nanoNS3: Simulating Bacterial Molecular Communication Based Nanonetworks in Network Simulator 3 *

Yubing Jian [a], Bhuvana Krishnaswamy [a], Caitlin M. Austin [b]
A. Ozan Bicen [a], Jorge E. Perdomo [b], Sagar C. Patel [b]
Ian F. Akyildiz [a], Craig R. Forest [b] and Raghupathy Sivakumar [a]
[a] School of Electrical and Computer Engineering
[b] George W. Woodruff School of Mechanical Engineering
Georgia Institute of Technology, Atlanta, GA, USA

ABSTRACT

We present *nanoNS3*, a network simulator for modeling Bacterial Molecular Communication (BMC) networks. *nanoNS3* is built atop the Network Simulator 3 (ns-3). *nanoNS3* is designed to achieve the following goals: 1) accurately and realistically model real world BMC, 2) maintain high computational efficiency, 3) allow newly designed protocols to be implemented easily. *nanoNS3* incorporates the channel, physical (PHY) and medium access control (MAC) layers of the network stack. The simulator has models that accurately represents receiver response, microfluidic channel loss, modulation, and amplitude addressing designed specifically for BMC networks. We outline the design and architecture of *nanoNS3*, and then validate the aforementioned features through simulation and experimental results.

Keywords

BMC Simulator, ns-3, Diffusion-based Molecular Communication, Experimental-based Simulator

1. INTRODUCTION

Molecular communication is an emerging field of communication between nodes using chemical molecules. It is a multidisciplinary field with concepts from biology, chemistry, information theory and communication used in tandem to develop molecular communication systems. The communication between nodes can in turn trigger the development of sophisticated practical applications that require cooperation. The medium for the molecular communication and hence the transceivers differ based on the applications, environment, signals to be sensed, etc. In recent years, bacteria have emerged as a promising candidate for molecular communication nodes or transceivers for biological applications. Engineered bacteria is used in toxicology to detect metals [1] and arsenic pollution [2]. In this work, we focus on molecular communication with bacteria as transmitter and receiver nodes.

There exist many works focusing on the theoretical analysis of BMC. [3] analyzes theoretical limits of information rate and [4–6] propose mathematical models for the channel and transceiver of BMC. Protocols and algorithms that are designed to improve the throughput performance of BMC have been studied in [7, 8]. BMC is a super-slow communication mechanism [8] as it takes 10x to 100x of minutes per signal for the receiver response. Thus, using experimental analysis to validate the performance of each state-of-the-art algorithm is extremely time consuming. Also, exactly replicating the experimental setup for different algorithms is difficult. Thus, building a computer-based BMC simulator to analyze the performance of different BMC algorithms is an important problem. In this work, we focus on building a network simulator atop ns-3, so that different algorithms can be implemented in the simulator and the performance of those algorithms can be analyzed and compared with each other. The easy-to-use layered approach of ns-3 has resulted in it becoming one of the most popular network simulators.

There have been other attempts to build molecular communication simulators [9–14]. Accurate modeling of receiver response is a key factor in the simulator. Existing simulators use a simplified approximation of receiver response thus affecting the accuracy of the simulation. A detailed analysis of related work is presented in Section 2. The major contributions of this work are thus the following: 1) An accurate bacterial receiver response module is built in *nanoNS3*. The bacterial receiver response model is validated using experimental results. 2) A microfluidic channel loss model is implemented in *nanoNS3* with user-defined geometries and properties. 3) A bit level communication with On-Off keying modulation scheme is implemented in *nanoNS3*. 4) In *nanoNS3*, new attributes are added to a new node class in ns-3 to define a bacterial transmitter, a bacterial receiver and channel parameters. 5) An amplitude addressing mechanism is built in *nanoNS3*. Based on the current features in *nanoNS3*, it is easy to extend the functionality of *nanoNS3* to incorporate other related BMC research. The current version of *nanoNS3* is available to be downloaded at: http://www2.ece.gatech.edu/research/GNAN/ns-allinone-3.24.zip.

The rest of the paper is organized as follows. In Section 2, we discuss challenges in building a network simulator for

*This work was supported in part by the National Science Foundation under grant CNS-1110947.

NANOCOM'16, September 28-30, 2016, New York, NY, USA

DOI: http://dx.doi.org/10.1145/2967446.2967464

BMC networks and review existing molecular communication simulators. In Section 3, we describe the architecture of *nanoNS3* and in Section 4, we explain briefly the protocols implemented in *nanoNS3*. Finally, in Section 5, we present performance results for *nanoNS3*, and in Section 6 we present some conclusions.

