International Journal of Computer Information Systems and Industrial Management Applications
ISSN 2150-7988 Volume 18(1s) 2026 pp. 1-10
https://doi.org/10.70917/ijcisim-2026-2039
Article

Simulation Framework for MAC Protocol Validation in Molecular Sensor Networks Using STM32-Based Embedded Systems

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Abstract: In order to validate a Medium Access Control (MAC) protocol based on molecular communication that is implemented on an STM32 embedded platform, this paper presents a dual-environment Phase-1 simulation framework. The suggested approach combines MATLAB-based molecular channel modeling with Proteus-based embedded firmware validation. The framework enables pre-hardware verification of ADC-based molecular signal detection, pump-driven transmission logic, and throughput estimation under flow-assisted diffusion. Mathematical derivations for the molecular channel response and throughput optimization are provided. Simulation results establish theoretical throughput limits and validate MAC timing feasibility prior to experimental implementation.
Keywords: diffusion channel, mac protocol, molecular communication, nanosensor networks, throughput optimization

1. Introduction

Molecular communication (MC) is a bio-inspired communication paradigm in which information is transmitted through chemical molecules rather than electromagnetic waves. [1], [2]. Such systems are particularly relevant in biomedical sensing, targeted drug delivery, and nanoscale networking environments.[3], [4], [5]. However, designing efficient MAC protocols for molecular communication systems presents challenges due to diffusion delay, inter-symbol interference (ISI), and stochastic propagation [3], [4], [10]

This paper presents a Phase-1 simulation framework that validates both aspects prior to hardware realization.

2. Phase-1 Simulation Architecture

Prior to hardware realization, the proposed MAC protocols and STM32 control logic will be validated using software-based simulations. Proteus will be employed for embedded system and sensor interface simulation, while MATLAB will be used to model molecular channel behavior and throughput characteristics. This hybrid simulation approach minimizes hardware risk and ensures design correctness before experimental validation. The proposed simulation architecture consists of two parallel environments:

I. Proteus-based STM32 embedded simulation

II. MATLAB-based molecular channel modeling

A system-level overview is shown in Fig. 1.

The suggested molecular communication MAC protocol's Phase-1: Simulation and Model-Based Validation Workflow is depicted in the figure. It shows the validation of the molecular communication system through the use of molecular channel modeling, as well as STM32 logic simulation, before the final implementation. On the left, Proteus software is used for the development, compilation, and validation of the firmware logic used in the STM32,

including ADC logic, pump control, and symbol detection. This gives us simulated sensor outputs, mimicking the reception of molecular signals. On the right, MATLAB is used to validate the molecular communication channel, including the convection diffusion equations used in modeling the molecular communication channel, validating the throughput, impulse response, and ISI. MAC layer validation is done by combining the firmware logic and the channel modeling. Phase-1 validation results, including the modeled molecular signals, validated firmware logic, and the optimized throughput curve, are obtained without the cost and risks associated with the final implementation.

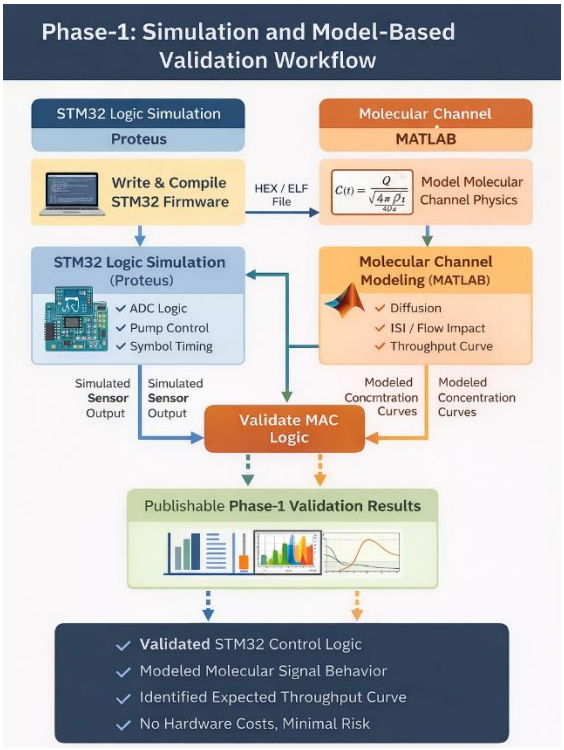

Fig. 1 : Phase-1: Simulation and Model-Based Validation Workflow

3. Proteus-Based Embedded Validation

The objective of Proteus simulation is to validate:

- STM32 firmware execution
- ADC-based molecular signal detection
- Pump control logic
- MAC timing behavior
- UART-based throughput logging

This stage emulates the molecular communication process at the signal level without physical chemical interaction.

