"Wet bits": A Microfluidic Communication Link: Definition, Analysis and Experimentation

DIPARTIMENTO
DI INGEGNERIA
DELL'INFORMAZIONE

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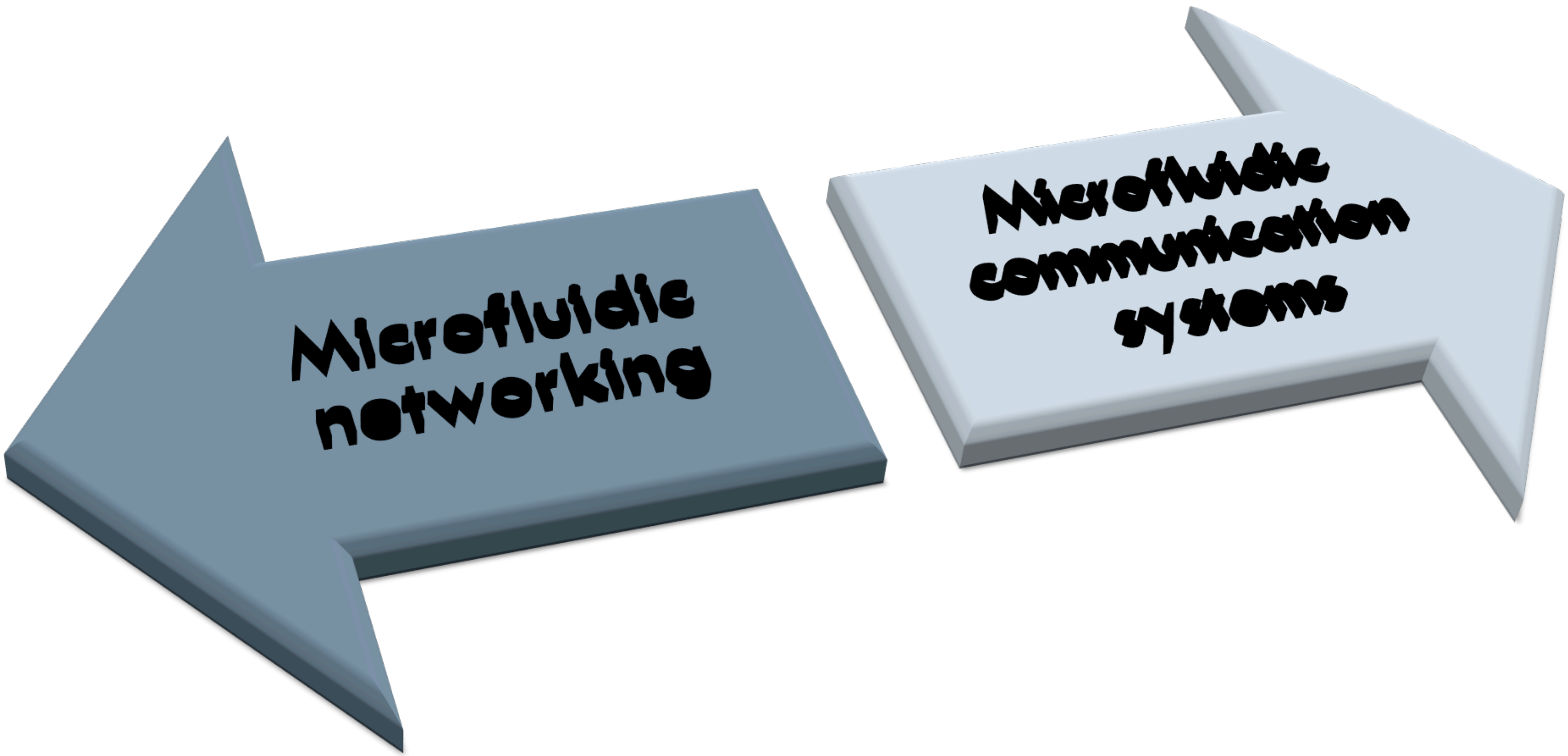
Most of experimental pictures in this presentations are complimentary from Prof. Mistura (Univ. of Padova)

Outline

- Microfluidics and its applications
  - Lab on Chip
  - Research interests
- Our contribution
- Experimental setup
- Results
- Conclusion

Engineering view of microfluidic challenges



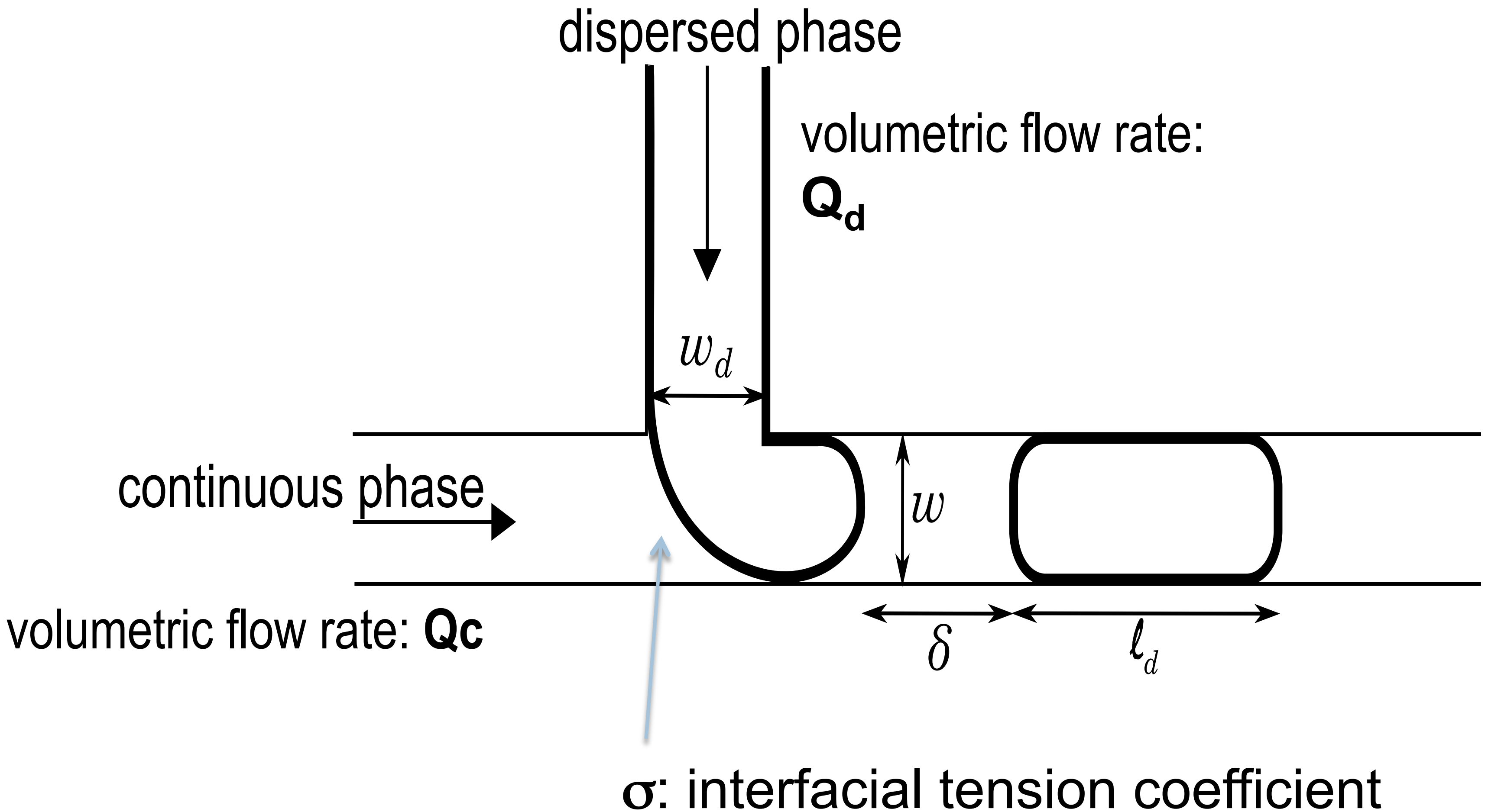
In this talk…

Microfluidic communication systems

Our contribution

- Goal: transmit information in a microfluidic channel
  - Start from a basic PAM-like modulation
  - Use droplet length/interdistance as modulated signal
  - Perform experimental tests
  - Evaluate system performance
  - Speculate on possible evolution