2. BACKGROUND AND RELATED WORK

Experimental analysis and verification of BMC networks are time-consuming [8]. Receiver response to an input chemical signal takes few hundred minutes, and hence experimental verification of different algorithms is extremely time inefficient. Also, since the receiver nodes are live bacteria, it is difficult to replicate parameters across different experiments. Due to the complexity of the experimental setup and the time involved, it is difficult to vary different parameters like channel characteristics or characteristics of the transmitted signal. A computer-based BMC simulator is thus necessary to analyze the performance of new or state-of-the-art algorithms developed for BMC networks. The objective of *nanoNS3* is thus to simulate BMC networks with genetically engineered bacterial transceivers in a microfluidic environment. Based on the extensible property of *nanoNS3*, customized BMC related features can also be implemented in *nanoNS3*.

Implementing a molecular communication simulator with bacteria as transceivers has the following challenges. 1) The response of a bacterial receiver to chemical molecules involves multiple processes [6] and is non-linear. Accurate modeling of the receiver response is important to simulate a molecular communication network with bacterial transceivers. 2) Due to the dynamic nature of the system, algorithms developed for BMC networks differ from traditional communication algorithms significantly. Implementing state-of-the-art protocols is important and is not a trivial extension of the traditional communication modules. 3) The simulator should have high computational efficiency in simulating large BMC networks and long packet sizes.

In this context, we have developed *nanoNS3* that addresses the challenges identified in building a BMC network simulator. *nanoNS3* is built on top of ns-3, which is a discrete event based simulator. A discrete event based simulator is best suited for simulating processes with long delays. BMC networks are super-slow networks with very long transmission delays. Thus, using ns-3 helps *nanoNS3* to be time efficient. ns-3 borrows concepts from [15] focusing on building a scalable network simulator, so ns-3 is also equipped with good scalability performance. Therefore, we choose to develop our BMC network simulator on top of ns-3 allowing us to address one of the challenges viz., simulation time efficiency and simulating large networks. Some of the advantages of using ns-3 are as follows: 1) good computational efficiency for large networks, and 2) open sourced availability and ease of extensibility that enable other users to implement state-of-art algorithms as needed. *nanoNS3* is developed and validated using experiments that rely on genetically engineered bacteria in microfluidic environments.

Some of the existing simulators focus on the physical transmission and reception of molecules by simulating individual molecules and tracking their propagation leading to time inefficient simulation. In contrast, *nanoNS3* simulates bit-level transmission and reception instead of molecular level transmission and reception. This leads to higher computational efficiency. *nanoNS3* is able to simulate how transmitted bits are modulated to pulses at transmitter side, and how the concentration of molecules is propagated and attenuated through a microfluidic channel. At receiver side, the biological response of how N-Acyl homoserine lactone (AHL) diffuses through the biofilm material and subsequently across the bacteria membrane is simulated. Then, the receiver can identify the ID of the transmitter based on the received concentration. Afterwards, the receiver can demodulate the received concentration to recover the transmitted information.

There are several existing works focused on simulating Molecular Communication (MC) [9–13]. These approaches validate their respective simulators using numerical analysis or purely simplified theoretical models. Thus, the simulators are not verified against real-life behaviors. NanoNS is built on top of Network Simulator 2 (ns-2), and it provides various nanoscale communication paradigms based on a diffusive MC channel [9]. This work only presents the details of the channel layer, and it simulates the diffusion and reception process using a single equation, which may not be accurate in the practical situation. This work simulates MC using molecules based approach, which is time consuming as the molecule scales (for practical cases, the size of molecules is immense). Also, this work is based on ns-2 which is computationally inefficient with regards to memory usage and CPU utilization. Currently, ns-2 is not actively maintained, and the most recent version of ns-2 was released in 2011. In [10], N3Sim is developed based on the diffusion propagation channel to model MC networks. N3Sim is built on a customized simulator. Using customized simulator is likely to lose the advantages of dedicated network simulators like ns-3 (e.g. scalability and computational efficiency). Also, network layers higher than the PHY layer is absent in N3Sim. Nano-Sim developed in [11] is also built on top of ns-3, and it provides functions to model Electromagnetic (EM) wave based nanonetworks. Similar like our work, Nano-Sim utilizes the framework and advantages of ns-3 to build EM-based nano simulator. The transmission/reception scheme in Nano-Sim is orthogonal to the work in this paper. Thus, it is feasible to combine *nanoNS3* with Nano-Sim, since they are both implemented atop ns-3. Other than aforementioned MC simulators, [14] proposes a simulation framework that is adaptable to any kind of nano bearer and [14] is also validated using experimental analysis in [16], but it is developed using a customized simulator. Thus, it is likely to lose the advantages of dedicated network simulators. To the best of our knowledge, *nanoNS3* is the first BMC network simulator validated using experimental systems with both channel attenuation and modulation analysis.

