Hamming-Distance-Based Valve-Switching Optimization for Control-Layer Multiplexing in Flow-Based Microfluidic Biochips

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Outline

- Background
- Problem Formulation
- Contributions
- Hamming-Distance-Based Valve-Switching
- Experimental Results
- Summary

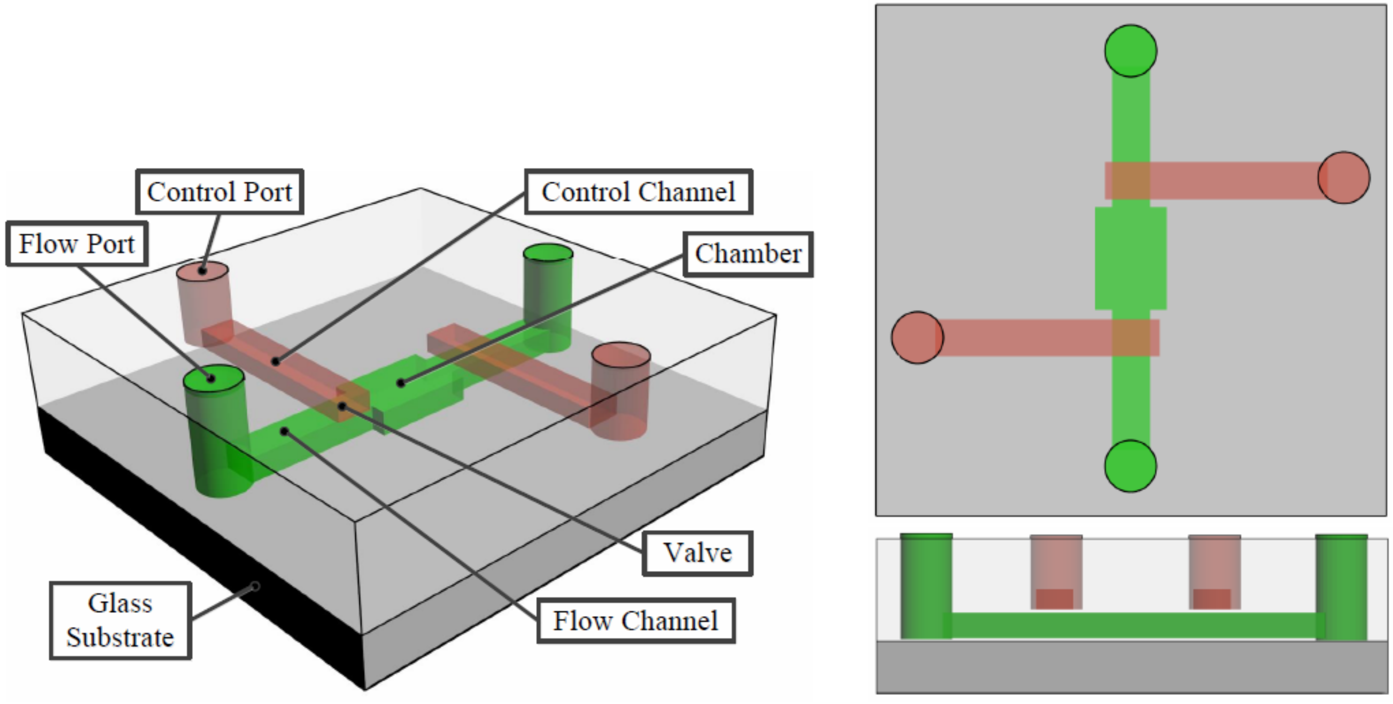
Flow-Based Microfluidic Biochips

- One of the many different types of biochips
- Based on multilayer soft lithography technology
- Functional units are fabricated by elastomer material (polydimethylsiloxane, PDMS)

http://groups.csail.mit.edu/cag/biostream/

Schematic of Flow-Based Biochips

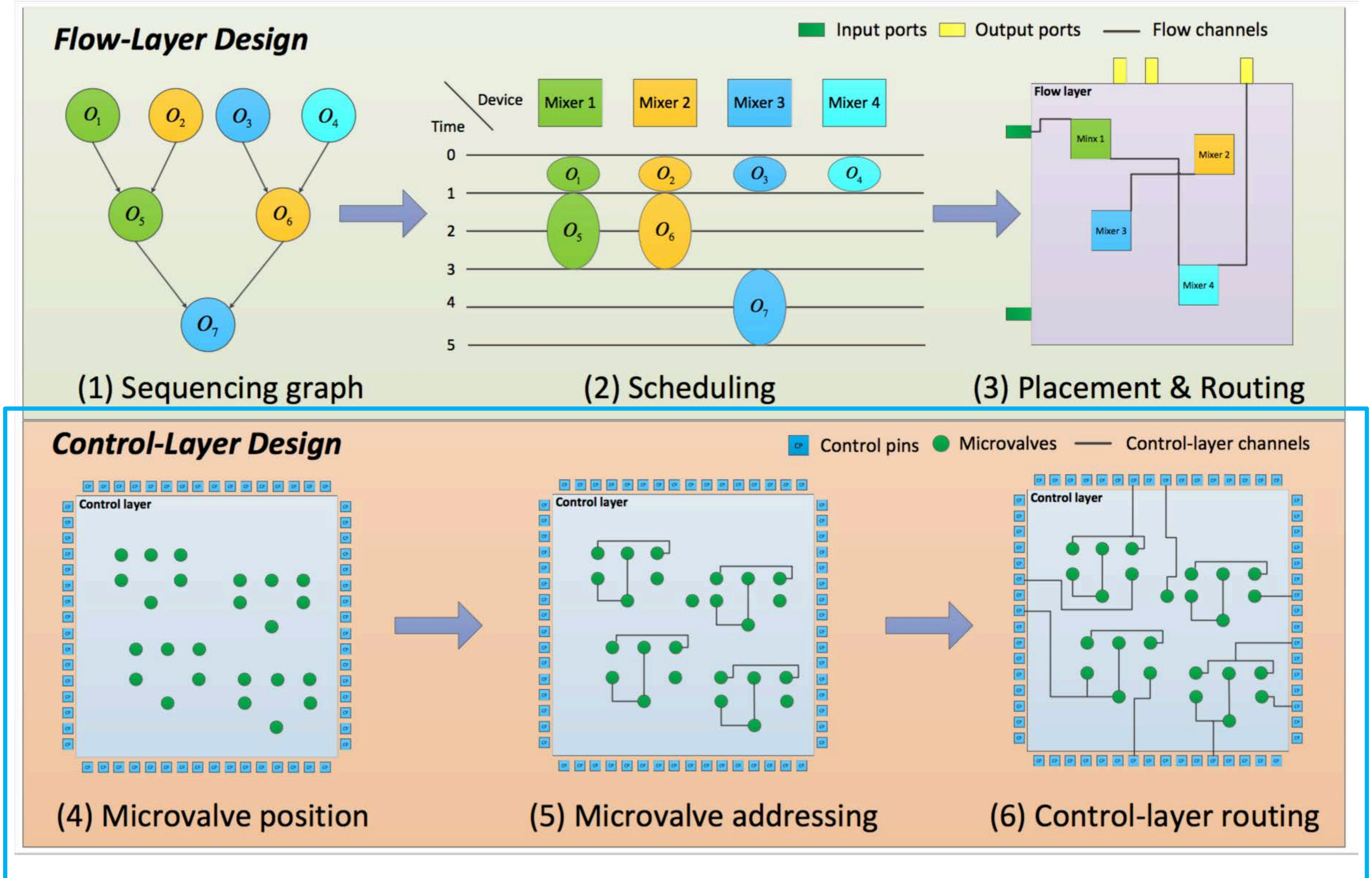
Flow-layer: components & flow channels
Control-layer: control channels
Microvalve: between control-layer and flow-layer



(a) 3D view. (b) Top and side views.

Qin Wang, Yizhong Ru, Hailong Yao, Tsung-Yi Ho, Yici Cai, "Sequence-pair-based placement and routing for flow-based microfluidic biochips" *Proc. of ASPDAC*, pp. 587-592, 2016.

