Preliminary Results on a Novel Testbed for the Experimental Validation of Redox-based Molecular-to-Electrical Communication

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***Abstract*—Real-time interaction between biological systems and electronic devices holds transformative potential for biomedical applications, such as continuous health monitoring and responsive therapeutic interventions. Molecular communication (MC) allows the transmission of information via biochemical signals, facilitating integration with electronic systems. A core method in MC is Molecular-to-Electrical (M2E) communication, where biosensors transform molecular interactions into electrical signals. Electrochemical redox-based sensing is notable for its precision and adaptability, making it ideal for diagnostic monitoring and biofeedback therapies. This paper introduces a novel experimental testbed to examine redox-based M2E communication, yielding preliminary experimental results. These results are compared with those from a simulation framework, refined to reflect the testbed's peculiarities. This comparison encourages ongoing experimental and simulation-based exploration of redox-based M2E communication systems, advancing its viability for biohybrid systems in applications like the Internet of Bio-Nano Things (IoBNT).**

***Index Terms*—Molecular Communication, Sensor, Redox, Testbed, Validation.**

I. Introduction

Real-time communication between biological entities and electronic systems represents a transformative advancement with significant implications for applications in biomedical sciences, healthcare, and bioengineering, such as the regulation of drug delivery in implants or the monitoring of physiological parameters in wearable sensors. Furthermore, the integration of biological signals with computational systems enable new diagnostic tools, adaptive treatment strategies, and advances in biohybrid systems for research and clinical use [1], [2].

Molecular communication (MC) is a cutting-edge paradigm that enables the transfer of information between biological entities through chemical signals, mimicking natural communication mechanisms found in living organisms [3]. It plays a pivotal role in achieving real-time communication between biology and electronics. For example, implantable drug delivery systems can use molecular signals to regulate drug dosages in response to the body's physiological conditions [4].

Molecular-to-Electrical (M2E) communication generally involves biosensors that utilize various methods, including optical [5], [6], piezoelectric, and electrochemical mechanisms, to detect and convert molecular data into electronic signals. Specifically, redox-based electrochemical biosensors sense electron transfers tied to specific biochemical interactions involving redox-active molecules. The presence of these molecules (e.g., ROS and antioxidants) facilitates electron transfers that alter oxidation states [7], vital for maintaining cellular homeostasis and metabolic balance [8]. This functionality is ideal for precise, dynamic communication in applications such as continuous health monitoring, diagnostics, and biofeedback-based therapies.

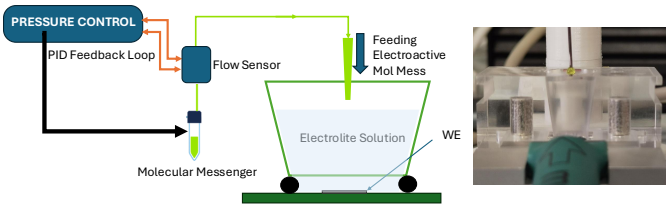

Fig. 1: Schematic of the proposed experimental testbed for redox-based molecular-to-electrical communication.

In this paper, we consider an electrochemical setup in which the solution, even if it is quiescent, presents a concentration gradient that induces a concentration-driven diffusion process over the standard electrochemical-driven diffusion process at the electrode observed in [9]. This allowed us to gain further insights into the communication channel and to further engineer it based on our simulation model. The rest of the paper is organized as follows. In Sec. II, we discuss the testbed developed for redox-based M2E communication. Sec. III includes preliminary validation of the testbed, comparison with the simulation model, and discussion. Finally, we conclude the paper in Sec. IV.

II. Testbed Design

The experimental setup was meticulously designed to accomplish the controlled release and detection of electrochemically active molecular messengers. A schematic representation of the setup is provided in Fig. 1, complemented by an actual photograph of the electrochemistry-based receiver. The system comprises a pressure-regulated delivery mechanism (from Elveflow, France), a monitoring and feedback control system, and an electrochemical detection unit.

