Institute for Digital Communications

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Bachelor Thesis

Experimental Investigation of Molecular Communication in Branched Pipe Systems

Molecular communications (MC) is a communications engineering paradigm where information is conveyed via molecules rather than electromagnetic wave (EM) signals. In the human body, *natural* MC enables essential biological processes like cellular signaling and neuronal communication. *Synthetic* MC builds on these natural mechanisms, using engineered MC systems to realize medical applications such as early cancer detection [1], targeted drug delivery [2], and health monitoring [3]. Many of these applications rely on the cardiovascular system (CVS) as primary communication pathway, where signaling molecules in the bloodstream either deliver therapeutic agents directly to diseased tissues, or report diagnostic information about disease presence and progression, enabling precise and responsive treatments.

Mathematical models characterizing molecule transport in fluid environments such as the CVS can guide the design of medical MC applications. Crucially, however, these models make simplifying assumptions about reality and thus require experimental validation to ensure their accuracy and reliability. This can be achieved using *MC testbeds* [4], which provide controlled environments that despite still being simplified, are designed such that they approximate natural conditions closely enough to yield meaningful experimental insights.

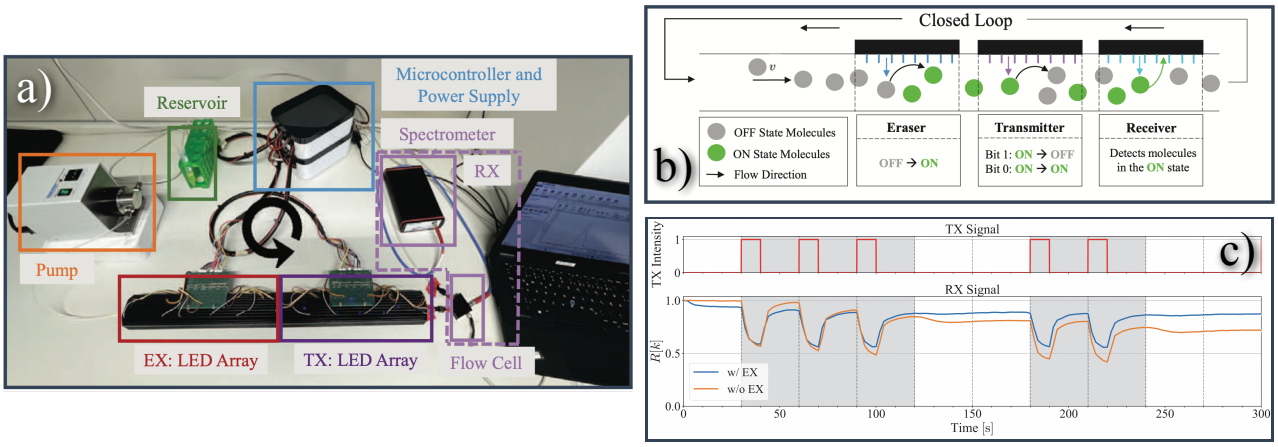

Figure 1: Testbed in [4]. a) Building blocks of the experimental closed-loop setup using GFPD as signaling molecule. The setup comprises a reservoir, a pump, connecting pipes, LED arrays for EX and TX, and the RX which consists of an LED connected to a fluorescence flow cell and a spectrometer. b) Schematic representation of the pipe containing GFPD dissolved in fluid. The GFPDs can be switched to the "ON" state and to the "OFF" state by the EX and TX, respectively, while the state of GFPD can be determined at the RX. c) Exemplary transmitted and received signal.

To this end, the closed-loop MC testbed in [4] was developed at FAU, see Fig. 1. It operates as a fluidic system, designed to simulate molecular signaling in the CVS. The testbed circulates a solution containing the photoswitchable green fluorescent protein Dreiklang (GFPD) through a system of pipes with a pump-driven flow and supports continuous information transfer by using light to switch GFPD molecules between fluorescent "ON" and non-fluorescent "OFF" states, see Fig. 1a). Binary information is encoded by modulating the fluorescence states at the transmitter (TX) via light and is decoded by detecting fluorescence changes at the receiver (RX). An additional component, the eraser (EX), can be used to reset molecules back to the "ON" state before the molecules get modulated by the TX again, hereby mitigating inter-symbol interference, see Fig. 1b). The closed-loop design supports long-duration experiments, allowing multiple passes of the signaling molecules through the testbed to simulate sustained molecular signaling in the CVS, see Fig. 1c).

While the testbed mirrors the CVS by operating in a closed-loop configuration and using biocompatible signaling molecules, its channel remains relatively simple, consisting of a single

straight pipe. In contrast, in the CVS, highly branched vessel structures are prevalent. Therefore, the next step in enhancing the testbed's design is to incorporate a branched pipe channel topology, study the effects of the branched channel on the received signal, and compare experimental results to theoretical model predictions. To effectively isolate the impact of the branched channel, as a first step, the EX will be activated to mitigate the effects of inter-loop molecule interference.

The main objectives of this thesis can be summarized as follows:

- Review literature on theoretical MC models for particle transport in branched channels and on branched MC testbeds.
- Get familiar with the working principle of the testbed in [4], including the experimental setup and its operation.
- Choose a branched channel topology inspired by the CVS and incorporate it into the existing testbed.
- Carry out message transmission experiments and measure the received signals. This should be repeated for multiple different branched channels to evaluate how various topologies affect the received signal.
- Compare measured received signals to predictions made by an existing theoretical model for molecule transport and reception in branched pipe channels.

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