Control-Layer Design



H. Yao, Q. Wang, Y. Ru, and T.-Y. Ho, “Integrated Flow-Control Co-Design Methodology for Flow-Based Microfluidic Biochips” *IEEE Design & Test*, vol. 32, no. 6, pp. 60-68, 2015

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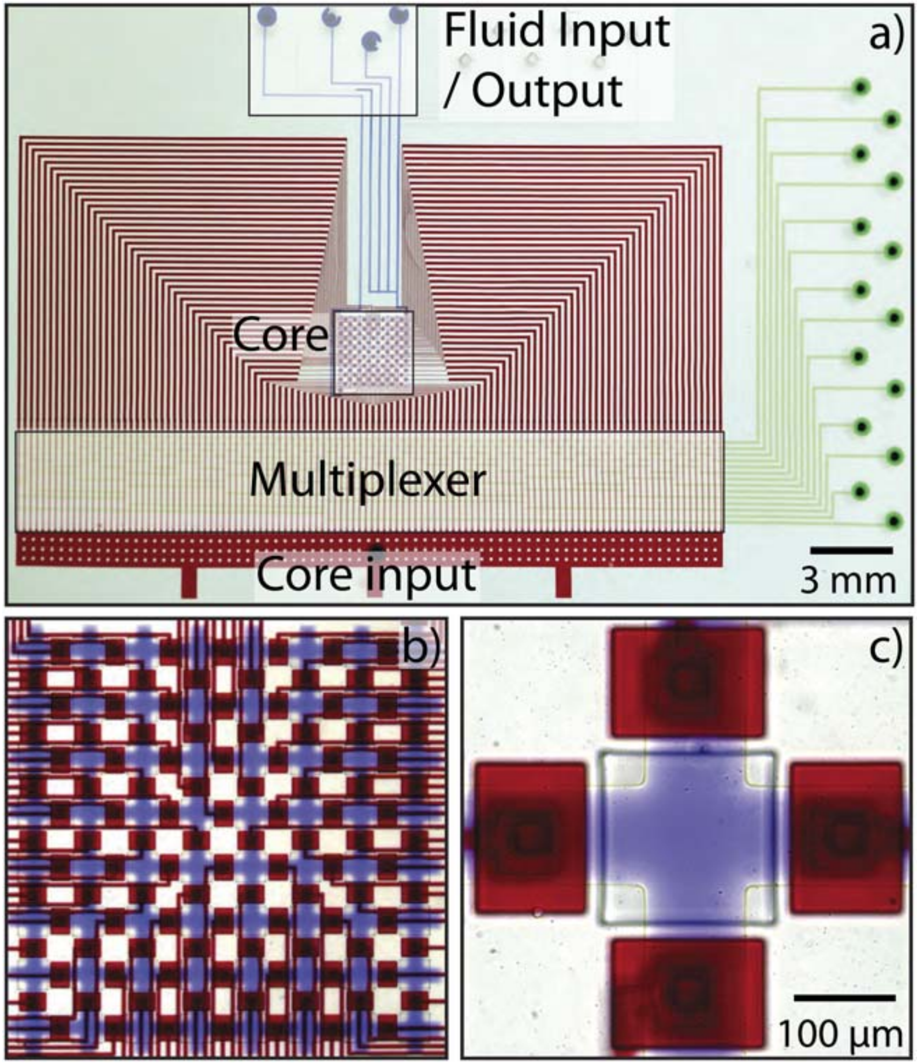
Multiplexer



The huge number of microvalves

⬇ Increase

control layer complexity

⬆ Decrease

Control microvalves in a software-programmable way

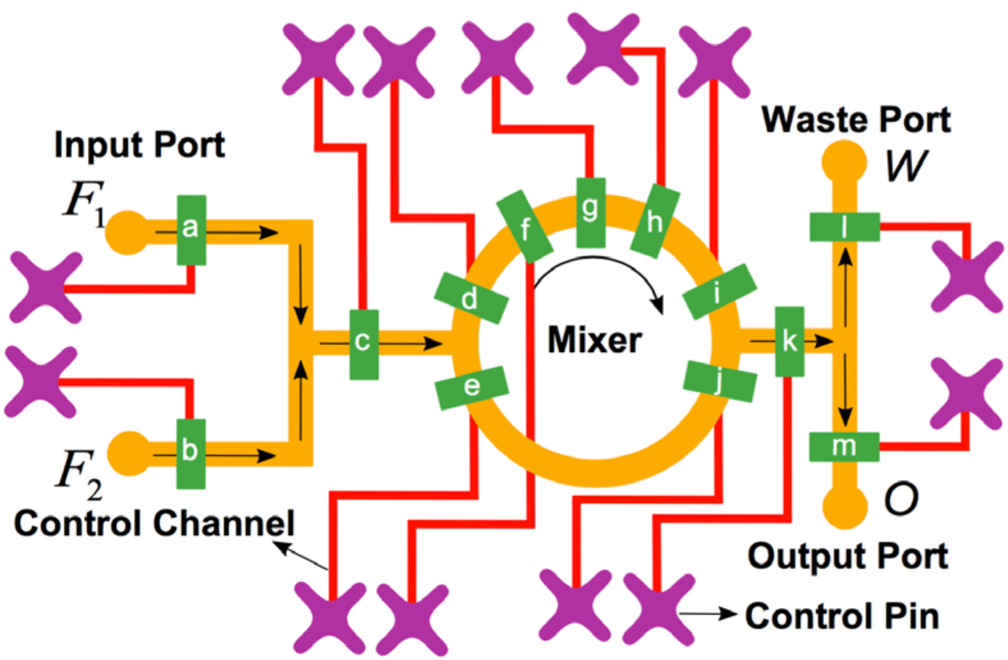
⬆

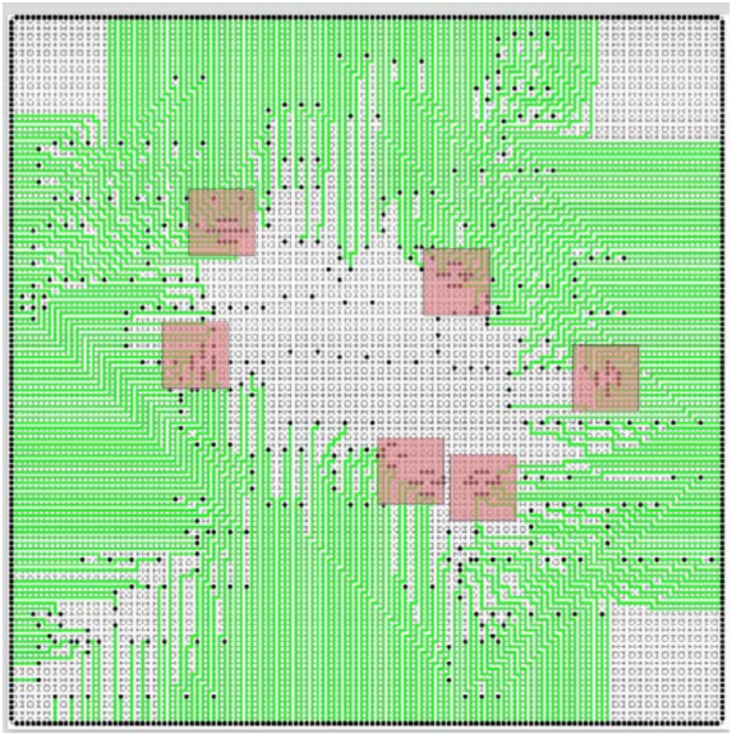
Introduce an additional layer on the top of control layer

L. M. Fidalgo, S. J. Maerkl, "A software-programmable microfluidic device for automated biology," *Lab on a Chip*, vol. 11, no. 9, pp. 1612-1619, 2011.

