Propagation Models for Nanocommunication Networks

Ian F. Akyildiz, **Josep Miquel Jornet** and **Massimiliano Pierobon**
Broadband Wireless Networking Laboratory
School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, GA 30332, USA
Email: {ian, jmjm3, mpierobon3}@ece.gatech.edu

Abstract—**Nanotechnology is enabling the development of devices in a scale ranging from one to a few hundred nanometers. Communication among these nano-devices will expand the capabilities and applications of individual devices both in terms of complexity and range of operation, enabling new applications of nanotechnology in the medical, environmental and military fields as well as in consumer and industrial goods. Despite major progress in the design and manufacturing of these devices has been accomplished to date, it is still not clear how they are going to communicate. Two main alternatives for communication among nano-devices have been envisioned, namely, molecular communication, i.e., the transmission of information encoded in molecules, and nano-electromagnetic communication, which is defined as the transmission and reception of electromagnetic radiation from nanoscale components based on novel nanomaterials. In this paper, propagation models for both communication paradigms are discussed, emphasizing the challenges in nanocommunication networks.**

I. INTRODUCTION

Nanotechnology is enabling the development of devices in a scale ranging from one to a few hundred nanometers which are able to perform simple tasks such as sensing, computing, data storing, or actuation. *Nanocommunication* [1], i.e., the transmission of information among nano-devices, will expand the capabilities of individual devices both in terms of complexity and range of operation. The resulting *nanonetworks* will boost the range of applications of nanotechnology in the biomedical, environmental and military fields as well as in consumer and industrial goods. Amongst others, Wireless Nanosensor Networks [2], i.e., the interconnection of hundreds or thousands of nanosensors and nanoactuators placed in locations as diverse as inside the human body or in a battlefield, are one of the most promising applications of this new paradigm.

For the time being, it is still not clear how these nano-devices will communicate. Two main alternatives for nanocommunication have been envisioned, namely, molecular communication and nano-electromagnetic communication:

- *Molecular communication* is defined as the transmission and reception of information encoded in molecules [1]. Molecular transceivers will be easy to integrate in nano-devices due to their size and domain of operation. These transceivers are able to react to specific molecules and to release others as a response to an internal command or after performing some type of processing. The released molecules are propagated in the medium following either passive or active transport.
- *Nano-electromagnetic communication* is defined as the transmission and reception of electromagnetic radiation from components based on novel nanomaterials [22]. Recent advancements in molecular and carbon electronics have opened the door to a new generation of electronic nano-components such as nano-batteries, nano-memories, logical circuitry in the nanoscale and even nano-antennas [8]. From a communication perspective, the unique properties observed in novel nanomaterials will decide on the specific bandwidths for emission of electromagnetic radiation, the time lag of the emission, or the magnitude of the emitted power for a given input energy.

In this paper, we provide propagation models for both molecular communication and nano-electromagnetic communication for nanoscale networks. The rest of the paper is organized as follows. In Sec. II, a new end-to-end model for molecular communication based on molecule diffusion is introduced, emphasizing the novelties of this paradigm. In Sec. III, a propagation model for nanoscale terahertz communication is provided, highlighting the communication challenges that this alternative pose. Finally, the paper is concluded in Sec. IV.

II. PROPAGATION MODEL FOR MOLECULAR COMMUNICATION

Molecular Communication (MC) is a nanocommunication paradigm whose study can be approached through the observation of biology. A living organism (e.g., a bacterium or a multicellular organism) involved in MC reacts to specific molecules, performs some information processing, and releases other molecules in response. In the following, we first review different molecule propagation techniques that we can observe in biology. Then, we outline the physical end-to-end model developed in [17], which aims at an interpretation of the *diffusion-based* molecular communication, in terms of molecular transmitter, molecular channel and molecular receiver, as shown in Fig. 1.

