A Two-Stage ILP-Based Droplet Routing Algorithm For Pin-Constrained Digital Microfluidic Biochips

2010 ACM International Symposium on Physical Design (ISPD'10)

Tsung-Wei Huang and Tsung-Yi Ho
http://eda.csie.ncku.edu.tw
Department of Computer Science and Information Engineering
National Cheng Kung University
Tainan, Taiwan

Outline

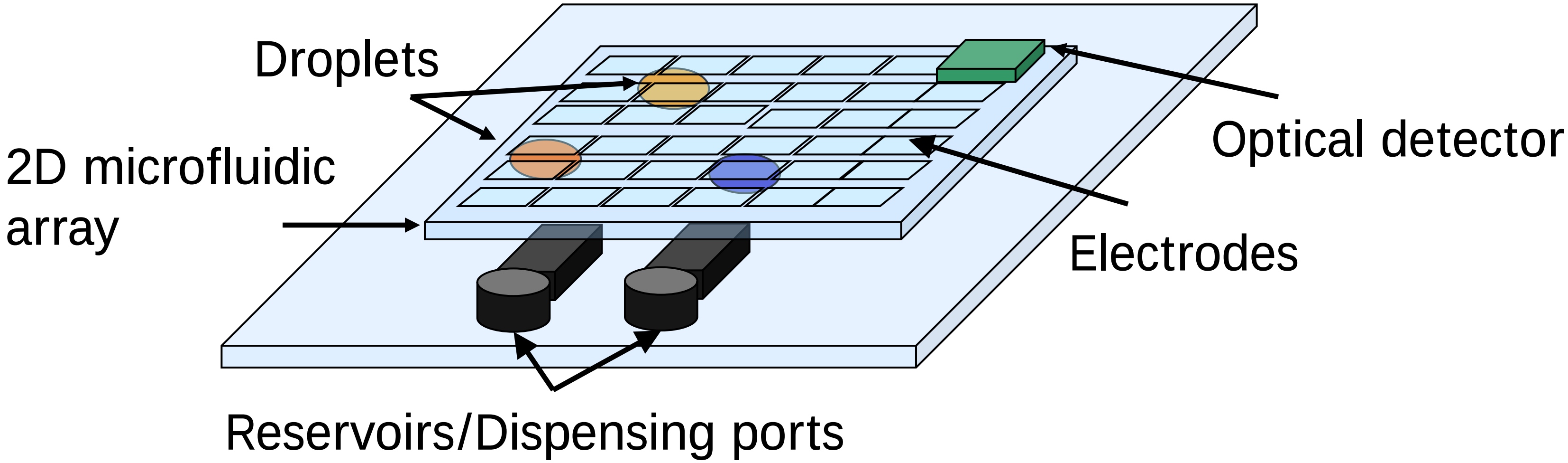
- Introduction
- Problem formulation
- Our contribution
- Basic ILP formulation
- Deterministic ILP formulation
- Experimental results
- Conclusion

Outline

- Introduction
  - Digital microfluidic biochips
  - Pin-constrained digital microfluidic biochips
  - Previous work and limitations
- Our contribution
- Problem formulation
- Basic ILP formulation
- Deterministic ILP formulation
- Experimental results
- Conclusion

Digital Microfluidic Biochips (DMFBs) (1/2)

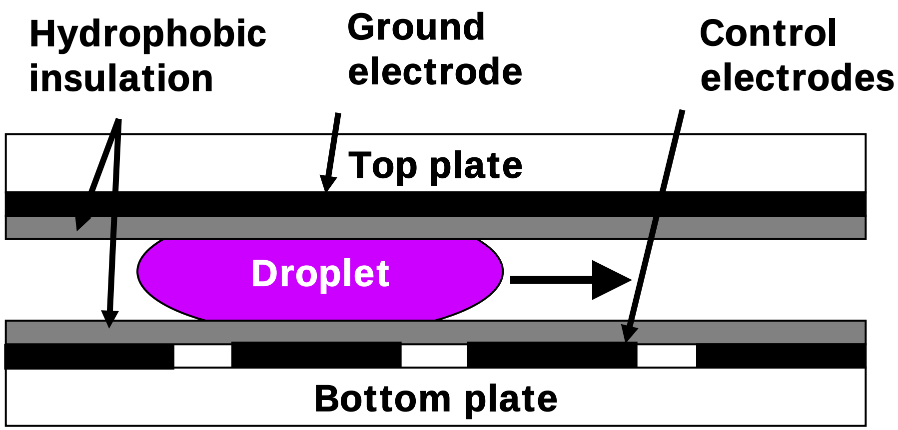
- Three main components:
  - **2D microfluidic array:** set of basic cells for biological reactions
  - **Reservoirs/dispensing ports:** for droplet generation
  - **Optical detectors:** detection of reaction result
- Perform laboratory procedures based on ***droplets***
  - **Droplet:** biological sample carrier



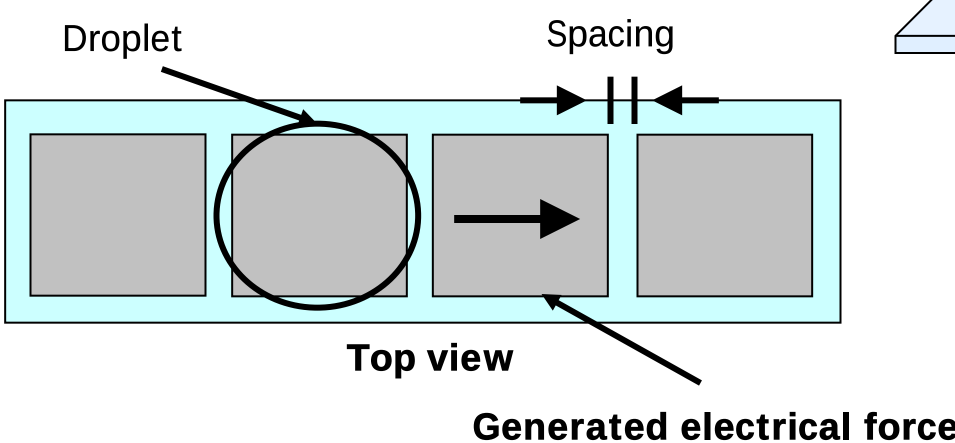
The schematic view of a biochip (Duke Univ.)