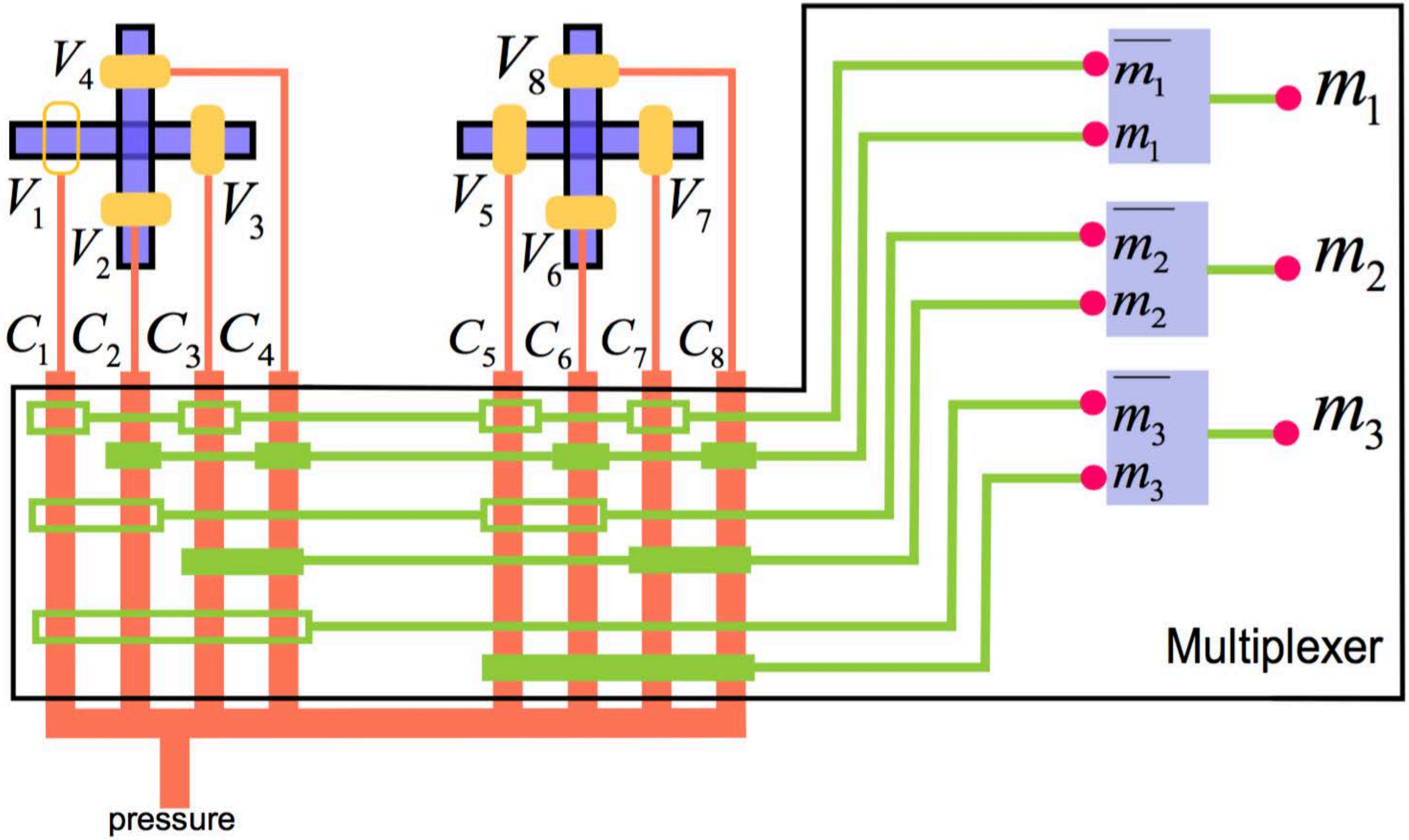
Motivation of multiplexer

- Add an additional layer on the top of control layer
- Time division is the key point of the multiplexer
- Decrease the number of control pins





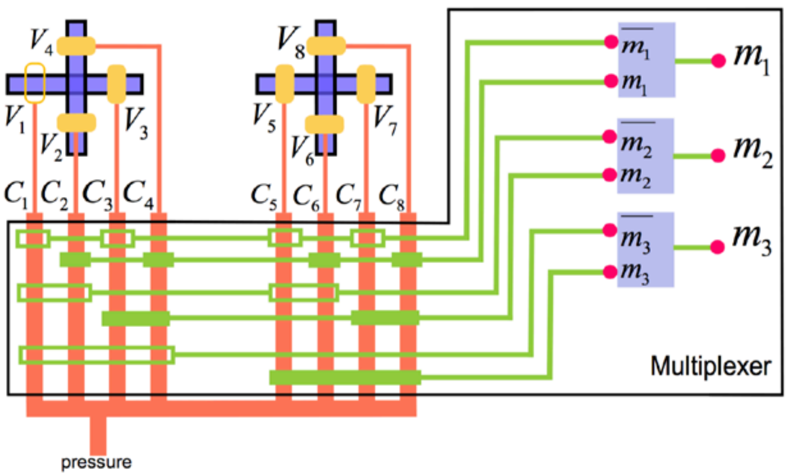
Principle of multiplexer



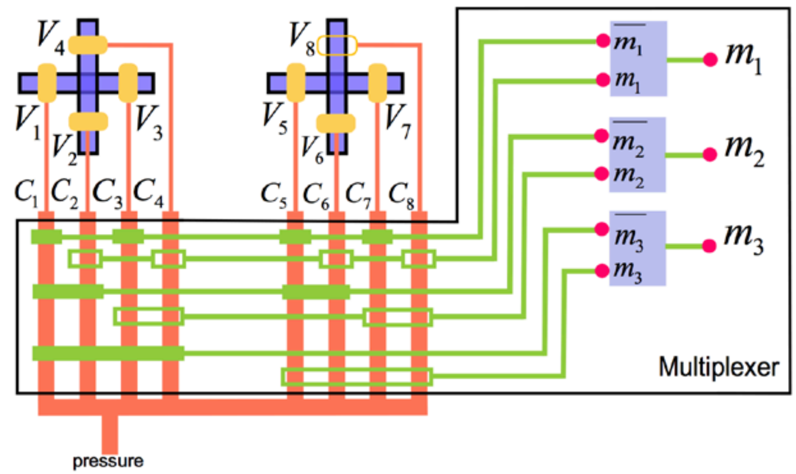
Time slice: **The time unit for** **control-valve** **switching in** **multiplexer.**

Time slot: **The time unit for** **valve** **switching in** **control layer.** **A time slot includes many time slices.**

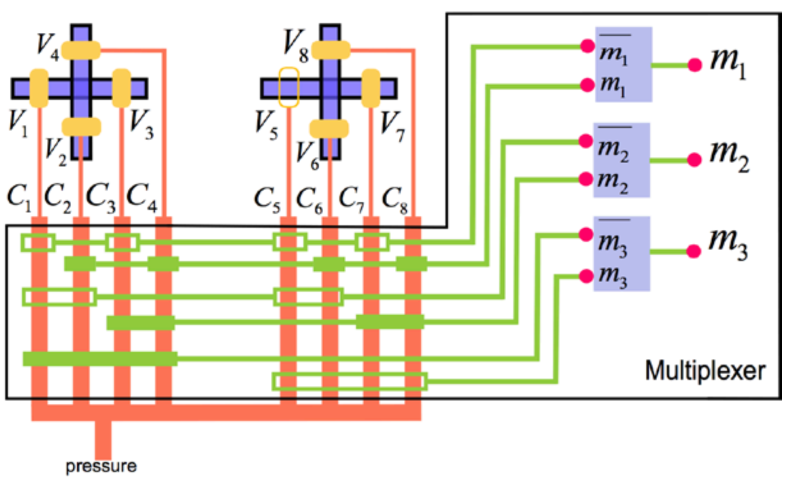
Control-Valve switching of multiplexer



(a) Time slice t_0 , V_1 open, (m_1, m_2, m_3) = "000"



(b) Time slice t_1 , V_8 open, (m_1, m_2, m_3) = "111"



(c) Time slice t_2 , V_5 open, (m_1, m_2, m_3) = "001"

Microvalves need to be switched

V_1 V_5 V_8

Switching order of microvalves

V_1 V_5 V_8

Control-valve sequence of multiplexer

"000" "001" "111"

Switching order optimization problem

Time	Actuation Sequences of Valves		Actuation Sequences of Multiplexer		Switching Times of Multiplexer	
	Solution_A	Solution_B	Solution_A	Solution_B	Solution_A	Solution_B
Current Time Step T_0	10000000	10000000	000	000	0	0
Time slice t_0						
A time slot	00001000	00000001	001	111	1	3
Time slice t_1						
	00000001	00001000	111	001	2	2
Next Time Step T_1	00001001	00001001	111	001	0	0
					Total: 3	Total: 5

Control-layer → Multiplexer

Microvalve → Control-valve

Switching order → Switching frequency

Motivation of our work

- The multiplexer needs to be switched when the states of microvalves are changed between every two adjacent time slots
- High switching frequency will make the multiplexer vulnerable and decrease the chip's reliability

Decrease the switching frequency of multiplexer

↓

Increase the lifetime of multiplexer and chip

Problem Formulation

Given The number of valves n

The actuation sequences of valves $C^t = \{C_1^t, C_2^t, C_3^t, \ldots, C_n^t,\}$

The beginning time step T_{begin}

The end time step T_{end}

$(t \in [T_{begin}, T_{end}])$

Find Switching order $S = \{M_{T_{begin}}, \ldots, M_{T_i}, M_{T_{i+1}}, \ldots M_{T_{end}}\}$

of multiplexer from T_{begin} to T_{end}

Objective Minimize the cost of total switching times of the control-valves in the multiplexer

Subject to All of the different control signals i C^t from current time step *t* to next time step *t* + 1 must be switched

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Contributions

- We observe for the first time the switching order optimization problem
- The first switching order optimization method is proposed
- The total switching frequency of multiplexer is greatly reduced
- The proposed Hamming-distance-based method obtains the solution very close to the optimal lower bound

