Nano Communication Networks 4 (2013) 164–171

Contents lists available at ScienceDirect

Nano Communication Networks

journal homepage: www.elsevier.com/locate/nanocomnet

Microfluidic networks: Design and simulation of pure hydrodynamic switching and medium access control☆

Lidia Donvito, Laura Galluccio, Alfio Lombardo, Giacomo Morabito *

DIEEI, Dipartimento di Ingegneria Elettrica Elettronica e Informatica, University of Catania, Italy

ARTICLE INFO

Article history:
Received 6 June 2013
Accepted 4 August 2013
Available online 30 August 2013

Keywords:
Microfluidics
Switching
MAC

ABSTRACT

In this paper, we consider the *Hydrodynamic Controlled microfluidic Network* (HCN) paradigm which is based on purely hydrodynamic microfluidic switching and medium access control. The HCN paradigm can be applied to build programmable microfluidic devices, i.e., Lab-on-a-Chips (LoCs), that by exploiting hydrodynamic effects only, route chemical or biological samples in a microfluidic network, in a controlled way. These microfluidic devices will be highly flexible and inexpensive, and thus are expected to become extremely competitive as compared to the alternative solutions for chemical and biological analysis and synthesis or cheap sensing. This paper provides the design guidelines for the microfluidic circuits implementing the switching function and the medium access control and illustrates through simulations the feasibility of the proposed idea.

1. Introduction

In the last decade, considerable research effort has been devoted to design microfluidic devices where small volumes of fluids are manipulated typically for the purpose of chemical and biological analysis and synthesis (e.g., drug delivery, biomolecule synthesis, diagnostic testing, DNA sequencing, cheap sensing, synthesis of micro-structured materials) [1–5]. To accomplish these goals, microfluidic devices consist of a series of microchannels, usually in silicon, glass or Polydimethylsiloxane (PDMS), where the reagents flow and interact. The advantages of using microfluidic systems come from the specific behavior of fluids at the micro scale, where factors such as surface tension, energy dissipation, and viscosity dominate, so that liquids flow in laminar streams without mixing together. In the recent past a large number of attempts have been made to define a framework, including hardware and software features, for realizing programmable microfluidic systems able to execute a large number of different elementary analyses within a single device [6–9,4]. A number of problems have prevented this very ambitious goal to be reached; however recently the introduction of an emerging approach denoted as *droplet-based microfluidics* [3,10], first, and the introduction of the innovative concept of bubble logic [2] later, have shown that the design of microfluidic networks aimed at supporting flexible, low-cost and scalable programmable microfluidic systems is feasible. In particular bubble logic paves the way to the introduction of both communication and networking functionalities in microfluidic devices. A first step in this direction has been proposed in [11] where the possibility of encoding information in the distance between consecutive droplets and/or bubbles has been introduced; later on [12–14] this encoding methodology has been used to represent the address information in a microfluidic networked system where the flow of bubbles is driven into a microchannel network by means of other properly timed bubbles.[1]

☆ A previous version of this work was presented at IEEE MoNaCom 2013 [24].

* Correspondence to: Viale Andrea Doria 6, 95125 Catania, Italy. Tel.: +39 095 7382355; fax: +39 095 7382397.

E-mail addresses: lidia.donvito@dieei.unict.it (L. Donvito), laura.galluccio@dieei.unict.it (L. Galluccio), alfio.lombardo@dieei.unict.it (A. Lombardo), giacomo.morabito@dieei.unict.it, morabito.giacomo@gmail.com (G. Morabito).

1878-7789/$ – see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.nancom.2013.08.002

[1] In the rest of this paper we will refer to the droplet case; however the same concepts and discussions apply to the bubble case.

The availability of such solutions may foster a paradigm shift in the microfluidic domain similar to the introduction of the network-on-a-chip concept in the system-on-a-chip domain [15]. Today's programmable droplets microfluidic chips, in fact, rely on the active droplets manipulation methods, such as the electrowetting-on-dielectric method, requiring a complex multilayer microfabrication process for the chip, external instrumentation for the operation and sometimes are not suitable for some biological settings due to the problems of biocompatibility of electrical signals on cells or biomolecules [1,16,17]. On the contrary the approach proposed in our work is to use purely hydrodynamic technologies to support networking capabilities in a network of microfluidic devices. Accordingly we consider the Hydrodynamic Controlled microfluidic Network paradigm (HCN).

