\[ V_0 = \sum_i g_i V_i \sum_i g_i, \quad (3) \]

In our case, the membrane has channels only for Ca\(^{2+}\) ions. We use the terms \( g_{Ca} \) and \( V_{Ca} \) to represent \( g_i \) and \( V_i \) for these channels. The reversal potential \( V_{Ca} \) is calculated by using Nernst equation and equals to:

\[ V_{Ca} = \frac{kT}{ze} \ln \frac{P_{out}}{P_{in}}, \quad (4) \]

where \( k \) is the Boltzmann constant, \( e \) is the electron charge, \( T \) is the temperature in Kelvin, \( z \) is the valence of the Ca\(^{2+}\) ion, \( P_{out} \) and \( P_{in} \) are the probabilities of finding a Ca\(^{2+}\) ion outside or inside the SER respectively. When the membrane is at rest, \( V_{Ca} \) equals \( V_0 \), however, when an external potential is applied, \( V_{Ca} \) increases. This increase opens the Ca\(^{2+}\) channels and discharges SER from Ca\(^{2+}\) ions. When the excitation is passed, special pores called pumps charge...
SER again with Ca$^{2+}$ ions. The charge and discharge of SER can be modeled as an equivalent capacitance and the inverse of the channel conductance can be modeled as an equivalent resistance in series with a voltage source. Therefore, the SER and its membrane can be modeled as an equivalent RC circuit, as shown in Fig. 8.

A. The Capacitance

The SER membrane separates two conductive liquids that contain free ions, thus, we have two conductors separated by an insulator. The potential difference across the membrane that separates a charge of a Ca$^{2+}$ ions $Q_{Ca}$ defines a capacitance $C_{Ca}$ that can be written as:

$$C_{Ca} = \frac{Q_{Ca}}{\Delta V_{Ca}}$$

Before calculating the potential difference $\Delta V_{Ca}$ by using the Gauss’s law, we define the permittivity $\varepsilon$ of the membrane as $\varepsilon = \varepsilon_r \varepsilon_0$, where $\varepsilon_r$ is the relative permittivity. SER in muscle cells is composed of tubule networks called cisternae, which have a diameter $r_{SER} = 50nm$. The SER tubules extend throughout muscle fiber filaments, so we assume that the length of SER tubules used in our designed receiver is $l = 1\mu m$. Assuming that the enclosed charge within SER’s volume is $Q_{Ca}$, then from Gauss’s law we can write the electric field at a distance $r$ as:

$$\vec{E}_{Ca} = \frac{Q_{Ca}}{\varepsilon} \left(\frac{1}{2\pi r}\right) \hat{r},$$

where $\hat{r}$ is the radial vector from the Ca$^{2+}$ charge at the origin of SER tubules to the surface of the membrane. The potential difference between the inside and the outside of the SER membrane is therefore written as:

$$\Delta V_{Ca} = -\int_{r_{SER}}^{r_{SER}+\delta} E_{Ca}.dr = -\frac{Q_{Ca}}{2\pi l r} \ln \left(1 + \frac{\delta}{r_{SER}}\right),$$

where $\delta$ is the thickness of the membrane. By substituting eq. 5 in eq. 7 we find:

$$C_{Ca} = \frac{2\pi l r}{\ln \left(1 + \frac{\delta}{r_{SER}}\right)}.$$

The membrane of SER does not need a high voltage to separate charges, because it is only two molecules thick ($\delta = 6 \times 10^{-9}m$), thus, we expect the membrane capacitance per area unit to be quite high. With the parameters values as given above, we estimate that the capacitance is $C_{Ca} \approx 4.5 \times 10^{-5}pF/\mu m^2$. Unlike the conductance, the capacitance of biological membranes is not influenced by the complexities of biological systems, which makes it constant.