Bit source: droplets generation



Droplet generation process

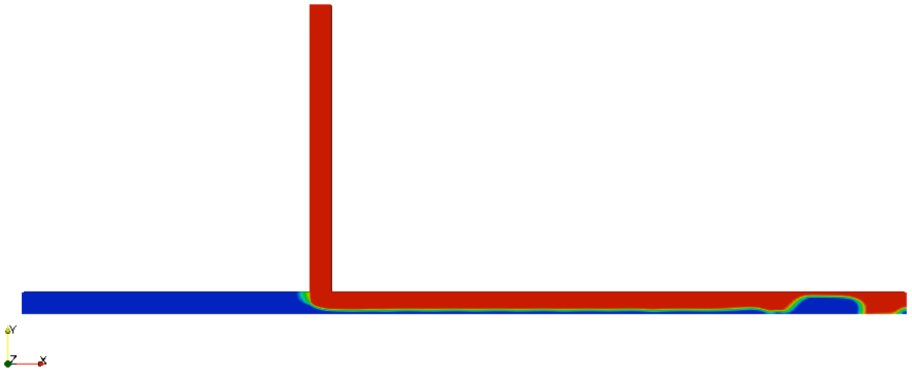
Capillary number: captures the relative magnitude of the viscous shear stress compared with the interfacial tension

$10^{-2} <$

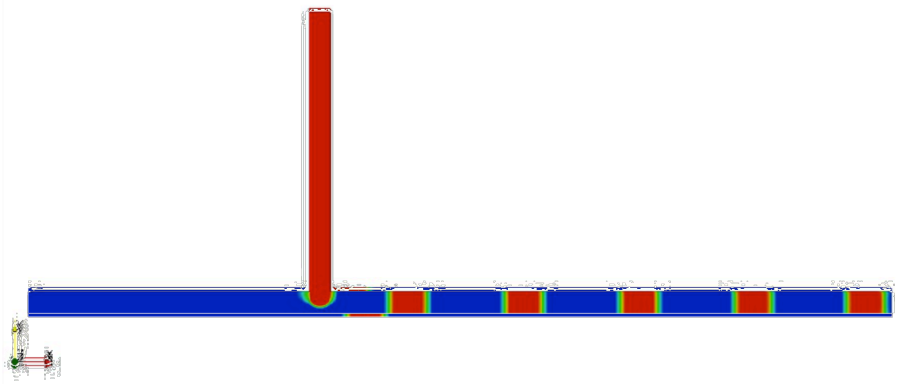
$$C_a = \frac{\mu_c Q_c}{\sigma h w}$$

$< 10^{-2}$

Drippling

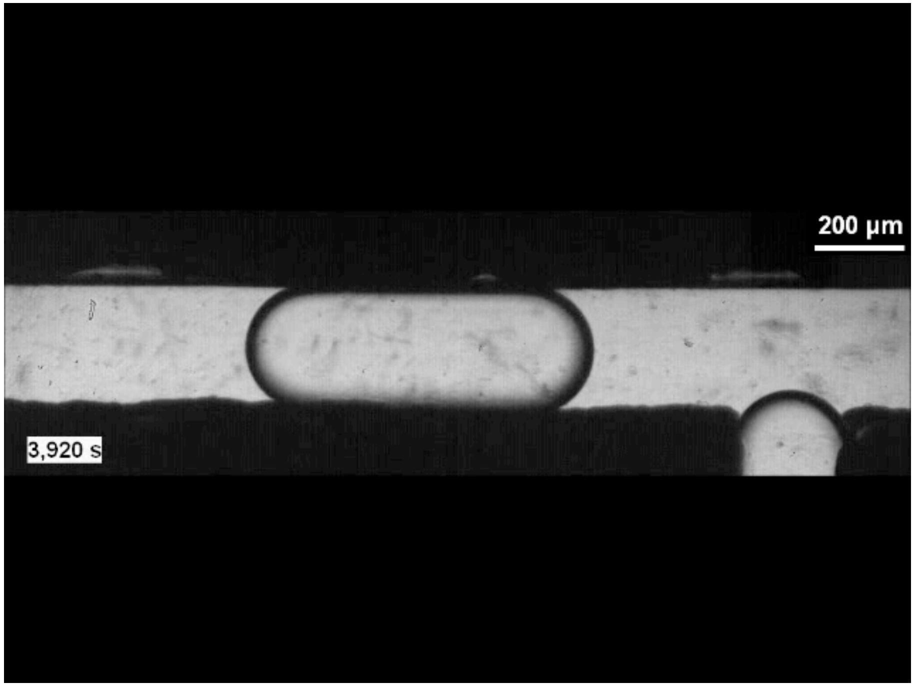


Squeezing

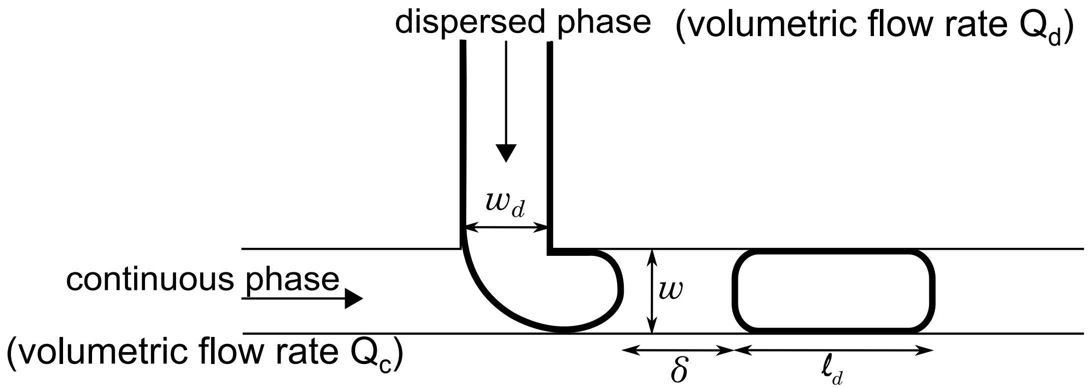


Droplets generation

$C_a < C_a^* \approx 10^{-2}$ ➔ **Squeezing regime ➔ droplet formation**



Droplets generation



$$L_d = w\left(1 + \xi\frac{Q_d}{Q_c}\right) \qquad \delta = L_d\frac{Q_c}{Q_d} + \frac{\pi w^3/6 - w^2 h}{Q_d w h}(Q_d + Q_c)$$

Constant
(~1)

- By changing input parameters, you can control (average) droplets length and spacing, but NOT independently!