Digital Microfluidic Biochips (DMFBs) (2/2)

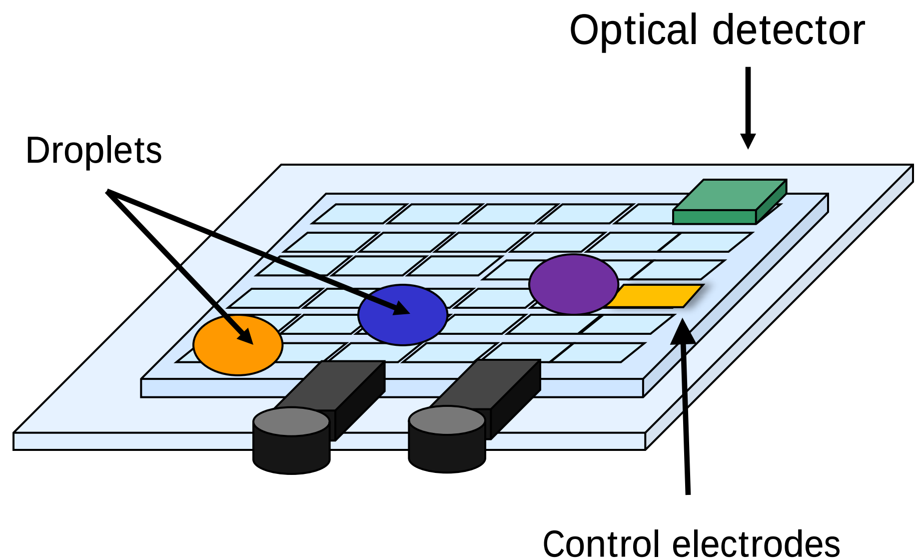
- Movement control of a droplet



Side view



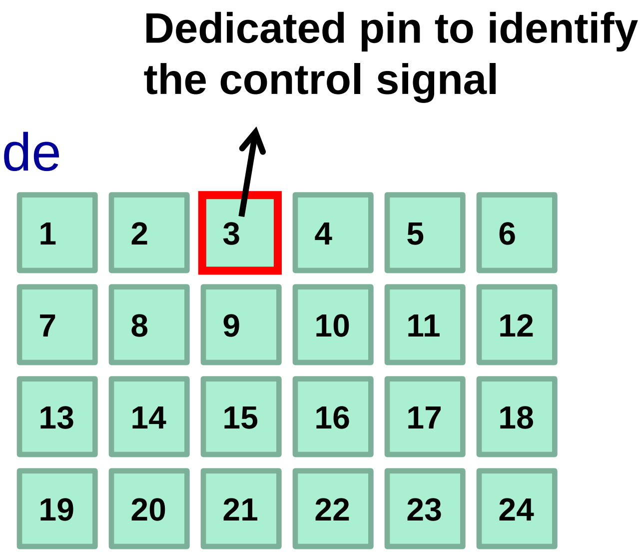
Top view



Pin-Constrained Digital Microfluidic Biochips

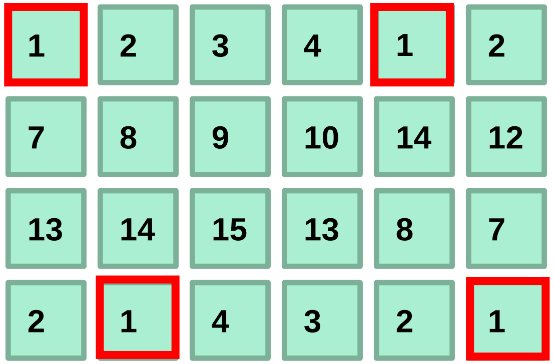
- Direct-addressing biochips
  - Dedicated control pin for each electrode
  - Maximum freedom of droplets
  - High demanded control pins

Control pins: 24



- Broadcast-addressing biochips *
  - A control pin can be shared by multiple electrodes
  - Flexible for pin-constrained DMFBs
  - Control pin sharing

Control pins: 15



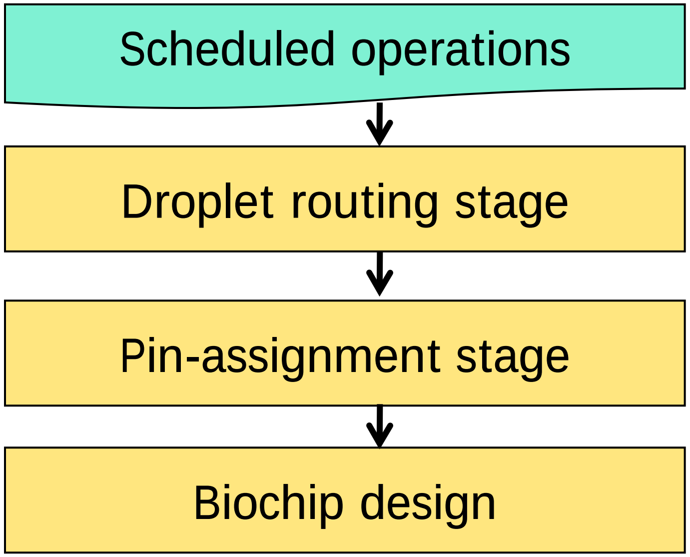
* [T. Xu and K. Chakrabarty, DAC’08]

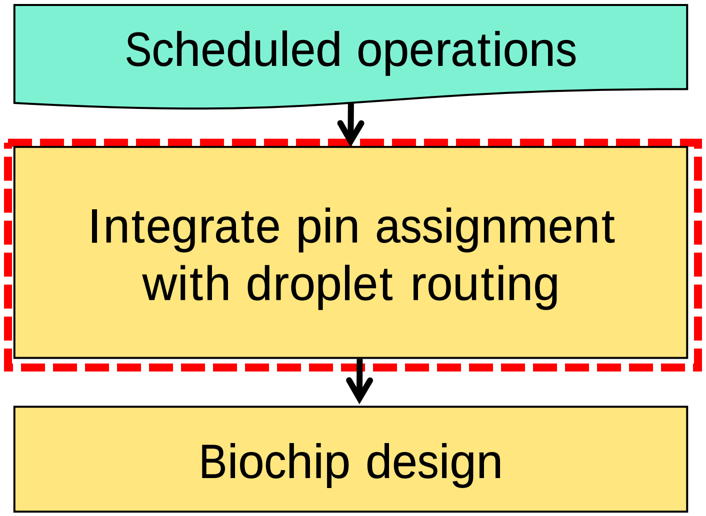
Previous Work and Limitation (1/2)