The molecular messenger utilized in this study is an aqueous equimolar solution of potassium ferrocyanide ($K_4[Fe(CN)_6]$, 0.09 M) and potassium ferricyanide ($K_3[Fe(CN)_6]$, 0.09 M), forming a Fe(II)/Fe(III) redox system (form Merck, Milan). This solution is introduced dropwise into the communication channel filled with a supporting electrolyte of potassium nitrate (KNO_3, 1 M). The communication channel has a total volume

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of 1 mL and is contained within a truncated conical vessel. At the base of this vessel resides the receiver, which is a screen-printed electrode (from Micrux, Spain) comprising a circular carbon-based working electrode with a diameter of 3 mm (7.1 mm^2), an auxiliary electrode, and a silver pseudo-reference electrode. The detection of the molecular messenger is performed using a potentiostat (from Zhaner, Zennium pro, Germany) configured to execute Cyclic Voltammetry (CV) at a scan rate of 50 mV/s, with a potential range from -100 mV to +900 mV. Upon release, the droplet of the molecular messenger solution spreads instantaneously over the surface of the electrolyte solution due to its relative lower density and then diffuses across the channel toward the electrode's surface. Notably, the experimental setup operates without any forced agitation, ensuring that diffusion governs molecular transport.

III. Results and Discussion

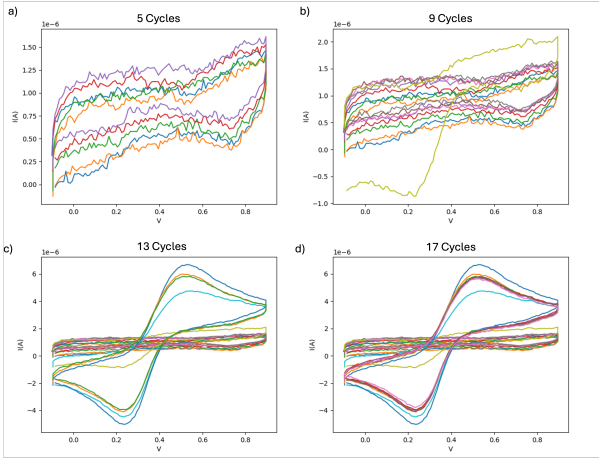

Fig. 2: CV curves recorded over time following the release of the molecular messenger droplet onto the communication channel surface. a) after 5 cycles, b) after 9 cycles, c) after 13 cycles, d) after 17 cycles

Figure 2 illustrates the trend of the CV curves acquired from the moment the droplet of molecular messenger solution is released onto the surface of the communication channel. Initially, the CV curves exhibit no significant electrochemical response, corresponding to the period during which the droplet begins to spread across the electrolyte solution and initiates the diffusion process toward the electrode.

After a few cycles ($\sim$9 cycles), the receiver detects a noticeable signal. As the diffusion process stabilizes (after $\sim$13 cycles), the CV curves attain a consistent and repeatable shape, characteristic of the expected electrochemical behavior of the Fe(II)/Fe(III) redox system, ensuring reliable and reproducible electrochemical detection. To further validate the experimental findings, we compared the CV curves obtained with the results from the simulation engine described in [9].

We believe that the differences in the two CV curves observed in Fig. 3 arise primarily for the following reasons: 1-D diffusion model which does not fully capture concentration-driven diffusion at the surface, exclusion of external electrochemical-based noises, and the estimated model parameter values. Our next steps include addressing the model

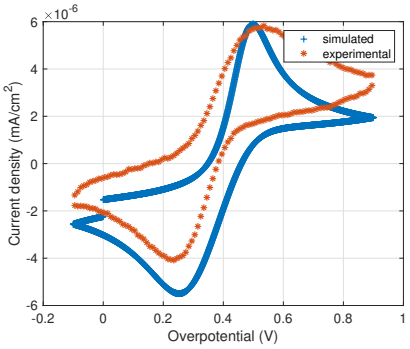

Fig. 3: Comparing the simulated and experimental CV curves

deficiencies as well as expanding the testbed capabilities in terms of efficiency and robustness. Future research will focus on improving system responsiveness, investigating alternative molecular messengers, and scaling the experimental setup to accommodate more complex communication scenarios.

IV. Conclusion

This experimental investigation successfully illustrates the practicality of utilizing electrochemically active molecular messengers for MC, a previously explored theoretical concept. The pioneering application of redox couples, in conjunction with an accurately controlled dropwise delivery mechanism and highly sensitive electrochemical detection, highlights the potential benefits of incorporating electrochemical processes into MC systems. The implementation of a multiple-droplet release strategy could further enhance communication capabilities, enabling complex transmission schemes within MC networks. Insights from this study establish a foundation for further exploration of electrochemical strategies in MC, offering promising prospects for advancing biomedical devices and nanoscale communication networks.

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