Macrophage-Inspired Nanorobots to Fast Recognition of Bacteria and Virus Through Electric Forces and Fields Patterns Inside of an Internet of Bio-Nano Things Network

Huber Nieto-Chaupis
Center of Research eHealth,
Universidad de Ciencias y Humanidades, Av. Universitaria 5175 Lima39 Perú
E-mail: huber.nieto@gmail.com

Abstract. We present computational simulations of the expected performance by a nanodevice that would play the role as an immune system cell such as the well-known macrophage, in the sense that these advanced devices can detect and perform interventions against aggregations of bacteria or virus. These prospective nanorobots would have the capability to recognize physical properties as well as to anticipate motion of bacteria and virus based entirely in electric interactions. The recognition of the type of bacteria is achieved through the continuous sensing of the electric interactions between the nanorobot and bacteria. A physics-based model entirely developed from the calculations of electric forces supports the content of this paper.

From the fact that nanorobots can exert electric forces on bacteria membrane based on the electric interactions basically. These engineered advanced devices are modeled through electrodynamics interactions that in a first instance might well described by the Jackson and Laplace equations in conjunction to the solution of the diffusion’s equation. By knowing forces and fields is possible to gain information about composition, motility and decisions made by bacteria and virus.

Once the intensity of the electric force has been estimated the nanorobot can perform concrete tasks. In this manner a frequency is associated for a range of intensity of field. Such frequency is related to a certain color. Thus, in according to color, morphology and motility of the bacteria aggregations the nanorobot executes a decision to break-off the ionic internal composition to decrease their kinematics.

Therefore, the distance between nanorobot and bacteria plays a crucial role in the simulations as to the fidelity of the recognition of the chemical compounds. The nanorobot learns about the type of bacteria through the frequency of oscillation.

While a macrophage swallow and absorbs biological and biochemical debris and compounds, the present proposal translates this concept to one inside of the territory of Classical Electrodynamics by which advanced nanodevices acquire firm capabilities to reduce bacteria capacities to break their homeostasis in short times.

The simulations have employed the method of bandwidth that allows to vary the field intensity through the resulting mathematical expressions. E-coli was used to test the model of this paper.
1. Introduction

Macrophages, these 21 micrometers size cells have their constitution in basis of metals and ions \[1\]|2\]. Macrophage behavior is seen as a possible example to be used as an artificial replacement inside of the nanotechnology. The crucial role of a macrophage cell is that of swallow debris, death cells and biochemical remains that are not part anymore of the biological processes through the process known as phagocytosis \[3\]|4\]|5\]|6\].

Artificial macrophages are supposed to deplete bacteria colonization through electrodynamics. The rapid sustainable growth of an aggressive bacteria population in healthy organisms can affect substantially their normal development and delay crucial biochemistry processes that are imminently needed to maintain their local and global homeostasis due to biochemical processes \[7\]|8\]|9\]|10\].

Because growth and social behavior of bacteria population are governed by nanocommunications \[11\]|12\] as well as exchange of messengers such as plasmids for instance. Bacteria might also use electric charges or ions inside of them to perform communications among them and therefore to continue the development of the population targeting sustainability of their society. All of them as part of the their main internal processes in bacteria seems to be those phophotransferase systems (PTS in short).

Clearly this homeostasis would be also crucial in bacteria to initialize communications each other in order to guarantee the wellness of the bacteria population and therefore to achieve successfully chemotaxis as well as tasks of colonization in host bodies.

By assuming random motility and mobility of bacteria aggregation. Bacteria population search the most optimal conditions of society’s growth as well as using properties like chemotaxis, selfish and competence behavior each other also\[13\]|14\]|15\]|16\]|17\]|18\].

Starting from the fact that bacteria depletion might be seen from the angle of bacteria communications so that the obstruction produced by intervention of Bio-Chemical nanoparticles that exploit the principles of electrodynamics.

The presence of a Bio-chemical nanoparticle in a bacteria population can break down communication among them implying subsequently the depletion of the bacteria population in a sustainable manner.

Because their position as a permanent defender in live beings clearly most of their central characteristics are seen as models of defense to develop artificial schemes of defense against the attack of bacteria and virus.

Based on this fact, the idea of using nanoparticles fully inspired in macrophage’s functions but working entirely in electrodynamics properties \[19\], this might be a manner to attenuate fast growth of populations targeting the depletion and dysfunctional behavior among them \[20\]|21\]|22\].

The consistency of a prospective implementation of a nanoparticle with these characteristics is based in the electric properties due to the fact of the presence of ions such as K\(^+\) and Na\(^+\) would fuel nanoparticles and provide electric features to interact with bacteria’s ions. Such interactions are driven by electrodynamics principles and random dynamics by assuming that the properties of motility and mobility are governed by deterministic rules rather than stochastic dynamics \[23\]|24\].