B. The Resistance

The pure phospholipid bilayer constructing the membrane is an excellent electrical insulator. It has very low conductance, but the mosaic proteins that span the surface of the membrane act as channels for ions and increase the conductance. The Ca$^{2+}$ current flowing through the SER membrane depends on the number of open channels by the applied external voltage. Depending on the type and age of SER, the number of channels can reach 143,400 in t-tubule type giving a density of 24.3 per $\mu m^2$ area [58]. By taking into account the infinitesimal area of channels, we consider the SER membrane as an infinite charged linear line and by using Gauss’s law we can write the Ca$^{2+}$ current $I_{Ca}$ of one channel as:

$$I_{Ca} = \sigma \int E_{Ca}.da = n\sigma \frac{\delta}{\varepsilon},$$

where $\sigma$ is the conductivity of one Ca$^{2+}$ channel, $n$ is the number of Ca$^{2+}$ channels and $\lambda = \frac{Q_{Ca}}{l}$. From eq. 2 we can calculate the resistance of Ca$^{2+}$ channels $R_{Ca}$ as been equal to:

$$R_{Ca} = \frac{V_{Ca}}{I_{Ca}},$$

and by substituting eq. 7 and eq. 9 in eq. 10 we get:

$$R_{Ca} = \frac{\ln \left(1 + \frac{\delta}{r_{SER}}\right)}{2\pi \sigma l}.$$  

$R_{Ca}$ is the equivalent resistance of $n$ resistances linked in parallel in our equivalent circuit. The conductivity of a Ca$^{2+}$ channel can reach $\sigma = 100pS$ [59], and thus, the mean value of the variable resistance can be approximated as $R_{Ca} \approx 5.28 \times 10^{14}\Omega$. The membrane resistance is highly variable in biological systems compared to its capacitance, because the membrane is so thin that a small change in the voltage creates an electric field within it. In order to validate our proposed RC circuit, we calculate the time constant of the circuit, which is the multiplication of the resistance and capacitance values that we approximated using our model. Then, we compare the result with the time constant of calcium channels found in experimental studies. Experimental studies show that the time constant in most calcium channels varies between 0.1s to 0.2s [60], [61]. Another experimental study [62] showed that the L-type channels found in cardiac muscles and the ones we use in our system can reach a time constant of 0.22s, which is very close to the value approximated by our proposed model $\tau = 0.23s$. Table 1 summarizes the equivalent resistance values of different numbers of channels.

C. Probability of Photon Emission

The presence of Ca$^{2+}$ ions near the photo-protein Aequorin triggers a bioluminescent reaction that emits blue light having wavelength close to the 470 nm. The movement of Ca$^{2+}$
ions inside the receiver follows Brownian motion until they randomly hit a photo-protein. Calculating the hitting rate of Ca$^{2+}$ ions on an Aequorin molecule is needed in order to determine the probability of triggering a bioluminescent reaction that emits one photon. To trigger a bioluminescent reaction that emits one photon, the Aequorin molecule should capture and hold 3 Ca$^{2+}$ ions [50].

The random movement of Ca$^{2+}$ ions inside the receiver, which, as mentioned earlier follows Brownian motion, forces the ions to spread in all directions. While they start from an initial small region at the location of SER, their random movement generates a uniform distribution of Ca$^{2+}$ ions within the volume. Because of the tiny size of the spherical receiver (1 $\mu$m) and the Ca$^{2+}$ ion’s diffusion speed in a liquid (approximately 0.33 ms$^{-1}$ in average at room temperature [63]) the distribution of Ca$^{2+}$ ions within the receiver reaches equilibrium fast, thus, it is safe to assume that the Ca$^{2+}$ ions distribution inside the receiver after their release becomes uniform practically instantly. Because of the globular crystal structure of Aequorin molecules, we can assume that these photo-proteins have a spherical shape. Moreover, by assuming that the distribution of Aequorin molecules is also uniform inside the receiver and that their concentration is significantly smaller than the concentration of Ca$^{2+}$ ions, it is realistic to assume that statistically speaking, each Aequorin molecule will be surrounded by the same number of Ca$^{2+}$ ions (in average). Also, in reference to a specific Aequorin molecule, those Ca$^{2+}$ molecules that are captured at certain specific time by other Aequorin molecules, will not impact noticeably the concentration of Ca$^{2+}$. Therefore, we can reformulate this problem into a spherically symmetric scenario where an Aequorin sphere is surrounded by a spherical shell of Ca$^{2+}$ ions with a random radius r inside a spherical receiver, as shown in Fig. 9. With spherical boundary conditions, Fick’s second equation can be written as:

$$\frac{\partial C_a}{\partial t} = D \frac{\partial}{\partial r} \left( r^2 \frac{\partial C_a}{\partial r} \right).$$

(12)

where $D$ is the diffusion coefficient and $C_a$ is Ca$^{2+}$ ions’ concentration. At steady state, Ca$^{2+}$ ions distribution becomes uniform, thus $\frac{\partial C_a}{\partial t} = 0$.

We consider a spherical Aequorin molecule (AM) of radius $r_a$ and a spherical shell of radius $r_b$, containing Ca$^{2+}$ ions. The binding speed of Ca$^{2+}$ ions to Aequorin $k$ is very high ($k = 2.6 \times 10^7 M^{-1}s^{-1}$ [64]). It is realistic to assume that every Ca$^{2+}$ ion reaching the surface of AM becomes attached, thus Ca$^{2+}$ ions concentration at $r = r_a$ is 0. The concentration of Ca$^{2+}$ ions at $r = r_b$ is $C_{ion}$. To simplify the analysis, we assume a captured Ca$^{2+}$ ion remains attached for a deterministic period of time $\Delta T$. When it happens that 3 Ca$^{2+}$ ions are attached on an AM simultaneously, the state of AM changes. It emits light and frees the Ca$^{2+}$ ions. We focus on a reference AM (RAM), which is ready to capture ions right after transmitting light. This assumption results in having RAM as a sink all the time. Macroscopically, the concentration $C_{ion}$ within the spherical volume is uniform.

Now we consider a modified scenario where RAM does not release but neutralizes the Ca$^{2+}$ ions it captures removing them permanently from the Ca$^{2+}$ population. This would reduce the average speed attachment of Ca$^{2+}$ ions and thus under this scenario, in average, the time it takes to have 3 Ca$^{2+}$ ion attachments will increase. We can take this scenario further by assuming that the concentration $C_{ion}$ is not uniform. Since RAM acts as a neutralizing attractor for Ca$^{2+}$ ions (sink), under this scenario, the concentration $C_{ion}$ at a distance $r_b$ from RAM reduces as we move closer to RAM. Thus, the number of Ca$^{2+}$ ions in the vicinity of RAM is lower ($C_{ion} \approx 0$), which increases the average time needed for an additional Ca$^{2+}$ ion to be neutralized by RAM.

We can go even further and assume that the concentration $C_{ion}$ is at infinite distance from the center of RAM ($r_b \to \infty$). In such case, the inward flux equals [65]:

$$J_a = 4\pi D r_a C_{ion}. \quad (13)$$

This corresponds to the average number of Ca$^{2+}$ ions absorbed and removed at the surface of RAM. Therefore, the average inter-arrival time between 2 successively received Ca$^{2+}$ ions is:

$$T_{av} = \frac{1}{J_a} = \frac{1}{4\pi D r_a C_{ion}}. \quad (14)$$

If we assume that $\Delta T \to \infty$, (i.e., there is no release of captured Ca$^{2+}$ ions), the average amount of emitted photons per unit of time by RAM equals:

$$L_{en} = \frac{J_a}{3} = \frac{4}{3} \pi D r_a C_{ion}. \quad (15)$$

Not releasing captured Ca$^{2+}$ ions reduces the population of Ca$^{2+}$ available for capture, thus, takes longer to have
an ion captured. Therefore, the calculated $L_{em}$ represents a lower bound of the actual emission intensity. The average time duration between successive emissions of light by RAM then equals:

$$T_{em} = 3T_{av} = \frac{3}{4\pi D_{a}C_{ion}}.$$  \hspace{1cm} (16)

If RAM captures a Ca\textsuperscript{2+} ion and it remains at its surface for a duration $\Delta T$ without capturing 2 other Ca\textsuperscript{2+} ions, then it will be neutralized and there will be no light emission.

