Towards Salinity-Based Communication in Microfluidic Channels

Stefan Angerbauer[1], Medina Hamidović[1], Andreas Springer[1], and Werner Haselmayr[1]
[1]Institute for Communications Engineering and RF-Systems, Johannes Kepler University Linz

I. Introduction

Molecular communication (MC) is a novel paradigm in communication engineering, aiming to operate in environments, were classical electromagnetic-wave-based methods reach their limits [1]. Some examples of such environments are tunnels and pipes on the macro-scale or the human/animal body on the micro- and nano-scale. Within the last decade numerous theoretical papers on the subject have been published. For example, [2] theoretically investigates MC in microfluidic channels. In order to verify and refine those results, different experimental platforms have been proposed. These setups differ in their size, propagation environment, signaling molecules and detection principle. Several works have considered microfluidic chips as experimental platform, for example [3] employs microbeads as signaling molecules together with an optical receiver and [4] uses single-stranded DNA molecules and a graphene-based field effect transistor for the detection. Recently, a few works have considered salinity-based information transmission [5] [6] on a larger scale using conventional tubes. In this work, we combine both approaches and propose a salinity-based molecular communication on a microfluidic chip. Unlike [5] and [6], we use a cheap and flexible in-house developed sensor as detector rather than a commercial available conductivity sensor. This provides full control over the detection process and simplifies possible adjustments. Moreover, all aformentioned works only consider binary information encoding, while the proposed testbed is suitable for non-binary information encoding and, thus, enables high transmission rates. The used microfluidic chip is fabricated using a simple and fast prototyping method and, thus, arbitrary channel structures can be implemented. This paves the way for the study of the very little investigated topic on MC in branched channels.

II. Working principles of the experimental setup

In this section, we first introduce the theoretical principles of measuring the salinity (salt-concentration) of water and then discuss the realization of the components of the experimental setup (i.e., transmitter, channel, and receiver).

A. Salinity of Water

According to [7], the salinity S of water can be approximately obtained through its conductivity σ

$$\sigma \approx aS + b, \tag{1}$$

where a and b denote parameters, which depend on the temperature and pressure of the fluid. For the following derivations, we assume, they are constant.
For a microfluidic channel with two plain electrodes, with area A, that are inserted at a distance L, we can calculate the conductance of the electrical path between these electrodes as follows

$$G = \frac{A\sigma}{L}. \tag{2}$$

Thus, we can infer the salinity in the channel at the location of the electrodes by measuring the conductance between them.

B. Transmitter

To describe the information encoding principle at the transmitter employing the salinity of water, we apply the well known analogy between electrical and hydraulic circuits. We assume, that the influence of the salt concentration of water on its hydraulic properties is negligible (see [8], [9]), i.e., the hydraulic resistances do not depend on the salt concentration. The microfluidic chip and the corresponding schematic are shown on the left and right hand side of Fig. 1, respectively. Using this analogy we can calculate the volume flows Q_1 and Q_2, which depend on the pressures applied at the inlets. If we assume that Q_1 carries water without salt ($S_1 = 0$) and Q_2 water with non-zero salinity ($S_2 > 0$), we can use the principle of mass-conservation to calculate the concentration S_{el} carried by the volume flow $Q_3 = Q_1 + Q_2$ to the electrodes in the chip

$$S_{\text{el}} = \frac{S_2 Q_2}{Q_1 + Q_2}. \tag{3}$$

Note that (1) only holds for perfect mixing of water and saltwater. Thus a mixing-structure taken from [10] is added to the chip (see Fig. 1)

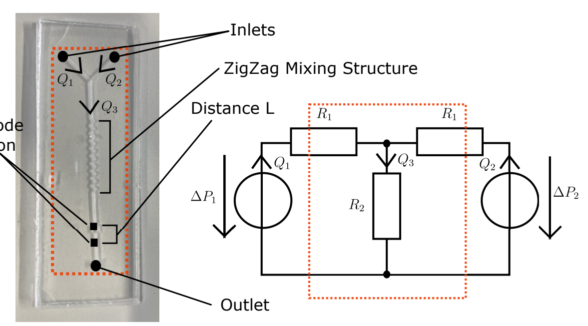

Fig. 1. Hydraulic analogy for the microfluidic chip used in this work. The resistances R_1 consist of the resistances of pumps and tubes (not shown in this figure) and the short parts of the Y-junction. The resistor R_2 is formed by the resistance of the output channels of the Y-junction with the mixing structure. The pressure differences are related to atmospheric pressure. The red dashed frame indicates the electric analogy of the shown microfluidic chip

Thus, by adjusting Q_1 and Q_2 through changing the applied input pressure differences, different symbols can be encoded in the salinity S_{el}.

C. Microfluidic Channel

In the this subsection, we calculate the time until a set salt concentration adjusted by Q_1 and Q_2 reaches the receiver. We assume that the volume flow Q_3 through the output channel of the Y-junction is held constant, i.e., the flow velocity v is constant. The assumption of constant velocity requires that the sum of the input pressures is constant. Moreover we assume, that the influence of diffusion is negligible (Peclet number $\mathrm{Pe} > 10^4$). Based on these assumptions we can derive the time t needed for the salt-concentration to flow from the Y-junction to the electrode as follows

$$t = \frac{d}{v} = \frac{d}{Q_3/(wh)} = \text{const}, \qquad (4)$$

where d denotes the distance between the Y-junction and the electrodes and w and h denote width and height of the microfluidic channel, respectively.