All these facts are of importance to relate this phenomenology to a stochastic computational simulation and measure the nanoparticle’s parameters by which the electric effect would have a imminent effect on the bacteria’s depletion in a consistent manner. The application of a physics scheme that aims to tackle the problem of bacteria growth requires to apply a geometry and define a set of equations which would be use to extract numerical values that would determine the effect of the injection of a density of nanoparticles in organisms already containing bacteria populations \[25\]|26\].
2. Macrophage-Inspired Nanoparticles.

- One of the main internal processes in bacteria seems to be those phosphotransferase systems (PTS in short) by which both sugar-PTS and Nitrogen-PTS are exchanging phosphates each other to keep the required homeostasis of the free positively charged Potassium $K^+$.  
- Clearly this homeostasis would be also crucial in bacteria to initialize communications each other in order to guarantee the wellness of the bacteria population and therefore to achieve successfully chemotaxis as well as tasks of colonization in host bodies.  
- Consider a single pair nanoparticle and bacterium. As depicted in Fig. (1), the case (A) where both are negatively charged would induce repulsion electric force among them. Under this circumstance both species are displaced away from each other. Therefore the mobility of both species are depending of the electric charges of their surfaces and internal ions.  
- In (B) is seen the case where the nanoparticle have changed the previous state to one where the voltage dependent ions channel allows the access of Na$^+$ and K$^+$ ions inside the nanoparticle continuously. This amount of positively charged ions migrate until to reach the opposite surface of the nanoparticle which is geometrically modeled by a cylindrical shape.  
- Thus this fact would induce attraction forces between both and producing the change of their spatial positions. It has an electric effect on the bacterium: the cancellation of the negative charges over the surface.  
- Therefore a fraction of the total charges or ions inside of bacterium are consistently depleted.  
- In (C) is seen the last step of the sequence: once the negative ions inside the bacterium are canceled then the total internal charge density is reconfigured and redistributing the ions to the sectors which were depleted.  
- This last step would cause obstruction on the bacteria communications each others. In order to model these processes we use electrostatics to find firstly the potential of an uniformly charged solid cylindric that would emulate a single bacterium with an internal composition.

**Figure 1.** Process of recognition through intensity of electric field, (A) attraction of repulsion is verified, (B) releasing ions, (D) attraction is done and the net charge inside the bacteria might be totally depleted leaving the bacteria unable to perform displacements.
of positive and negative ions.

- So the clear role of a macrophage-inspired nanorobot is that of destroying electrical capabilities of the bacteria aggregation.

3. The Physics Models

3.1. General Formulation

Consider a nanodevice and a single bacterium, having each other an internal net charge so that there is an electric force exerting but depending on the sign of each one. If one single bacterium begins to move through previous communications by the emission and reception of plasmids then we postulate that on them there is a net charge due to their internal composition based on ions.

The resulting dynamics of an object namely the nanorobot due to the presence of a charged aggregation of bacteria can be modeled by \( \vec{E} = -\nabla \Phi \) where \( \vec{E} \) and \( \Phi \) the electric field and scalar potential respectively. Since the electric field is directly related to the dynamics of the charged compound through the fundamental relation \( \vec{F} = Q \vec{E} \), the final velocity of the nanorobot with total charge \( Q \) and because the existence of an electric force can be estimated in a straightforward manner as:

\[
v_F = \frac{\Delta s}{\Delta t} = \sqrt{\left( v_i^2 - \frac{Q}{M} \int \nabla \Phi ds \right)}.
\]

where \( \Phi \) the electric potential that comes from the charge distribution of bacteria. Furthermore \( v_i \) initial velocity, \( Q \) total charge, \( M \) mass of one nano robot. Therefore the delay time can be estimated in a straightforward manner and reads as

\[
T_f = T_i + \int \frac{ds}{\sqrt{\left( v_i^2 - \frac{Q}{M} \int \nabla \Phi ds \right)}}.
\]

From the fact that the time \( T_f = T_i \) is a period because the electric interaction between nanorobot and bacteria aggregation, then the associated frequency is given by:

\[
\omega = 2\pi \sqrt{\frac{1}{\int \frac{ds}{\sqrt{\left( v_i^2 - \frac{Q}{M} \int \nabla \Phi ds \right)}}}}.
\]

Clearly the importance of the value of the electric potential \( \Phi \) exerted by the bacterium would define the frequency of oscillation of a nanorobot. Nevertheless, the trivial relation \( R = \frac{Q}{M} \) might inhibit the frequency of the dependence of the electric potential in the cases where this rate is small.

3.2. The Charged Disk as a Charged Bacterium

In Fig.2 the electric force between a single bacterium and nanorobot is sketched. We assume that the nanorobot transport a cargo of ions: Potassium for instance. Certainly this nanorobot is engineered built. Thus the nanorobot is a charged compound and the physics equations can help us to determine the fields and potentials.

