Microfludic Communications

(ELT-53406 Special Course on Networking)

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Contents of today’s lecture

- Introduction to Microfluidics
- Physical properties of microfluidics
- Microfluidic components
- Microfluidic communications
- Simulations
- Pure-hydrodynamic microfluidic switching
Microflows - Microfluidics

- Biocompatibility.
- In biotechnology, liquid is the medium for in-vivo and in-vitro environment.
- Small scale (scalability and efficiency).
- Simple application example: migration of nanoparticles or macromolecules through the interface of one liquid to another liquid (picture below)

DNA sequence analysis with MF

Fig. 2  Microfluidic system for analyzing the sequences of target molecules dispersed in a solution. Drops containing the probe sets are introduced into the microfluidic device and spaced by injection of oil, (A). The spaced drops then pass the picoinjector, where the solution containing the target DNA is injected. The injected drops are collected into a vial and incubated at room temperature for 1 h to allow the ligation reaction to complete, (B). They are then re-introduced into a droplet cytometer that spaces the drops and flows them through a laser, during which their fluorescence amplitudes are measured, (C). The drops are ~50 μm in diameter.

Fig. 4  Intensity time traces of drops after incubation and the completion of the ligation assay. The time traces for the assay (green, channel 1), and label dyes (red and purple, channels 2 and 3) are plotted on top of each other. The drops appear as peaks in intensity as a function of time, separated by dim gaps corresponding to the passage of the non-fluorescent interstitial oil. The amplitudes of the peaks for a given drop depend on the dye label values and the outcome of the ligation assay.
Labs-on-a-Chip Influenza Detection

- Throat swab is analyzed.
- Utilizing “restriction enzyme” to recognize certain sequence of DNA.
- The corresponding fragment runs through electrophoresis gel.
- The resulting fluorescent reveals the virus.
Integrated microchannel cooling

- Microfluidic channels for layered-chip cooling system
- Space efficiency
Why communication?

- Communication feature means automation possibility
- Biocompatible communication transmission
- New application opportunity, such as EcoBot.
Laminarity

- Laminar flow
  - Unidirectional
  - Even streamlines
  - More prevalent at low flow speeds and small scales
- Turbulent flow
  - Random Chaotic
  - More common at high flow speeds and larger scales
- Transition flow
  - Possibility to be either laminar or turbulent flow
  - Depends on other factors (surface roughness and flow uniformity)
Reynolds number

- Dimensionless number to define flow laminarity
- The ratio of inertia (convective forces) and viscous forces

- Laminar: $Re < 2000$
- Turbulent: $Re > 3000$

\[ Re = \frac{\text{inertial forces}}{\text{viscous forces}} = \frac{\rho v L}{\mu} = \frac{v L}{\nu} \]

where:
- $v$ is the mean velocity of the object relative to the fluid (SI units: m/s)
- $L$ is a characteristic linear dimension, (travelled length of the fluid; hydraulic diameter when dealing with river systems) (m)
- $\mu$ is the dynamic viscosity of the fluid (Pa·s or N·s/m² or kg/(m·s))
- $\nu$ is the kinematic viscosity ($\nu = \mu / \rho$) (m²/s)
- $\rho$ is the density of the fluid (kg/m³).
Viscosity

- Thickness of the fluid
- Newtonian fluid vs Non-Newtonian fluid
Surface wetting property

- **Hydrophobic**
  - Water-fearing
  - Meniscus angle > 90 degrees
  - More pressure needed

- **Hydrophilic**
  - Water-loving
  - Meniscus angle < 90 degrees
  - Less pressure needed
Microfluidics

Two-Phase Microfluidics

Digital
- Acoustic
- Electric

Droplet-based
- T-junction
- Flow focusing device
Droplet generator

- Channel geometry (T-junction & Flow Focusing Device)

- Valve (Piezoelectric & Solenoid)

http://www.curiejet.com/en/products/list.php?pin=3905b4c83672158dc6e0cbed5543e0b1&type=s

Droplet detector

- Optodetection
  - based on the light passing through the microchannel.
- Electric detection
  - based on electrical properties of the fluid (resistive & capacitive).
- Imaging detection
  - based on analysis of images captured by high speed cameras.