3. NETWORK ARCHITECTURE

nanoNS3 is developed atop ns-3 [17]. ns-3 is a discrete event, open source and widely used network simulator for internet systems, targeted primarily for research and educational use (ns-3 is developed in C++ and python). ns-3 is developed based on modules, and each individual module represents a protocol (e.g. TCP), a technology (e.g. WiFi) or an attribute of networks (e.g. mobility). It enables easy and convenient upgrade of source code and triggers the ease of extensibility in ns-3 by this modular implementation method. ns-3 is actively maintained and it is free software and licensed under GNU GPLv2 license. ns-3 has the best overall performance compared with other popular network

simulators [18]. E.g. ns-3 has the least memory usage for large scale network simulations compared with ns-2, OMNeT++, JiST and SimPy. Implementing *nanoNS3* in ns-3 has the following major advantages: 1) open sourced availability and ease of implementation for new algorithms, 2) high computational efficiency for large scale networks, and 3) supporting tools from ns-3 can be utilized directly (e.g. ns-3 logging and tracing systems).

3.1 nanoNS3 Network Architecture

The high-level structure of *nanoNS3* is shown in Fig. 1. The name of seven important classes with the structure of the corresponding network layers are given in Fig. 1. The functionality of each class is discussed briefly below:

- *NanoNetDevice*: It is similar to the Network Interface Card (NIC), and it can support different nano communication technologies (e.g. diffusive or EM wave based nano communication schemes) and corresponding protocols (e.g. amplitude addressing).
- *NanoNode*: It can be regarded as the physical device, and different *NanoNetDevices* can be integrated with *NanoNode* to provide corresponding communication technologies and protocols to enable *NanoNode* to communicate with each other.
- *NanoMessage*: This class is used to set up user defined applications for nano communications by controlling application-related parameters, e.g., packet arriving interval and packet size.
- *NanoRouting*: This class manages message forwarding by each *NanoNode*.
- *NanoMAC*: This class manages channel access of different *NanoNodes*, and it also manages MAC layer addressing mechanism.
- *NanoPHY*: This class is used to simulate the process of transmitters and receivers to transmit and receive the nano signals. The corresponding functionality of this class includes modulation, demodulation and receiver response.
- *NanoChannel*: This class is used to set up channel conditions, and then the channel loss can be calculated to simulate how the transmitted signals are propagated and attenuated in the corresponding microfluidic channel.

The parameters for each aforementioned class can be customized by users. Protocols implemented in $NanoMAC$, $NanoPHY$, and $NanoChannel$ will be discussed in Section 4.

4. PROTOCOLS IMPLEMENTED

nanoNS3 implements some of the basic protocols to simulate BMC networks. The important **4** models implemented in *nanoNS3* are: 1) Receiver response model, 2) Channel loss model, 3) On-Off Keying model, and 4) Amplitude addressing model.

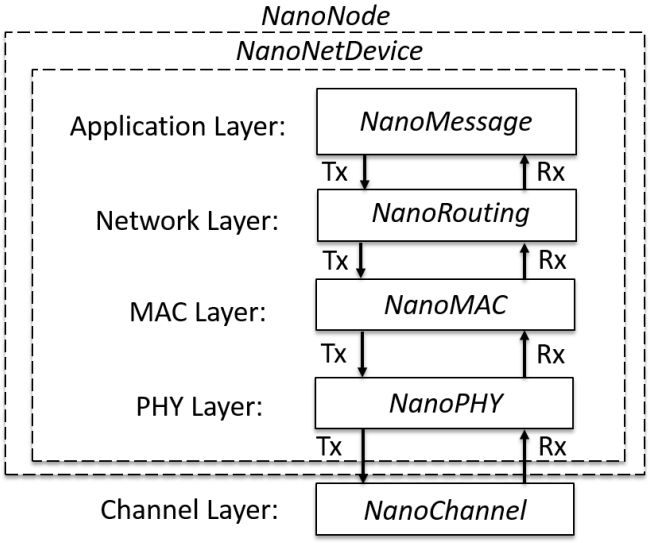


Figure 1: nanoNS3 Architecture

4.1 Receiver Response Model

As discussed in Section 2, accurate modeling of receiver response is important to simulate BMC networks. *nanoNS3* focuses on simulating BMC networks and hence modeling of response of bacteria to molecular signal is described in this section. The bacterial receiver implemented in this simulator is a population of genetically engineered *E. coli* bacteria that generates a Green Fluorescent Protein (GFP) on receiving AHL molecules. The transceivers are located in a microfluidic device connected by microfluidic pathways. The transmitter transmits molecules that are transported to the receiver through microfluidic pathways and the receiver emits green fluorescence. The relative fluorescence of the receiver bacteria indicates the signal received. [6] reviews the existing bacterial receiver models in a microfluidic environment and proposes a new model. [6] validates the model using experiments. In *nanoNS3*, we implement the following model proposed in [6].