We assume the density of this ideal cylinder to be \( \rho_N \) with a length \( L \) and radius \( R \) in this way the potential caused by this distribution of charge is calculated along the axis of the cylinder. Thus, the potential is calculated to a distance \( z \) from its center. We used the well-known result from the calculation of the electric potential of a charged disk along the axis. When this result
Figure 2. Sketch of the presence of an electric force between bacteria (right) and nanorobot (left). The net amount of bacteria would define the dynamics of the nanorobot.

is generalized to the case of volumetric density the potential and the electric field in cylindric coordinates can be written as:

\[ \Phi(z, R, L) = \frac{\rho N}{4\epsilon_0} \left( z + \frac{L}{2} \right) \sqrt{R^2 + \left( z + \frac{L}{2} \right)^2} - (z - \frac{L}{2}) \sqrt{R^2 + (z - \frac{L}{2})^2} + R^2 \ln \left[ \frac{z + \frac{L}{2} + \sqrt{R^2 + (z + \frac{L}{2})^2}}{z - \frac{L}{2} + \sqrt{R^2 + (z - \frac{L}{2})^2}} \right], \quad (4) \]

\[ \vec{E} = -\nabla \Phi(z, R, L) = -\frac{e N}{4\epsilon_0} \left[ L - \sqrt{R^2 + (z + \frac{L}{2})^2} + \sqrt{R^2 + (z - \frac{L}{2})^2} \right] \vec{z}. \quad (5) \]

When this field exert an electric force (repulsion or attraction on the charged bacteria to a distance \( z \). We assume that the total charge of an aggregation is \( Q_B \) with a mass \( M_B \) in this manner,

\[ \vec{F} = Q_B \vec{E} = -Q_B \nabla \Phi(z, R, L), \quad (6) \]

now from elementary dynamics, the displacements produced by the electric fields and forces are calculated from the inclusion of the term \( \vec{F} = M_B \frac{dv}{dt} = -Q_B \nabla \Phi(z, R, L) \). One can see that the left side of this equation is purely kinetic energy due to the displacement by either repulsion or attraction forces between nanorobot and bacterium. This situation for a single pair can be done for a chain or population of bacteria. Here we reinforce the hypothesis that these displacements would have an imminent impact on the communication and chemotaxis with others bacteria.

\[ \vec{F} = Q_B \vec{E} = -Q_B \nabla V(z, R, L) = \frac{M_B v dv}{dz}. \quad (7) \]

From the case of the dynamics of a charged disk we can derive in a straightforward manner the equations that govern the time of interaction between a nanorobot and an aggregation of bacteria, then we can write down:

\[ \int_{T_i}^{T_f} dT = T_f - T_i = \Delta T = \]
\[ = \int_{z_i}^{z_f} \frac{dz}{\sqrt{v_i^2 - \int_{z_i}^{z_f} dz \left\{ \frac{\rho N Q B^2}{2 \varepsilon_0 M B} \left[ L - \sqrt{R^2 + (z + \frac{L}{2})^2} + \sqrt{R^2 + (z - \frac{L}{2})^2} \right] \right\}} \]  

(8)

and the frequency is then given by:

\[ \omega = \frac{2\pi}{\int_{z_i}^{z_f} \frac{dz}{\sqrt{v_i^2 - \int_{z_i}^{z_f} dz \left\{ \beta \left[ L - \sqrt{R^2 + (z + \frac{L}{2})^2} + \sqrt{R^2 + (z - \frac{L}{2})^2} \right] \right\}}}} \]  

(9)

where \( \beta = \frac{\rho N Q B}{2 \varepsilon_0 M B} \).

3.3. Alternative Derivation

From the fact that the repulsion force produces a displacement on the nanorobot with charge \( Q_N \) and mass \( M_N \) because the charge of bacteria \( Q_B \) then for two fixed values along the longitudinal direction the simplest path to obtain the oscillation frequency is through the Coulomb’s force, so that we arrive to

\[ v_F^2 - v_I^2 = kQ_N Q_B M_N \left\{ \frac{1}{z_2} - \frac{1}{z_1} \right\}, \]  

(10)

it is noteworthy to remark that for our ends we require a certain dependence on the total mass of the bacteria aggregation, thus the mass and charge densities of a particular population reads as

\[ \rho = \frac{dM_B}{dV}, \]  

(11)

\[ \bar{\rho} = \frac{dQ_B}{dV}. \]  

(12)

then the bacteria net charge can be written in terms of densities and masses, so that we can arrive to

\[ Q_B = \bar{\rho} M_B, \]  

(13)

and (10) can be rewritten as \( v_F^2 = \frac{dz}{dt} \),

\[ v_F^2 - v_I^2 = kQ_N M_N \left( \frac{\bar{\rho}}{\rho} M_B \right) \left\{ \frac{1}{z_2} - \frac{1}{z_1} \right\}, \]  

(14)

\[ \frac{dz}{dt} = \sqrt{v_I^2 + kQ_N M_N \left( \frac{\bar{\rho}}{\rho} M_B \right) \left\{ \frac{1}{z_2} - \frac{1}{z_1} \right\}} \]  