- Droplet routing algorithms
  - Droplet routing in the synthesis of digital microfluidic biochips
    [Su et al, DATE'06]
  - Modeling and controlling parallel tasks in droplet based microfluidic systems
    [K. F. Böhringer, TCAD'06]
  - A network-flow based routing algorithm for digital microfluidic biochips
    [Yuh et al, ICCAD'07]
  - Integrated droplet routing in the synthesis of microfluidic biochips
    [T. Xu and K. Chakrabarty, DAC'07]
  - A high-performance droplet routing algorithm for digital microfluidic biochips
    [Cho and Pan, ISPD'08]
- Pin-constrained digital microfluidic biochips
  - Droplet-trace-based array partition and a pin assignment algorithm for the automated design of digital microfluidic biochips
    [T. Xu and K. Chakrabarty, CODES+ISSS'06]
  - Broadcast electrode-addressing for pin-constrained multi-functional digital microfluidic biochips
    [T. Xu and K. Chakrabarty, DAC'08]

Previous Work and Limitation (2/2)

- Limitations
  - Separately consider the routing stage and the pin-assignment stage
  - The solution quality is limited
    - **# of Control pins**
    - **# of Used cells**
    - **Execution time**





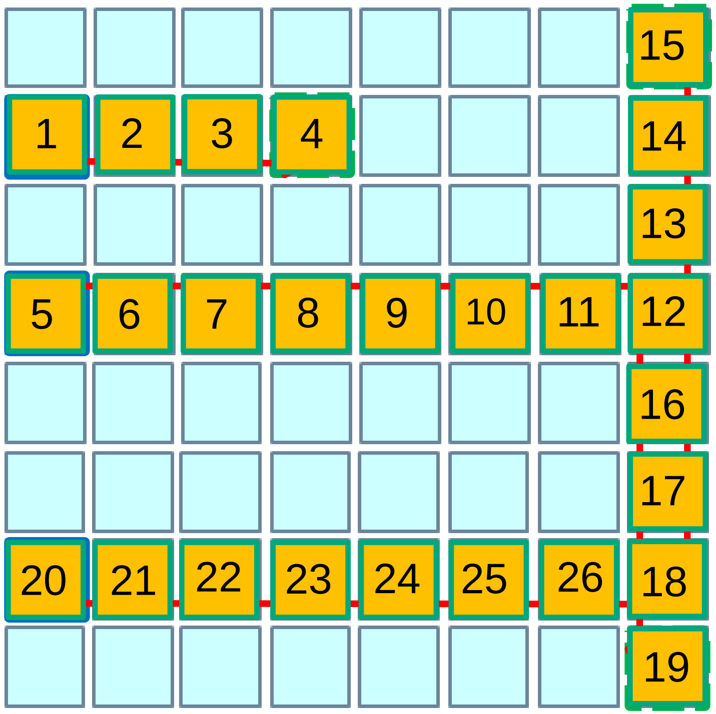
Ours integrated method **simultaneously** minimizes the # of control pins, # of used cells, and execution time for pin-constrained DMFBs.

Outline

- Introduction
- Our contribution
- Problem formulation
- Basic ILP formulation
- Deterministic ILP formulation
- Experimental results
- Conclusion

Previous Method – Direct Addressing

- Apply the direct addressing to a routing result
  - Separate pin assignment stage and routing stage

