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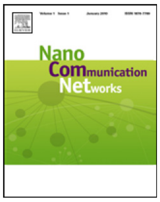

# Reception modeling of sphere-to-sphere molecular communication via diffusion

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ABSTRACT

As a widely accepted information transfer method in the nanonetworking domain, molecular communication via diffusion (MCvD) presents many advantages as well as challenges. In order to assess the capabilities and restrictions of MCvD, a thorough understanding of the reception process through the first passage time distribution holds utmost importance. As the network setup becomes more realistic, analytical derivations become increasingly difficult. Using statistical methods on empirical data is a remedy to this challenge. In this paper, we propose two novel heavy-tail distributions, which are well-equipped to model the first passage time distribution for a reflective sphere transmitter and a fully absorbing sphere receiver pair. We present their modeling power using the Kolmogorov–Smirnov goodness of fit test and how the modeling performance behaves under diverse deployment parameters. We also discuss the probability of molecule absorption, signal-to-interference ratio, and the advantages of using a reflective sphere transmitter.

## 1. Introduction

Nanotechnology, as a key technology with a variety of current and potential future applications, deals with matter in the atomic and the molecular scale [1]. Nanomachines are used to describe devices ranging in size from 0.1 to 10 μm and constructed of nano or molecular scale components [2]. Apart from the man-made nanomachines, bioengineered cells that are programmed for a specific task and have basic signaling capabilities [3] are also regarded as nanomachines from this study's point of view.

Operating at the nano-scale is expected to require high cooperation among multiple devices to make an impact on the macro scale. Clusters composed of such machines or cells cooperating with each other enable the realization of complex applications such as health monitoring, tissue engineering, biomedicine, nanomedicine, and environment monitoring [4,5]. Therefore, communication between these nodes is of high importance and the communication in that scale has different characteristics. Nanonetworking is a rapidly growing area of research due to the high level of collaboration needed by these devices. Specifically, it deals with the communication between nano and/or micro scale machines that has at least one component in the nano scale (up to 100 nm according to the definition of IEEE P1906.1 [6]), and controlled or engineered by humans.

Having ties to nanotechnology, biotechnology, and communication technology, molecular communication is an ever-growing interdisciplinary research area in the nanonetworking domain [4]. Molecular communication via diffusion (MCvD) focuses on micro- and nanomachines communicating through molecules emitted into a viscous communication medium. The infrastructureless nature and the propagation of molecules by free diffusion makes MCvD a very effective and energy efficient method of communication. The emitted molecules, called messenger molecules (MM), are the main instrument of information transmission through the environment. After emission, the MMs roam the communication medium according to the laws of free diffusion and the physical characteristics of the channel. Some of the MMs hit the receiver and the properties (type, amount, concentration, etc.) of the received molecules define the received signal.

From the communications perspective, one of the most critical components of assessing the capabilities and restrictions of MCvD is understanding the reception process. Many works in the literature define the reception process as the absorption and removal of the MMs from the communication environment [7–11]. In this case, MMs can only contribute to the received signal once. The duration from which an MM is released into the environment up to its removal from the environment upon contact with the receiver is called the first passage time. In the literature, examination of the

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reception process considering the first passage starts with the 1-D case [7,8]. In [9], the first passage time is investigated in a 1-D environment with drift. In both [7] and [9], the first passage time in the 1-D medium with drift is shown to follow an inverse Gaussian distribution. Using the inverse Gaussian and Lévy distributions for the first passage time is also a common practice in studying the capacity of molecular timing channels [12,13].

The first passage process in 3-D is more complex than the 1-D case; thus, studying it in a tractable manner requires making several assumptions on transmitter or channel properties. Two common assumptions are considering point transmitters and spherical receivers. In [10], the authors derive the expected number of absorbed MMs in an interval for the point transmitter and fully absorbing spherical receiver case. Another work under the same geometrical assumptions considers the case where the receiver surface has receptors [14]. The cases where the MMs degrade or the communication medium contains enzymes that neutralize the MMs are also investigated [15–17].

It is also possible to consider passive receivers in 3-D where the MMs diffuse freely in and out of the receiver body, thus contributing to the received signal more than once. The point transmitter and passive spherical setting is investigated in [18] both with and without the drift component. Additionally, the same environment with enzymes is also investigated [19].