A. Propagation Techniques

One of the key challenges in molecular communication is to characterize how molecules propagate through the medium [1]. For MC there are three main propagation techniques based on the type of molecule propagation. In the *walkway-based*

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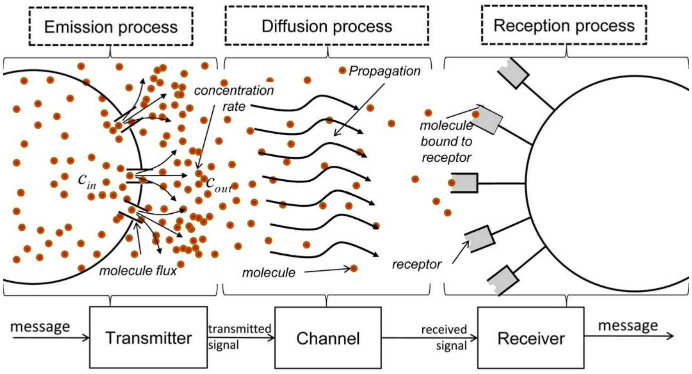

Fig. 1. Physical models of the Molecular Transmitter, the Molecular Channel and the Molecular Receiver.

technique, the molecules propagate through pre-defined pathways connecting the transmitter to the receiver by using carrier substances, such as molecular motors [24]. In the *flow-based* technique, the molecules propagate through diffusion in a fluidic medium whose flow and turbulence are guided and predictable. The hormonal communication through blood streams inside the human body is an example of this type of propagation of molecular information (hormones). The flow-based propagation can also be realized by using carrier entities whose motion can be constrained on the average along specific paths, despite showing a random component. A good example of this MC architecture is given by pheromonal communication in an ant colony. In the *diffusion-based* technique, the molecules propagate through their spontaneous diffusion in a fluidic medium [23]. In this case, the molecules can be subject solely to the laws of diffusion or can also be affected by non-predictable turbulence present in the fluidic medium. Pheromonal communication, when pheromones are released into a fluidic medium [6], such as air or water, is an example of diffusion-based architecture. Another example of this kind of transport is calcium signaling among cells [15].

To date, very limited research has been conducted to address the modeling and analysis of *diffusion-based* molecular communication and the according end-to-end behavior in nanocommunication networks. In [4], [5], a molecular receiver model is developed by taking the ligand-receptor binding mechanism into account [21]. However, in both papers, the diffusion process is not captured in terms of molecule propagation theory and, therefore, the end-to-end model reliability and accuracy are only accounted for the receiver side. Moreover, an ideal digital transmitter model is used and the performance evaluation is conducted based on an ideal synchronization between the transmitter and the receiver.

B. The Molecular Transmitter

The transmitter involves the release and capture of molecules into/from the environment, as shown in Fig. 1. Molecules are released or absorbed by means of a molecule flux which is able to modulate the molecule concentration rate at transmitter location as a function of the time. The transmitter stimulates an outgoing or ingoing molecule flux, thus encoding the input message into variations in the molecule concentration rate. The transmitter has a boundary which defines an inside molecule concentration c_{in}, and it is provided by apertures that connect the inside to the outside of the transmitter. A molecule flux is stimulated by a concentration gradient between the outside concentration c_{out} and the inside concentration c_{in}. The molecule concentration rate is constrained by the Fick's diffusion laws [9], [16] underlying the molecule exchange between the inside and the outside of the transmitter. The transmitter is able to change the inside molecule concentration in order to encode the input message into variations of the molecule concentration rate.

C. The Molecular Channel

The channel is physically related to the diffusion process that occurs when the concentration of molecules is not homogeneous, as shown in Fig. 1. The molecule concentration at the transmitter location, whose rate is modulated by the transmitter, activates the diffusion process, which is modeled by the Fick's diffusion laws [9], [16] and the relativistic diffusion theory [3]. The relativistic diffusion theory adds a new term to the Fick's second law accounting for a finite speed of propagation in the molecule concentration information. It is essential to account for the latter in order to model a propagation channel which must be in agreement with the theory of special relativity. During the diffusion process the molecules diffuse between the transmitter and the receiver following the trend of homogenizing their concentration. The molecule movement propagates the message that was encoded in the molecule concentration rate at the transmitter location. The channel delivers the message through variations on the molecule concentration at the receiver location, as a function of the time.

D. The Molecular Receiver

The receiver is physically related to the reception process and involves capture or release of molecules from/into the space by means of several chemical receptors, as shown in Fig. 1. A number of chemical receptors are used to receive information coming from the diffusion process. The capture and release of molecules is modeled according to the chemical theory of the ligand-receptor binding process [21]. The binding reaction occurs with a probability constant k_1^r when the receptor was not previously bound to a molecule. The release reaction occurs with a probability constant k_{-1}^r when there is a complex formed by a molecule and the chemical receptor. When a chemical receptor is bound to a molecule, it produces constant signal as output. The sum of all the receptor outputs provides the receiver with a reading of the local molecule concentration. Finally, the receiver decodes the message from the molecule concentration rate.