$$\frac{dAHL_i}{dt} = k_c(AHL_e - AHL_i) - k_1 {AHL_i}^2 LuxR^2 + k_1 C_1 \quad (1)$$

$$\frac{dC_1}{dt} = k_1 {AHL_i}^2 LuxR^2 - k_1 C_1 - k_2 C_2 P_{Lux} \quad (2)$$

$$\frac{dC_2}{dt} = k_2 C_1 P_{Lux} - k_2 C_2 - k_{tr} C_2 \quad (3)$$

$$\frac{dLuxR}{dt} = k_{Lc} - 2C_1 - 2C_2 \quad (4)$$

$$\frac{dGFP_i}{dt} = k_{tr} C_2 - k_{Gm} GFP_i - k_{Gd} GFP_i \quad (5)$$

$$\frac{dGFP_m}{dt} = k_{Gm} G + i - k_{Gd} GFP_m \quad (6)$$

AHL_e and AHL_i are the external and internal concentrations of molecules at the receiver. $LuxR, C_1, C_2$, and GFP_i represent internal parameters of the receiver bacteria.

GFP_m represents the concentration of GFP which in turn represents the relative fluorescence at the receiver. Vector $k = [k_c, k_1, k_2, k_{Lc}, k_{tr}, k_{Gd}, k_{Gm}]$ represents rate constants of the processes in the receiver. The equations and corresponding derivation are explained in detail in [6].

The above equations are used to model the channel and receiver response in *nanoNS3*. The transmitter module generates bits and those bits are input to the modulator and channel model followed by these equations to simulate the GFP response of the receiver. A numerical inverse of these equations is used to sample and quantize the received signal which is then fed to the demodulator to process. This model gives a bit level response of the receiver.

4.2 Channel Loss Model

Microfluidic channel loss model is an important component for BMC simulators, which provides insights for how concentration signals are attenuated while propagating in mircrofluidic channel. [5] provides a comprehensive coverage of the microfluidic channels with fluid flow for diffusion-based Flow-induced Molecular Communication (FMC). In FMC, the fluid is flowing through a microfluidic channel and it serves as a communication channel to connect patches of molecular transmitter and receiver, such as bacterial habitat. In [5], an analytic study of the propagation of the molecules in the form of impulse response is performed incorporating the physical system parameters. The goal of the propagation loss model is to determine the channel loss effects caused on the molecular signal with respect to the distance, fluid flow parameters (pressure drop, flow velocity, microfluidic channel geometry and fluid type), and type of the molecule (diffusion constant). In [5], channel loss models for the basic microfluidic channel shapes (straight and turning) and cross-sections (rectangular, square, elliptical, circular) are developed incorporating the characteristics of the fluid flow and mass transport in the microfluidic channels. In *nanoNS3*, we implement the models presented in [5]. In the interest of brevity, we will illustrate rectangular cross-section microfluidic channel loss model in this section, and evaluate the specific microfluidic channel loss model in Section 5. The governing set of equations for the channel loss in a rectangular microfluidic channel are given as [5].

$$G_{rect} = \frac{h^3 w}{12\mu l} * (1 - 0.63\frac{h}{w}) \tag{7}$$

$$u_{rect} = G_{rect} * \triangle p \tag{8}$$

$$\tau_{rect} = l/u_{rect} \tag{9}$$

$$TF_{rect} = e^{-(k^2 D + jku_{rect}) * \tau_{rect}} \tag{10}$$

where G_{rect}, u_{rect} are the hydraulic conductance of the microfluidic channel and area-averaged flow rate, respectively. G_{rect} is a function of channel cross-section shape, dimensions, and viscosity of the fluid (μ). u_{rect} is a function of pressure drop ($\triangle$p) and G_{rect}. τ_{rect} and TF_{rect} are the delay and attenuation of channel, respectively. h and w represent the channel height and width. l and D are the length of the straight channel and Taylor dispersion-adjusted diffusion constant. The detailed explanations for all microfluidic channel loss models are given in [5].