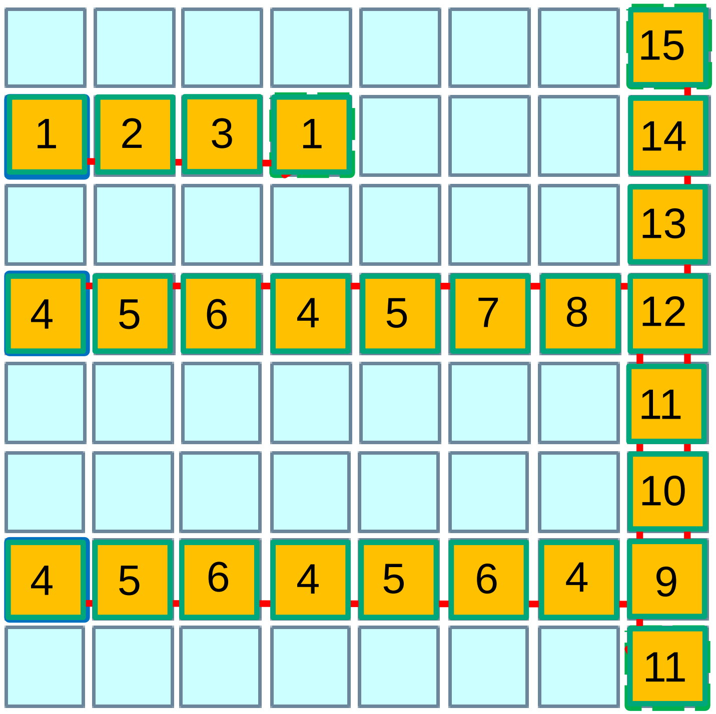


Control Pins: 26
Used Cell: 26
execution time: 18

# of control pins = # of used cells

Previous Method (1/2) – Broadcast Addressing

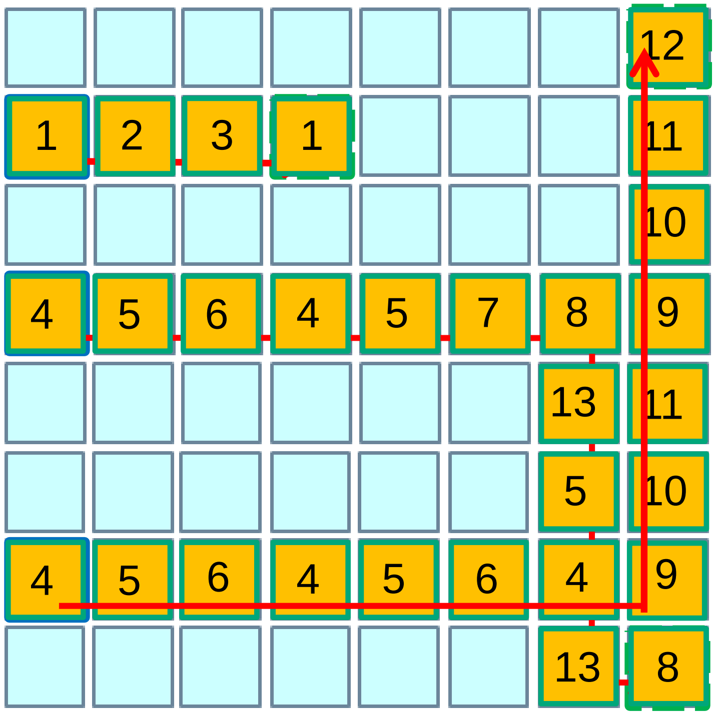
- Apply the broadcast addressing to a routing result
  - Separate pin assignment stage and routing stage



Control Pins: 15
Used Cell: 26
execution time: 18

Previous Method (2/2) – Broadcast Addressing

- Simply **integrate** the broadcast addressing with droplet routing



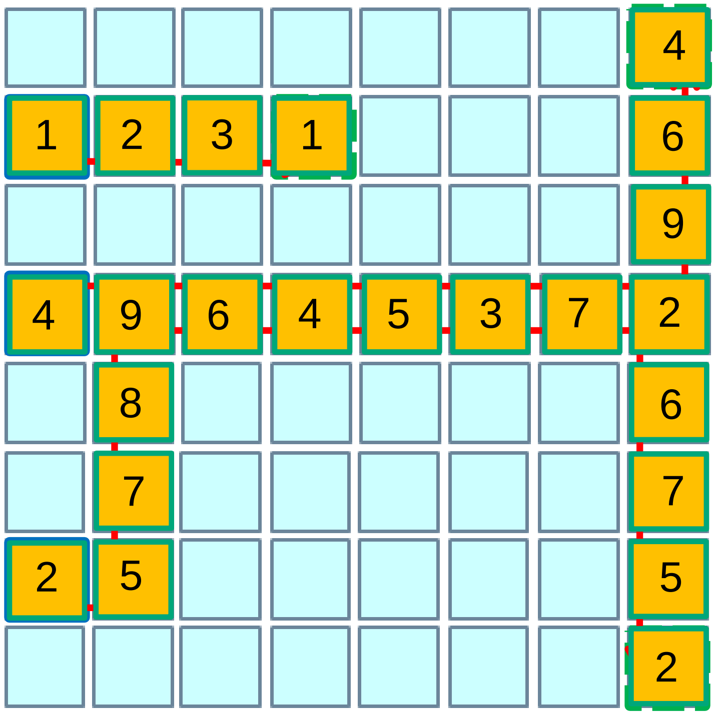
Control Pins: 15
Used Cell: 26
execution time: 18

Control Pins: 13
Used Cell: 29
execution time: 20

May increase the # of used cells and execution time

Ours (1/2)

- Integrate broadcast addressing with droplet routing while simultaneously minimizing the # of control pins, # of used cells, and execution time



Control Pins: 15
Used Cell: 26
execution time: 18

Control Pins: 13
Used Cell: 29
execution time: 20

Control Pins: 9
Used Cell: 23
execution time: 15

Minimized # of control pins
Minimized # of used cells
Minimized execution time

Ours (2/2)

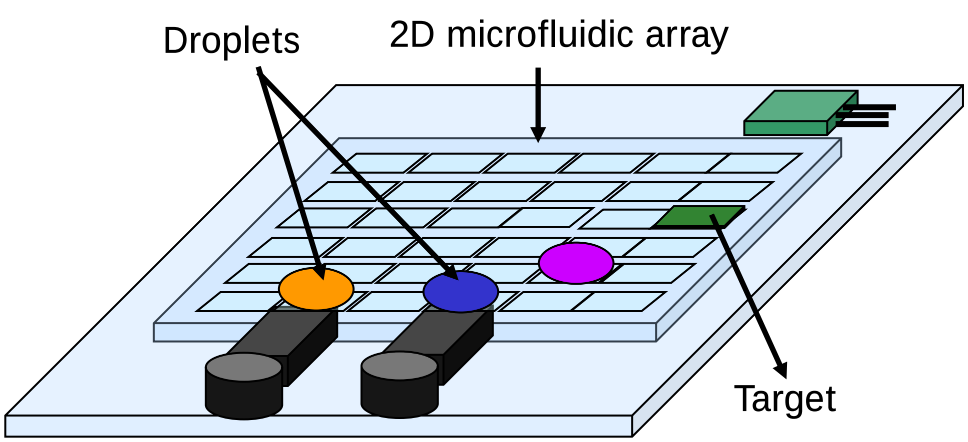
- Contributions:
  - We propose the first algorithm that integrates the broadcast-addressing with droplet routing problem, while simultaneously minimizing the # of control pins, # of used cells, and execution time
  - A basic ILP formulation is introduced to obtain an optimal solution
  - A two-stage ILP-based algorithm is presented to tackle the complexity of the basic ILP formulation

Outline

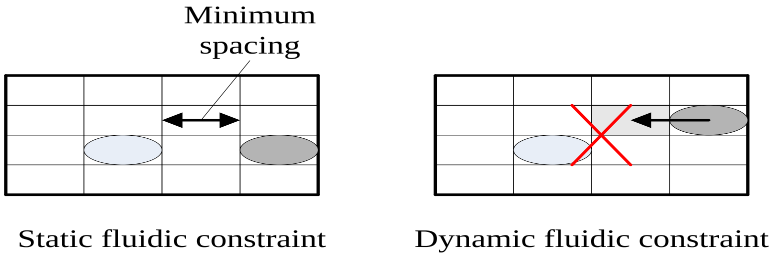
- Introduction
- Our contribution
- Problem formulation
- Basic ILP formulation
- Deterministic ILP formulation
- Experimental results
- Conclusion

Problem Formulation

- **Input:** A netlist of *n droplets* $D = \{d_1, d_2, \ldots, d_n\}$, *the* locations of modules
- **Objective:** Route all droplets from their source cells to their target cells while ***minimizing the # of control pins, # of used cells, and execution time*** for high throughput designs
- **Constraint:** Fluidic and timing constraints should be satisfied.