(15)

and finally the frequency dependent on the dynamical variables and kinematics can be written in a straightforward manner as

\[ \omega = \sqrt{v_I^2 + kQ_N M_N \left( \frac{\bar{\rho}}{\rho} \left[ \sum_{\ell=1}^L M_{B,\ell} \right] \right) \left[ \frac{1}{z_2} - \frac{1}{z_1} \right]} \]  

(16)
Figure 3. Sketch for sensing bacteria: (A) An aggregation of bacteria exert electric potential due to their negative charge. (B) Front of them a single nanorobot perceives electric attraction. (C) Once the dynamics have started the emission of an electromagnetic pulse is emitted. Depending on the intensity of the fields the nanorobot can identify which bacteria might be, a frequency of oscillation is attained.

where $M_{B,\ell} = \sum_{\ell=1}^{L} M_{\ell}$ is assumed $L$ single bacterium constitute the population that is the cause of the longitudinal displacement of the nanorobot. Clearly the spatial movement of the nanorobot might be also random.

Eq.(16) is a relevant result of the Coulomb-like physics in the sense that there is a clear connection between a frequency and lab data such as the mass of a bacteria population.

4. Classical Electrodynamics to Model Spatial Paths of Bacteria

Under the assumption that the fields of a single bacterium can be modeled by a cylinder shape, one attractive formalism is the one given by the well-known Jackson’s potential that uses advanced mathematical methodologies inside of Classical Electrodynamics [19].

Thus we proceed to use $\vec{E} = -\nabla \Phi(\vec{r},\vec{r}_B)$. With this results we extract the charge density through th Gauss’s Law: $\rho_B = \nabla \vec{E}$, Finally the usage of the Poisson’s equation allows to derive the charge density directly: $\rho_B = -\epsilon_0 \nabla^2 \Phi(\vec{r},\vec{r}_B)$.

The Jackson’s potential is then calculated from one inner point inside of a cylinder that model a possible morphology of a single bacterium. The Potassium ion is the responsible to generate electric potential and field. So that we can write the explicit form of the potential calculated in $r_B$ caused by a charge $Q$ located in $r$. By assuming that the cylinder has a height $L$ and a radius $a$, the closed-form solution of the Jackson’s potential is written exactly as:

$$\Phi(\vec{r},\vec{r}_B) = \frac{2Q}{\pi \epsilon L a^2} \sum_{\ell,m,n} e^{i\ell(\theta-\theta')} \sin \left( \frac{\ell \pi z}{L} \right) \sin \left( \frac{\ell \pi z'}{L} \right) J_m \left( \frac{\xi_{m,n} r}{a} \right) J_m \left( \frac{\xi_{m,n} r'}{a} \right)$$

where $\epsilon$ the relative static permittivity constant and is related to dielectric constant with a value equivalent to water, which is lying in the rage of 1 up to 100. In praxis, a suitable choice is
the value of 80, same as water. The modes \( \xi_{m,n} \) are depending on the integers \( m \) and \( n \) as consequence of the usage of the variables separation. The \( J_m \) are called integer-order Bessel functions and essentially depend on the radial variable. All these definitions satisfy \((2\ell_T)^2 » (\frac{\xi_{m,n}}{\alpha})^2 \) and \( \frac{\xi_{m,n}}{\alpha} \to \infty \), \( \Phi \to 0 \). With Eq.(17) in hands we are going to apply the Poisson’s equation given by \( \rho_B = -e\nabla^2\Phi(\mathbf{r},r_B) \) where the operator \( \nabla \) acts onto the \( r_B \) coordinate.

In this way we proceed to find the charge density. After of operating the Poisson’s equation the radial part for instance is written as, with \( \mathbf{r}_B \to \mathbf{r} \)

\[
\rho_B(\mathbf{r}) = -e\nabla^2\Phi(\mathbf{r},r_B) = \frac{2Q}{\pi\epsilon L a^2} \sum_{\ell,m,n} \frac{\text{Exp}[im(\theta - \theta')]}{(\ell^2 T^2)^2} J_m^2(\xi_{m,n}) \times
\]

\[
\sin\left(\frac{\ell \pi z}{L}\right) \sin\left(\frac{\ell \pi z'}{L}\right) \xi_{m,n} J_{m+1}(\frac{\xi_{m,n} r'}{a}) \left[ J_{-2+m}(\frac{\xi_{m,n} r}{a}) + J_{2+m}(\frac{\xi_{m,n} r}{a}) - 2J_m(\frac{\xi_{m,n} r}{a}) \right]. \tag{18}
\]

4.1. Ionic Charge Densities

As seen in Eq.(18) the infinite composition of terms resulting in the Jackson’s potential implies the presence of an infinite number of charged compounds. Therefore, we can group the number of charged compounds in according to their proposed interpretation: Potassium ions, external ions and the interference which also would play the role as noise or background.

In order to derive the whole set of charge densities we take advantage of the well known Poisson’s equation \( 4\pi\nabla^2\Phi(\mathbf{r},r) = -\frac{\rho}{\epsilon} \).

Working out under the umbrella of the cylindrical coordinates system the calculation of the charge densities requires the direct application of the Laplacian in such coordinate system.