E. End-to-end Communication Parameters

We analyze in [17] the end-to-end model in terms of normalized gain and delay that a message experiences through the cascade of the transmitter, the channel and the receiver whose mathematical models are explained in [17] and stems from the physical processes explained above. For the end-to-end model:

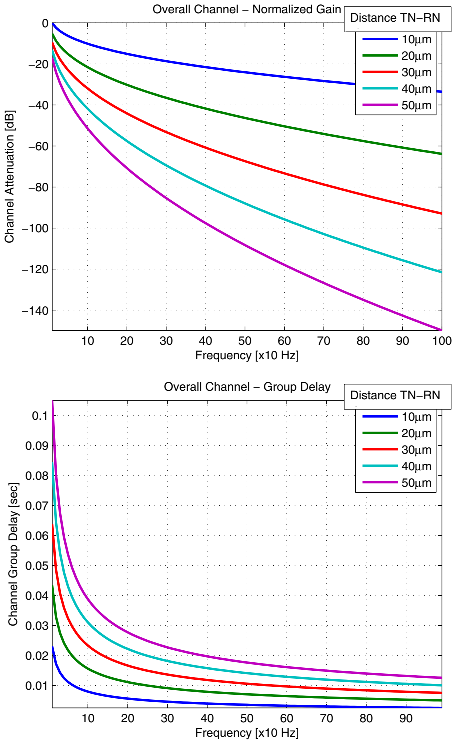

Fig. 2. The normalized gain (top) and delay (bottom) for the end-to-end model for molecular communication.

- The *normalized gain* is computed by multiplying the normalized gain contributions coming from the molecular transmitter, the molecular channel and the molecular receiver.
- The *delay* is obtained by summation of the delay contributions coming from the molecular transmitter, the molecular channel and the molecular receiver.

In Fig. 2 we show the numerical results in terms of *normalized gain* and *delay* for the overall end-to-end model, for a transmitter-receiver distance from $0\mu m$ to $50\mu m$, a number of receptors equal to 10 and a diffusion coefficient $D \sim 10^{-6} m^2 sec^{-1}$ (calcium molecules diffusing in cellular cytoplasm [11]). The frequency spectrum considered in these results ranges from 0Hz to 1kHz. Although we believe that there is no biological justification for taking into account this frequency range, we are expecting to study networks of new devices which will be able to exploit the MC end-to-end model by using various modulation techniques, even the ones not used by biological entities. For this, we believe that the results in this frequency range could help the future development of nanoscale communication systems. We do not consider a wider frequency range since the results up to 1kHz already show clearly the trend of the end-to-end model attenuation and delay as functions of the frequency.

F. Open Research Challenges

The physical end-to-end model developed in [17] opens up many novel research challenges directed towards a thorough characterization of the diffusion-based molecular communication. The primary goals will be met by applying an information theoretical approach to study the end-to-end communication in terms of noise, mutual information and, consequently, capacity and throughput. We believe that this will be achieved by taking into account the discrete nature of the molecular diffusion medium and the unavoidable randomness in molecule behavior. As a second step, the study of suitable modulation and coding schemes, either derived from classical communication or newly defined, will help the design of the overall molecular communication system between nanoscale devices. Further, we envisage networking applications stemming from the establishment of molecular communication links among many nanoscale devices. The study of network architectures and protocols based on molecular communication will enable a wide range of new applications.

III. PROPAGATION MODEL FOR NANO-ELECTROMAGNETIC COMMUNICATION

Reducing the antenna of a classical wireless device down to a few hundreds of nanometers would require the use of extremely high operating frequencies, compromising the feasibility of electromagnetic wireless communication among nanodevices. However, the usage of graphene to fabricate nanoantennas can overcome this limitation. Indeed, the wave propagation velocity in carbon nanotubes (CNTs) and graphene nanoribbons (GNRs) can be up to one hundred times below the speed of light in vacuum depending on the structure geometry, temperature and Fermi energy [10]. As a result, the resonant frequency of nano-antennas based on graphene can be up to two orders of magnitude below that of nano-antennas built with non-carbon materials [7]. In [14], we show that both nano-patch antennas based on GNRs and nano-dipole antennas based on CNTs around 1 μm long resonate in the terahertz band (0.1 - 10.0 THz). From this result, we envision future nano-electromagnetic networks operating in the terahertz band and, thus, there is a need to characterize the terahertz channel in the nanoscale.