- **Fluidic constraint**



- **Timing constraint**
  - **Maximum available executed time**

Outline

- Introduction
- Problem formulation
- Our contribution
- Basic ILP formulation
  - Objective function
  - Basic constraints
  - Electrode constraints
  - Broadcast-addressing constraints
  - Limitations
- Deterministic ILP formulation
- Experimental results
- Conclusion

Objective Function

- Objective function
  - Minimize the # of control pins (product cost)
  - Minimize the # of used cells (fault-tolerance)
  - Minimize the execution time (reliability)

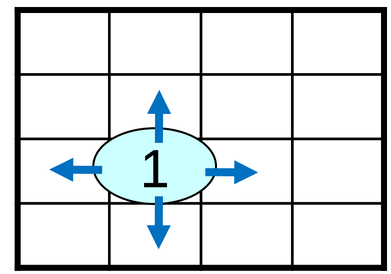
$$Minimize: \alpha \sum up(p) + \beta \sum uc(x, y) + \gamma T_l$$

# of control pins **# of used cells** **execution time**

where α, β, and γ are user-defined parameters

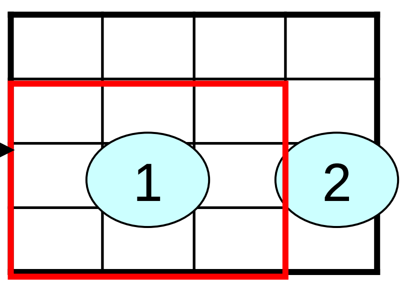
Basic Constraints

- Source/target requirement
  - All droplets locate at their sources at time zero
  - A droplet stays at its target once reaching it
- Exclusive constraint
  - Each droplet has only one location at a time step
- Droplet movement constraint
  - A droplet can move to four adjacent cells or stall

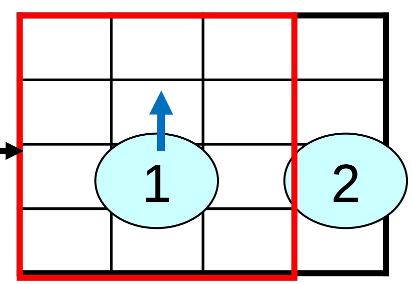


- Static/dynamic fluidic constraint
  - No other droplets are in the 3x3 region centered by a droplet **at time t / within t ~ t+1**

Static fluidic constraint



Dynamic fluidic constraint



Electrode Constraints (1/2)

- Electrode constraints
  - To model the control of droplets by turning on/off the actuation voltage of electrodes
- Activation type
  - **“1”** represents the activated electrode **(turn on)**
  - **“0”** represents the deactivated electrode **(turn off)**
  - **“X”** represents the don’t care (both “1” and “0” are legal)
- Formulation technique
  - Extract the cells that **“must-be-activated”**
  - Extract the cells that **“must-be-deactivated”**

Electrode Constraints (2/2)

- Illustration

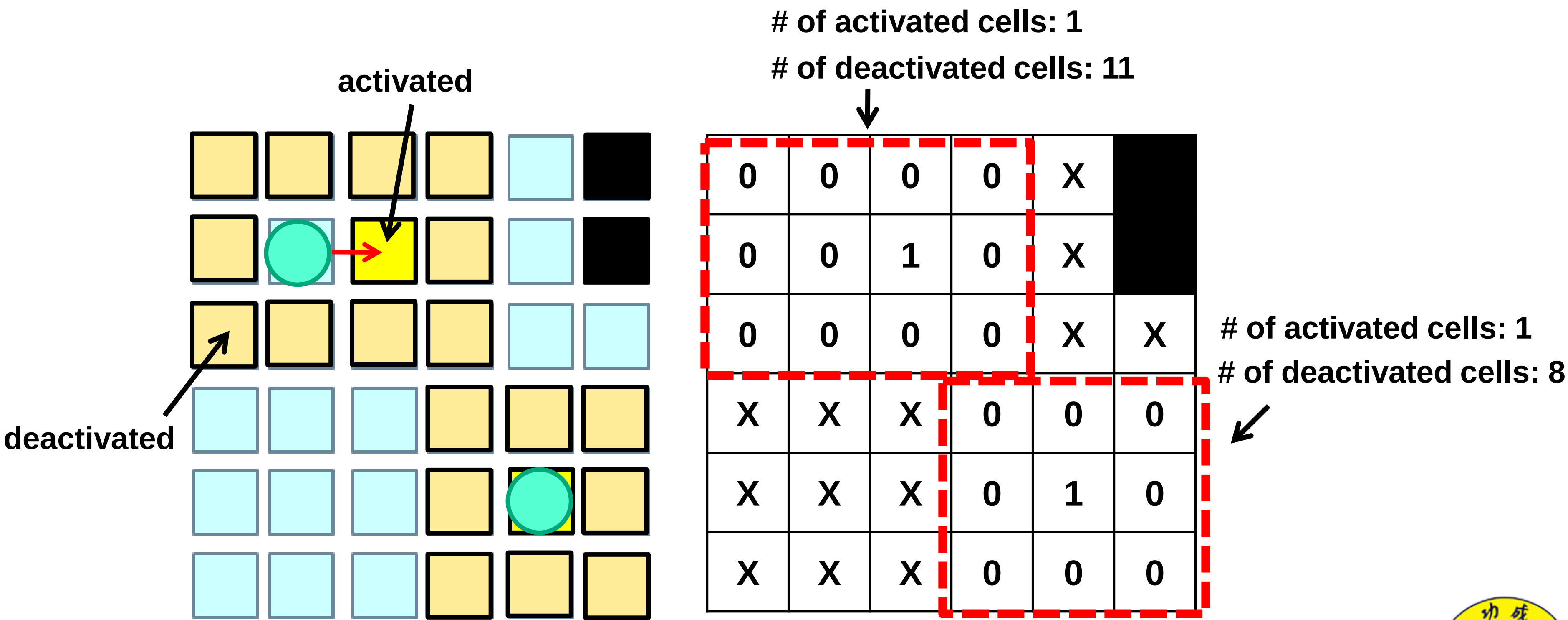
Must be deactivated(0)