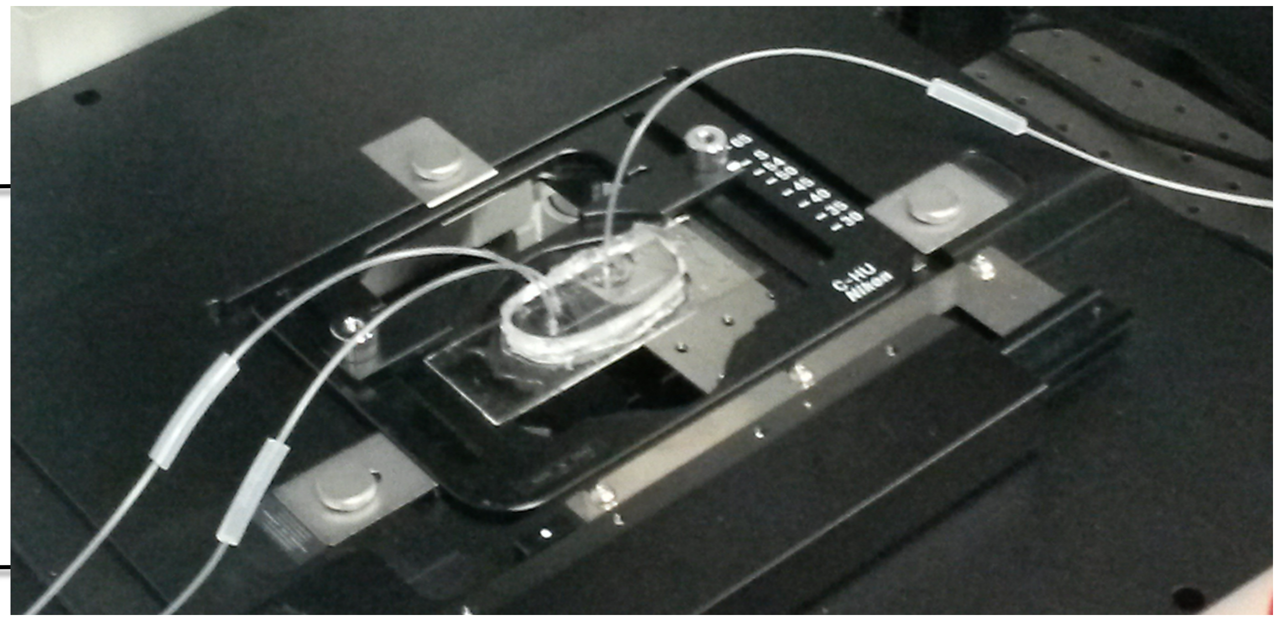
Modulation

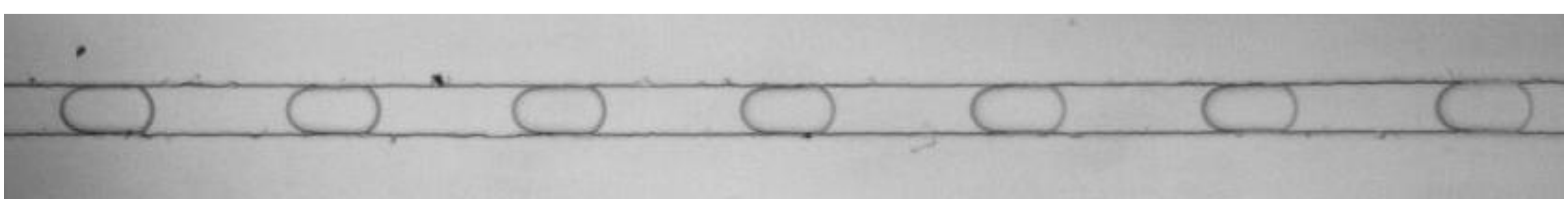
Bit string	00	01	10	11	
PAM symbols	0	1	2	3	
Droplet length	$L_d^{(0)}$	$L_d^{(1)}$	$L_d^{(2)}$	$L_d^{(3)}$	
Dispersed flow Q_d:	0.5	1	1.5	2	[µl/min]

Continuous flow Q_c: 5 [µl/min]

Arbitrary choice!
Sufficient inter-droplet distance

Experimental setup





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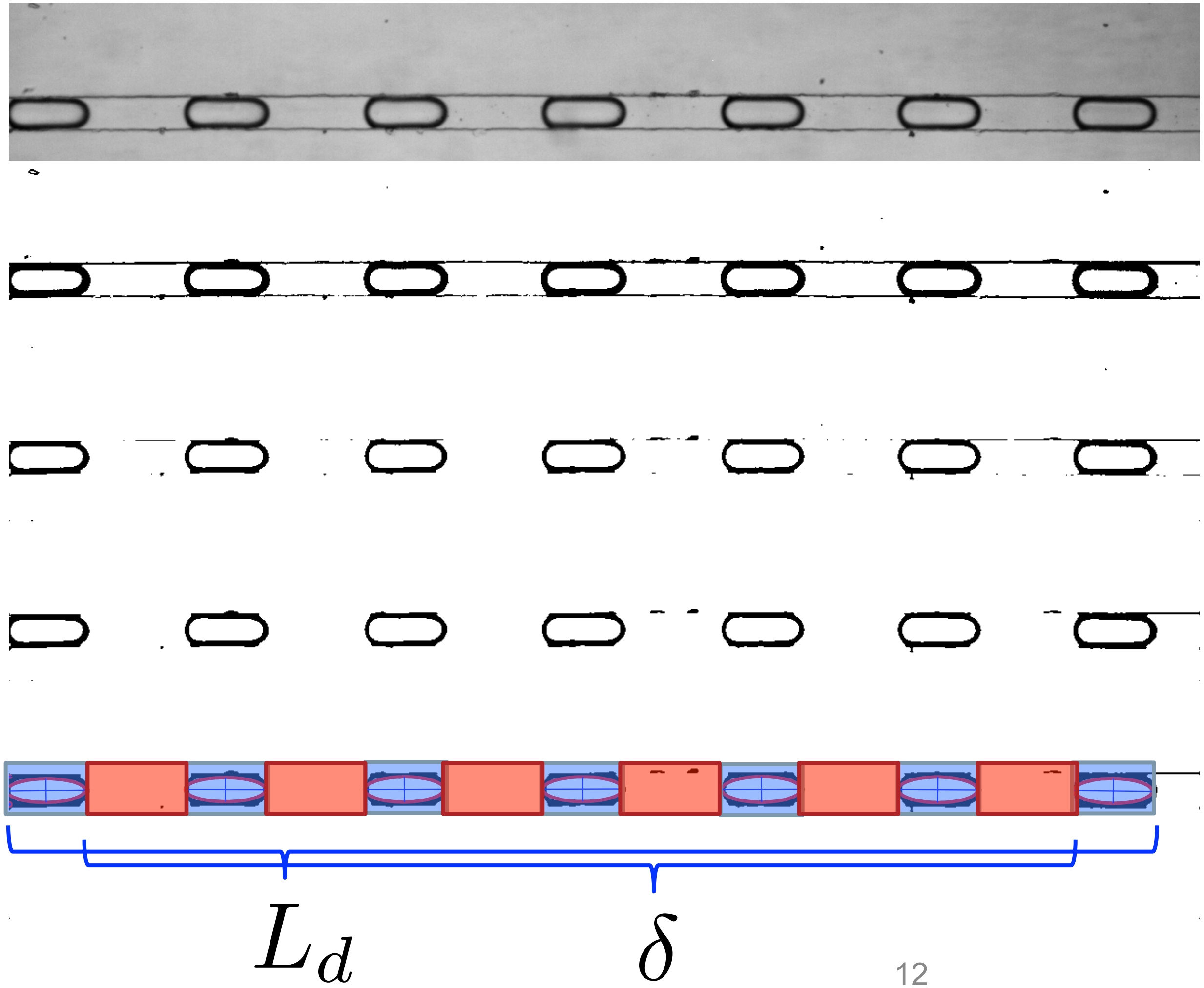
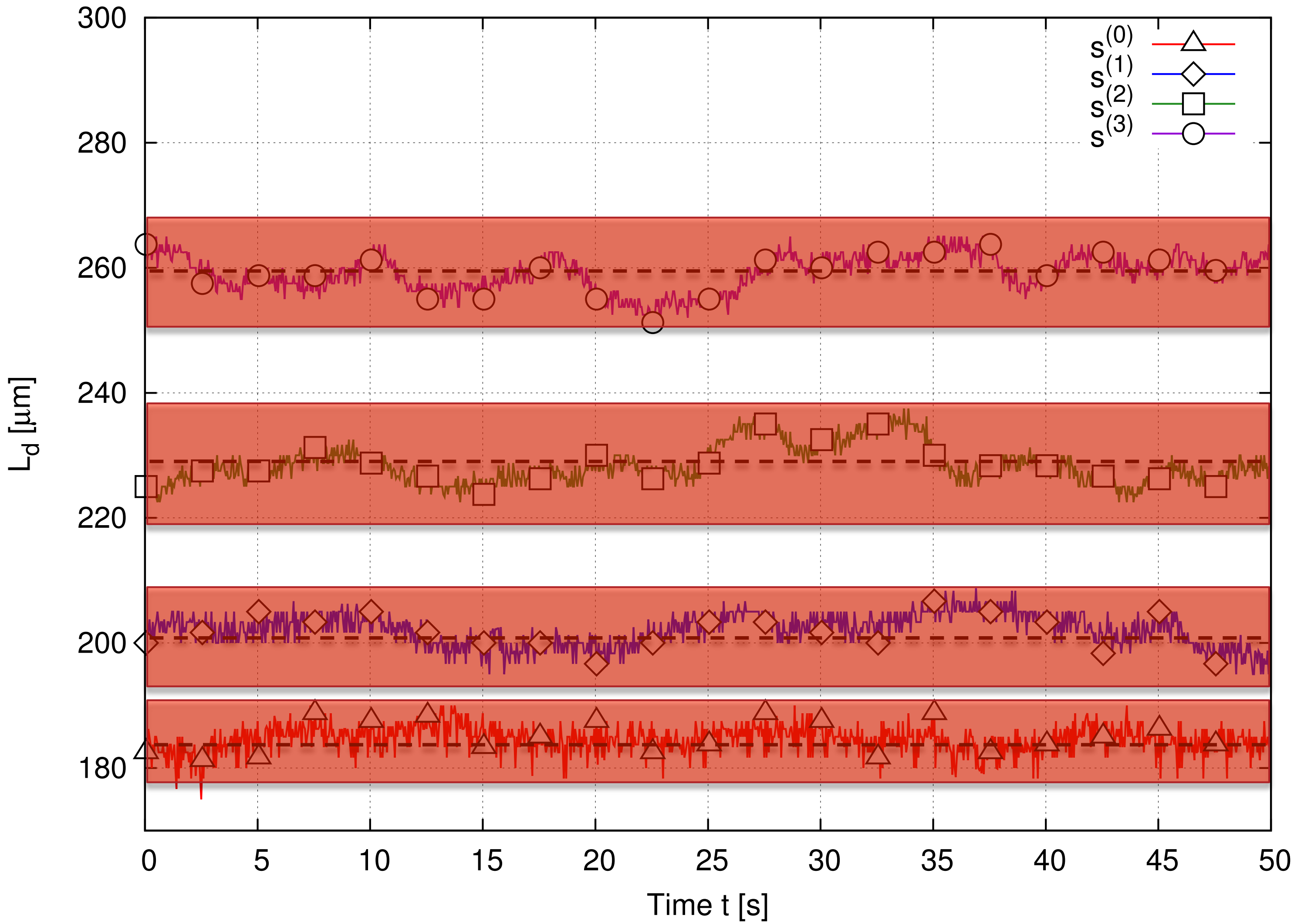
Frame processing