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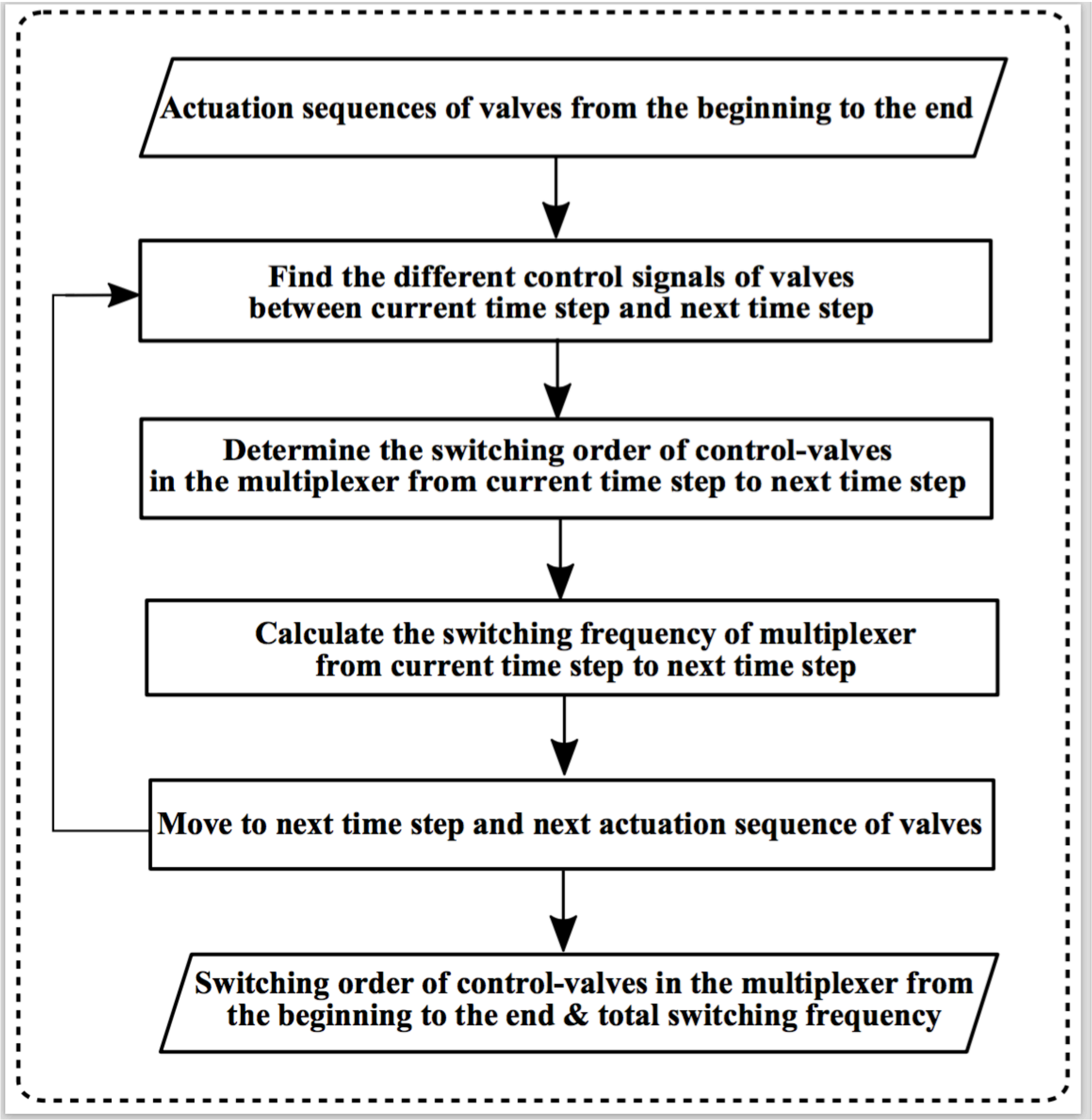
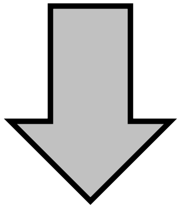
Overall design flow of our approach



Major Problems

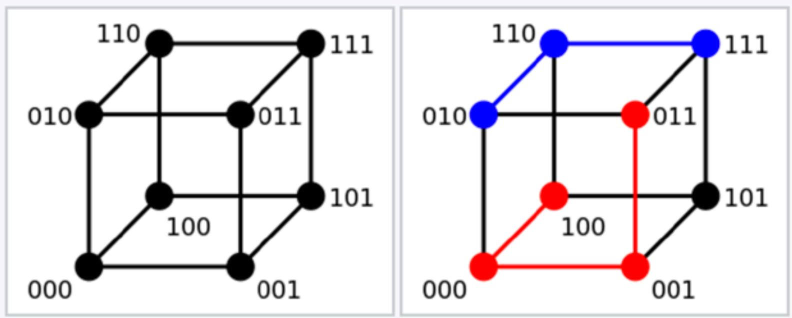
Switching order of microvalves



Switching frequency of control-valves

Hamming-distance

- Widely used in information theory and coding theory
- Definition: For two strings of equal length, it is the number of positions at which the corresponding symbols are different.
- It measures the minimum number of substitutions required to change one string into the other



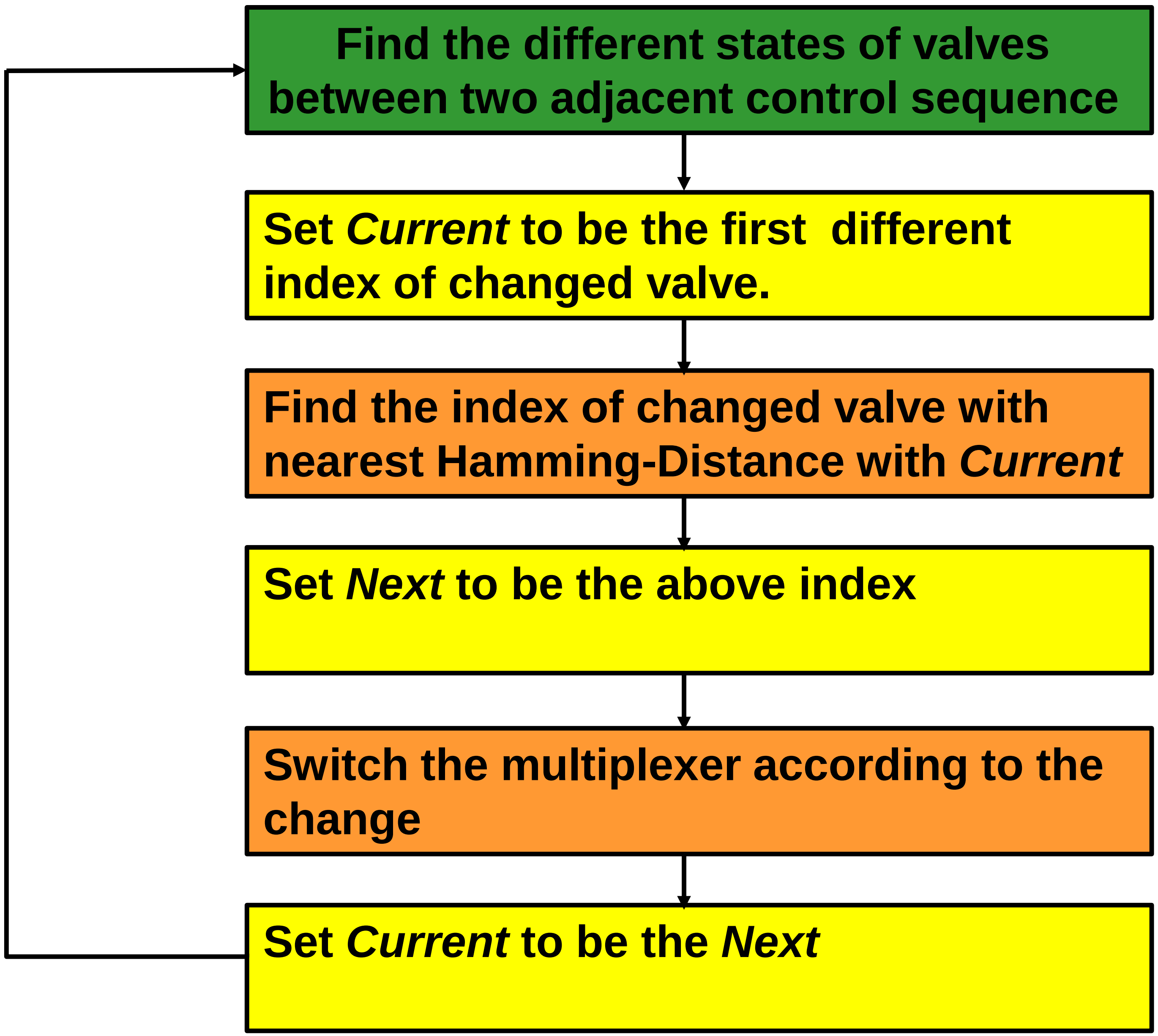
3-bit binary cube for finding Hamming distance

Two example distances: 100→011 has distance 3; 010→111 has distance 2

The minimum distance between any two vertices is the Hamming distance between the two binary strings.

R. W. Hamming, "Error detecting and error correcting codes," Proc. of Bell System Technical Journal, vol. 29, no. 2, pp. 147-160, 1950.

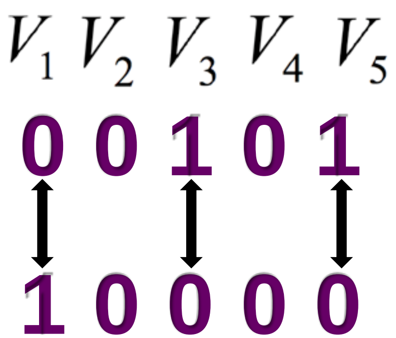
Hamming-based valve switching optimization

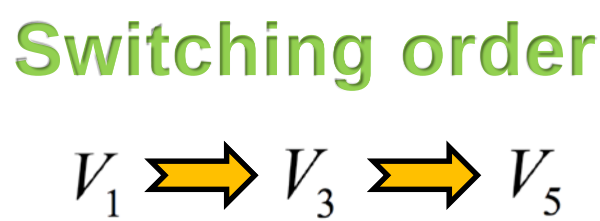


Optimal lower bound & Simple method

- Optimal lower bound
  - For valves in control layer, each change of states results in at least one switching time of control-valves in the multiplexer
  - Thus, the optimal lower bound is the total number of changed states of valves from the beginning time step to the end time step.