As mentioned earlier, the movement of Ca\textsuperscript{2+} ions within the medium is a Brownian motion process, which manifests a 3D random walk. A very large number of Ca\textsuperscript{2+} ions are located at the vicinity of RAM, some of them reaching the surface of RAM because of the random walk and they become attached. As per our approximative model, they become neutralized and leave the pool of Ca\textsuperscript{2+} ions. The probability $q$ that a specific Ca\textsuperscript{2+} ion will reach RAM is very small. However, because of the extremely high number of Ca\textsuperscript{2+} ions, a rate of $J_{a}$ hits (of Ca\textsuperscript{2+} ions) per unit of time occurs. This behavior can be modeled with a limit Poisson process [66]. The probability of having $m$ Ca\textsuperscript{2+} ions reach (and become neutralized in our case) during a time interval of duration $\tau$ equals:

$$p_{n}(m) = \frac{\Lambda(\tau)^{m}}{m!}e^{-\Lambda(\tau)}, \hspace{1cm} (17)$$

where $\Lambda(\tau) = J_{a}\tau$. Assuming that at time instance $t_{0}$, RAM emitted a photon, it would have released all Ca\textsuperscript{2+} ions attached to it. The time elapsing until RAM is hit by another Ca\textsuperscript{2+} ion after $t_{0}$ is $T_{1}$. In order to have light emission, the following 2 Ca\textsuperscript{2+} hits should occur within the interval $[t_{0} + T_{1}; t_{0} + T_{1} + \Delta T]$ in order for RAM to emit light. We assume the 2nd hit happens $T_{2}$ time units after the first and the 3rd hit happen $T_{3}$ time units after the second hit. For having light emission, the following condition should hold: $T_{2} + T_{3} \leq \Delta T$. The probability of not having light emission equals the probability of not having any Ca\textsuperscript{2+} hits or only 1 hit within the time window of $\Delta T$. This probability equals to:

$$P_{NL}(0) = p_{n}(0) + p_{n}(1) = (1 + J_{a}\Delta T)e^{-J_{a}\Delta T}. \hspace{1cm} (18)$$

When light is emitted, the average duration for the process to complete equals:

$$T_{lem} = T_{1} + T_{2} + T_{3} = 3T_{av}, \hspace{1cm} (19)$$

The rate then equals:

$$S_{lem} = \frac{1}{T_{lem}}[1 - (1 + J_{a}\Delta T)e^{-J_{a}\Delta T}]. \hspace{1cm} (20)$$

In the above equation, we have scaled the emission rate by taking into consideration the cases we do not have 2 arrivals prior to the expiration of the $\Delta T$ interval. Note that the calculated value $S_{LEM}$ is a lower bound of the illumination intensity. The average time $T_{av}$ includes events where the duration’s summation of 2 successive interarrival times exceeds $\Delta T$. These events have been removed from $S_{LEM}$ through the multiplication with $[1 - (1 + J_{a}\Delta T)e^{-J_{a}\Delta T}]$. For $T_{av} \ll \Delta T$, the lower bound is expected to be tight.

In this paper, the concentration of the released Ca\textsuperscript{2+} ions occurring during each symbol interval is obtained numerically by using Simulink in MATLAB, which represents the voltage across the capacitor in the proposed equivalent circuit.