After of applying twice the operator \( \nabla \) we have the following set of charge densities labeled by its origin: signal or ions Potassium \( K^+ \) that is denotes by \( \rho_S \), others ions as the noise to the signal denoted by \( \rho_N \) and the full interference \( \rho_I \). Thus, the explicit form of the resulting charge densities are written as follows:

\[
4\pi\nabla^2\Phi(\mathbf{r},r) = \rho_S + \rho_N + \rho_I = -J_m\left(\frac{\xi_{m,n} r}{a}\right) J_m\left(\frac{\xi_{m,n} r'}{a}\right) \times
\]

\[
\cos(m(\theta - \theta'))\sin\left(\frac{\ell \pi z}{L}\right) \sin\left(\frac{\ell \pi z'}{L}\right) + \frac{1}{4} J_m\left(\frac{\xi_{m,n} r}{a}\right) \times
\]

\[
\left( \frac{1}{4} \left( J_{m-2}(\frac{\xi_{m,n} r}{a}) - J_m(\frac{\xi_{m,n} r}{a}) \right) - \frac{1}{4} \left( J_{m}(\frac{\xi_{m,n} r}{a}) - J_{m+2}(\frac{\xi_{m,n} r}{a}) \right) \right) \times
\]

\[
\cos(m(\theta - \theta'))\sin\left(\frac{\ell \pi z}{L}\right) \sin\left(\frac{\ell \pi z'}{L}\right) - \frac{m^2}{r} \left( J_m(\frac{\xi_{m,n} r}{a}) J_m(\frac{\xi_{m,n} r}{a}) \cos(m(\theta - \theta')) \sin\left(\frac{\ell \pi z}{L}\right) \sin\left(\frac{\ell \pi z'}{L}\right) \right)
\]

\[
+ \frac{1}{4} J_m\left(\frac{\xi_{m,n} r}{a}\right) \left( J_{m-1}(\frac{\xi_{m,n} r}{a}) - J_{m+1}(\frac{\xi_{m,n} r}{a}) \right) \cos(m(\theta - \theta')) \sin\left(\frac{\ell \pi z}{L}\right) \sin\left(\frac{\ell \pi z'}{L}\right). \tag{19}
\]

Thus, we can see that the charge density of signal is proportional to the product of sins and Bessel’s functions times the Cos of the angular difference. This structure is actually in somewhat
Figure 4. Total charge from the usage of Eq.(21). We used the package Wolfram [27].

proportional to the solution of the diffusion’s equation also in cylindric coordinates. Therefore the charger density of pure $K^+$ ions obey to a flux of charge moving out or in the bacterium body. It is in full agreement to the biochemical PTS where both sugar and Nitrogen are constantly regulating the homeostasis through the stability of Potassium ions in continue manner.

The signal charge density is explicitly written as (including the constants that multiplies the full expression of Eq.(19),

$$
\rho_S(\vec{r}, \vec{r}') = -\frac{\epsilon L a^2}{8 Q} J_m \left( \frac{\xi_{m,n,r}}{a} \right) J_m \left( \frac{\xi_{m,n,r'}}{a} \right) \cos(m(\theta - \theta')) \sin \left( \frac{m \pi z}{L} \right) \sin \left( \frac{m \pi z'}{L} \right). 
$$

(20)

Therefore the total charge from the ionic compounds mainly from Potassium $K^+$ is obtained from the volumetric integration,

$$
Q = \mu = -\frac{\epsilon L a^2}{8 Q} \int d^3\vec{r} d^3\vec{r}' \rho_S(\vec{r}, \vec{r}').
$$

In Fig. 4 is seen the plotting of charge density for signal i.e. Potassium ions inside of bacteria for various orders of Bessel’s functions as pairs for $n, m$ as dictated by the Eq.(21). The sinusoid morphology of the curves has as origin to the usage of the integer order Bessel functions fact that governs the radial part of the fields. Since Eq.(21) denotes the signal, the lowest modes in short distances appear to be as the ones that where charge acquire highest values, so under a scenario of opposite signs the attraction is stronger so the nanorobot can efficiently to emulate a macrophage.

5. Electric Forces as Nanocommunication Signals

Clearly the integration of each component of Eq.(19) would return the respective charge of all contributions to the electric potential in the point $\vec{r}$ or $\vec{r'}$. Now we assume for instance that the electric force exerted from charged species either by one from Potassium ion inside of a single bacterium, might be seen as a signal of bacteria communication. Therefore we can define the
total charges as follows:

\[ Q_S = \int dz' dr' \sum_{m} M_j \left( \frac{\xi_{m,n} r'}{a} \right) J_{m-2} \left( \frac{\xi_{m,n} r'}{a} \right) \sin \left( \frac{\ell \pi z'}{L} \right), \]  

(21)

\[ Q_N = \int dr dr z K \sum_{k} k J_k \left( \frac{\xi_{k,n} r}{a} \right) J_k \left( \frac{\xi_{k,n} r}{a} \right) \sin \left( \frac{\ell \pi z}{L} \right), \]  

(22)

\[ Q_I = \int dz \frac{1}{4} J_q \left( \frac{\xi_{q,n} r}{a} \right) J_q \left( \frac{\xi_{q,n} r}{a} \right) \sin \left( \frac{\ell \pi z}{L} \right), \]  

(23)

### Full Electric Force

Thus, with the resulting \( Q_B = \int \rho_B(r) \), a straightforward method to estimate the electric force between macrophage represented by a nanorobot and bacteria is done through the simple Coulomb force, so that we need to use solutions of the diffusion’s equation by solving for \( \rho_B(r, t) \).