Namasivayam, Vijay, Rongsheng Lin, Brian Johnson, Sundaresh Brahmendra, Zafar Razzacki, David T. Burke, and Mark A. Burns.
"Advances in on-chip photodetection for applications in miniaturized genetic analysis systems."
Flow rate controller

- Gravity-Driven Hydrostatic Pressure
- Pressure Pump
- Syringe Pump
- Peristaltic Pump
- Electro-osmotic Pump
- Reciprocating Diaphragm Micropump
Protocol Stack

- Physical Layer: Raw bit transmission over physical link
- Medium Access Control Layer: Addressing and Access Control

**Medium Access Control Layer**
- Centralized System
- Decentralized (Random Access) System

**Physical Layer**
- Modulation Schemes: OOK, CtS
- Forward Error Correction: Parity Check
Physical Layer

- On-off Keying (OOK)

- Communication through Silence (CtS)
  - Decimal
  - Hexadecimal
# Conversion Table

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Continuous Data Transmission

- Single Start/Stop
  - Each message has its own start and stop bits.

- Piggyback
  - Common start/stop bit.
Detection Data Processing

• Level-crossing method
  - utilizing the threshold level to determine the existence of water or air in the microchannel

• Integrated metric method
  - integrates the detected values for certain amount of time to avoid false detection due to additive system noises to the output of detector.
Data Rate

- OOK

\[ T_b = \frac{L_b}{v} \]

\[ R^{[OOK]} = \frac{1}{T_b} = \frac{v}{L_b} \]

- CtS
  - Decimal

\[ D_{10} = T_{\text{min}} + \frac{2^n - 1}{F_c} = T_{\text{min}} + \frac{P_{10}}{F_c}, \quad n \in \mathbb{Z}^* \]

\[ R_{10}^{[SSS]} = \frac{n}{2T_b + 2T_{\text{min}} + \frac{2^n - 1}{F_c}} = \frac{n}{2T_b + T_{\text{min}} + D_{10}} \]

\[ R_{10}^{[PB]} = \frac{n}{T_b + T_{\text{min}} + \frac{2^n - 1}{F_c}} = \frac{n}{T_b + D_{10}} \]
Data Rate

- CtS

  ➢ Hexadecimal

\[
D_{16} = T_b + 2T_{\text{min}} + \frac{P_{10} - \left( 15 \times \left\lfloor \frac{P_{10}}{16} \right\rfloor \right)}{F_c}
\]

\[
= T_b + 2T_{\text{min}} + \frac{P_{16}}{F_c}, \quad n = 0, 1, \ldots, 8.
\]

\[
R^{[SSS]}_{16} = \frac{n}{3T_b + 3T_{\text{min}} + \frac{P_{16}}{F_c}} = \frac{n}{2T_b + T_{\text{min}} + D_{16}}
\]

\[
R^{[PB]}_{16} = \frac{n}{2T_b + 2T_{\text{min}} + \frac{P_{16}}{F_c}} = \frac{n}{T_b + D_{16}}
\]

start/stop

payload = 14 (Dec)

start/stop

payload = 11 (Dec)
Noise

• injection-inaccuracy noise
  - The microdroplet injector/pump may be inaccurate in term of injection time and injected microdroplet volume/size.

• pressure-maintenance noise
  - Pressure instability is related to velocity fluctuations along the transmission channel.

• detection noise
  - The detector output is also affected by non-ideal operation of the droplet detection apparatus.