- Camera frame
- Binary image
- Lowpass Wiener filter
- Median filter
- Connected components identification

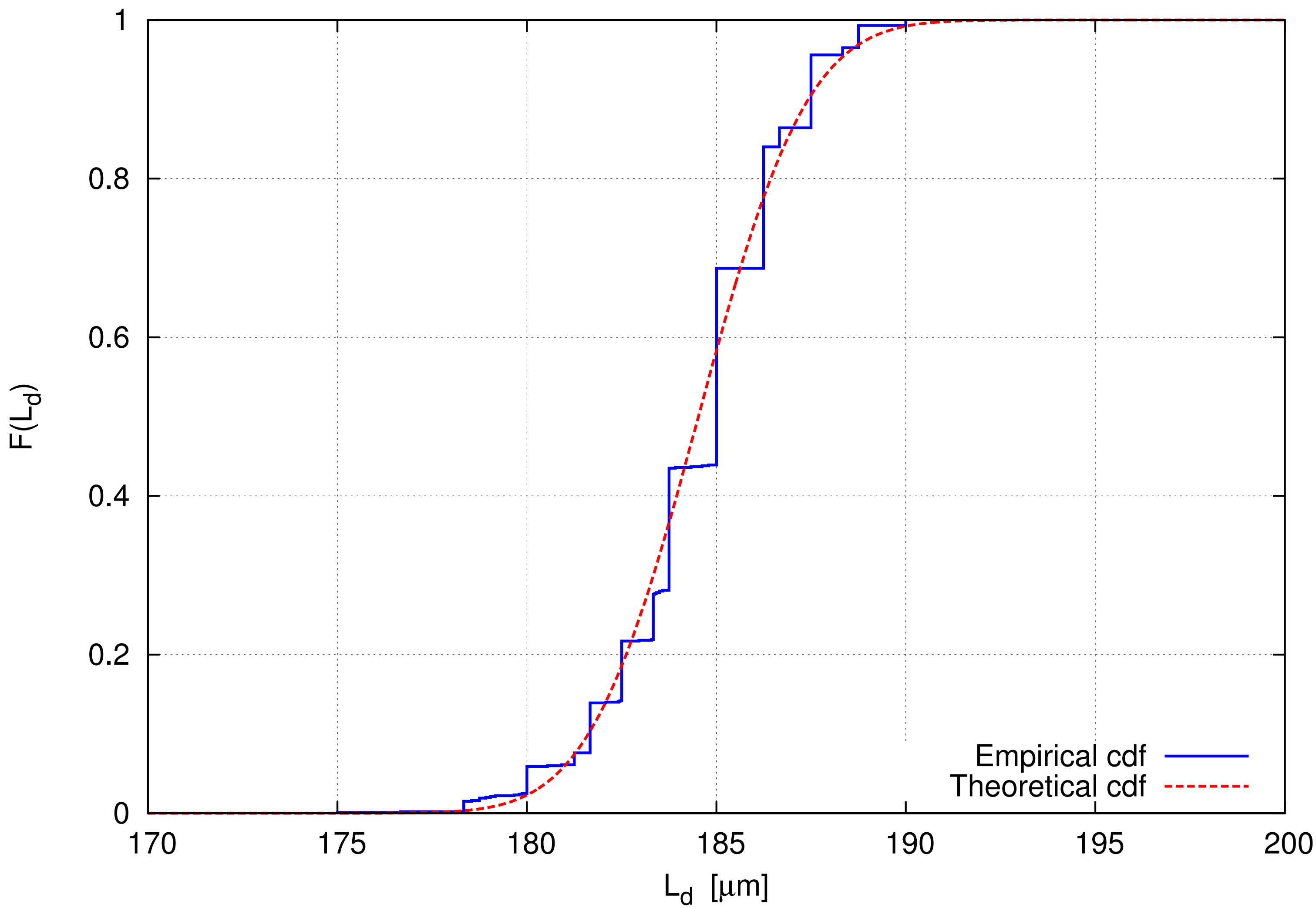
Droplet lengths



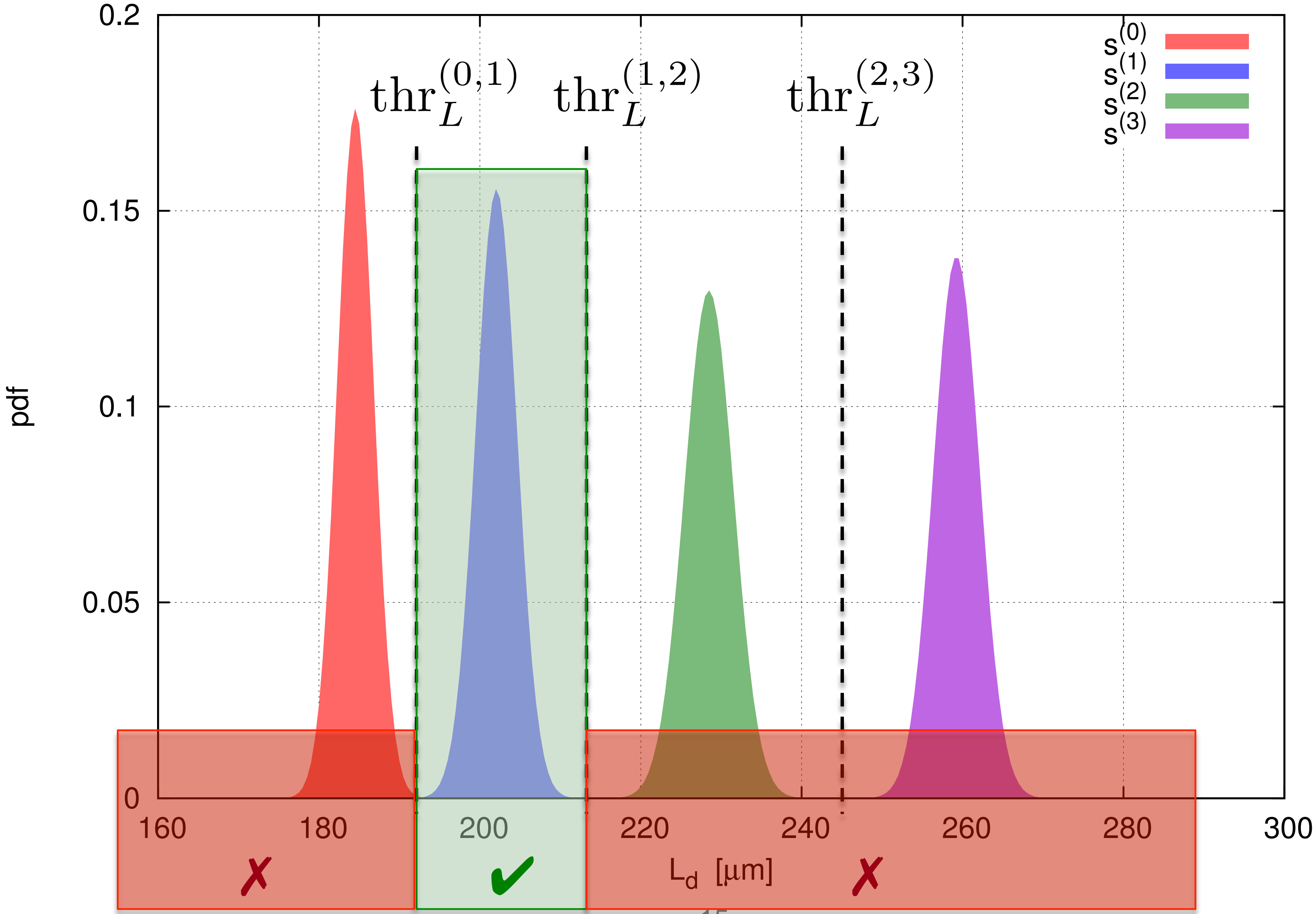
$$\bar{L}_d^{(i)}$$

$$\sigma_d^{(i)}$$

Droplets length distribution



Symbols PDFs



Error probability

- Assuming equally likely symbols

$$e = \frac{1}{4}\sum_{i=0}^{3} P(E|s^{(i)})$$

	Droplet-length PAM			Inter-droplet distance PAM		
i	$\bar{L}_d^{(i)}$	$\sigma_d^{(i)}$	$\mathrm{thr}_L^{(i,i+1)}$	$\bar{\delta}^{(i)}$	$\sigma_\delta^{(i)}$	$\mathrm{thr}_\delta^{(i,i+1)}$
0	184.52	2.26	193.29	769.65	14.04	679.5107
1	202.05	2.56	215.26	589.37	15.30	513.0877