- Simple method
  - The decision of switching order is based on the order of valve's relative position





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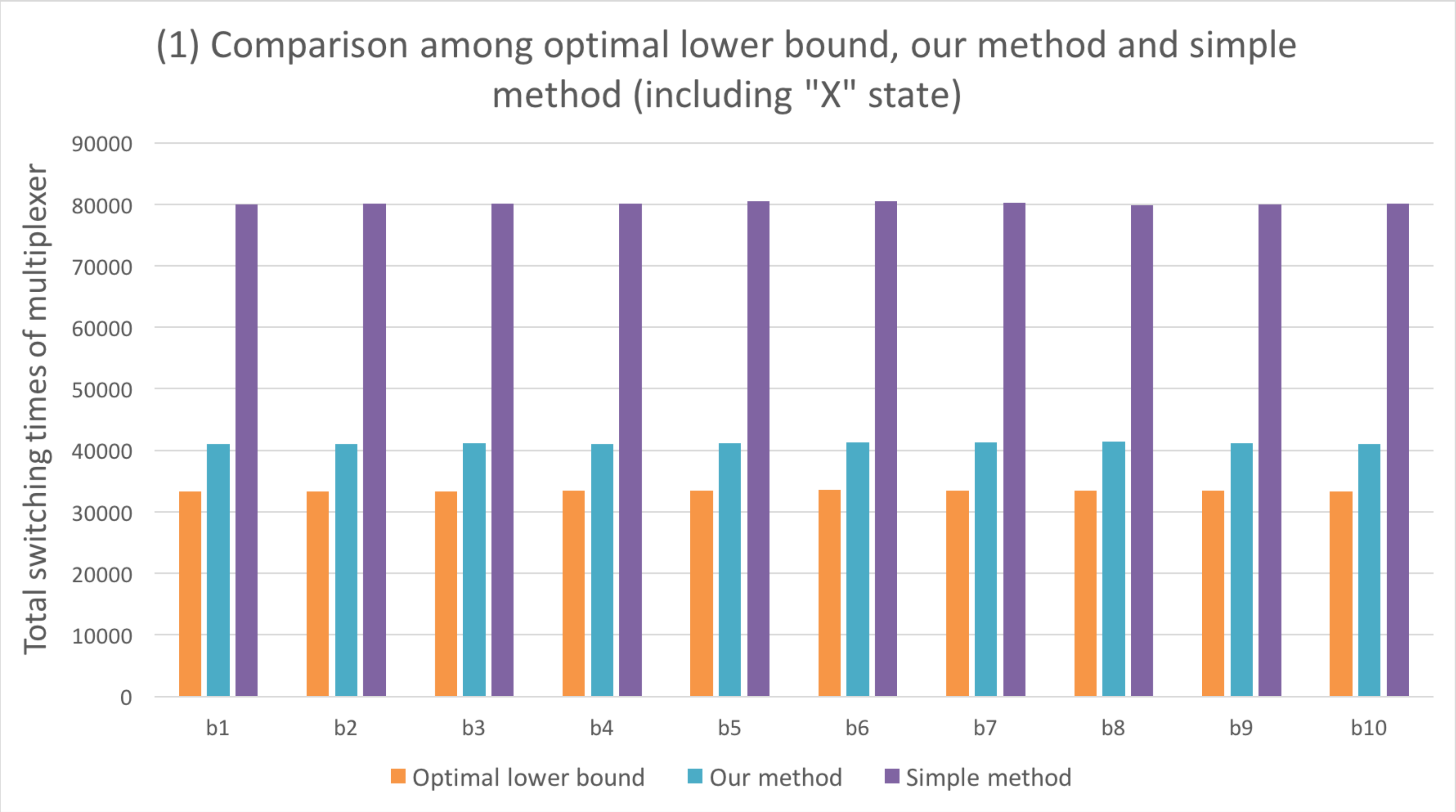
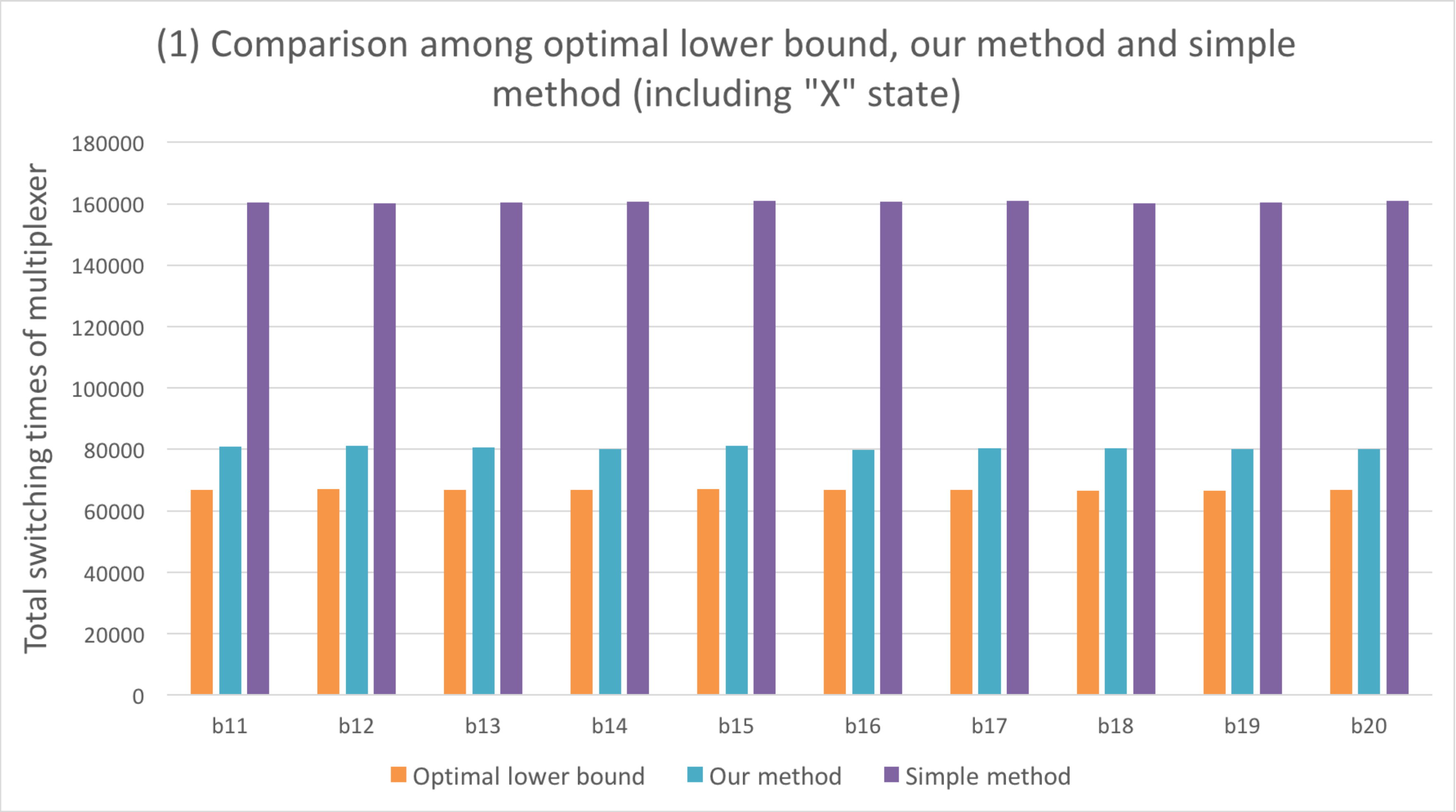
Our Method VS. Simple Method (b1-b10)