Must be activated (1)

Blockage

Droplet

Don’t care (X)



Broadcast-Addressing Constraints

- Broadcast-addressing constraints
  - Model the pin assignment by “compatible” activation sequences

Electrode	E_1	E_2	E_3	E_4	E_5	E_6	E_7	E_8	E_9	E_{10}	E_{11}	E_{12}
Activation sequence	1	1	0	0	0	X	X	0	X	X	X	X
	0	0	1	1	1	0	0	1	X	X	X	X
	0	0	0	0	0	1	1	0	0	0	X	X
	X	X	0	0	0	0	0	0	1	1	0	0
	X	X	X	X	1	0	0	1	X	X	1	1

Merge: E_4 and E_5 0100X+01001 → 01001

Pin-assignment result		
Pin	Electrodes	Merged activation sequence
1	E_4, E_5	0 1 0 0 1

or

Pin-assignment result		
Pin	Electrodes	Merged activation sequence
1	E_4	0 1 0 0 X
2	E_5	0 1 0 0 1

Merge: E_5 and E_6 01001+X0100 → Invalid

Limitations

- Pros and cons
  - Advantage: ***an optimal solution***
  - Drawback: ***only feasible to small applications***
- Multi-objectives optimization
  - Simultaneously consider the optimization of the #of control pins, # of used cells, and execution time
  - Introduce a high solution space
- Many formulation constraints
  - High # of variables
  - High # of constraints

Outline

- Introduction
- Problem formulation
- Our contribution
- Basic ILP formulation
- Deterministic ILP formulation
  - Two-stage ILP-based routing algorithm
- Experimental results
- Conclusion

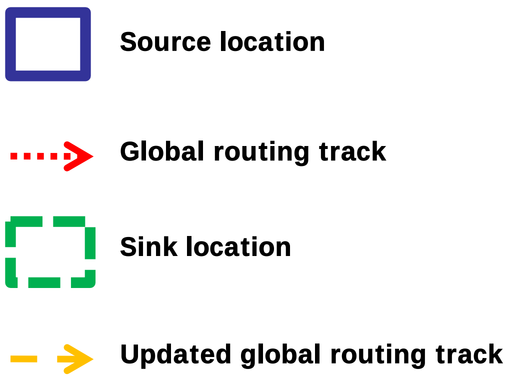
Two-Stage ILP-Based Routing Algorithm

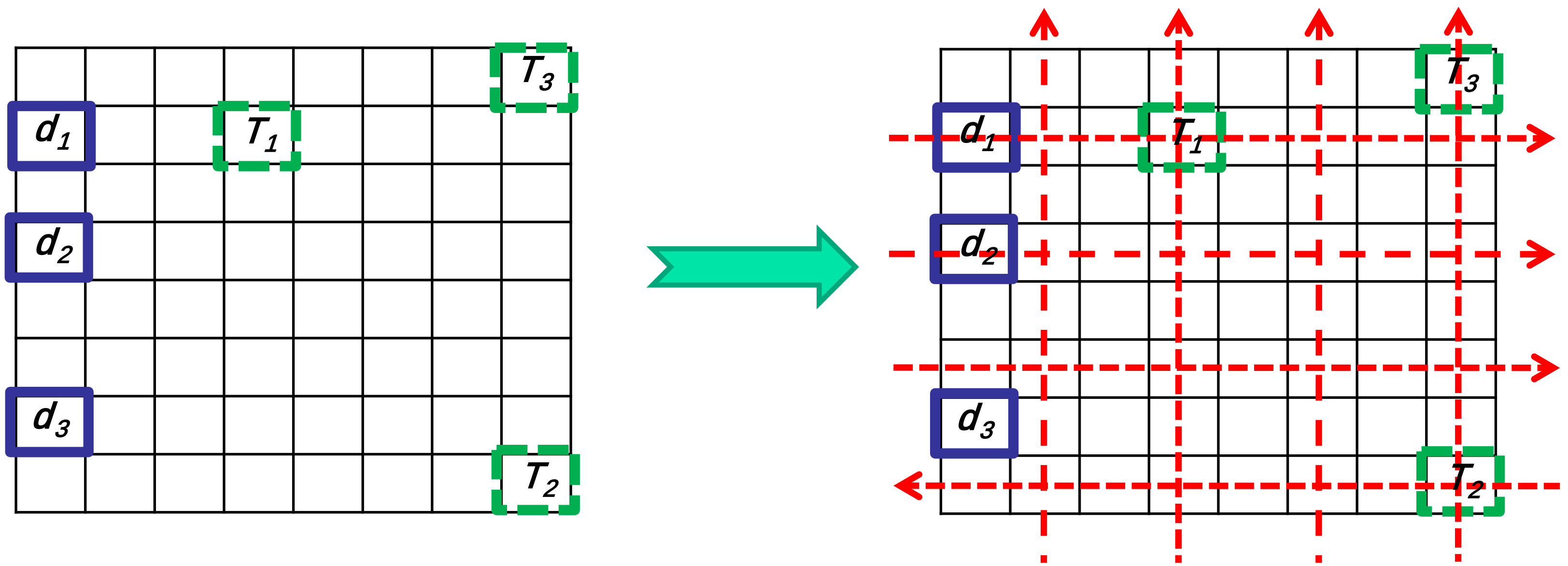
- First stage
  - Major goal: **reduce the solution space**
  - Global routing
    - Obtain an initial routing paths