VI. BIT ERROR PROBABILITY

The emitted light intensity is proportional to the released Ca\textsuperscript{2+} concentration for each symbol interval, which is proportional to the pulsed electrical current transmitted through the nanowire. Thus, we can modulate the transmitted information by varying the intensity of the electrons sent through the nanowire. The demodulation of information is done by detecting the variation in the intensity of bioluminescent light emitted by the receiver. In this paper, we use the Concentration Shift Keying (CSK) modulation technique [67], where a bit is decoded at the receiver as ‘1’ if molecules concentration measured over the symbol interval reaches or exceeds a predetermined threshold at a symbol interval, otherwise, it is ‘0’.

A. ISD Receiver

We assume that the waveform of the received signal shown in Fig. 10 is $S_{1}(t)$. We also assume that the transmission starts at time 0 and lasts a period $T$, where $T$ represents the symbol duration, which equals $T = 10 \mu s$ in this study. The strength of the signal within the $[0, T]$ period is:

$$E_{s} = \int_{0}^{T} S_{1}(t)dt. \hspace{1cm} (21)$$

Our objective is to detect the symbol $b_{k+1}$, the transmission and detection period of which takes place in the interval $[kT, (k+1)T]$. In order to do so, we need to calculate the Inter-Symbol Interference (ISI) present during this period. The ISI is equal to:

$$S_{ISI}(t) = \sum_{j=1}^{k} b_{j}S_{1}(t - (j - 1)T), \hspace{1cm} (22)$$

where $b_{j}$ are transmitted symbols, $b_{j} \in \{0; 1\}$. In this study, we consider Integrate, sample and Dump (ISD) receiver. The strength of ISI energy collected by the ISD receiver during the $kT \ll t \ll (k + 1)T$ interval equals:

$$E_{ISI}(k + 1) = \sum_{j=1}^{k} b_{j} \int_{0}^{T} S_{1}((k - j + 1)T + t)dt. \hspace{1cm} (23)$$

Should $b_{k+1} = 1$, the presence of ISI helps to make a correct detection because the accumulated ISI shifts the signal energy collected by the ISD detector at higher values. ISI becomes destructive when $b_{k+1} = 0$. Thus, the worst case is when $b_{j} = 1 \forall j \ll \ell \ll k$. In this case:

$$E'_{ISI}(k + 1) = \int_{0}^{\infty} S_{1}(t)dt = E_{ISI}^{ALL,1}. \hspace{1cm} (24)$$

As explained in Section 2, there is a small quantity of Ca\textsuperscript{2+} ions which is always present in the medium causing a very
The response of the designed receiver with 1000 calcium channels.

Fig. 10. The response of the designed receiver with 1000 calcium channels.

low Ca\(^{2+}\)-independent light emission (The intensity of this emission is not dependent on Ca\(^{2+}\) concentration). Moreover, experimental studies showed that Aequorin molecules are sensitive to temperature fluctuations in the medium [68]. Body temperature increases the Ca\(^{2+}\)-independent light emission, and thus, the temperature fluctuations in the medium generates random Ca\(^{2+}\)-independent light emissions creating a noise in our received signal. We assume this noise to be Additive White Gaussian Noise (AWGN) of power \(N_\sigma\) and average \(\overline{N}_{av}\). The reason why we considered AWGN noise is that the light introduced by Ca\(^{2+}\)-independent emissions can be regarded as the sum of small photons of a very large number of sources, namely individual Aequorin molecules. The majority of these sources behave independently due to their calcium independence. Therefore, the total Ca\(^{2+}\)-independent light emission is the sum of a very large number of independent and identically distributed random variables. By applying the central limit theorem, this Ca\(^{2+}\)-independent light emission can be approximated by Gaussian distribution, hence the assumption of AWGN noise. The study in [68] converted the bioluminescent counts into constant rate as (counts.s\(^{-1}\)/remaining active Aequorin) and showed that the average noise \(\overline{N}_{av}\) can reach 0.002 s\(^{-1}\), which is approximately one tenth of the intensity of the transmitted signal (0.02 pMole per symbol duration).

Fig. 11. Optimal location of the proposed threshold.