4.3 On-Off Keying (OOK) Model

Modulation is the process of varying the properties of a signal to convey the *information*. Modulation determines the rate of transmission. ns-3 allows users to change modulation by changing the transmission rate. In *nanoNS3*, we implement bit level simulation and hence implement a module for modulation. OOK is one of the simplest modulation techniques and majority of works on BMC assume OOK as the modulation technique. OOK transmits a rectangular pulse of amplitude/concentration A for a duration of T_1 time units to send bit 1 and no signal for T_2 time units to send bit 0. OOK module in *nanoNS3* generates a rectangular pulse of a given amplitude and a given duration. Then, the generated rectangular pulse is fed to the channel model.

4.4 Amplitude Addressing Model

The models mentioned above (receiver response, channel loss and OOK) model the channel and physical layer of BMC networks. A MAC protocol is required in a network with multiple sources to achieve fairness and reduce collisions. MAC protocols used in wired or wireless networks as implemented in ns-3 increase the delay and decrease the throughput in a super-slow network like the BMC network. [7] considers a multiple sources and single receiver topology and proposes a MAC protocol to improve the BMC network throughput. Multiple sources transmitting to a single receiver is a typical sensing network scenario. [7] proposes a local addressing mechanism which implicitly performs MAC, and it is implemented in *nanoNS3*. [7] analyses the advantages and disadvantages of various addressing mechanisms and proposes *Amplitude Addressing* for BMC networks. *Amplitude Addressing* assigns distinct amplitudes to each user in a BMC network and each user uses the assigned amplitude with OOK to transmit information. The receiver receives the sum of the transmitted amplitudes which are then resolved to identify the individual amplitude thus solving addressing and MAC in the local network. A global address is required to map local address to the source. *nanoNS3* does not have a global addressing module, but MAC address of ns-3 nodes can be used as a global address module in simulations.

5. RESULTS

In this section, we present the evaluation results of *nanoNS3* using both simulation-based and experimental-based validation for the **4** models mentioned in Section 4. *nanoNS3* provides two examples of scenario setup: 1) single Tx and single Rx, and 2) multiple Txs and single Rx.

5.1 Methodology

In this section, we validate *nanoNS3* with protocols mentioned in Section 4. For the receiver response model, we validate the simulation results of *nanoNS3* with results from MATLAB analytic model used in [6] and experiments. For amplitude addressing model, we validate *nanoNS3* with python simulator used in [7]. For channel loss model, we validate *nanoNS3* with MATLAB analytical model used in [5]. Unless otherwise mentioned, the transceivers used are bacteria and the carrier signal is a molecular signal. To validate the performance of the aforementioned models in *nanoNS3*, the following scenarios are used:

- Single Tx and single Rx scenario: It is a single link

Table 1: Simulation Parameters for Receiver Response

Parameters	Default Settings
Tx sequence	1000100010
Modulation	OOK
Tx pulses amplitude	15 μM
Tx pulses width	50min
$threshld$	7.5μM
k_c	254/60
k_{Gm}	1.8/60
k_{Gd}	39/60
k_{tr}	1334/60
k_{Lc}	1200/60
k_1	20/60
k_2	200/60

scenario where one transmitter sends signals to one receiver. The default transmitted molecular concentration is set as 15 μM.

- Multiple Txs and single Rx scenario: Multiple transmitters send signals to a single receiver in this scenario. The amplitude assigned to each transmitter is based on the mechanisms shown in [7], and two examples will be given in Section 5.4.

5.2 Receiver Response

We implement the receiver response model derived in [6]. The set of differential equations presented in [6] defines the GFP response of the receiver bacteria to a given concentration of molecules. We built an *Inverse model* of the receiver response at the receiver to estimate the molecules received from the receiver GFP response.

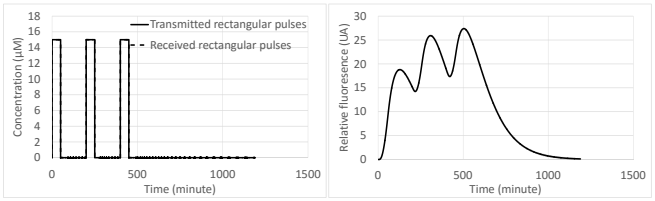
We validate *nanoNS3* receiver response in two steps. First, we verify the numerical inverse response using simulations. A transmitter sends information using OOK, i.e. rectangular pulses of a fixed amplitude and a fixed duration for bit 1 and no signal for bit 0. The rectangular pulses are input to *Forward response* generating receiver GFP response which is then fed to *Inverse response* derived numerically that estimates the signal transmitted based on the GFP response. Second, we compare the forward receiver response obtained from simulator with the response from experiments. We also input the receiver response from experiments to the *Inverse model* and compare the estimated signal with the actual transmitted signal.