It would demand to count with the temporal dependence given by \( \text{Exp}(\lambda Dt) \). Therefore it’s possible to demonstrate that using the space-time evolution of the charge density the corresponding electric force is given by

\[ F(r, t) = \rho_0 Q \text{Exp}(\lambda Dt) \sum_{m} \sin \left( \frac{k \pi z}{L} \right) \left( 1 - \frac{2}{k^2} \right) \frac{J_{k} \left( \frac{\xi_{k,n} r}{a} \right) J_{k} \left( \frac{\xi_{k,n} r}{a} \right)}{J_{k+1} \left( \frac{\xi_{k,n} r}{a} \right) \sqrt{\left( \frac{\xi_{k,n} r}{a} \right)^2 + \left( \frac{k \pi}{L} \right)^2}} \]  

(24)

6. Destroying and Swallowing Bacteria

Once the PTS are started the flux of Potassium ions inside the allowed volume of the bacterium. The flux of positive charges allows us to define the electric potential that satisfies the Ohm law to some extent: \( \delta V = IR \) where \( I \) the current produced by the flux of ions and \( R \) the resistance to this flux which is perceived physically as the constant fluctuation of the flux of ions that might to produce instability on the homeostasis of bacterium due to other sources of electric charges surrounding the bacterium. In this manner when ions flux are interrupt, bacteria lost their capabilities to carry out communications through exchange of plasmids.

These outsider contributions would make perturbation to the Potassium flux and bacterium homeostasis. Therefore, taking into account that \( I = \frac{\delta Q}{\Delta T} \), then the resistance to the homeostasis of Potassium ions in bacterium is given by

\[ R = \frac{\Delta V \Delta T}{Q}. \]  

(25)

Therefore, only when this resistance is high enough bacteria would guarantee to exert reliable communication each other. Since \( Q \) total charge is the volumetric integration of the individual terms of Eq.(25), we focus now in the term that is seen as the interference to the electric potential created by the Potassium’s electrodynamics which is proportional to the product of two Bessel’s functions. Since the presence of the term \( r^{-2} \), then by using the identity:

\[ \int_0^r \frac{J_n(r)J_{-m}(r)}{r^2} = \frac{J_n(r)J_{-m}(r)}{r(n - m + 1)} + O(m^{-2}) \]  

(26)

where \( O(m^{-2}) \) denotes the terms proportional to \( m^{-2}, m^{-3} \), and \( m^{-4} \). Therefore we can build the resistance to the bacterium communication as

\[ \mathcal{R} = \int_0^2 dr \frac{\Delta V \Delta T}{Q}, \]  

(27)
Figure 5. The estimated BER using the logarithm as written in Eq.(29) for different values of the order of the Bessel functions as function of the axial coordinate expressed in µm. We use the pair \((-m, m)\) as defined in Eq.(26).

and the usage of the identity Eq.(26) [28] we can arrive to

\[
\mathcal{R} = \int_{0}^{z} \frac{\Delta V \Delta T dr}{r J_m(r) J_{-m}(r)} = -\frac{\pi \Delta V \Delta T}{2 \sin(m\pi)} \ln \left( \frac{J_{-m}(z)}{J_m(z)} \right)
\]

(28)

With all these definitions we can estimate the Bit Error Rate (BER) since Eq.(9) BER depends essentially on the distance axial \(z\), therefore BER is defined as follows:

\[
\text{BER} = \log \left( \frac{Q_S}{Q_B + \mathcal{R}} \right)
\]

(29)

where \(Q_S\) is the signal, or those electrical manifestations of bacteria among themselves. In addition \(\mathcal{D}\) denotes the distances between a pair of charged compounds: the bacterium charge \(Q_B\) and the nanorobot charge \(Q_N\).

According to Fig.5, BER is peaked as consequence of the usage of the sinusoidal functions and the Bessel functions as well. In top panel, the case for the first values of \(q\) demonstrating that in those species whose association is inside the range of a few nm, the BER reaches in average a 50%.

In bottom panel, various plots up to \(q = 9\) are displayed. The low values of BER would demonstrate that bacteria’s quorum might be good enough to pursue purposes of colonization. Thus, for those values beyond 8nm, bacteria turns out to be stable to accomplish tasks of chemotaxis for example[29].
6.1. Macrophage Activity Simulation

E-coli Example

In order to illustrate the ideas presented in this paper we use lab information of E-coli bacteria: diameter=1µm, large=2µm and a mass of $10^{-12}$g. With this information we fill the parameters from Eq.(24).