2	228.47	3.08	243.85	436.80	9.44	397.8275
3	259.24	2.88	/	358.85	4.09	/
e_L	$1.80 \cdot 10^{-5}$			e_δ	$8.95 \cdot 10^{-7}$	

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Timing: chip period

- **"Chip" period:** time occupied by one droplet-space

Droplet speed

$$\tau_d \stackrel{\text{def}}{=} (L_d + \delta_d)\frac{wh}{Q_d + Q_c}$$

- Depends on the transmitted symbol!
- Order of hundred of milliseconds

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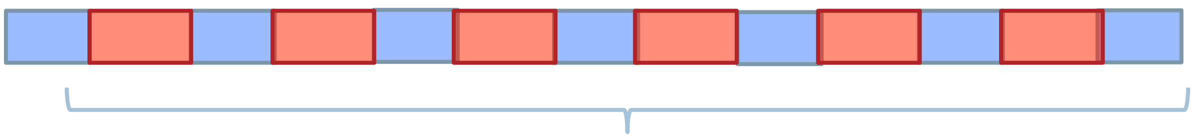
Timing: Symbol period

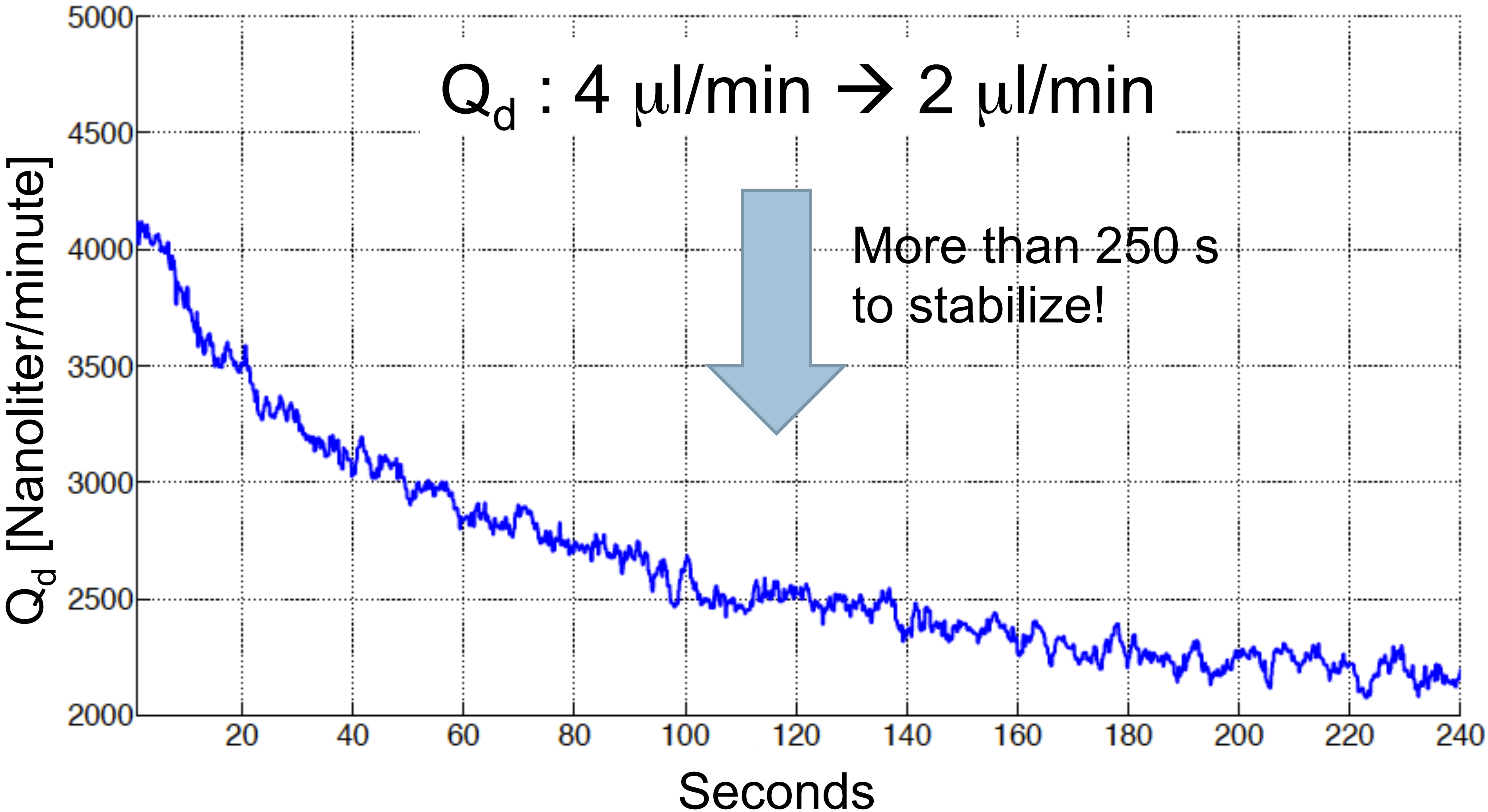
- **Symbol period:** time to collect enough droplet-space pairs to take decision