To this purpose, we address a system architecture consisting of a physical ring topology implementing a logical star topology as shown in Fig. 1. All packets are generated by or delivered to the central hub connected to the same ring; the hub performs a managing role which incorporates both the system logic necessary to perform job scheduling, and the sorting functionalities among the individual elements. For this reason we will name this hub *microfluidic router* μR. It is evident that the μR is connected to other boundary elements, such as pumps, by using standard electrical/electronic interfaces in order to control the injection of reagents into the system.

Similar to what is done in the network-on-chip domain, we assume that a networking element that we call Microfluidic Network Interface (MNI) is attached to each element to perform the operations required for efficient, flexible and reliable exchange of samples with the other elements. More specifically, basic objectives of the *i*-th MNI are:

- to detect droplets that must be delivered to the *i*-th element and switch them accordingly,
- to appropriately insert droplets generated by the *i*-th element in the shared microfluidic channel only when this is "possible".

In other words, the MNI is responsible for switching and medium access control. In this paper we will describe how these functionalities can be implemented and provide a validation for both.

The rest of this paper is organized as follows. In Section 2 we describe the design of the switching functionalities and assess these through simulations. In Section 3 we focus on the medium access control performed by the MNI. Finally, in Section 4 conclusions are drawn.

2. Switching droplets in HCN

Let us suppose that the samples which should be chemically treated or analyzed by the HCN are included in a *payload droplet*. In order to route the payload droplet appropriately, our HCN switching scheme exploits another droplet, which is called *header droplet*, used for network signaling only and, in particular, for encoding the destination address. The *destination address* is encoded in D_{HP}, that is the distance between the header droplet and the payload

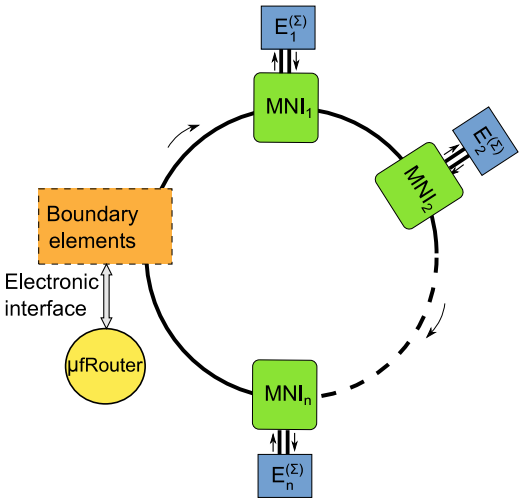

Fig. 1. HCN system architecture.

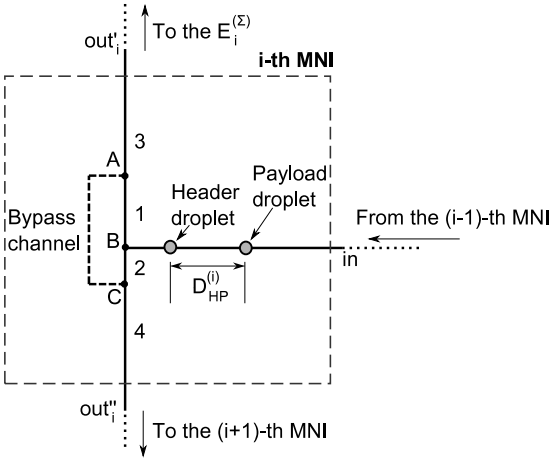

Fig. 2. HCN switching block of the *i*-th MNI.

droplet. The HCN switching block of the *i*-th MNI consists of the T-junction circuit shown in Fig. 2. This circuit has one inlet coming from the previous MNI in the ring, i.e. the $(i-1)$-th MNI. The inlet is connected to a pipe which bifurcates in *B* in two opposite pipes denoted as pipe 1 and pipe 2.

The points at the end of pipe 1 and pipe 2, denoted as *A* and *C*, respectively, are connected by a channel characterized by a very low hydrodynamic resistance, which we denote as *bypass channel*. Then, pipes 1 and 2 continue into pipes 3 and 4, respectively.

At the end of pipes 3 and 4 there are two outlets: the outlet out_i' at the end of pipe 3 is connected to the *i*-th element, $E_i^{(\Sigma)}$, while the outlet out_i'' at the end of pipe 4 is connected to the inlet of the $(i+1)$-th MNI.

The bypass channel connecting *A* and *C* is used as a pressure shunt to equalize the pressure at these two points [18]. Accordingly, the pressure difference between points *B* and *A*, which we denote as $\Delta P_i^{(BA)}$, is equal to the pressure difference between points *B* and *C*, which we denote as $\Delta P_i^{(BC)}$. This occurrence makes the droplet behavior