Channel Attenuation in Droplet-based Microfluidic Networks: First Experimental Studies

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I. Introduction

Droplet-based microfluidics is a subset of microfluidic technology that involve the manipulation and analysis of small volumes of liquid. These droplets are formed and transported through microfabricated channels and can be used for a variety of applications, such as chemical synthesis, cell culture, and genetic analysis. Over the years, droplet-based microfluidics has been realized through devices known as Lab-on-a-Chip (LoC) and have found applications inhav a wide range of fields including chemical synthesis, biology, and drug discovery.

In order to realize programmable and flexible LoC devices, a novel communication paradigm called microfluidic networks (MN) for droplet-based microfluidics has been introduced [1]. The paradigm of MN is based on classical communication concepts that are extended to the microfluidic domain. In such context, the definition of microfluidic switching (μfSwitching) which enables dynamical assigning of the droplets' path is introduced as the core of MN.

The concept of μfSwitching is accomplished by utilizing two types of droplets, specifically a so-called *header* droplet in front of the droplet containing the biochemical samples, so-called *payload* droplet. Header droplets are only used for signaling and contain no sample. The target location of the payload droplet is encoded in the distance between the payload and header droplet, and this concept is known as droplet by distance (DbD) switching [1]. For error-free DbD switching it is therefore crucial to maintain a stable inter-droplet distance, since payload and header droplets probably travel through multiple microfluidic channels until they reach μfSwitch.

Previous works provide rather limited investigation of the effects of a microfluidic channel on the distance between the payload and header droplet. The limitations primarily came from the fact that in order to investigate the distance between only two droplets, sophisticated droplet generators, so-called Droplet-on-Demand (DoD) had to be realized. Due to the complex realizations of such generators most investigations were carried out on trains (sequences) of droplets, rather than on controlled groups of droplets. However, the channel attenuation effects significantly vary with the number of droplets in the channel. Thus, in order to create more precise channel models, investigations using DoD have to be carried out. Furthermore, longer microfluidic channels (few centimetres) should be considered to allow for investigations of various parameters that could cause variations in the inter-droplet distances over a longer period of time. Please note, that long microfluidic channels are important components in microfluidics in form of meander mixing channels and, thus, are likely to be used in every application of MN. Therefore, it is crucial for the applicability of MN to investigate the effects of such channels.

First investigations of microfluidic channel effects were provided in [2], where it was postulated that the distance between the droplets changes as they traverse the microfluidic channel and this variation in the distance was considered as an additive noise. However, it was shown that the variance in the droplet distance is very small, in any point in the channel and that the channel noise is independent of the distance between the droplets. Although these results offered first insights into the microfluidic channel modeling, they were still verified only through simulations of a sequence of droplets traversing the channel and not for a single payload-header droplet pair. Additionally, only short microfluidic channels of a few milimeters were considered.

In this work, we utilize the DoD method proposed in [3] to precisely generate isolated payload-header droplet pairs. Then, we investigate, for the first time, the attenuation effects that a long microfluidic channel exerts on the distance of the droplet pairs and present first practical insights into the observed behaviour.

II. Practical Realization

Microfluidic chip for investigating channel attenuation effects, consists of a 14cm long microfluidic channel. It is fabricated using a fast and simple in-house developed fabricating method that combines 3D printing with PDMS (Polydimethylsiloxan) material. We have used a pressure controller (Fluigent, MFCS EZ) to induce pressure to the inlets. The pressure controller is able to apply a sequence of pulses through the microfluidics automation tool. For capturing the results we have used an integrated high-speed camera.

To generate an isolated group of two droplets (cf. Fig. 2) where the inter-droplet distance can be finely tuned, a simple

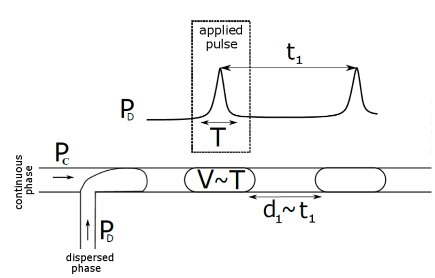

Fig. 1. Illustration of DoD generation using positive pressure pulses [3].