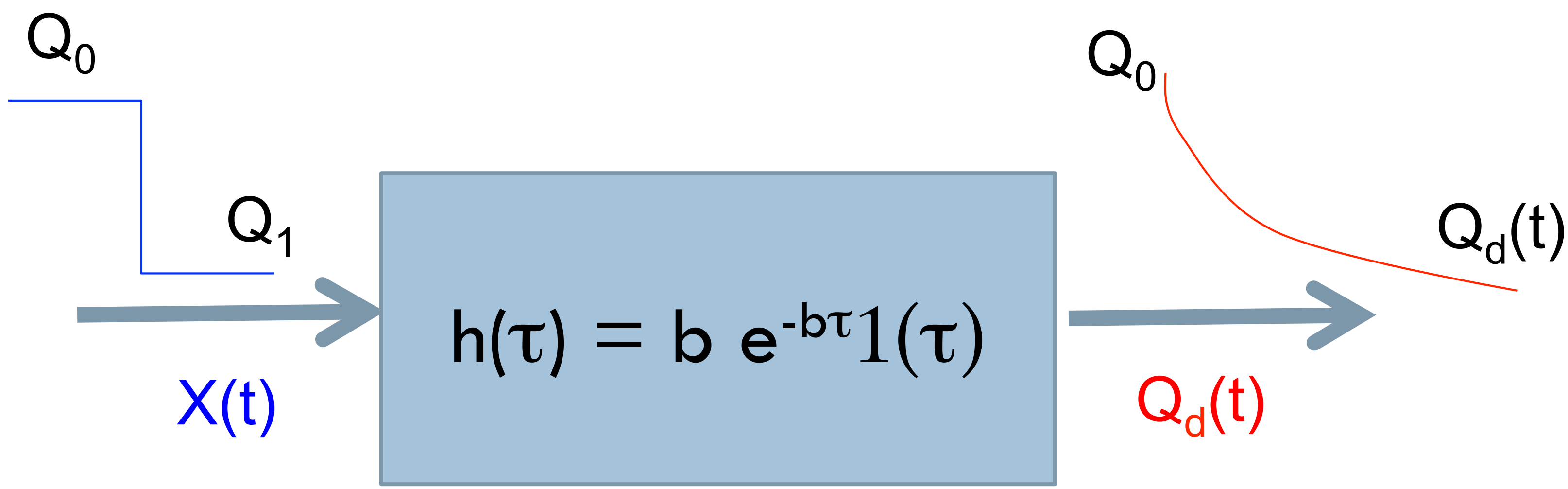
k_d pairs → $T_d \stackrel{\text{def}}{=} k_d \tau_d$

- The larger k_d, the lower the decoding error probability
- $k_d = 10$ → T_d order of seconds (and P_{err}~1e-6)

Timing: symbol switching time



Modeling transient behavior



$$Q_d(t) = Q_0 + \underbrace{(Q_1 - Q_0)}_{\Delta Q}(1 - e^{-bt})$$

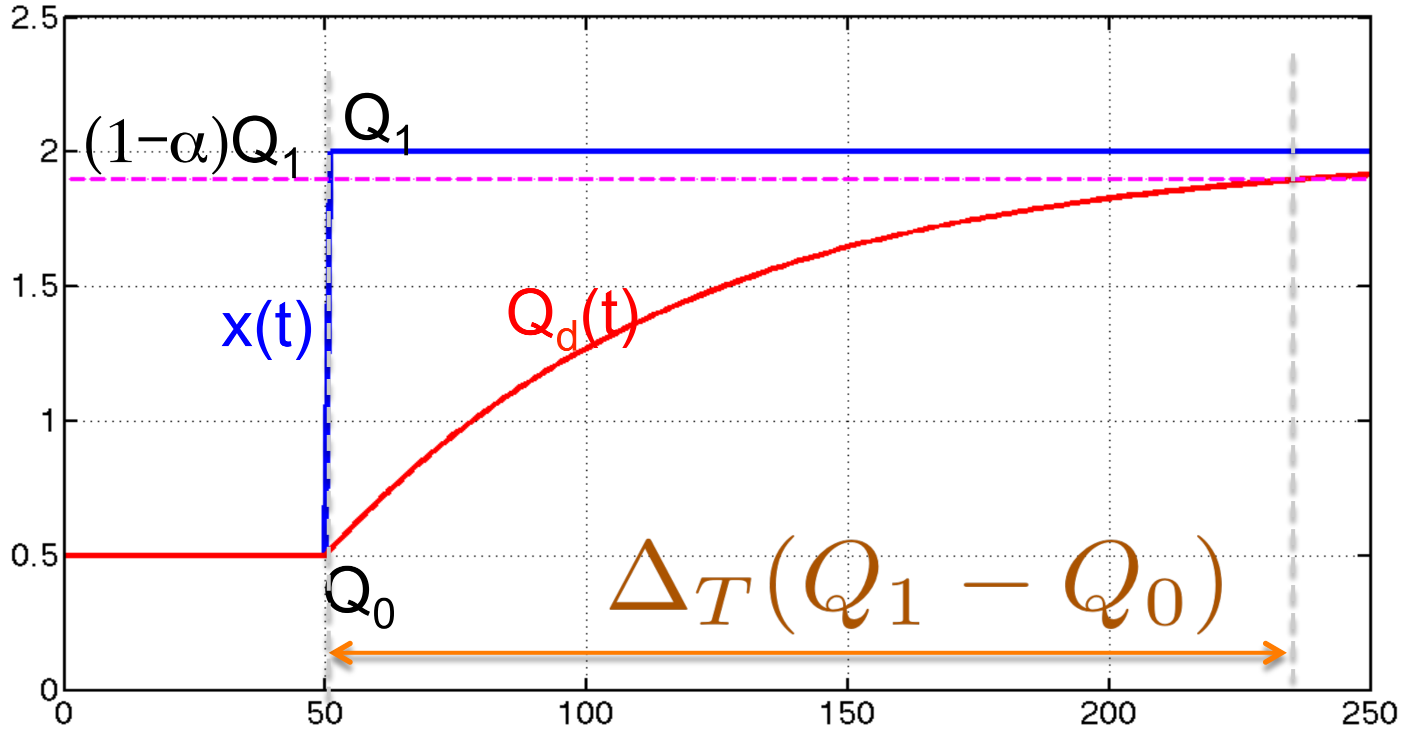
Time constant

Experimental estimate of b

Flow change ($Q_0 \rightarrow Q_1$)	b
3000-2000	0.01388
4000-2000	0.01513
5000-2000	0.01554
2000-3000	0.01542
4000-3000	0.01384
5000-3000	0.0172
2000-4000	0.01263
3000-4000	0.01525
5000-4000	0.01461
2000-5000	0.01411
3000-5000	0.01366
4000-5000	0.0118

$$b \simeq 0.014423$$

Symbol switching time definition



$$\Delta_T(Q_1 - Q_0) = \frac{1}{b} \ln\left(\left|\frac{1}{\alpha}\left(1 - \frac{Q_0}{Q_1}\right)\right|\right)$$