3.1. System Architecture

The schematic is shown in Fig. 2. The simulated system consists of:

- STM32 microcontroller (STM32F103 equivalent model)
- Analog voltage source (molecular signal emulator)
- RC filter (signal conditioning)

- DC motor or LED (pump emulator)
- Virtual terminal (UART monitoring)

The analog source represents molecular concentration variation, while the GPIO-controlled motor represents molecular emission.

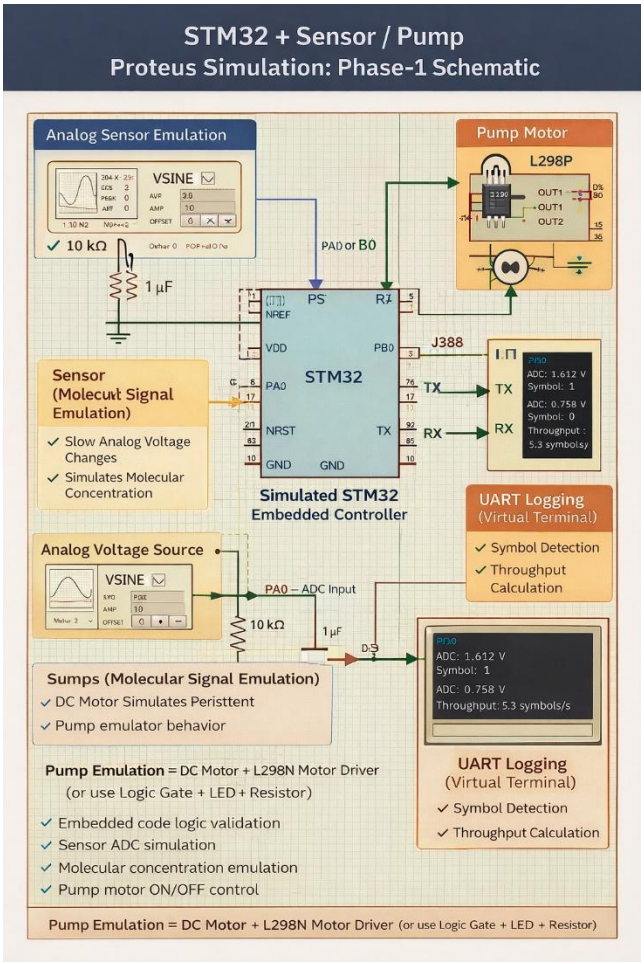

Fig. 2: STM32 + Sensor/Pump Proteus Simulation – Phase-1 Schematic

The figure below illustrates the Proteus simulation configuration for the Phase-1 scenario to validate the molecular communication MAC framework on the STM32 embedded platform. In this scenario, the simulated molecular communication system comprises the STM32 microcontroller as the main entity that interacts with the molecular signal emulator and the pump actuator model. On the left side of the figure above, the analog sensor emulation block generates a voltage signal that represents the molecular concentration. This signal is then sent to the RC conditioning circuit and the ADC input (PA0) of the STM32 microcontroller.The ADC receives the analog concentration signal and processes it into digital values for threshold-based symbol detection. The right side of the figure shows the pump motor module driven by the microcontroller via the L298N motor driver for simulating the molecular transmission process. The UART virtual terminal is used for real-time logging of the ADC values, symbol detection, and throughput calculation.

3.2 ADC-Based Molecular Signal Detection

In molecular communication testbed, a slow-varying analog voltage signal is produced by the sensor or its emulator in simulation, which represents the concentration of molecules detected over time. However, as a microcontroller like STM32 works with digital information, it is necessary that this analog voltage signal be converted into its digital form using its Analog-to-Digital Converter [14], [15].

The sensor emulator produces a slow-varying analog signal (V(t)) representing molecular concentration. The ADC samples:

$$ADC = \frac{Vref}{V(t)} \times (2^n - 1) \quad (1)$$

Where:

- $V(t)$= Instantaneous analog voltage from the sensor
- $Vref$ = 3.3V = Reference voltage of STM32
- n = 12 = ADC resolution (12-bit)
- $2^n - 1 = 4095$= Maximum ADC count value
- This means:
- If V(t)=0V→ ADC = 0
- If V(t)=3.3 → ADC = 4095

Intermediate voltages are linearly scaled between 0 and 4095.Thus, the ADC digitizes the molecular concentration signal into discrete levels given by equation 1.