In Fig.6 different scenarios of the possible activity of macrophage-inspired nanorobot. It was done with the combination of Eq(16) and (24). For this exercise we use the method of bandwidth in WOLFRAM. The values are acquired from the electric force. Thus we provide values for the signal (nanorobot) and the bacterium. We assume that all this information is inside of the total electric force Eq.(24).

Once the electrodynamics is solved then we pass to estimate the frequencies. In top left raw plot the apparition of two well defined forms are perceived as the nanorobot and the bacterium. It is possible with the correct usage of the charges $Q_N$ and $Q_B$. When distances (top middle plot) are small we can claim that there is a swallowing activity (top right plot). The attraction is then seen as a action to swallow agents that cannot be recognized by the nanorobot.

On the down plots we have associated to each frequency a color that would characterize to the aggregation of bacteria. In left down plot we can see that both the nanorobot and bacteria aggregation are separated each other by less than 0.3µm. Once the nanorobot has established the distance, then the device is able to sense what type of force might be exerted. Thus, we can see in the down middle plot the attraction is responsible to perform interactions. In right down plot the addition of charges to the nanorobot due to attraction forces would reconfigure the total charge of the macrophage-inspired nanorobot. Below we briefly describe the algorithm of the possible operationalization of a nanorobot. In Fig.(7) up to 12 different scenarios of possible actions of a macrophage-inspired nanorobot are shown. Scale spatial is given in nm. The radial part is on the axes. The conversion to Cartesian coordinates is achieved through changes. correspondence. In first row, plot (1) is one example of how the nanorobot is moved up as cause of the electric field. In plot (2), the attraction force makes that all negative charge compound get closer to nanorobot. Once all of them were fully attracted, the net mass and charge of nanorobot is configured for next task, plot. (3). Second row show in plot (4) the weak intensity of the electric force as seen in the recognition of a two agents. To be closer the nanorobot performs a displacement. The nanorobot here has already swallowed as seen in two red areas in it as seen in plot (5). In plot (6) the electric force is intense as product of the attraction due to various charged compounds having inside Potassium K. Same interesting facts

MACROPHAGE-INSPIRED NANOROBOT ALGORITHM

1. DEFINE CONSTANTS
2. CALCULATES CHARGES
3. RANDOM LOCATIONS
4. CALCULATES FORCES
5. CALCULATES FREQUENCY
6. IF DISTANCES ARE SMALL THEN
7. PERFORMS SWALLOW
8. ADD SWALLOWED CHARGES
9. END IF
10. NEXT TASK: SEARCH NEW PATHOGEN
11. END

possible actions of a macrophage-inspired nanorobot are shown. Scale spatial is given in nm. The radial part is on the axes. The conversion to Cartesian coordinates is achieved through changes. correspondence. In first row, plot (1) is one example of how the nanorobot is moved up as cause of the electric field. In plot (2), the attraction force makes that all negative charge compound get closer to nanorobot. Once all of them were fully attracted, the net mass and charge of nanorobot is configured for next task, plot. (3). Second row show in plot (4) the weak intensity of the electric force as seen in the recognition of a two agents. To be closer the nanorobot performs a displacement. The nanorobot here has already swallowed as seen in two red areas in it as seen in plot (5). In plot (6) the electric force is intense as product of the attraction due to various charged compounds having inside Potassium K. Same interesting facts
Figure 6. Computational simulation of a nanorobot activity intaking rare charged compounds through electric forces. We assumed that the attraction between the nanorobot and the agent is perceived as an action of swallowing. This enhances the net charge of the nanorobot.

are seen in third row, as in plot (7) where simulations were able to emulate the case where bacteria can cheat as seen in plot (8) where bacteria with opposite signs attract among them in order to form a neutral compound that inhibits to be attracted or repulsed by the nanorobot. Cheating among bacteria is well-known as seen in Pseudomonas aeruginosa [27]. From the view of the physics, it does not allow the nanorobot to perform any action because the electric force is too small that no any action is taken. However the mechanisms of PTS are a window by which bacteria becomes a weak source of electric field. So depending on the sign of the net charge, attraction can be done successfully as seen in plot (9). In last row, plot (10) displays a possible scenario of interaction between a neutral compound. It can also be interpreted as a case of low frequency so that the nanorobot perceived too low signal. In plots (11) and (12), the final configuration of a possible nanorobot after of swallowed bacteria by sensing on electric fields, are displayed.

References

[1] Pete Chandrangsu, Christopher Rensing, Metal homeostasis and resistance in bacteria, Nature Reviews Microbiology volume 15, pages 338-350 (2017).