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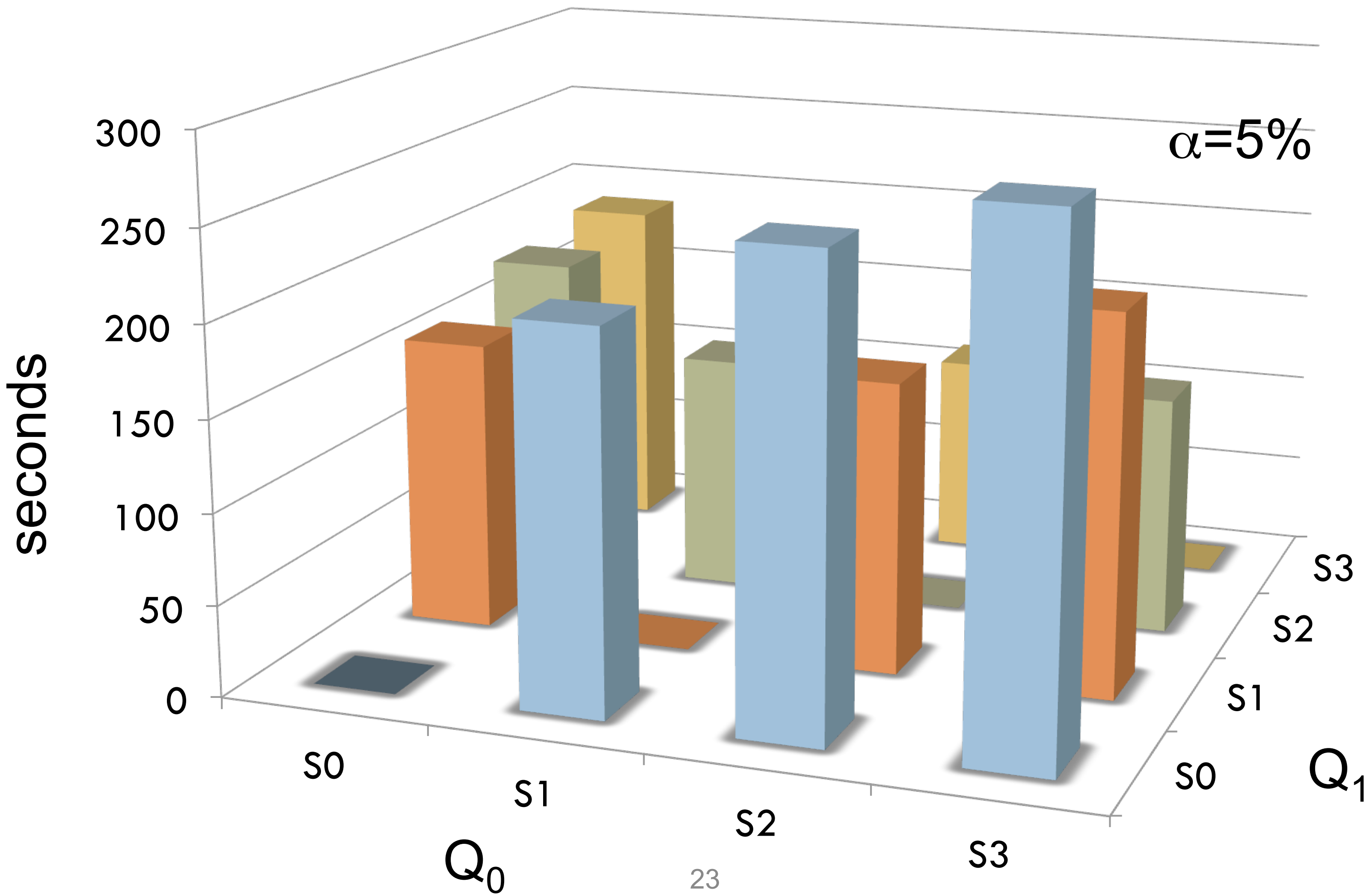
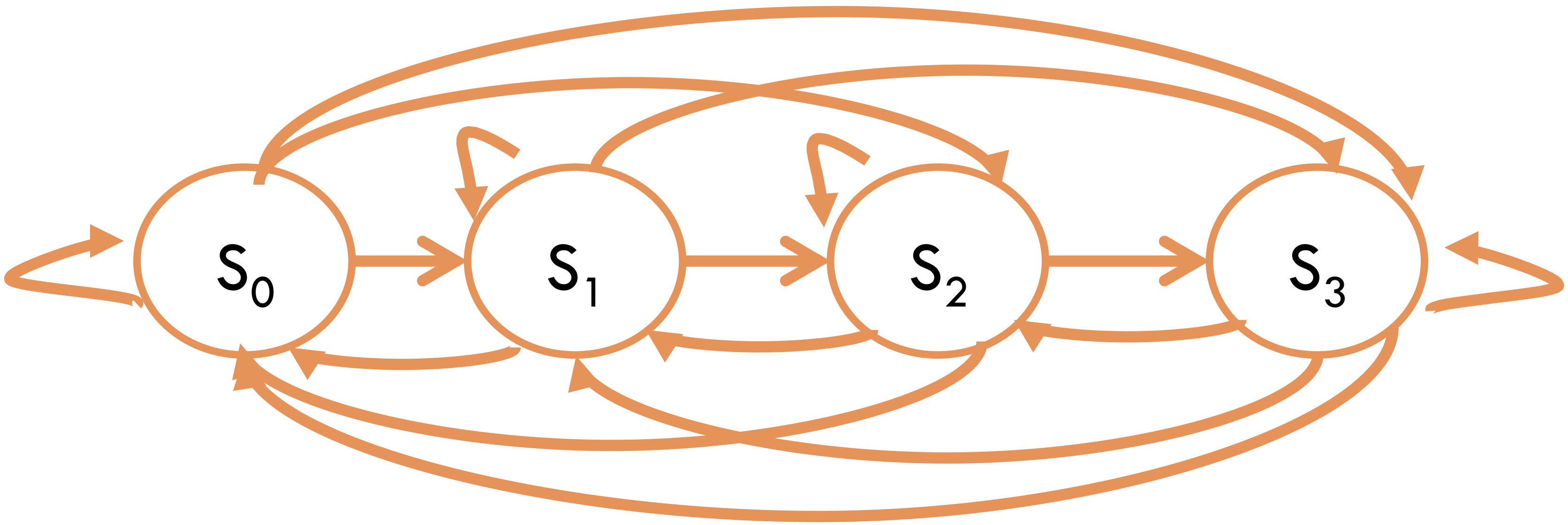
Symbol switching times for our PAM



Observations

- In our setting, symbol periods are dominated by symbol switching times
- We can play with symbol margin (α) and symbol length (k_d) to better balance the timing
  - Larger α → shorter transient → more noisy droplet lengths/distances → higher error probability → longer k_d to compensate → longer symbol period
- We can play with channel coding to improved bitrate

Source model



$$\mathbf{P} = \begin{bmatrix} P_{0,0} & P_{0,1} & P_{0,2} & P_{0,3} \\ P_{1,0} & P_{1,1} & P_{1,2} & P_{1,3} \\ P_{2,0} & P_{2,1} & P_{2,2} & P_{2,3} \\ P_{3,0} & P_{3,1} & P_{3,2} & P_{3,3} \end{bmatrix} \overset{t\to\infty}{\Rightarrow} \pi = [\pi(0), \pi(1), \pi(2), \pi(3)]$$