The few terahertz channel models existing to date [20], [25] are aimed to characterize the communication between devices that are several meters far. On the contrary, thinking of nanoscale communication, there is a need to understand and model the terahertz channel in the very short range, i.e., for distances much below 1 meter. In the following, the main characteristics of the terahertz channel in the nanoscale are reviewed by using a new propagation model based on radiative transfer theory, firstly introduced in [13].

A. Path-loss

The total path-loss for a traveling wave in the terahertz band is defined as the addition of the spreading loss and the molecular absorption loss. The spreading loss accounts for the attenuation due to the expansion of the wave as it propagates through the medium, and it depends only on the signal frequency and the transmission distance. The absorption loss accounts for the attenuation that a propagating wave will suffer because of molecular absorption, i.e., the process by which part of the wave energy is converted into internal kinetic energy to some of the molecules which are found in the medium [12]. This depends on the concentration and the particular mixture of molecules encountered along the

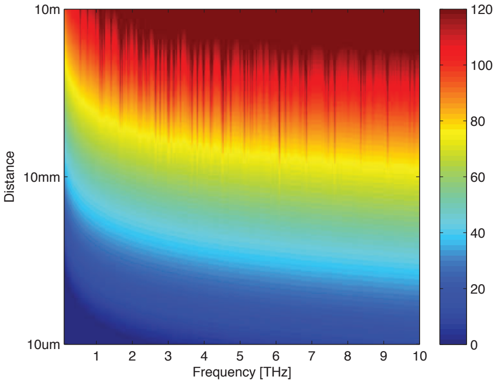

Fig. 3. Total path-loss in dB as a function of frequency and distance that an EM wave will suffer when propagating in a standard medium with 1% of water vapor molecules (the values for path-loss have been truncated at 120 dB to avoid masking relevant transmission windows in the short-range).

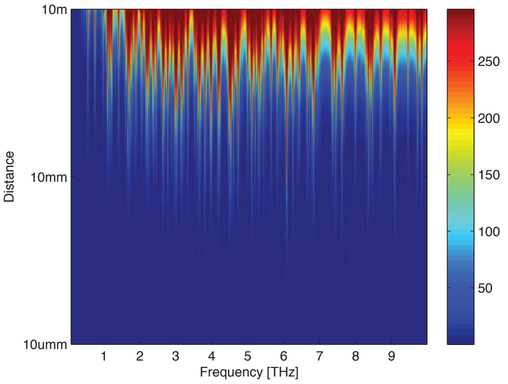

Fig. 4. Electromagnetic noise temperature in Kelvin as a function of frequency and distance in a standard medium with 1% of water vapor molecules.

path. Different types of molecules have different resonant frequencies and, in addition, the absorption at each resonance is not confided to a single center frequency, but spread over a range of frequencies. As a result, the terahertz channel is very frequency-selective. The details of the path-loss computation are given in [13].

In Fig. 3, the total path-loss for an electromagnetic wave in the terahertz band is shown as a function of both frequency (x-axis) and distance (y-axis), in standard room conditions (pressure 1 atm, temperature 296 K) with 1% of water molecules. This figure has been obtained using the propagation model for the nanoscale terahertz channel introduced in [13]. Due to the spreading loss, the total path-loss increases with both distance and frequency independently of the molecular composition of the channel, similarly to conventional communication models in the megahertz or few gigahertz frequency ranges. However, the presence of several molecules along the path, and specially water vapor, defines several peaks of attenuation for distances above a few tens of millimeters. The power and width of these picks is related to the number of absorbing molecules. Assuming that their concentration is homogeneous in space, this number increases proportionally with distance, but we can also think of non-uniform concentrations or even sudden bursts of molecules traversing the network.