Another source of noise that we did not consider in this study is the fluctuations in the signal’s amplitude, which is caused by the randomness associated with the firing of photons. These fluctuations are small and they are ignored in this study because we are using high light intensities. However, in the case where low light intensities are used, these noisy small fluctuations can increase the error probability, which we will consider in our future work.

We also assume that the waveform \(S(t)\) expands over \((L + 1)\) symbol periods \(T\), i.e., \(S(t) = 0\) for \(t < 0\) and \(t > (L+1)T\). The ISI accumulated in \(L\) symbols will influence the decision of \(b_{k+1}\). We define the vector

\[
B(L; k + 1) = [b_{k-L}, b_{k-L+1}, \ldots, b_k]
\]

\(B(0; k)\) has no content. The level of ISI generated at the output of the ISD receiver when having \(L\) of previously transmitted symbols equals:

\[
E_{ISI}(B(L; k+1)) = \sum_{j=1}^{L} b_{k+1-j} \int_0^T S_1(\tau + (j - 1)T) d\tau,
\]

(25)

B. Bit Error Probability Over All Possible Patterns

The bit error probability of \(b_{k+1}\) for this specific vector \(B(L; k)\) equals:

\[
P_e(B(L; k+1)) = P(b_{k+1} = 1) P(\eta < -\left(\frac{E}{2} + \overline{N}_{av} + E_{ISI} B(L; k+1)\right) + P(b_{k+1} = 0) P(\eta > \left(\frac{E}{2} - \overline{N}_{av} - E_{ISI} B(L; k+1)\right)),
\]

(26)

where \(\eta\) is Gaussian random variable having variance \(N_\sigma\). \(\overline{N}_{av}\) is the noisy optical energy generated by the Ca\(^{2+}\)-independent light emission caused by temperature fluctuations in the medium. The probability can be calculated as follows:

\[
P_e(B(L; k+1)) = P(b_{k+1} = 1) Q\left(\frac{E + \overline{N}_{av} + E_{ISI} B(L; k+1)}{\sqrt{N_\sigma}}\right) + P(b_{k+1} = 0) Q\left(\frac{E - \overline{N}_{av} - E_{ISI} B(L; k+1)}{\sqrt{N_\sigma}}\right).
\]

(27)
where \( Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^\infty e^{-y^2/2} dy \). In order to calculate the bit error probability over all possible patterns that \( B(L; k + 1) \) can have, we define \( D(L) \) as the set containing all possible combinations that can be produced by a vector \( V_L(m) \) containing \( L \) binary elements, i.e. \( V_L(m) = [a_1, a_2, a_3, \ldots, a_L] \) where \( a_j \in \{0, 1\}, 1 \leq j \leq L \). Note that the probability of each of these patterns to occur equal \( 2^{-L} \). If \( B(L; k + 1) = V_L(m) \not\in V_L(m) \leq D(L) \), the bit error probability over all possible patterns equals:

\[
P_e(b_{k+1}) = 2^{-L} \sum_{m=1}^{L} P(b_{k+1} = 1) Q \left( \frac{x - N_{ao} - E_{ISI}(V_L(m))}{\sqrt{N_\sigma}} \right) + P(b_{k+1} = 0) Q \left( \frac{x - N_{ao} + E_{ISI}(V_L(m))}{\sqrt{N_\sigma}} \right), \tag{28}
\]

### C. Optimal Threshold Location for ALL1 Case

We proceed to calculate the optimal threshold’s position for the case \( B(L; k + 1) = V_{ALL1} = [1; 1; 1; \ldots; 1] \). The ISI at the output of the ISD receiver in the case where all interfering bits are ‘1’ is calculated in eq. 25 and the bit error probability for this case has been provided in eq. 28. The 2 levels at the output of the ISD receiver are \( E + N_{ao} + E_{ISI}^{ALL1} \) (for \( b_{k+1} = 1 \)) and \( E_{ISI}^{ALL1} + N_{ao} \) (for \( b_{k+1} = 0 \)). The optimal location of the threshold is in the middle of Line 2 and Line 3 shown in Fig. 11. By placing the threshold at the optimal position, the bit error probability equals:

\[
P_e(b_{k+1}) = Q \left( \frac{x}{\sqrt{N_\sigma}} \right). \tag{29}
\]