[2] Rammal H, Bour C, Dubus M, Entz L, Combining Calcium Phosphates with Polysaccharides: A Bone-Inspired Material Modulating Monocyte/Macrophage Early Inflammatory Response, Int J Mol Sci. 2018 Nov 3;19(11). pii: E3458. doi: 10.3390/ijms19113458.
Figure 7. Different scenarios where a nanorobot exerts actions of swallowing rare agents that are adjacent to the nano device. In all of them same nanorobot parameters keep the same. From top to down the variations are in the side of the bacteria aggregation, from a net charge from 0.000001 to 0.1C, where $C =$ charge electric units. In right side column we can see that finally the nanorobot appears to be swallowed all debris and agents that exhibit electric charge like Potassium.
[3] Song Y, Streptococcus mutans activates the AIM2, NLRP3 and NLRC4 inflammasomes in human THP-1 macrophages. Int J Oral Sci. 2018 Aug 6;10(3):23. doi: 10.1038/s41368-018-0024-z.
[4] Liu L, Sha R, Yang, Impact of Morphology on Iron Oxide Nanoparticles-Induced Inflammasome Activation in Macrophages. ACS Appl Mater Interfaces. 2018 Nov 6. doi: 10.1021/acsami.8b17474.
[5] Weiss G, Role of divalent metals in infectious disease susceptibility and outcome. Clin Microbiol Infect. 2018 Jan;24(1):16-23. doi: 10.1016/j.cmi.2017.01.018. Epub 2017 Jan 29.
[6] Hodgkinson V, Copper homeostasis at the host-pathogen interface, J Biol Chem. 2012 Apr 20;287(17):13549-55. doi: 10.1074/jbc.R111.316406. Epub 2012 Mar 2.
[7] Ladomersky E, Copper tolerance and virulence in bacteria, Metallomics. 2015 Jun;7(6):957-64. doi: 10.1039/c5mt00327f.
[8] Chaturvedi KS, Pathogenic adaptations to host-derived antibacterial copper, Send to Front Cell Infect Microbiol. 2018 Jan;24(1):16-23. doi: 10.1038/s41368-018-0024-z.
[9] Fu Y, Copper transport and trafficking at the host-bacterial pathogen interface, Acc Chem Res. 2014 Dec 16;47(12):3605-13. doi: 10.1021/ar500300m. Epub 2014 Oct 13.
[10] Djoko KY, The Role of Copper and Zinc Toxicity in Innate Immune Defense against Bacterial Pathogens, J Biol Chem. 2015 Jul 31;290(31):18954-61. doi: 10.1074/jbc.R115.647099. Epub 2015 Jun 8.
[11] Sian L, Stafford, Metal ions in macrophage antimicrobial pathways: emerging roles for zinc and copper, Biosci Rep. 2013; 33(4): e00049. Published online 2013 Jul 16. Prepublished online 2013 Jun 5.
[12] Katharina Pfleger Grau : regulatory roles of the bacterial nitrogen related phosphotransferase system, Trends in Microbiology, vol 18, Issue 5, 205-214 (2010),
[13] Bige D. Unluturk; Sasitharan Balasubramaniam; Jan F. Akyildiz The Impact of Social Behavior on the Attenuation and Delay of Bacterial Nanonetworks IEEE Transactions on NanoBioscience Year: 2016, Volume: 15, Issue: 8 Pages: 959 - 969
[14] Bige D. Unluturk; M. Siblee Islam; Sasitharan Balasubramaniam; Stepan Ivanov, Towards Concurrent Data Transmission: Exploiting Plasmid Diversity by Bacterial Conjugation, IEEE Transactions on NanoBioscience, Year: 2017, Volume: 16, Issue: 4, Pages: 287 - 298.
[15] Roche H, Godin J, Gage D. Biochemical Characterization of a Nitrogen-Type Phosphotransferase System Reveals that Enzyme EINtr Integrates Carbon and Nitrogen Signaling in Sinorhizobium meliloti, J. Bacteriol. May 2014 vol. 196 no. 10 1901-1907.
[16] Akyildiz, I. F., Pierobon, M., Balasubramaniam, S., and Koucheryavy, Y. (2015). The internet of Bio-Nano things. IEEE Communications Magazine, 53(3), 32-40.
[17] Sasitharan Balasubramaniam, Guest Editorial Special Issue on the Internet of Nano Things, IEEE Internet of Things Journal ( Volume: 3, Issue: 1, Feb. 2016 ).
[18] Pavel Boronin, Vitaly Petrov, Dmitri Moltchanov, Yevgeni Koucheryavy, Josep Miquel Jornet, Capacity and throughput analysis of nanoscale machine communication through transparency windows in the terahertz band, Nano Communication Networks Volume 5, Issue 3, January 2014, Pages 72-82.
[19] J. D. Jackson, Classical Electrodynamics, 3rd ed., Wiley, New York, Chap. 3. Prob 3.23, Pg. 142. (1999).
[20] Wolfram Mathematica, https://www.wolfram.com/mathematica/.
[21] ShahMohammadian, H., Messier, G.G., Magierowski, S., Nano-machine molecular communication over a moving propagation medium, Nano Communication Networks Volume 4, Issue 3, September 2013, Pages 142-153.