5.2.1 Receiver response : simulation validation

In this section, we validate the inverse receiver response model using OOK. Fig. 2a and Fig. 2b present the transmitted and received rectangular pulses for the input bits and forward receiver response, respectively. The corresponding simulation parameters are shown in Table 1. As we can see from Fig. 2a, the transmitted rectangular pulses exactly match the received rectangular pulses. This result illustrates that the receiver can recover the transmitted pulses in *nanoNS3*. The corresponding forward receiver response for the transmitted rectangular pulses is given in Fig. 2b.

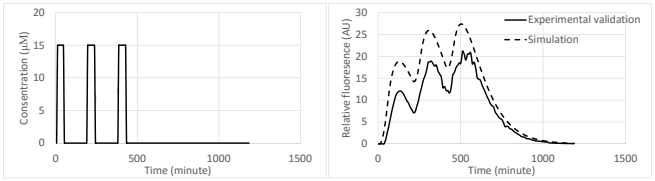
5.2.2 Receiver response : experimental validation

In this section, we validate the receiver response model using experimental results. Experimental setup used to obtain these results are the same as explained in [6]. We compare



(a) Tx/Rx pulses comparison (b) Forward receiver response

Figure 2: Simulation Validation



(a) Experimental Tx pulses (b) Forward receiver response

Figure 3: Experimental Validation

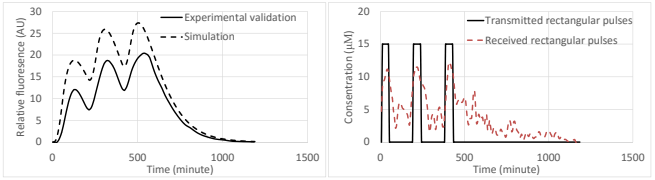
the receiver response obtained from experiments and simulations. We also verify the inverse of receiver response. The receiver response from experiments is input to the inverse model and we compare the estimated transmitted signal with the actual transmitted signal.

Forward receiver response validation

Fig. 3a presents the transmitted rectangular pulses. Fig. 3b shows the simulation results and experimental results of the forward receiver response. It can be observed that the simulation and experimental results have the similar trends (peaks of each pulse in experimental results can be exactly captured by simulation). Four different Tx sequences with 10 bits in each sequence are set as Tx sequence in the experimental apparatus, and each of them shows the similar trend as the presented results.

Inverse receiver response validation

Based on the experimental results of forward receiver response, we validated the inverse of the receiver response. From Fig. 3b, it is clear that experimental results of forward receiver response is not as smooth as the simulation results of forward receiver response. In order to get rid of noises and system errors, we use Loess smooth function (with 10% span) in MATLAB to smooth the experimental results. The corresponding experimental results are shown in Fig. 4a. Then, we input those smoothed experimental results to the inverse of receiver response model in *nanoNS3*, and we succeeded to recover the transmitted bits at the receiver side. From Fig. 4b, it can be observed that the peaks of transmitted and received pulses match with each other. In order to demodulate the received pulses, we calculate the average concentration for the pulse duration of each bit, where average concentration for bit i is represented as Ave_i. We set a threshold to determine the bit level, where $threshold$ is set as half of transmitted concentration. Received bit is determined by the following equation:



(a) Processed experimental results (b) Processed experimental results validation

Figure 4: Experimental Validation

Table 2: Simulation Parameters for Channel Loss

Parameters	Default Settings
Channel shape	rectangular
Turning angle	30 degree
viscosity	10^{-3}Pa*s
D	$10 * 10^{-10} m^2/s$
$\triangle p$	500 pa
l	10mm
h	$6\mu m$
w	$25\mu m$

$$\text{Received bit} = \begin{cases} 1 & \text{if } Ave_i >= threshold \\ 0 & \text{if } Ave_i < threshold \end{cases}$$

Utilizing this method, we can achieve **100%** of demodulation rate for the presented case of experimental results. The average demodulation rate of four sets of experimental results achieves **92.5%**.