- Second stage
  - Major goal: **accelerate the searching time**
  - Incremental ILP-based routing method
    - Iteratively select an un-routed droplet
    - Route this droplet with previous routing solutions

Global Routing

- Global routing
  - Preferred routing tracks construction
    - Reduce the design complexity
  - A* maze search for min-cost routing path
    - Orderly routing along these tracks
    - Minimized used cells





T.-W. Huang, C.-H. Lin and T.-Y. Ho, " A Contamination Aware Droplet Routing Algorithm for Digital Microfluidic Biochips," *Proceedings of ACM/IEEE ICCAD 2009*

Incremental ILP-Based Routing (1/3)

- Net criticality calculation
  - Determine the routing order globally
    - Consider the interferences and congestion issue between droplets
    - A droplet d_i is said to be critical if d_i has fewer possible routing solutions

$$crit(d_i) = \frac{(|E_b^i| + |E_s^i|) - |E_t^i|}{|BB_i|}$$

$$E_b^i = \{c \mid c \in E_b \cap BB_i\}$$

$$E_s^i = \{c \mid c \in E_{s_j} \cap BB_i, \forall d_j \in D / d_i\}$$

$$E_t^i = \{c \mid c \in E_{t_j} \cap BB_i, \forall d_j \in D / d_i\}$$

Incremental ILP-Based Routing (2/3)

- Deterministic ILP
  - Select an un-routed droplet
  - Routing resources: ***M_i***
    - Maximum available routing time T_l^i
    - Maximum available control pins P_l^i
  - Increasing scalar: ***IS***
    - Growth rate of routing resources

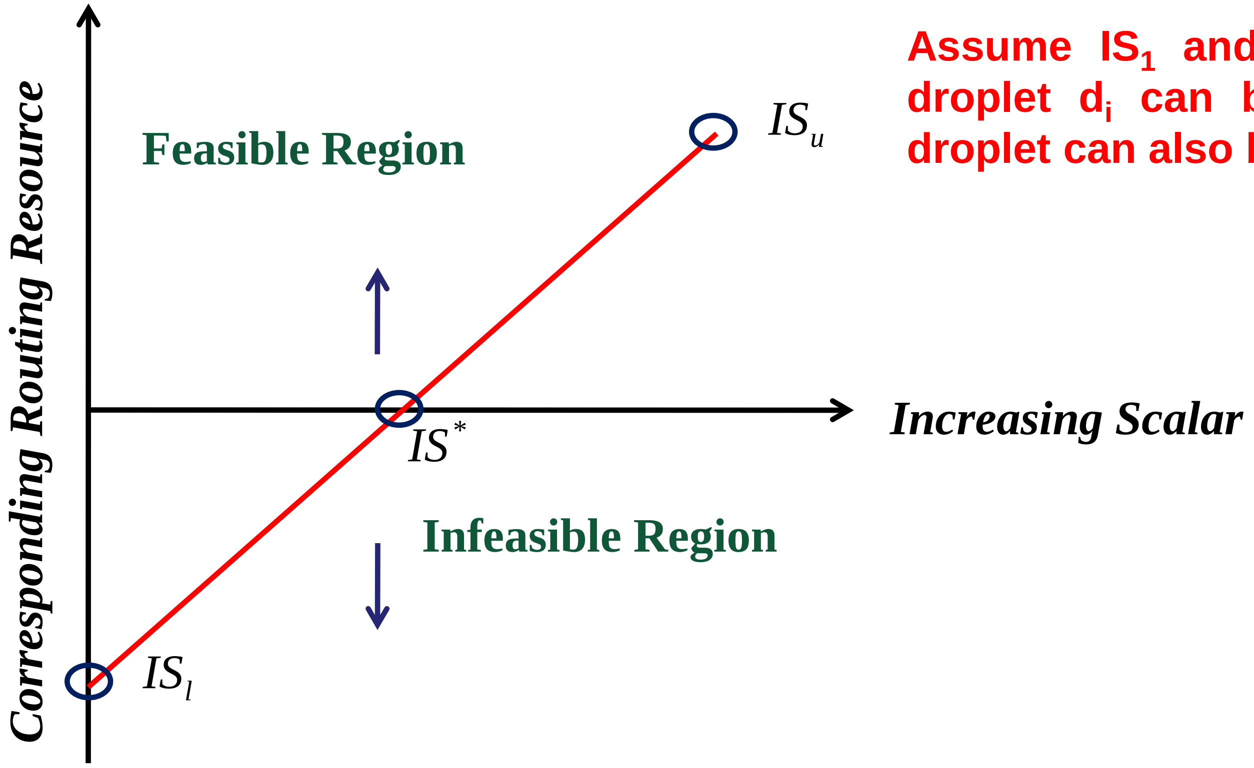
$$M_i = (T_l^i + \sigma_1 IS) + (P_l^i + \sigma_2 IS)$$

  - Major goal:
    - Determine the feasibility with the given routing resources
    - Objective function:

$$Minimize : c$$

Incremental ILP-Based Routing (3/3)

- Monotonic property
  - Binary solution search method
  - Logarithmic number of searching iterations



Assume IS_1 and IS_2 where $IS_1 < IS_2$, if droplet d_i can be routed with IS_1, then droplet can also be routed with IS_2

Outline

- Introduction
- Problem formulation
- Our contribution
- Basic ILP formulation
- Deterministic ILP formulation
- Experimental results
- Conclusion

Experimental Results (1/5)

- Implement our algorithm in C++ language on a 2 GHz 64-bit Linux machine with 16GB memory

- Compare with
  - Network flow algorithm [P.-H Yuh et al, ICCAD'07]
  - High performance [M. Cho and D. Z. Pan, TCAD'08]

- Statistic of benchmarks

Benchmark	Size	#Sub	T_{max}	#Nets	$\#D_{max}$
vitro_1	16 X 16	11	20	28	5
vitro_2	14 X 14	15	20	35	6
protein_1	21 X 21	64	20	181	6
protein_2	13 X 13	78	20	178	6

■ Size: size of microfluidic array. ■ #Sub: # of subproblems. ■ T_{max}: timing constraint.
■ #Nets: total # of nets. ■ $\#D_{max}$: maximum # of droplets among subproblems.