In this paper, we assume that the probabilities \( P(b_{k+1} = 1) \) and \( P(b_{k+1} = 0) \) are equally probable. For analytical results, the ISI is calculated as follows:

\[
E_{ISI} = \sum_{i=1}^{L} b_i C_{max} e^{-t_i/\tau_c}, \tag{30}
\]

where \( \tau_c \) is the time constant of the equivalent circuit and \( C_{max} \) is the peak of the signal. Eq. 30 is the receding part of the waveform produced by the RC circuit we used to model the system in section 4.

### VII. Performance Evaluation and Numerical Results

In order to evaluate the performance of the designed receiver, we used Simulink in MATLAB to simulate the proposed equivalent circuit shown in Fig. 12. The parameters we used in this study were presented in Table I and mentioned in the sections above. The output at the capacitance represents the released \( Ca^{2+} \) ions concentration by SER occurring during each bit interval. Fig. 10 shows the response of the designed receiver with 1000 \( Ca^{2+} \) channels. The current sent through the nanowire excites SER’s membrane and increases its resting potential (-75 mV), calculated in eq. 2, by 40 mV, which allows the opening of \( Ca^{2+} \) channels. The output of the capacitance increases rapidly to reach equilibrium at 0.2 pMole of \( Ca^{2+} \) ions, then when the excitation stops, SER starts absorbing the released \( Ca^{2+} \) ions and the output decreases until they vanish from the medium. The intensity of the emitted light follows the concentration of \( Ca^{2+} \) ions; when the concentration is at its peak, the light intensity is also at its peak. When the \( Ca^{2+} \) ions vanish from the medium, the light turns off. The 0.2 pMole peak of \( Ca^{2+} \) ions concentration can generate a light intensity of 16.6 (mW/mm²),² which is safe to be used in vivo for medical applications as confirmed by the experimental study reported in [69].

### A. Number of \( Ca^{2+} \) Channels

For miniaturization reasons, we use a small surface area of SER, which may contain 1000 \( Ca^{2+} \) channels or less. The smaller the number of \( Ca^{2+} \) channels, the smaller the size of the designed receiver. In this study, we used different number of channels in SER membrane: 50, 100, 500 and 1000 channels. In the model, these channels represent resistances connected in parallel in the proposed equivalent circuit. The values of the equivalent resistances for each number of channels are provided in Table I. We plotted the output of the equivalent circuit as function of time.

Fig. 13 displays the output of the proposed receiver generated by different number of channels. A random sequence of 37 bits was generated and was used as transmitted information. The particular sequence is the following: [1 0 1 1 0 1 0 1 1 0 0 0 0 0 0 0 1 0 0 1 1 0 0 0 0 1 0 1 0 0 1 1 1 1 0 1]. We notice that with 500 and 1000 opened channels, SER can release 0.2 pM of \( Ca^{2+} \) ions and reach equilibrium. For the case of 1000 channels, molecular concentration decreases considerably faster compared to when 50 channels are open. With 1000 opened channels, SER absorbs the released \( Ca^{2+} \) ions after the excitation terminates at a rate that is 500 times faster compared to when 50 channels are opened, 12 times faster than the case of 100 channels and 3 times faster than the case of 500 channels. This rapid absorption of \( Ca^{2+} \) ions decreases the intersymbol interference between previous and next bits.

²The light intensity generated in this study is calculated with this equation: Light intensity (W/m²) = [Ca²⁺]N_Ahc / 3i, where \( N_A \) is the number of Avogadro, \( h \) is the Planck constant, \( c \) is the speed of light and \( \lambda \) is the wavelength of the emitted light (480 nm). \( N_Ahc = 0.1196 J.m/mol \).
The response of the receiver in Fig. 10 also revealed that only an intensity of around 1 nA is needed to open 1000 channels. This is due to the fact that the membrane’s thickness is so small (6 nm) that a tiny excitation can change the voltage at the channels and open them. The sensitivity of SERs membrane to the electric current is one of the reasons why we use it to detect electrons in our designed receiver for wired nano-communication systems.