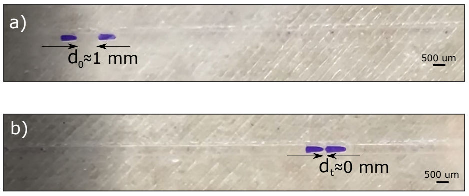

Fig. 2. Distance reduction effects inside a long microfluidic channel. a) inter-droplet distance at the injection site of the channel, d_0=1 mm, and b) inter-droplet distance at the end of the channel, d_t=0 mm

T-junction generator is used, as shown in Fig. 1. To initiate a droplet generation, a pressure pulse is applied to the dispersed phase inlet, where the duration of the pulse correlates to the volume/size of the droplet, and the time between two successive pulses corresponds to the time between the droplets.

III. Experimental Results

For the experiments, two droplets of 500 μm in size are generated and carried over the 14 cm long microfluidic channel. Three different initial inter-droplet distances (~4 mm, ~5 mm and ~8 mm) were used and temporal evolution of the distance reduction is investigated.

The obtained results on the distance reduction are shown in Fig. 3. As it can be seen, the inter-droplet distance decreases over time, primarily more gradual at the beginning but steeper towards the end of the channel. Moreover, the distance reduction is more pronounced for smaller initial inter-droplet distances. This indicates that, the microfluidic channel exerts stronger effects on the droplets that are closer to each other, whereas the the effects of the channel could be minimized if the distance between the droplets is sufficiently large.

To investigate the effects of a microfluidic channel on the distance reduction based on the number of droplets inside the channel, we extended the experiments to groups of three and four droplets. The droplet size was kept at 500 μm for all experiments and all experiments were conducted with initial inter-droplet distances of $d_0 \sim 5$ mm. As it can be seen in Fig.3, channel attenuation effects are in both cases dominantely exerted on the inter-droplet distance between the last two droplets, namely, d_{2-3} for the experiment with three droplets, and d_{3-4} for the experiment with four droplets. Whereas other inter-droplet distances remain stable over time. This result is the first practical evidence of the microfluidic channel attenuation effects being dependent on the number of droplets traversing the channel.

IV. Discussion and Conclusion

In this work, the first practical investigation of the attenuation effects over long microfluidic channels on the inter-droplet distances within the isolated groups of droplets, was presented. The results obtained have shown that long channels can cause significant inter-droplet distance reductions, which consequently causes information loss in MN. Under some conditions, more precisely, when inter-droplet distances are small and comparable to the size of the droplets, the distance reduction could be so dominant that the droplets eventually merge into one single droplet, ultimately causing complete information loss in MN. This implies that, in order to minimize

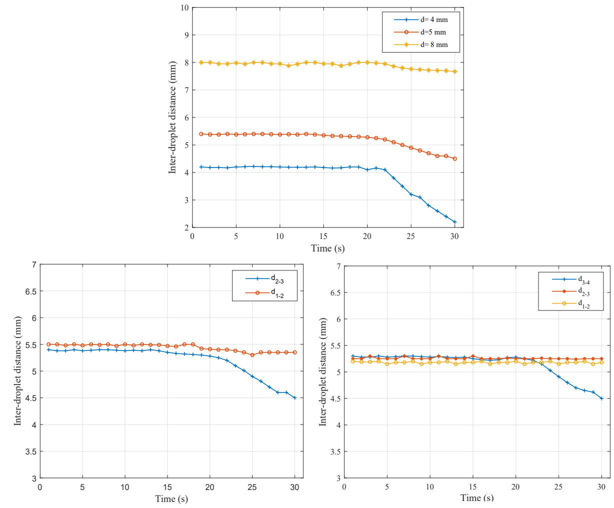

Fig. 3. Experimental results on the channel attenuation effects. **Top**: experiment with three different inter-droplet distances ~4 mm, ~5 mm and ~8 mm. **Bottom left**: experiment with three droplets, **bottom right**: experiment with four droplets.

channel attenuation effects, larger distances should be used for the transmission. However, it is important to keep in mind that the inter-droplet distances may not be chosen completely arbitrary during the μfSwitch design and in this case new switching strategies might be needed. Moreover, it was shown that the channel effects strongly depend on the number of droplets inside the channel. Here, it can be concluded that in a group of droplets, the last inter-droplet distances always experiences the largest attenuation. The results obtained in all experiments strongly agree with the governing theory which states that in a group of droplets, the last droplet always attains highest velocity due to the reduced drag forces acting on it [4]. This implies that, the last droplet will always tend to move towards the droplets that precede it. Additional experimental data and a detailed mathematical model for the behaviour of long microfluidic channels on isolated groups of droplets will be crucial for further development and applicability of MN, and is planned as a future step of this work.

V. Acknowledgment

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