Symbol detection is performed as:

$$S = \begin{cases} 1, & ADC > \gamma \\ 0, & ADC \leq \gamma \end{cases} \quad (2)$$

where γ is the detection threshold.

When molecules arrive at the receiver: Concentration increases , Sensor voltage $V(t)$rises and ADC value increases. If the ADC value exceeds the threshold γ, the system interprets it as a transmitted symbol "1". If it remains below the threshold, it is interpreted as "0" given by equation 2 .

- If $\gamma$is too low → Noise may be detected as signal (false positives)
- If $\gamma$is too high → Weak but valid signals may be missed (false negatives)

This mechanism of using the ADC can be seen as an essential interface between molecular physics and electronic devices, as it can be used to translate the concentration of biochemical molecules into an electrical signal. As the voltage output from the sensor can be seen as an analogy of the presence of molecules, this can be converted into a digital output through the ADC of the STM32, thus converting the chemical information into binary symbols, which can be used in the process of communication. It can thus be seen that the ADC and threshold logic can be used as the receiver layer of the proposed molecular MAC protocol.

3.3 Embedded Throughput Calculation

Throughput is defined as the ratio of detected symbols to the total time of transmission, given by equation 3. It is proven that there is an optimal range of pump speeds where the maximum throughput can be obtained. It can be calculated as:

$$Tembedded = \frac{Nsuccess}{Nelapsed} \quad (3)$$

This validates real-time feasibility of MAC-layer performance estimation.

3.4 Limitations of Proteus Simulation

- No physical diffusion modeling
- No sensor electrochemical dynamics
- No real fluidic delay

However, it effectively validates embedded logic correctness before hardware procurement.

4. Mathematical Modeling of the Molecular Channel

MATLAB simulation models the physical behavior of molecular propagation in a flow-assisted diffusion channel. This establishes theoretical throughput limits and informs MAC parameter selection. [3], [4], [10]

4.1 Diffusion Equation Derivation

Molecular propagation in a one-dimensional flow-assisted medium is governed by the convection-diffusion equation 4. [3], [4], [10]:

$$\partial C(x,t)/\partial t = D\,\partial^2 C(x,t)/\partial x^2 - v\,\partial C(x,t)/\partial x \quad (4)$$

The peak arrival time is approximately t_peak ≈ x/v under c

Where:

- D: diffusion coefficient
- V : flow velocity
- C(x,t): concentration

4.2 Impulse Response Solution

For impulse release (Q) at (x=0), the analytical solution is:

$$C(x,t) = \left(\frac{Q}{\sqrt{4\pi Dt}}\right) \exp\left(-\frac{(x-vt)^2}{4Dt}\right) \quad (5)$$

Where:

- D= diffusion coefficient
- v= flow velocity (pump-dependent)
- x= transmitter–receiver distance
- Q= molecules released

This equation describes the temporal evolution of concentration at the receiver. This represents the channel impulse response given by eqaution 5.[3], [4], [10].

4.3 Peak Arrival Time

Peak concentration occurs when:

$$\frac{dC}{dT} = 0 \quad (6)$$

Approximating dominant convection regime:

$$tpeak \approx \frac{x}{v} \quad (7)$$

The equations 6 and 7 directly links pump speed to symbol arrival time.

4.4 Inter-Symbol Interference (ISI)

Due to molecule persistence in the channel, consecutive symbol pulses overlap. MATLAB enables visualization of this inter-symbol interference (ISI), which directly impacts:

- Symbol duration selection
- Guard interval design
- MAC scheduling efficiency

For transmitted bit sequence (b_k), total concentration is given by equation 8:

$C_{total}(t) = \sum_{k=0}^{N} b_k \mathrm{C}(\mathrm{t} - \mathrm{k}T_s)$ (8)

Where: T_s: symbol duration

Overlapping tails produce ISI, limiting achievable throughput [3], [5], [13], [14].

5. Throughput Optimization Analysis

Theoretical throughput and capacity formulations for molecular communication systems are based on prior capacity analysis frameworks given by equation 9. [3], [7], [13]

5.1Theoretical Throughput

$T_{theoretical} = \frac{1}{T_s} \times (1 - P_e)$ (9)

Where: Ts = Symbol duration (seconds per symbol)

- $\frac{1}{T_s}$ = Maximum possible symbol transmission rate (symbols per second)
- P_e= Symbol error probability
- $(1-P_e)$= Probability of correct symbol detection.