Average Improvement 48.6%   Max Improvement 48.8%

b1-b10: The number of valves is 1024, and the total number of time slots is 100

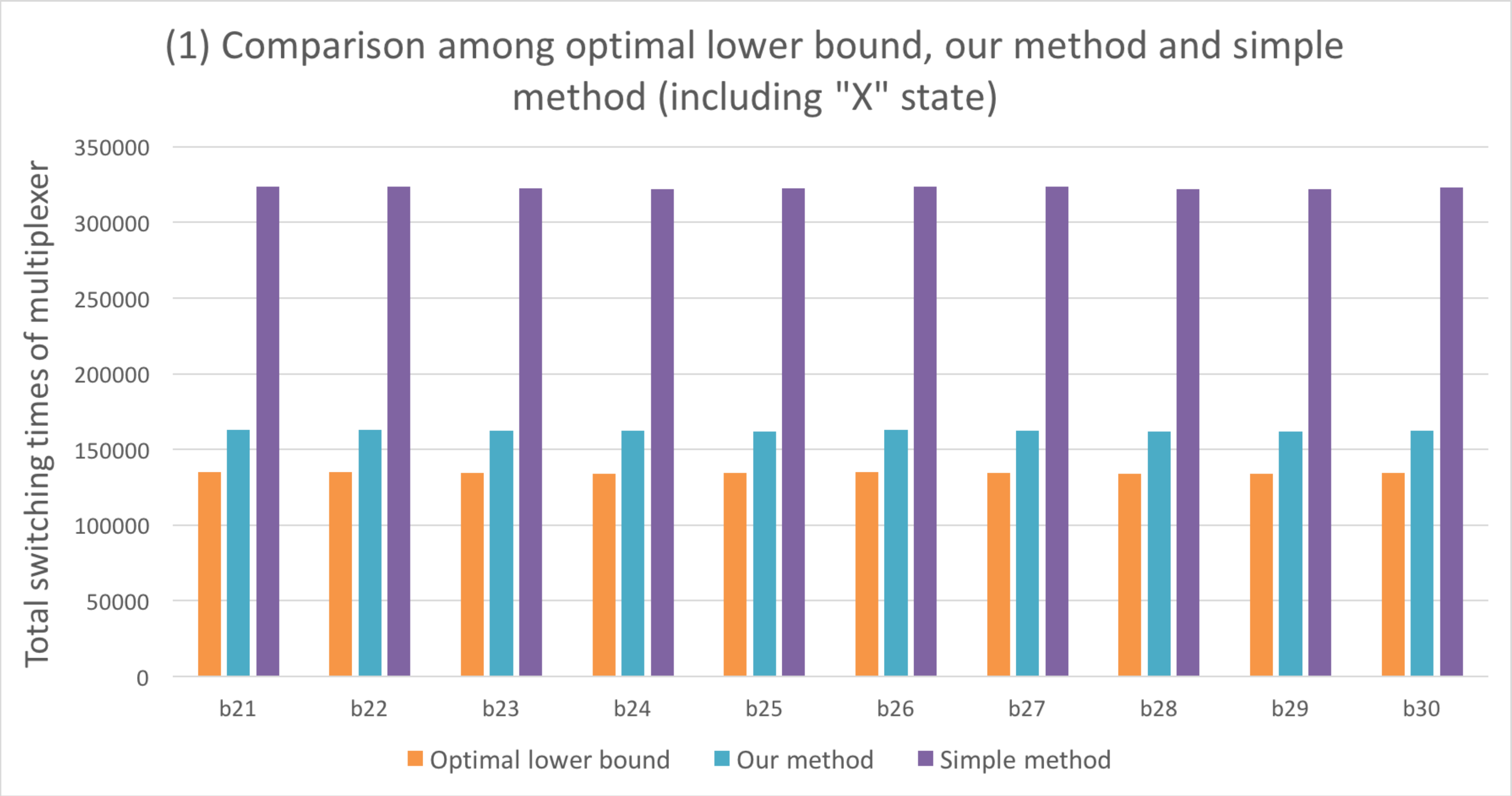
Our Method VS. Simple Method (b11-b20)



Average Improvement 49.7%   Max Improvement 50.2%

b11-b20: The number of valves is 2048, and the total number of time slots is 100

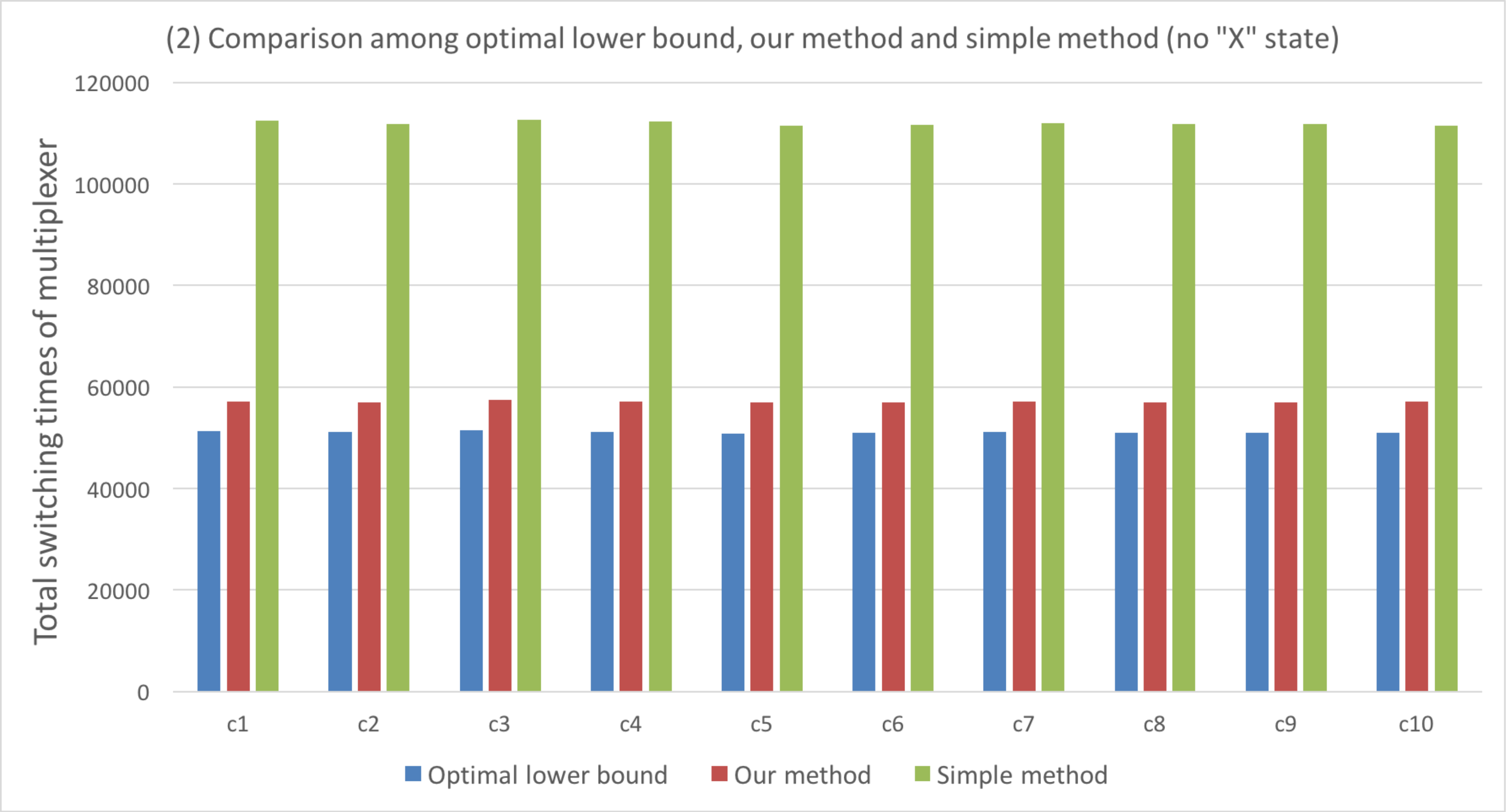
Our Method VS. Simple Method (b21-b30)



Average Improvement 49.6%   Max Improvement 49.7%

b21-b30: The number of valves is 2048, and the total number of time slots is 200

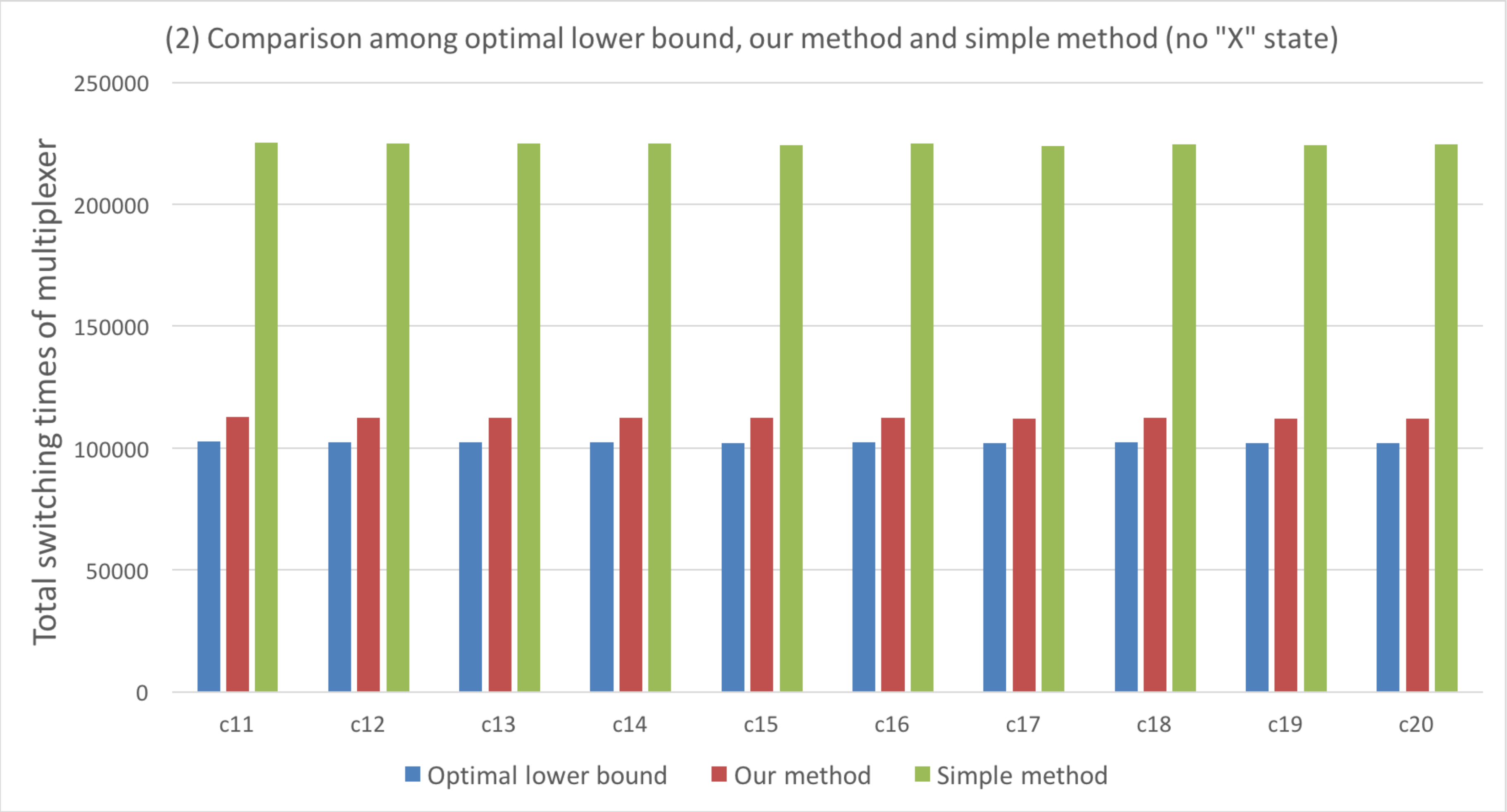
Our Method VS. Simple Method (c1-c10)