B. Noise

The ambient noise in the terahertz channel is mainly contributed by the molecular noise. The absorption from molecules present in the medium does not only attenuate the transmitted signal, but it also introduces noise [12]. The equivalent noise temperature at the receiver will be determined by the number and the particular mixture of molecules found along the path. In addition, the molecular noise is neither gaussian nor white. Indeed, because of the different resonant frequencies of each type of molecules, the power spectral density of noise is not flat, but has several peaks. This type of noise will only appear when transmitting, i.e., there will be no noise unless the channel is being used.

In Fig. 4, the molecular noise temperature in Kelvin created by an electromagnetic wave in the terahertz band is shown as a function of both frequency (x-axis) and distance (y-axis), in standard room conditions (pressure 1 atm, temperature 296 K) with 1% of water molecules. This figure has been obtained using the propagation model for the nanoscale terahertz channel introduced in [13]. The molecular noise will only become significant for transmission distances above a few tens of millimeters.

C. Bandwidth and channel capacity

Molecular absorption will determine the usable bandwidth of the terahertz channel. Therefore, the available bandwidth will depend on the molecular composition of the channel and the transmission distance. Within a nanonetwork, it is unlikely to achieve single-hop transmission distances above a few tens of millimeters. Within this range, the available bandwidth is almost the entire band, ranging from a few hundreds of gigahertz to almost ten terahertz. As a result, the predicted channel capacity of wireless nanosensor networks in the terahertz band is promisingly very large, in the order of a few terabits per second [13].

D. Additional channel effects: multi-path propagation and nanoparticle scattering

In addition to very high path-loss and molecular noise, multi-path fading and nanoparticle scattering affect the signal propagation:

- *Multi-path fading*: depending on the scenario in which nanosensor devices will be deployed, multiple copies of the transmitted signal will reach the receiver. The combination of these copies will result in oscillations of the power detected in reception. The amplitude of each reflection will depend on the distance that it has traveled and the type of material, shape and roughness of the surface on which it has been reflected. For example, common materials found in an office, or even the human skin, have non negligible roughness that can damage the amplitude and phase of the reflected signal. Therefore, in order to properly account for these multiple reflections and develop new shadow fading models, it will be necessary to, first, characterize the reflection coefficients from common materials found in the envisaged scenarios and, second, use adequate models for scattering from rough surfaces. Some initial studies have been conducted in [18], [19], but a particularization for the nanoscale is missing.

- *Particle scattering*: molecules and other particles in the medium can create scattering effects on the transmitted signal. These effects can be considered almost negligible in some applications, but can drastically affect the communication performance between nanosensors in other situations. For example, the diameter of a water vapor molecule is around 0.28 nm, more than 5 orders of magnitude below the wavelength of a signal in the terahertz frequency range (between 30 and 3000 μm). The scattering by particles much smaller than the signal wavelength is known as Rayleigh scattering [12] and can be taken into account as an additional power loss. However, when thinking of a scenario containing synthesized nano-structures, magnetic nanoparticles or nanoshells, it will be necessary to understand, model and account for their scattering of the transmitted wave. These models do not exist to date.

E. Open Research Challenges

Several research challenges for nano-electromagnetic communication are summarized in what follows. First, new propagation models for the nanoscale terahertz channel need to be developed by incorporating both multi-path effects and nanoparticle scattering. In addition, the interaction of terahertz radiation with nanoscale biological entities needs to be studied. Our vision is that these models can benefit from current research on terahertz imaging techniques. Second, there is a need to develop new information encoding and modulation techniques able to efficiently exploit the properties of the terahertz channel. We believe that by the exchange of sub-picosecond long pulses, nano-devices will be able to achieve very high transmission rates while still keeping the complexity of the electromagnetic transceiver simple enough. Finally, networking protocols and architectures suitable for electromagnetic wireless nanonetworks are required by taking into account communication capabilities and energy limitations of nanoscale devices.

IV. CONCLUSIONS

Wireless nanocommunication networks will have a great impact in almost every field of our society ranging from healthcare to homeland security or environmental protection. In this paper we have looked at propagation models for nanocommunication networks and provided solutions for molecular communication as well as nano-electromagnetic communication in the nanoscale.

Molecular communication and nano-electromagnetic communication offer two different alternatives for the propagation of information in the nano-meter domain. We do not think that either the former or the latter will play a dominant role in future nanonetworks. On the contrary, we believe that those two alternatives will coexist and the choice whether to use molecular or nano-electromagnetic communication will depend on the specific nanoscale application domain.

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