In this paper, we consider a reflecting spherical transmitter and fully absorbing spherical receiver. This setting is more realistic than the point transmitter case in terms of molecular communication since the MMs will not appear out of a singularity in the communication medium, but rather be emitted from a transmitting body that is capable of MM production. Furthermore, using a reflective transmitter has an advantage of providing directivity gain [20]. Recent studies about the first passage time in the literature have been carried out under the spherical transmitter assumption [20–24]. In [24], a very simplistic method is proposed to model the reception process for the reflective spherical transmitter case using machine learning. Reflecting spherical transmitters are considered together with inter-symbol interference issues in [21,22]. An analytical study for the first passage time is carried out in [23] for a passive spherical transmitter (i.e. the MMs diffuse freely in and out of the transmitter).

As of yet, no analytical solution exists for the first passage time distribution in sphere-to-sphere MCvD for a reflective transmitter and an absorbing receiver. The methodology presented in [10] for the point transmitter and absorbing spherical receiver is not generalizable to the sphere-to-sphere setting. This is due to the fact that the authors in [10] use the radial symmetry about the receiver body in their derivations, which cannot be adapted to our setting due to the lack of symmetry originating from the reflective transmitter.

In this paper, we aim to overcome the difficulty of the analytical derivation approach by modeling the first passage time distribution using a statistical approach. The contributions of this paper can be summarized as follows:

- We investigate suitable parametric distribution alternatives to represent the first passage time distribution for sphere-to-sphere MCvD.
- We derive and introduce two new heavy-tail distributions, namely generalized beta-generated inverse of generalized gamma (GBIGG) and Kummer beta-generated inverse of generalized gamma (KBIGG), to the communications domain.
- The distributions that we introduce serve as efficient tools for analyzing the first passage time probability in sphere-to-sphere MCvD. Once the parameters have been evaluated for the given environment, the first passage time probability can be represented with a few parameters, instead of storing empirical first passage time distributions or running simulations again.
- Using classical error metrics, we test the modeling performance of these distributions under diverse and challenging scenarios by comparing them against empirical densities obtained from extensive simulations.
- In addition, we rigorously test and affirm the modeling success of our proposed distributions using the powerful Kolmogorov–Smirnov goodness of fit test.
- The approach that we describe in this paper enables us to investigate the probability of absorption and signal-to-interference ratio, both of which could not be calculated using simulations otherwise.
- We emphasize the advantages of using a reflective sphere transmitter over the point transmitter.
- The distributions that we propose in this work make it easier to conduct further research such as inter-symbol interference, modulation, and channel capacity for sphere-to-sphere MCvD.

The remainder of this paper is organized as follows: In Section 2, we present the sphere-to-sphere MCvD system model, and explain our motivation for choosing to work with a reflective sphere transmitter. In Section 3, we present the candidate distributions for modeling the first passage time distribution of sphere-to-sphere MCvD, along with two novel heavy-tail distributions. We present and validate the modeling performance of the candidate distributions in Section 4, followed by a preliminary network performance analysis. We conclude with a summary of key observations and future directions in Section 5.

## 2. Sphere-to-sphere molecular communication via diffusion system model

We model a communication system composed of a fluid environment and a pair of devices, each called Nanonetworking-enabled Node (NeN); one as the transmitter and the other as the receiver. The NeNs are inspired by the cells in the sense that they are able to produce energy by converting raw materials in their surroundings. In this work, we assume that the NeNs have the basic functionalities necessary for communication and are able to use part of the produced energy for communication purposes.

In MCvD, the information transfer is achieved between the transmitter and the receiver via the diffusion-based propagation of specific MMs [25]. The MMs can be chosen as a specific type of protein, peptide, DNA sequence, or other molecular structure.

The MCvD system is composed of five main processes: encoding, emission, propagation, reception, and decoding. As we show in Fig. 1, emission, propagation, and the reception processes are in the focus of this paper.

Both the transmitter and the receiver are assumed to have spherical bodies, with radii denoted as $r_{tx}$ and $r_{rx}$, respectively. In our work, we consider a reflective transmitter which upon emission of MMs, does not absorb them back. The MMs are emitted from the region closest to the receiver. In contrast, the receiver is capable of absorbing MMs such that whenever an MM contacts the body of the receiver, the molecule is received by being absorbed from the environment. The transmitter and the receiver NeNs are deployed $d$ μm apart in a 3-D no-drift liquid medium that has viscosity and temperature similar to blood.

### 2.1. Messenger molecule propagation via Brownian motion

Propagation process consists of the free diffusion of MMs in the molecular scale when the environment does not have any drift. In

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