B. Bode Diagram

When using an SER with 1000 Ca$^{2+}$ channels, SER will need around 0.24 $\mu$s to absorb 63% of Ca$^{2+}$ ions released in the medium, 0.48 $\mu$s to absorb 85% and 0.71 $\mu$s to absorb 95% as shown in Fig. 14. Only 1 $\mu$s is needed for an SER with 1000 Ca$^{2+}$ channels after a symbol interval to absorb practically all Ca$^{2+}$ ions from the medium, which drastically reduces intersymbol interference. This reduction in ISI allows for an increase in the system’s frequency response.

The Bode diagram in Fig. 15 shows the frequency response of the proposed system with 1000 Ca$^{2+}$ channels. We used the transfer function of the proposed equivalent circuit to plot the Bode diagram, which shows the magnitude in dB (10log(1) = 0 dB) and the phase of the transfer function versus frequency. What we observe is that the power spectral response remains unchanged for up to 200 kHz. Also, the phase response changes by less than 10 degrees within the spectrum up to 100 kHz. These conditions correspond to close to ideal channel conditions; the introduced distortion is minimal. Thus, it is reasonable to conclude that good performance for symbol transmission speeds in the vicinity of 100,000 symbols per second is expected, which is much faster than the frequency of the neurons inside the human brain.

C. Bit Error Probability

To evaluate the performance of the designed receiver, we calculate the bit error probability through simulations ran using Simulink MATLAB and the bit error probability analysis presented in eq. 30. The parameters used are provided in Table I. Fig. 16 shows analytical and simulation results of bit error probability as function of SNR with 1000 calcium channels. We observe that the change in bit error probability when sending a different number of bits is very small and can hardly be noticed. When sending higher number of bits, there is a very small increase in bit error probability. This increase is caused by the noise represented by the calcium molecules.
remaining in the medium, which causes the emission of noisy photons. We also notice that the analytical and simulation results are a perfect match for 100 bits.

Fig. 17 shows the bit error probability as function of the SNR when sending 1000 bits for different number of channels. The results show that the more calcium channels we have in the SER, the better the performance of the proposed receiver. However, if we use more channels, the size of the designed receiver increases, which creates a trade-off between better performance and size miniaturization. It can also be seen that the results of the bit error probability when using 1000 and 500 channels are very close. Thus, by using SER with 500 channel, one can have the same performance as that obtained by using 1000 channels with half the size of the receiver, which can be a very good solution to the explained trade-off.

VIII. Conclusion

Building conductive nanowires between nanomachines by using the ability of certain polymers to self-assemble is a newly proposed method for implementing wired communication at the nanoscale. Despite the very high achievable throughput of wired nano-communication systems due to the use of electrons as information carriers, the detection of electrons at the nanometric scale is very challenging. This paper proposes a bio-inspired receiver that uses Smooth Endoplasmatic Reticulum (SER) to detect the transmitted electrons by measuring the released Ca²⁺ ions concentration with the photo-protein Aequorin that emits a blue light in the presence of Ca²⁺ ions. To better design the receiver, we simulate the construction of the nanowire, present its electrical characteristics and calculate its maximum capacity. We modeled the dynamic of SER with an equivalent circuit, and we derived the analytical expression of their components. We calculated the error probability of photons emission for each electrical pulse detected and we simulated the proposed equivalent circuit. We also proposed an optimal threshold for Integrate, sample and dump (ISD) receiver and we calculated the error probability of bits detection over all possible patterns to evaluate the performance of the designed receiver. The results of this study showed that the designed receiver is efficient and can accurately detect the electrons sent through a conductive nanowire in wired nano-communication networks.

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