To conclude, *nanoNS3* provides an experimental-based receiver response model:

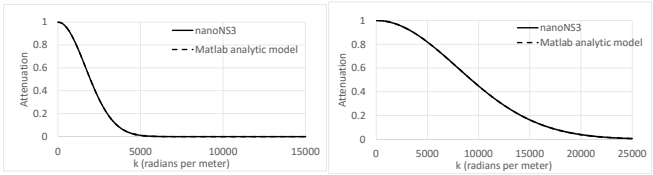
For the receiver response model, the simulation results of nanoNS3 *match the simulation results of MATLAB analytic model. The implemented model enables higher layer protocols in* nanoNS3 *to achieve high accuracy of their simulation performance.*

5.3 Channel Loss

In this section, we compare the channel loss model in single Tx and single Rx scenario. We compare the results obtained by *nanoNS3* with respect to the MATLAB using the described analytic channel loss model in Section 4.2. The objective is to show that the numerical results of *nanoNS3* match the numerical results from MATLAB for the analytic model channel loss model. The details of the default parameter settings are shown in Table 2.

Fig. 5a and 5b illustrate how the impulse response attenuation of straight and turning channel varies with frequency (radians per meter), respectively. We observe that the channel loss module implemented in *nanoNS3* provides the exactly same results with the analytic model evaluation in MATLAB for both Fig. 5a and 5b.

To conclude, *nanoNS3* provides a microfluidic channel loss model:



(a) Straight rectangular channel (b) Turning rectangular channel

Figure 5: Channel loss validation

Table 3: Simulation Parameters for Amplitude Addressing

Parameters	Default Settings
Number of Tx bits	100
Amplitude assignment mechanism	Integer/Binary
Tx pulses width	50mins
Tx pulses interval	20mins
p_t	0.5
Max amplitude	$15\mu M$
Number of Tx users	5

The simulation results of nanoNS3 *match the simulation results of MATLAB analytic model. More channel properties and other channel loss model can be easily implemented in* nanoNS3 *based on the implemented channel loss model.*

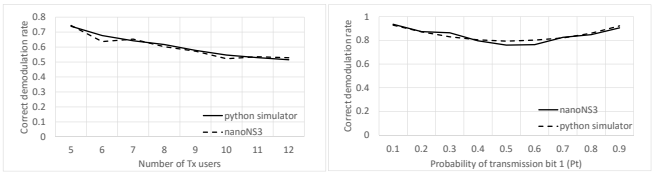
5.4 Amplitude Addressing

In this section, we validate the amplitude addressing mechanism in multiple Txs and single Rx scenario. We compare the performance of *nanoNS3* versus the custom built python simulator used in [7]. The objective is to show that the simulation results of *nanoNS3* match the simulation results from the aforementioned python simulator. The details of default parameter settings are shown in Table 3. Two examples of amplitude assignment mechanism will be briefly introduced. For integer amplitude assignment mechanism, each user is assigned with a unique amplitude based on the node ID. E.g. amplitudes {1,2,3} are assigned to transmitters with ID {1,2,3} with one-to-one correspondence. For binary amplitude assignment mechanism, amplitudes {1,2,4,8} are assigned to transmitters with ID {1,2,3,4} with one-to-one correspondence.

Fig. 6a plots the demodulation accuracy at the receiver for varying input load for integer amplitude assignment. As we can see from Fig. 6a, the performance of *nanoNS3* is very close to that of the custom built python simulator used in [7]. Fig. 6b plots the decoding accuracy at the receiver for varying input load using binary amplitude assignment. It can be observed that the simulation results of *nanoNS3* and the python simulator are very close to each other.

To conclude, *nanoNS3* provides an amplitude addressing mechanism:

The simulation results of nanoNS3 *match the simulation results of the python simulator. Based on the implemented addressing model, the performance of higher layer protocols can be explored (e.g. routing mechanisms).*



(a) Integer Tx sequence (b) Binary Tx sequence

Figure 6: Amplitude Addressing Validation

6. CONCLUSIONS

In this paper, we describe *nanoNS3*, a new network simulator built atop ns-3 for BMC networks. The choice of the ns-3 simulator allows high computational efficiency for large scale networks and easy implementation of new algorithms. An accurate model of the bacterial receiver response to chemical signals modulated using OOK is implemented. A microfluidic channel loss model that incorporates the physical system parameters is implemented in *nanoNS3*. A source addressing protocol that implicitly solves MAC issues is also implemented in *nanoNS3*. *nanoNS3* thus focuses on the channel, PHY and MAC layers of the network protocol stack. Due to the lack of upper layer protocols in BMC network, *nanoNS3* only provides an application layer model for upper layers. By making use of the layered architecture of ns-3, it is possible to use existing IP, transport and application layer protocols in ns-3 to test the performance of BMC networks. For future work, we plan to improve the completeness of *nanoNS3* by implementing new features such as channel capacity and transmission error analysis presented in [3]. Moreover, we will explore merging *nanoNS3* with other MC simulators that are also implemented atop ns-3, in order to move closer to the vision of a general purpose MC simulator.