D. Receiver

At the receiver, the transmitted salt concentration is measured through the conductance between the electrodes. The block diagram of the used electrical circuit is shown in Fig. 2. The principle is as follows: The sinusoidal signal of the oscillator (at a sufficiently heigh frequency [11]) is fed into the amplifier circuit formed by the operational amplifier, the resistance R, and the device-under-test (DUT), i.e., conductance between the electrodes. Due to the fact that the information about the conductance is now encoded in the amplitude of the amplified sine-wave we can infer it by rectifying this signal. Finally, we converted the rectified signal to the digital domain using an analog-digital-converter (ADC), which makes it available for further processing on the RaspberryPi (RPI).

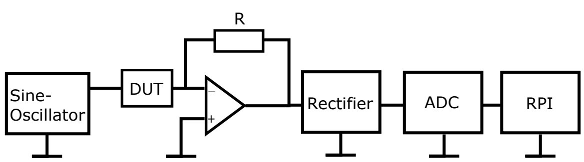

Fig. 2. Schematic diagram of the conductivity measurement circuit.

III. Experimental results

For the first experiments, we used the microfluidic chip shown in Fig. 1. The chip was fabricated using an in-house all Polydimetylsiloxan (PDMS)-based approach, which allows simple, fast, and cheap prototyping. All channels of the chip have a width of $750\,\mu\text{m}$ and a hight of $1000\,\mu\text{m}$. The first experimental results were obtained injecting different saltwater concentrations into one branch of the Y-junction and no fluid in the other. We used the following saltwater concentrations: $0\,\text{g/L}$, $2.5\,\text{g/L}$, $5\,\text{g/L}$, $7.5\,\text{g/L}$ and $10\,\text{g/L}$. Fig. 3 shows the output of the detection circuit when the saltwater concentrations given before are incremented and decremented. In particular, different syringes with different concentrations are used, which are changed manually. We observe, that the levels are well distinguishable and reproducable

Please note that the aprupt drop in output level results from air bubbles stemming from changing the syringe for different concentrations. However, in the future the syringes will be replaced by electronically controlled mirofluidic pumps, which will eliminate this problem. These initial results clearly indicated that the proposed experimental setup is very well suited for multi-level modulation schemes which will enable high transmission rates.

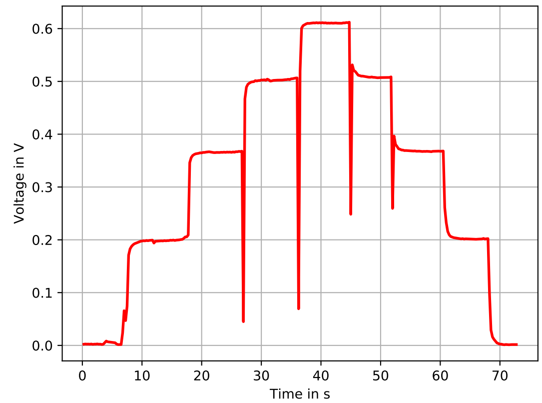

Fig. 3. Output of the conductance measurement circuit

IV. Conclusion and Outlook

In this paper, we reported on our current status in developing a microfluidic salinity-based communication testbed. Through initial experimental results we already demonstrated, that different concentration levels can be very well distinguished at the receiver. In a next step, we will include microfluidic pumps to automatically control the pressures, which will enable actual data transmission. Furthermore we will verify our theoretical results (e.g. (3)) and characterize the system (e.g., data rate limit, end-to-end communication model).

References

[1] N. Farsad, H. B. Yilmaz, A. Eckford, C. -B. Chae and W. Guo, "A Comprehensive Survey of Recent Advancements in Molecular Communication," in IEEE Communications Surveys and Tutorials, vol. 18, pp. 1887-1919, 2016.

[2] A. O. Bicen and I. F. Akyildiz, "Molecular transport in microfluidic channels for flow-induced molecular communication," in *Proc. IEEE Int. Conf. Communications* , pp. 766-770, 2013.

[3] M.G. Durmaz, *et al.*,, "Preliminary Studies on Flow Assisted Propagation of Fluorescent Microbeads in Microfluidic Channels for Molecular Communication", in *Proc. 12th EAI International Conference.* pp. 294-302, 2020.

[4] M. Kuscu, H. Ramezani, E. Dinc, *et al.*, "Fabrication and microfluidic analysis of graphene-based molecular communication receiver for Internet of Nano Things (IoNT)". Sci Rep 11, pp. 1-20, 2021

[5] A. Al-Helali, B. Liang and N. Nasser, "Novel molecular signaling method and system for molecular communication in human body," IEEE Access, vol. 8, pp. 119361-119375, 2020

[6] J. Wang, D. Hu, C. Shetty, and H. Hassanieh, "Understanding and embracing the complexities of the molecular communication channel in liquids",in *Proc. Int. Conf. Mobile Computing and Networking*, pp. 1-15, 2020

[7] S. Thirumalini and J. Kurian, "Correlation between Electrical Conductivity and Total Dissolved Solids in Natural Waters," Malaysian Journal of Science, vol. 28, pp. 55-61, 2009.

[8] M. H. Sharqawy, J. H. Lienhard and S. M. Zubair. "The thermophysical properties of seawater: A review of existing correlations and data", Desalination and Water Treatment, pp. 354–380, 2010

[9] P. Stephan, *et al.*, eds. VDI-Wärmeatlas: Fachlicher Träger VDI-Gesellschaft Verfahrenstechnik und Chemieingenieurwesen Berlin, DE, Springer-Verlag, 2019.

[10] V. Mengeaud, J. Josserand and H. Girault, "Mixing processes in a zigzag microchannel: finite element simulations and optical study", Anal Chem., pp. 4279-4286, 2002.

[11] D. Pletcher, R. Greff, R. Peat, L.M. Peter and J. Robinson, *Instrumental Methods in Electrochemistry*, Cambridge, MA, USA: Elsevier, 2001.