Average Improvement 48.8%   Max Improvement 49.1%

c1-c10: The number of valves is 1024, and the total number of time slots is 100

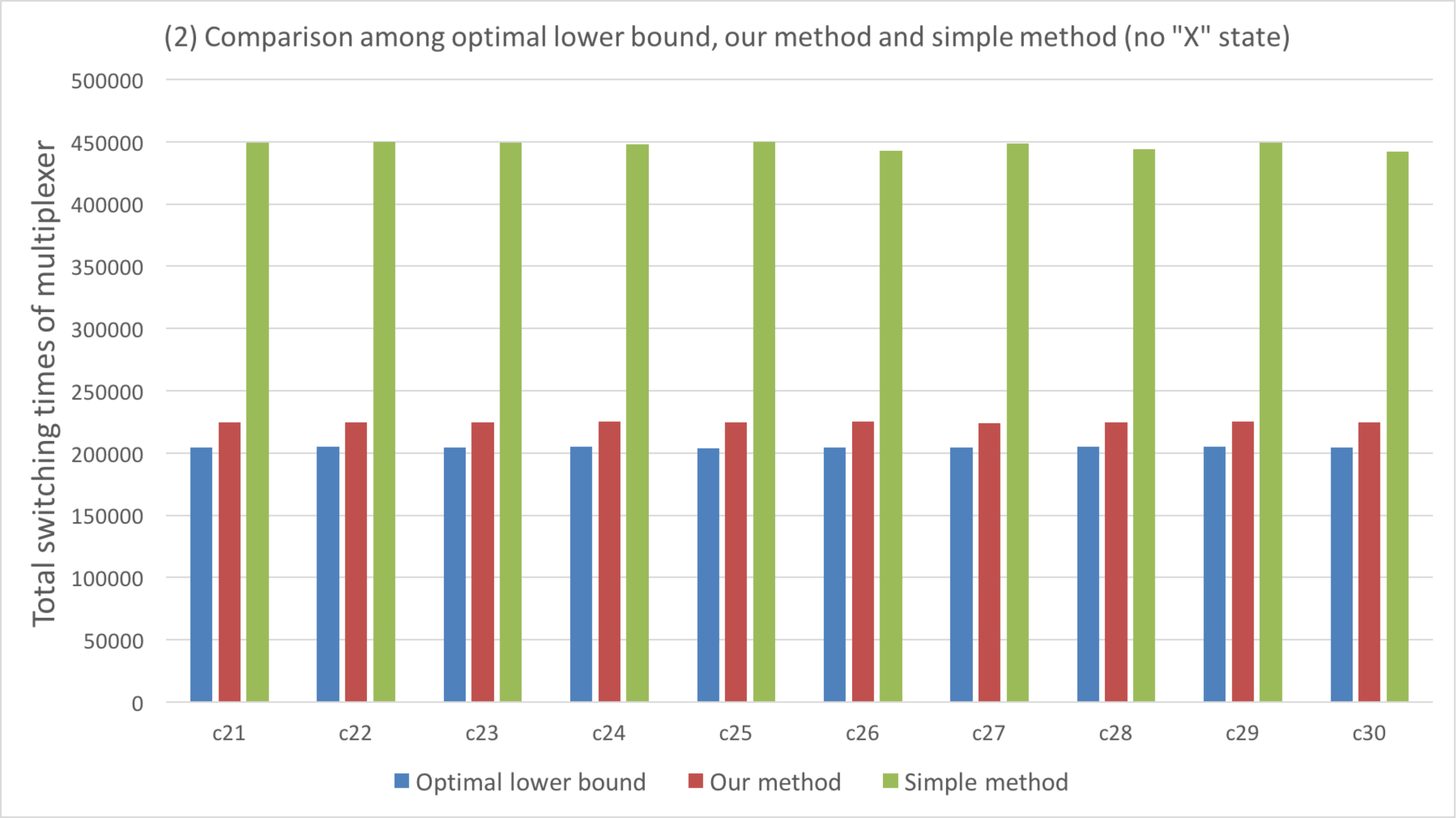
Our Method VS. Simple Method (c11-c20)



Average Improvement 49.8%   Max Improvement 50%

c11-c20: The number of valves is 2048, and the total number of time slots is 100

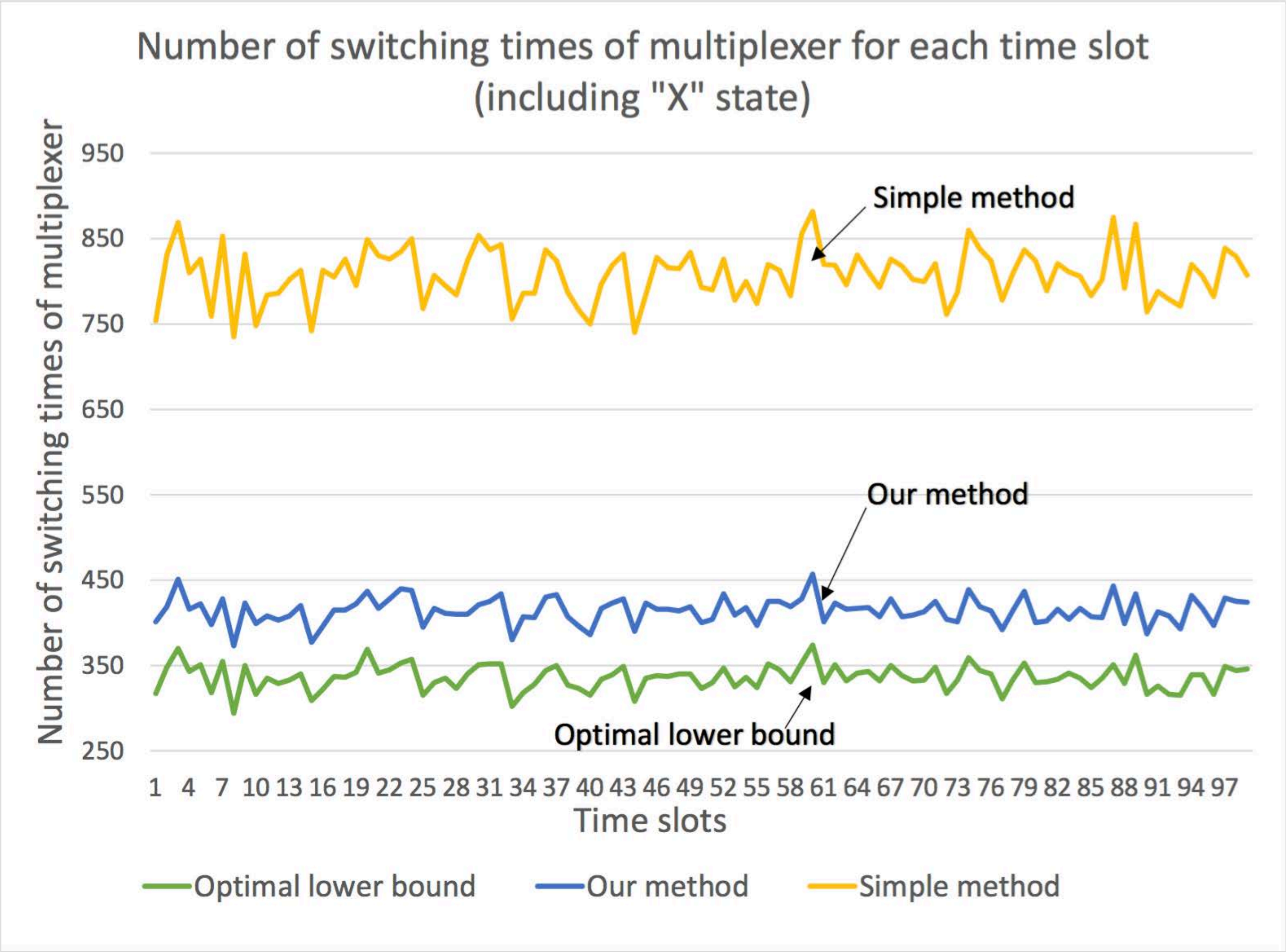
Our Method VS. Simple Method (c21-c30)