5.2. Error Probability Approximation

Assuming Gaussian noise:

$Pe = Q\left(\frac{Cpeak-\gamma}{\sigma}\right)$ (10)

Incorporating detection probability, throughput becomes:

$T = \frac{1}{Ts} * \left(1 - Q\left(\frac{Cpeak-\gamma}{\sigma}\right)\right)$ (11)

Simulation results obtained by equation 11 indicate a bell-shaped throughput curve as flow velocity increases. Low flow results in diffusion dominance, while excessive flow leads to instability [14], [15]..

5.3 Flow Velocity Impact

- Low (v): Diffusion dominant → low Cpeak
- Moderate (v): Optimal laminar regime → maximum throughput
- High (v): Reduced detection stability

This produces a bell-shaped throughput curve (see Fig. 3).

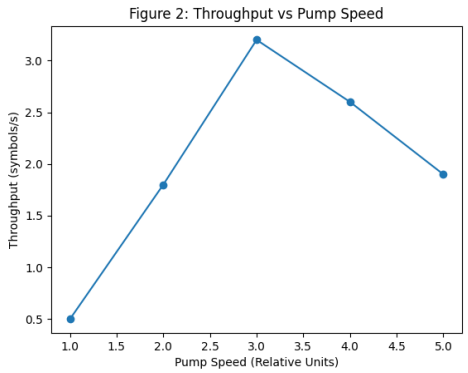

Fig. 3: Throughput vs Pump Speed (MATLAB Simulation)

When the speed of the pump is increased, the peak molecular concentration (Cpeak) at the receiver end will be higher because a larger number of molecules will be pumped at a higher speed. A higher (Cpeak) will provide a wider margin for detection above the threshold. Consequently, the probability of error (Pe) will be minimized. As the probability of error (Pe) decreases, the number of correct symbols received will be higher. Hence, the throughput will be higher. If the speed of the pump is made very high, turbulence in the channel will be produced. Consequently, the noise variance (sigma) will be higher, increasing the probability of error (Pe). As the probability of error (Pe) increases, the throughput will start to decrease. Hence, the shape of the throughput will be a bell shape. [10], [13].

6. MATLAB-Based Channel Simulation

MATLAB simulates the physical model of molecular propagation within the flow-assisted diffusion channel. This helps to set the theoretical limits for throughput and determine the parameters for the MAC protocol.

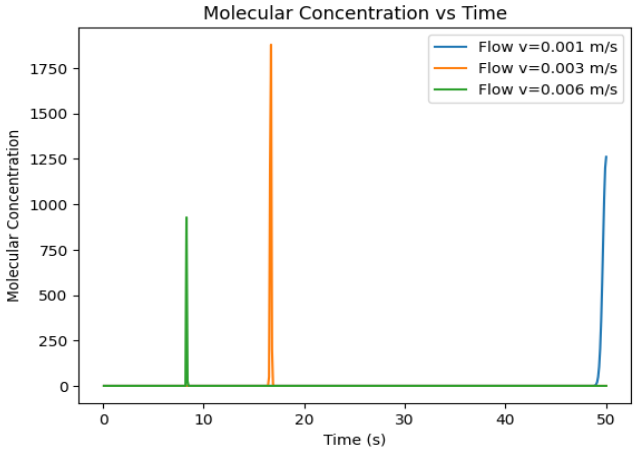

Fig. 4: Molecular Concentration vs Time at Different Flow Velocities

The molecular concentration over time graph shows the trade-off associated with diffusion and flow within molecular communication systems. At lower pump speeds, the system will be dominated by diffusion, causing the molecules to take a longer time to reach the detector and resulting in a spread-out concentration profile. At medium pump speeds, the effect of convection on the molecules will be evident, resulting in a sharp and well-defined concentration profile. This represents the ideal operating point for the system, where the signal will be strong and well-defined for better detection. At higher pump speeds, the molecules will be received at the detector before the slower-moving molecules, causing instability and noise within the signal.Plot concentration vs time. The concentration plot is shown in Fig. 4.

From the ISI analysis plot above, there is an overlap in the pulses that correspond to the transmission of successive symbols. The overlap represents the memory of the channel. The overlap of the pulses indicates that there will be detection errors in the communication process. The above graph highlights the significance of guard time in the design of the MAC protocol. From the pulses' separation in the above graph, the optimal guard time can be determined to reduce ISI.