Mean source bitrate

Mean number of information bits per symbol

$$I = \sum_{h=0}^{m-1} -\pi(h)\log_2(\pi(h))$$

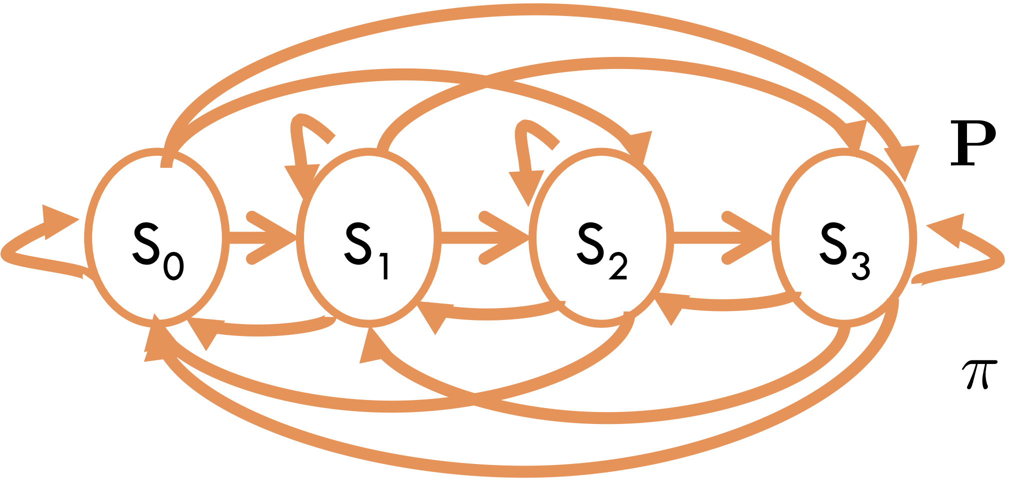
Mean symbol duration (included transition to next symbol)

$$T = \sum_{h=0}^{m-1} \pi(h) \sum_{j=0}^{m-1} P_{j,h}(T_d(h) + \Delta(S_h \to S_j))$$

Mean source bitrate

$$R = \frac{I}{T}$$

4 PAM balanced



$$\mathbf{P} = \begin{bmatrix} 0.25 & 0.25 & 0.25 & 0.25 \\ 0.25 & 0.25 & 0.25 & 0.25 \\ 0.25 & 0.25 & 0.25 & 0.25 \\ 0.25 & 0.25 & 0.25 & 0.25 \end{bmatrix}$$

$$\pi = [0.25,\ 0.25,\ 0.25,\ 0.25]$$

I = 2 bits/symbol

T ~ 136.3 s/symbol

R ~ 0.0147 bit/s= 0.880 bit/min

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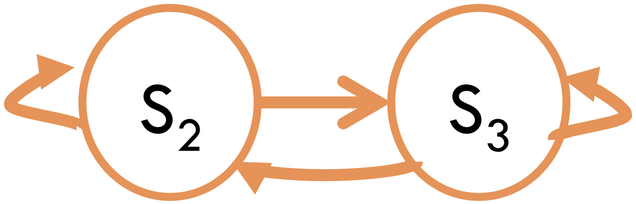
2 PAM balanced



$$\mathbf{P} = \begin{bmatrix} 0.5 & 0.5 \\ 0.5 & 0.5 \end{bmatrix}$$

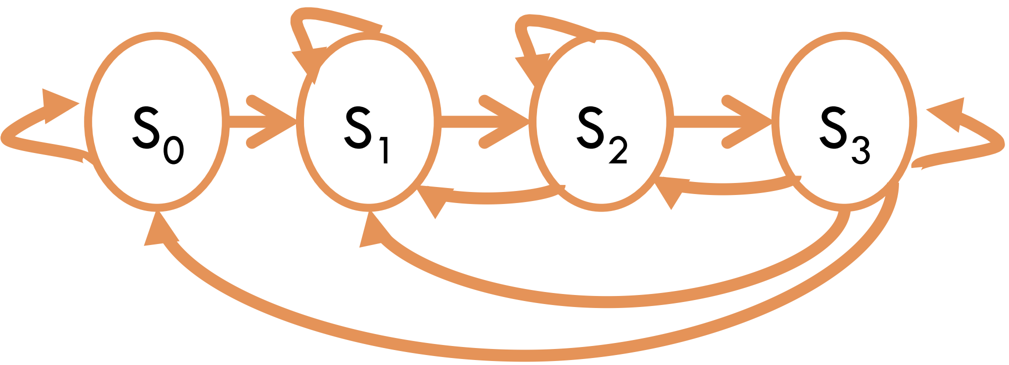
$$\pi = [0.5,\ 0.5]$$

I = 1 bits/symbol

T ~ 60.97 s/symbol

R ~ 0.0164 bit/s=0,984 bit/min

4 PAM unbalanced



$$\mathbf{P} = \begin{bmatrix} 0.5 & 0.5 & 0 & 0 \\ 0 & 0.5 & 0.5 & 0 \\ 0 & 0 & 0.5 & 0.5 \\ 0.1 & 0.1 & 0.3 & 0.5 \end{bmatrix}$$

$$\pi = [0.0769,\ 0.1538,\ 0.3846,\ 0.3846]$$

I = 1.76 bits/symbol

T ~ 72.0 s/symbol

R ~ 0.0245 bit/s=1,467 bit/min

Wrapping up

- This work:
  - investigated the feasibility of extending communication concept to microfluidics
  - implemented basic modulation technique based on length/interdistance
  - evaluated system performance with experimental data
    - Both droplet length and inter-droplet distance can carry information bits
    - Inter-distance is generally preferable BUT, in complex network, it can vary as droplets stream along the channels
      - See Biral & Zanella, NanoComNet 2013
    - Source bitrate depends on transmitted sequence!!!

Looking forward…

- optimal setting of parameters to maximize PAM bitrate
- more sophisticated modulations
  - Combining length and distance
  - Using other circuits to dynamically change droplet inter-distance
- consider other performance indexes
  - delay, energy consumption

- **Figure out a possible application scenario!!!**

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And YES... you can publish this stuff!

- W. Haselmayr, A. Biral, A. Grimmer, A. Zanella, R. Wille, A. Springer, "Addressing Multiple Nodes in Networked Labs-on-Chips without Payload Re-injection" in the Proceedings of the 2017 International Conference on Communications (ICC) Paris, France, 21-25 May 2017
- A. Biral, D. Zordan, A. Zanella, "Modeling, simulation and experimentation of droplet-based microfluidic networks" IEEE Transactions on Molecular, Biological, and Multi-Scale Communications, vol. 1, no. 2, pp. 122-134, June 2015.
- A. Biral, A. Zanella, "Introducing purely hydrodynamic networking functionalities into microfluidic systems" Nano Communication Networks, Elsevier, vol. 4, n0. 4, pp 205-215, 2013. DOI: 10.1016/j.nancom.2013.09.00
- Andrea Biral, Andrea Zanella (2013). Introducing purely hydrodynamic networking mechanisms in microfluidic systems. In: 2013 IEEE International Conference on Communications Workshops (ICC). p. 798-803, ISBN: 9781467357531, Budapest, Hungary, 9-13 June 2013
- A. Biral, D. Zordan, A. Zanella, "Simulating macroscopic behavior of droplet-based microfluidic systems" in the Proceedings of IEEE Global Communications Conference Dec. 6-10, 2015, San Diego, CA, USA
- A. Biral, D. Zordan, A. Zanella, "Transmitting information with microfluidic systems" in the Proceedings of the IEEE International Conference on Communications (ICC 2015), June 8-12, 2015, London, UK.
- A. Zanella, A. Biral, "Design and Analysis of a Microfluidic Bus Network with Bypass Channels" in the Proceedings of IEEE ICC 2014 10-14 June, 2014, Sydney, Australia.

"When bits get wet" A Microfluidic Communication Link: Definition, Analysis and Experimentation

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Any questions?