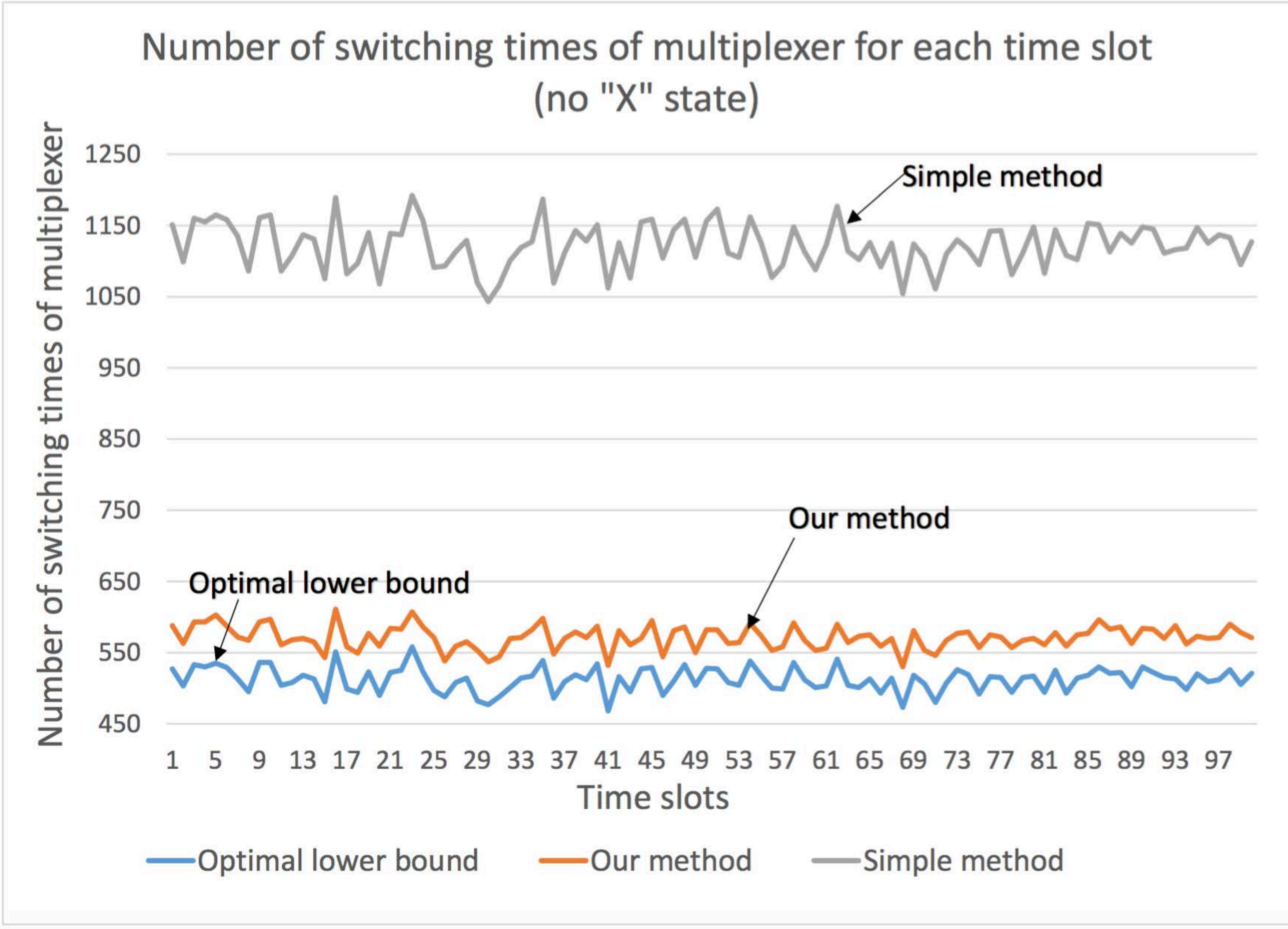
Average Improvement 49.3%   Max Improvement 50%

c21-c30: The number of valves is 2048, and the total number of time slots is 200

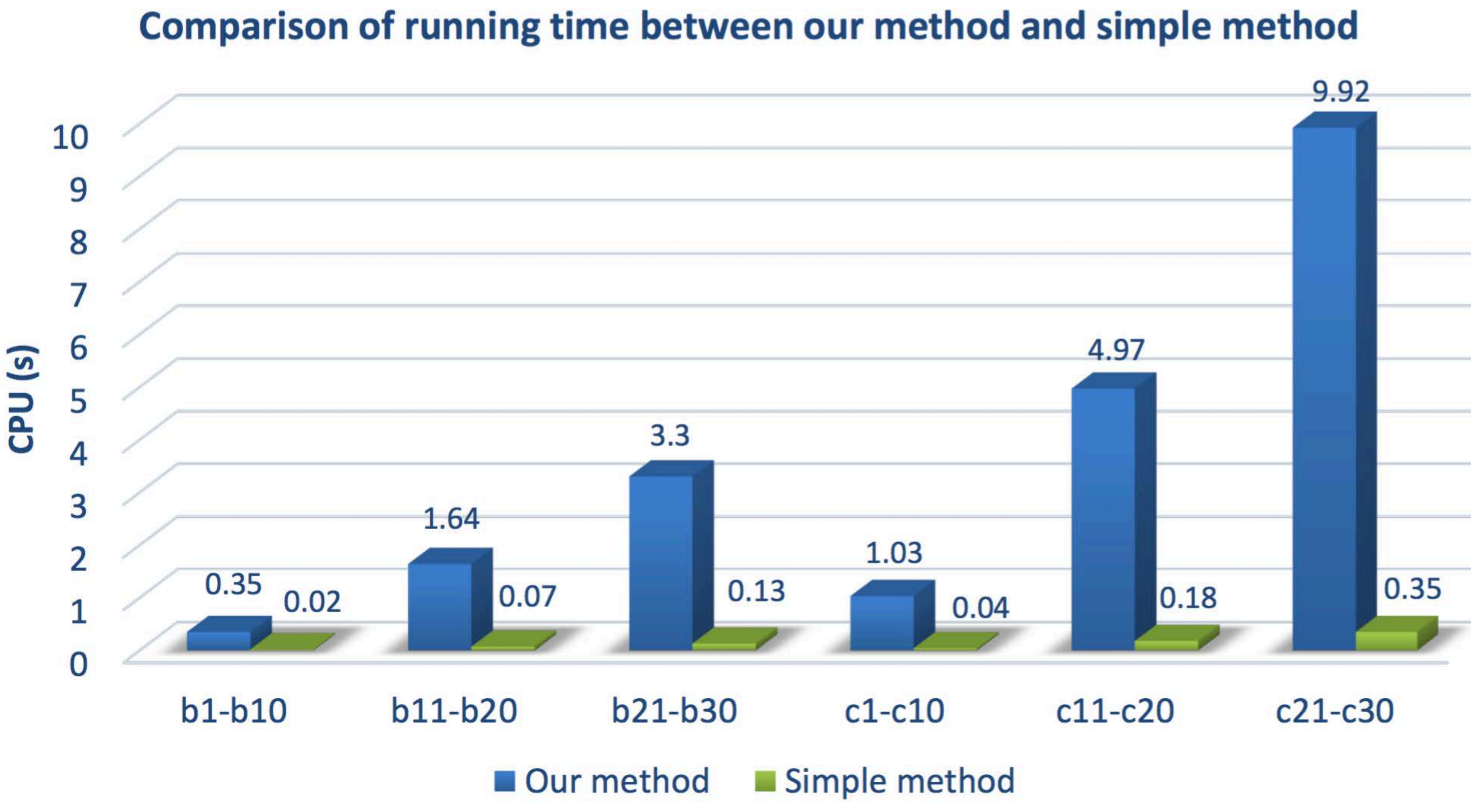
Number of switching times of multiplexer (with “X” state)



Number of switching times of multiplexer (no “X” state)



Running time



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Summary

- By introducing the multiplexer, the number of off-chip control pins in flow-based microfluidic biochips can be reduced dramatically
- Time division is the key point of the multiplexer
- A switching order optimization method based on Hamming-Distance for control-valves in the multiplexer
- Experimental evaluations show that our method is effective and efficient

Thank you!