7. REFERENCES

[1] T. Charrier, C. Chapeau, L. Bendria, P. Picart, P. Daniel, and G. Thouand, "A multi-channel bioluminescent bacterial biosensor for the on-line detection of metals and toxicity. part ii: technical development and proof of concept of the biosensor," *Analytical and Bioanalytical Chemistry*, vol. 400, no. 4, pp. 1061–1070, 2011.

[2] J. Stocker, D. Balluch, M. Gsell, H. Harms, J. Feliciano, S. Daunert, K. A. Malik, and J. R. van der Meer, "Development of a set of simple bacterial biosensors for quantitative and rapid measurements of arsenite and arsenate in potable water," *Environmental Science & Technology*, vol. 37, no. 20, pp. 4743–4750, 2003.

[3] A. Einolghozati, M. Sardari, and F. Fekri, "Design and analysis of wireless communication systems using diffusion-based molecular communication among bacteria," *IEEE Transactions on Wireless Communications*, vol. 12, no. 12, pp. 6096–6105, 2013.

[4] M. Pierobon and I. F. Akyildiz, "A statistical–physical model of interference in diffusion-based molecular nanonetworks," *IEEE Transactions on Communications*, vol. 62, no. 6, pp. 2085–2095, 2014.

[5] A. O. Bicen and I. F. Akyildiz, "System-theoretic analysis and least-squares design of microfluidic channels for flow-induced molecular communication," *IEEE Transactions on Signal Processing*, vol. 61, no. 20, pp. 5000–5013, 2013.

[6] C. M. Austin, W. Stoy, P. Su, M. C. Harber, J. P. Bardill, B. K. Hammer, and C. R. Forest, "Modeling and validation of autoinducer-mediated bacterial gene expression in microfluidic environments," *Biomicrofluidics*, vol. 8, no. 3, art. no. 034116, 2014.

[7] B. Krishnaswamy and R. Sivakumar, "Source addressing and medium access control in bacterial communication networks," *2nd ACM Annual International Conference on Nanoscale Computing and Communication*, pp. 1–6, 2015.

[8] B. Krishnaswamy, C. M. Austin, J. P. Bardill, D. Russakow, G. L. Holst, B. K. Hammer, C. R. Forest, and R. Sivakumar, "Time-elapse communication: Bacterial communication on a microfluidic chip," *IEEE Transactions on Communications*, vol. 61, no. 12, pp. 5139–5151, 2013.

[9] E. Gul, B. Atakan, and O. B. Akan, "Nanons: A nanoscale network simulator framework for molecular communications," *Nano Communication Networks*, vol. 1, no. 2, pp. 138–156, 2010.

[10] I. Llatser, D. Demiray, A. Cabellos-Aparicio, D. T. Altilar, and E. Alarcón, "N3sim: Simulation framework for diffusion-based molecular communication nanonetworks," *Simulation Modelling Practice and Theory*, vol. 42, pp. 210–222, 2014.

[11] G. Piro, L. A. Grieco, G. Boggia, and P. Camarda, "Nano-sim: simulating electromagnetic-based nanonetworks in the network simulator 3," *6th International ICST Conference on Simulation Tools and Techniques*, pp. 203–210, 2013.

[12] Calcomsim: https://sites.google.com/site/calcomsimulator/.

[13] Comsol-multiphysics: https://www.comsol.com/comsol-multiphysics.

[14] L. Felicetti, M. Femminella, and G. Reali, "A simulation tool for nanoscale biological networks," *Nano Communication Networks*, vol. 3, no. 1, pp. 2–18, 2012.

[15] R. M. Fujimoto, K. Perumalla, A. Park, H. Wu, M. H. Ammar, and G. F. Riley, "Large-scale network simulation: how big? how fast?" *11th IEEE/ACM International Symposium on Modeling, Analysis and Simulation of Computer Telecommunications Systems*, pp. 116–123, 2003.

[16] L. Felicetti, M. Femminella, G. Reali, P. Gresele, M. Malvestiti, and J. N. Daigle, "Modeling cd40-based molecular communications in blood vessels," *IEEE Transactions on Nanobioscience*, vol. 13, no. 3, pp. 230–243, 2014.

[17] Network simulator 3 : https://www.nsnam.org/.

[18] E. Weingartner, H. Vom Lehn, and K. Wehrle, "A performance comparison of recent network simulators," *IEEE International Conference on Communications*, pp. 1–5, 2009.