Experimental Results (2/5)

- Comparison of the # of control pins

Benchmark	Direct Addressing		Broadcast Addressing		Two-Stage ILP		
	[11]	[4]	[11]+[10]	[4]+[10]	[11]+IILP	[4]+IILP	Ours
	P_{avg}	P_{avg}	P_{avg}	P_{avg}	P_{avg}	P_{avg}	P_{avg}
vitro_1	21.55	23.45	9.48	10.11	9.11	9.49	4.51
vitro_2	15.73	16.40	8.95	10.64	8.03	9.21	5.01
protein_1	25.28	26.38	9.52	10.55	8.54	9.25	5.43
protein_2	12.03	12.35	8.73	8.55	7.72	7.38	4.43
	3.82	4.03	1.90	2.06	1.73	1.83	1

[4] M. Cho and D. Z. Pan, “A high-performance droplet routing algorithm for digital microfluidic biochips,” IEEE Trans. on CAD, vol. 27, no. 10, pp. 1714-1724, Oct. 2008.

[10] T. Xu and K. Chakrabarty, “Broadcast electrode-addressing for pin-constrained multi-functional digital microuidic biochips," Proc. IEEE/ACM DAC, pp. 173-178, Jun. 2008.

[11] P.-H. Yuh, C.-L. Yang, and Y.-W. Chang, “BioRoute: A network-flow based routing algorithm for digital microfluidic biochips,” Proc. IEEE/ACM ICCAD, pp. 752-757, Nov. 2007.

Experimental Results (3/5)

- Comparison of the # of used cells

Benchmark	Direct Addressing		Broadcast Addressing		Two-Stage ILP		
	[11]	[4]	[11]+[10]	[4]+[10]	[11]+IILP	[4]+IILP	Ours
	U.C.	U.C.	U.C.	U.C.	U.C.	U.C.	U.C.
vitro_1	237	258	237	258	231	243	231
vitro_2	236	246	236	246	231	229	229
protein_1	1618	1688	1618	1688	1597	1627	1582
protein_2	939	963	939	963	927	943	930
	1.02	1.07	1.02	1.07	1.00	1.02	1

[4] M. Cho and D. Z. Pan, "A high-performance droplet routing algorithm for digital microfluidic biochips," IEEE Trans. on CAD, vol. 27, no. 10, pp. 1714-1724, Oct. 2008.

[10] T. Xu and K. Chakrabarty, "Broadcast electrode-addressing for pin-constrained multi-functional digital microuidic biochips," Proc. IEEE/ACM DAC, pp. 173-178, Jun. 2008.

[11] P.-H. Yuh, C.-L. Yang, and Y.-W. Chang, "BioRoute: A network-flow based routing algorithm for digital microfluidic biochips," Proc. IEEE/ACM ICCAD, pp. 752-757, Nov. 2007.

Experimental Results (4/5)

- Comparison of the execution time

Benchmark	Direct Addressing		Broadcast Addressing		Two-Stage ILP		
	[11]	[4]	[11]+[10]	[4]+[10]	[11]+IILP	[4]+IILP	Ours
	Avg. T_l	Avg. T_l	Avg. T_l	Avg. T_l	Avg. T_l	Avg. T_l	Avg. T_l
vitro_1	13.00	14.30	13.00	14.30	12.47	13.55	12.41
vitro_2	11.33	12.00	11.33	12.00	11.01	11.48	10.46
protein_1	16.31	16.55	16.31	16.55	16.08	15.44	15.42
protein_2	10.51	12.19	10.51	12.19	10.33	11.52	10.22
	1.05	1.14	1.05	1.14	1.03	1.08	1

[4] M. Cho and D. Z. Pan, "A high-performance droplet routing algorithm for digital microfluidic biochips," IEEE Trans. on CAD, vol. 27, no. 10, pp. 1714-1724, Oct. 2008.

[10] T. Xu and K. Chakrabarty, "Broadcast electrode-addressing for pin-constrained multi-functional digital microuidic biochips," Proc. IEEE/ACM DAC, pp. 173-178, Jun. 2008.

[11] P.-H. Yuh, C.-L. Yang, and Y.-W. Chang, "BioRoute: A network-flow based routing algorithm for digital microfluidic biochips," Proc. IEEE/ACM ICCAD, pp. 752-757, Nov. 2007.

Experimental Results (5/5)

- Comparison of the runtime

Benchmark	Basic ILP	[11]+IILP	[4]+IILP	Ours
	CPU (min)	CPU (sec)	CPU (sec)	CPU (sec)
vitro_1	> 7200	14.33	15.31	10.11
vitro_2	> 7200	16.49	18.38	8.32
protein_1	> 7200	28.43	34.51	30.13
protein_2	> 7200	22.16	28.33	21.38
	N.C.	1.34	1.55	1

[4] M. Cho and D. Z. Pan, “A high-performance droplet routing algorithm for digital microfluidic biochips,” IEEE Trans. on CAD, vol. 27, no. 10, pp. 1714-1724, Oct. 2008.

[10] T. Xu and K. Chakrabarty, “Broadcast electrode-addressing for pin-constrained multi-functional digital microuidic biochips," Proc. IEEE/ACM DAC, pp. 173-178, Jun. 2008.

[11] P.-H. Yuh, C.-L. Yang, and Y.-W. Chang, “BioRoute: A network-flow based routing algorithm for digital microfluidic biochips,” Proc. IEEE/ACM ICCAD, pp. 752-757, Nov. 2007.

Outline

- Introduction
- Problem formulation
- Our contribution
- Basic ILP formulation
- Deterministic ILP formulation
- Experimental results
- Conclusion

Conclusion

- We proposed the first algorithm that integrates the broadcast-addressing with the droplet routing problem while simultaneously minimizing the # of control pins, # of used cells, and execution time

- A basic ILP formulation is introduced to optimally solve this problem

- A two-stage ILP-based routing algorithm is also presented to tackle the complexity of the basic ILP formulation

- Experimental results demonstrate that our algorithm achieves the best results in terms of the # of control pins, # of used cells, and execution time.

Thank You for Your Attention!