• All of the noises follow gaussian distributed.
Overall system noise

\[ \sigma_E^2(l) = 0, k_I^2(l)\sigma_I^2 + \sigma_P^2 + \sigma_D^2 \]

\[ \mathcal{N}_{\text{err}}(0, \sigma_{\text{err}}^2) \]
Symbol Error Rate

\[ p_E(l) = 2Pr \left( x > \hat{x} + \mu + \frac{T_c}{2} \right) = 2 \left( \int_{\hat{x} + \mu + \frac{T_c}{2}}^{\infty} p_X(x) \, dx \right) = 2Q \left( \frac{\hat{x} + \mu + \frac{T_c}{2} - \hat{x}}{\sigma_E(l)} \right) = 2Q \left( \frac{T_c}{2\sigma_E(l)} \right), \]

\[ G = R[1 - p_E(l)] \]
Addressing

• Physical Addressing
  - provided by the length of the droplet itself.

\[ T_b^{[i]} = T_b + [(i - 1) \Delta T_b], \quad i = 1, 2, \ldots, N \]

• Digital Addressing
  - represented by a certain value associated with each system on the microfluidic device.
  - encoded using either OOK or CtS modulation scheme and then sent as a header of the message.
  - More number of destinations leads to larger addressing space.
  - requires fixed droplet size resulting in simpler requirements for droplet generation apparatus.
Access Control

- Centralized System
  - Central Unit (CU) as controller and scheduler
  - Two scheduling schemes:
    - Payload-based scheduling - Exact payload allocation
      \[ L_T^i = 2[L_b + L_{\text{min}} + \Delta T_b(i - 1)] + L_d \]
    - Maximum-time-based scheduling - Maximum payload allocation
      \[ L_T^i = 2[L_b + L_{\text{min}} + \Delta T_b(i - 1)] + L_{d\_\text{max}} \]
Central Unit (CU)

- **Time - Length - Volume Conversion**
  - converts the information to time (operating frequency)
  - calculates the exact length (flow speed)
  - correlates the length to required time and volume of droplet injection.

- **Synchronization**
  - handles the calculation and synchronization load.
  - avoids collisions during transmission

- **Droplet Position Tracking**
  - keeping the record of droplets data in the memory temporarily.
  - precise injection estimation time.
Access Control

- Decentralized (Randomized) System
  - Combination of TDMA, CSMA, CDMA.
  - TDMA - for resource fairness.
  - CSMA - for coalescence avoidance.
  - CDMA - for interference avoidance.

\[ L_T^i = 2[L_b + L_{\text{min}} + \Delta T_b (i - 1)] + L_{d\_max} + L_{cs} \]
Fairness problem

• Microfluidic communication is flow-based, unidirectional, simplex communication.
• Unequal transmission opportunity by nature.
• Earlier transmitter has higher priority/opportunity to occupy the transmission channel.
• Problem arises especially in high traffic condition
Fairness problem - solution

- Relocation of stations (traffic-demand based)
  - The transmitter whose traffic demand is lowest should be located at the beginning of the order along the direction of the flow.

- Priority based access
  - By default, the priority is unequal.
    \[ P^{(1)} < P^{(2)} < P^{(3)} < \ldots < P^{(N-1)} < P^{(N)} \]
  - Applying transmission probability based algorithm.
Fairness problem (TDMA)

\[ T_{\text{slot}} = 2\left(T_b^{[N]} + T_{\text{min}}\right) + T_{d\_max} + T_{cs} \]

\[ L_T^i = 2\left[L_b + L_{\text{min}} + \Delta(N - 1)\right] + L_{d\_max} + L_{cs} \]
Probability based Algorithm

- Algorithm which makes equal priority.

\[ P^{(1)} < P^{(2)} < P^{(3)} < \ldots < P^{(N-1)} < P^{(N)} \]

\[ P^{(1)} = P^{(2)} = P^{(3)} = \ldots = P^{(N-1)} = P^{(N)} \]

\[ \gamma_i = \frac{p_i}{\sum_{j=i}^{N} p_j}, \quad i = 2, 3, \ldots, N \]

\[ \gamma_i = \frac{p}{\sum_{j=i}^{N} p} = \frac{1}{(N - i + 1)}, \quad i = 2, 3, \ldots, N \]
Routing/Switching

- Pressure Repeater - maintaining flow rate.
- Directing information to the correct path.
- Two possible switching architecture:
  - Store-and-forward router
    Requires routing table, produces delay
  - Switch-through router
    purely hydrodynamic architecture, based on pressure difference between paths, complex hardware design.