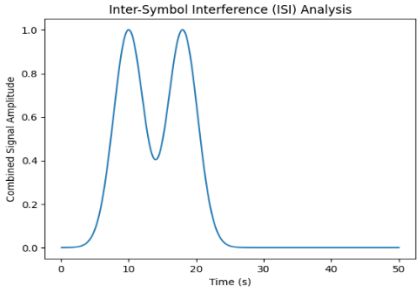

Fig. 5: ISI analysis

The graph showing throughput and symbol duration demonstrates the inverse proportion between the symbol time and the rate at which data is transmitted. The reduction in symbol duration improves the theoretical throughput but may increase the possibility of ISI and detection errors due to inadequate settling time. The increase in symbol duration minimizes errors but also limits the data rate. The curve can be used to find the optimum symbol duration. This discussion has a direct application in tuning the protocols in the MAC layer.

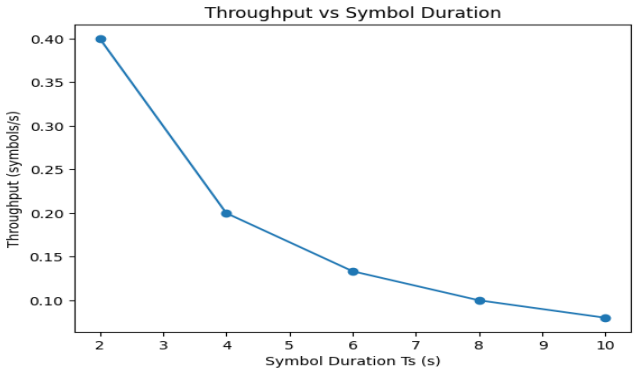

Fig. 6: Throughput versus symbol duration

The graph showing the accuracy of detection versus threshold clearly illustrates the influence that the selection of the receiver threshold has on the performance of the classifier in classifying the symbols. When the threshold is low, there is a possibility that noise will be detected as a signal, hence lowering the accuracy of detection. When the threshold is increased, the accuracy of detection improves until it reaches a point at which the separation between the signals and noise is optimal. When the threshold is too high, there is a possibility that legitimate signals will be missed, as illustrated in this graph.

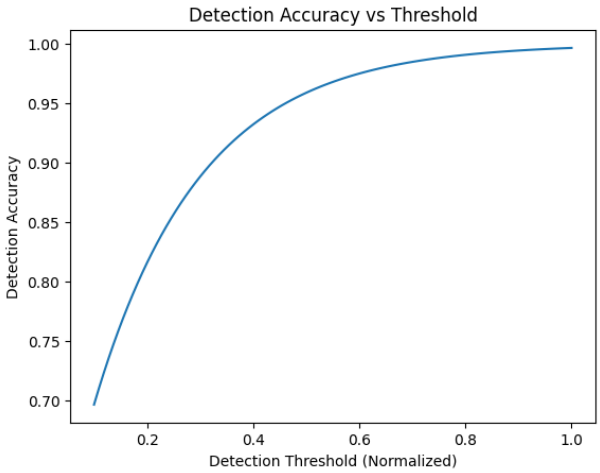

Fig. 7: Detection Accuracy versus Threshold

7. Result

The proposed Phase-1 Simulation Framework shows that:

1. MAC logic can be implemented on STM32 hardware.
2. Molecular propagation has physical throughput constraints.
3. Optimal pump speed exists for maximum efficiency.
4. Embedded throughput estimation is feasible.
5. Integrated Validation strategy

Table 1. Integrated Validation strategy

Proteus	**MATLAB**
Firmware validation	Channel physics
ADC threshold testing	Diffusion modeling
Pump timing control	Throughput optimization

This dual validation ensures:

- Correct embedded implementation
- Theoretically sound MAC design

This methodology significantly reduces hardware risk and strengthens experimental reliability.

8. Conclusion

A complete pre-hardware simulation framework for the validation of the MAC protocol in the context of the molecular sensor network has been proposed. The derivations of the convection-diffusion channel model have been incorporated with embedded-level validation, thus providing a strong basis for the development of the MAC protocol [1]–[7], [10], [13].

Conflicts of Interest

"The authors declare that there is no conflict of interest regarding the publication of this paper."

Funding Statement

Authors should state how the research and publication of their article was funded, by naming financially supporting bodies followed by any associated grant numbers in square brackets.

Acknowledgments

The authors would like to extend their heartfelt thanks to the department and the college for providing the necessary facilities that have enabled the completion of this research.

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