## Table 4.1 Initial Variables

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<thead>
<tr>
<th>Parameter</th>
<th>Value [Unit]</th>
<th>Description</th>
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<tr>
<td>Dynamic viscosity water</td>
<td>1E-3 [Ns/m²]</td>
<td>Room temperature</td>
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<tr>
<td>Dynamic viscosity air</td>
<td>1.98E-3 [Ns/m²]</td>
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<tr>
<td>Diameter</td>
<td>50/100 [µm]</td>
<td>Channel total length</td>
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<tr>
<td>Length</td>
<td>4 [cm]</td>
<td>Channel hydraulic</td>
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<td>Surface tension</td>
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<td>Dynamic contact angle</td>
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<td>Contact angle hydrophilic</td>
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<td>K</td>
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<td>N</td>
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<td>Initial pressure</td>
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## Table 4.2 Simulation result with no droplet

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<th>Channel Diameter [µm]</th>
<th>ΔP [mbar]</th>
<th>Q [µl/s]</th>
<th>v [mm/s]</th>
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## Table 4.3 Simulation result with 1 droplet

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<th>Channel Diameter [µm]</th>
<th>ΔP&lt;sub&gt;capillary&lt;/sub&gt; [mbar]</th>
<th>ΔP&lt;sub&gt;friction&lt;/sub&gt; [mbar]</th>
<th>ΔP&lt;sub&gt;total&lt;/sub&gt; [mbar]</th>
<th>v [mm/s]</th>
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Single Transmitter-Receiver (PB)

(a) Data rate as a function of $T_b$ (Payload size = 8 bits).
(b) Data rate as a function of $F_c$ (Payload size = 8 bits).
(c) Data rate as a function of $T_b$ (Payload size = 5 bits).
(d) Data rate as a function of $F_c$ (Payload size = 5 bits).
(e) Data rate as a function of payload.

Figure 4.1 Performance of OOK and CIS modulation schemes in PB regime.
Single Transmitter-Receiver (SSS)

Figure 4.2 Performance of OOK and CTS SSS modulation schemes.
Multiple Transmitters- Receivers

- Two and three pairs of transmitter-receiver.
- Payload-based and Maximum-time-based schemes.
- Payload-based is more efficient in resource utilization.
- On the maximum payload transmission, both schemes converge.

*Figure 4.3 Overall throughput as a function of transmitted payload size.*
Decentralized system fairness

- Jain Fairness Index to indicate share fairness of system resource.
- One million cycles of transmission simulation.

\[ J(x_1, x_2, \ldots, x_n) = \frac{\left( \sum_{i=1}^{n} x_i \right)^2}{n \cdot \sum_{i=1}^{n} x_i^2} \]

*Figure 4.4* Per-station throughput.
Switching in microfluidic system

- Pure hydrodynamic control for networking LoC.
- Element for droplet processing, Microfluidic Network Interface (MNI) as an exchange.
Structure

- Header - address - payload.
- Addressing - CtS is used instead of OOK.

Fig. 2. Droplet encoding: a) presence/absence of droplets; b) distance between droplets.

Fig. 10. Distance-based switching.
Simulation Design

Fig. 12. Configuration considered for simulations.
Fig. 14. Simulation results for the case in which the payload droplet is addressed to the $i$-th element $E_i^{(\Sigma)}$.

(a) Condition before the header droplet arrives at $B$.

(b) Condition after the payload droplet leaves $B$. 
Fig. 15. Simulation results for the case in which the payload droplet is addressed to the $(i+1)$-th element $E^{(\Sigma)}_{i+1}$.

(a) Condition before the payload droplet arrives at the point $B$ of the $i$-th MNI.

(b) Condition after the payload droplet leaves the point $B$ of the $i$-th MNI.

(c) Condition after the payload droplet leaves the point $B$ of the $(i+1)$-th MNI.
Experiment

- Continuous Phase: Fluorinated oil FC-3283.
- Dispersed phase: aqueous dye.
What you should have learnt today...

- Basics of microfluidics.
- Microfluidic communication protocols.
- Microfluidic communication challenges.
- Analysis of microfluidic transmission system.

