Design-for-Reliability and Probability-Based Fault Tolerance for Paper-Based Digital Microfluidic Biochips with Multiple Faults

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Outline

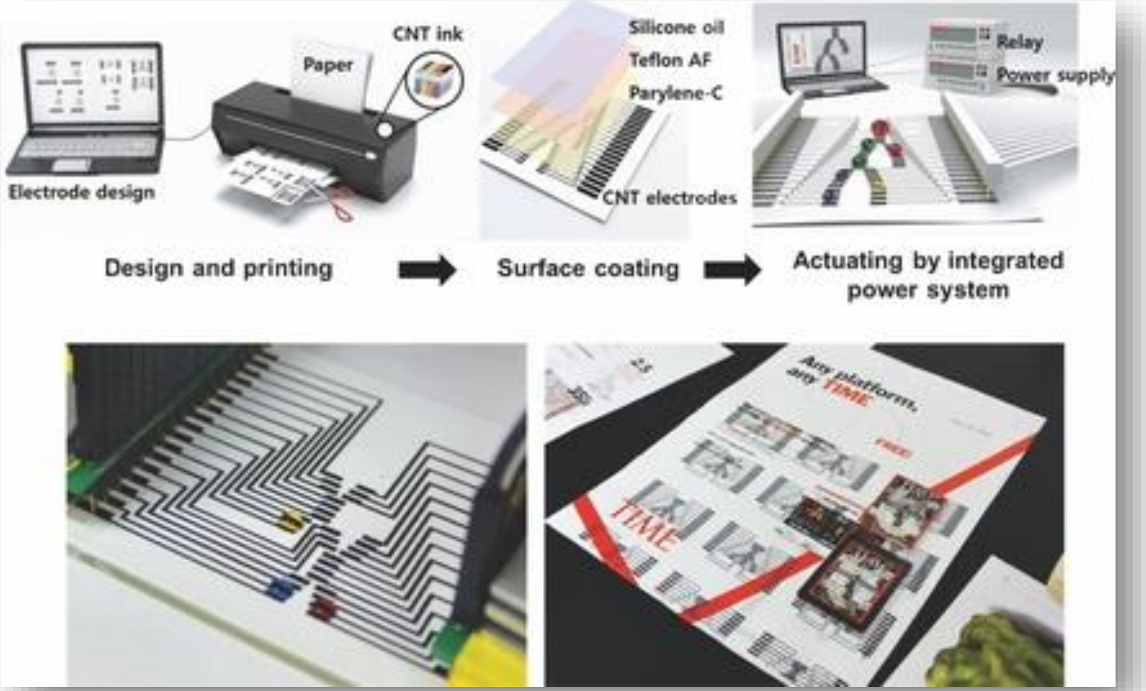
- Background
- Contributions & Motivations
- Fault Models and Assumptions
- Design-for-Reliability Design Flow
- On-the-fly Probability-Based Diagnosis and Fault Tolerance Procedure
- Experimental Results
- Conclusion

Paper-Based Digital Microfluidic Biochips

- Biochip
  - Miniaturized lab that perform a bioassay
  - Digital Microfluidic Biochip
  - Control bioassay process by Electrowetting

- PB-DMFBs
  - Lab-on-paper
  - An ASSURED diagnostics solution
    - Affordable
    - Sensitive
    - Specific
    - User-friendly
    - Rapid
    - Equipment-free
    - Deliverable to end-users

The manufacturing process of PB-DMFBs [1]



[1] H. Ko, et al., "Active digital microfluidic paper chips with inkjet-printed patterned electrodes," Advanced Materials, Vol. 26, No. 15, pp. 2335-2340, 2014.

Reliability on PB-DMFBs

- Paper-based microfluidic devices are designed for diagnostics of pandemic, including Ebola, Malaria, and COVID-19
- PB-DMFBs may be affected by physical defects
  - This leads to an incorrect functionality of droplet manipulations
    1. Waste of reagents and samples
       - Bought with high prices or collected with effort
    2. Inefficient usage of human resource
       - The professionals have to check the meaning of the incorrect outcomes
       - Then perform the repetition of the diagnostics
    3. Risk of exposure and infection
       - Re-collecting samples for the new diagnostic
       - A false negative of diagnostics may happen
- To ensure the one-pass diagnostic with the correct functionality, reliability issues have to be considered

Limitations for Appling DMFBs Reliability Methods

- No fully programmable electrode array
  - Most DMFBs are manufactured for general applications, while PB-DMFBs are designed for a specific purpose
- Electrical field interference
  - A single-layer paper substrate for both droplet routing and conductive wire routing
- Low dependence on cyber-physical systems to meet ASSURED
- Only the single fault assumption is considered
  - It is possible to have multiple faults in a PB-DMFB due to entangled electrodes, and conductive wire routing

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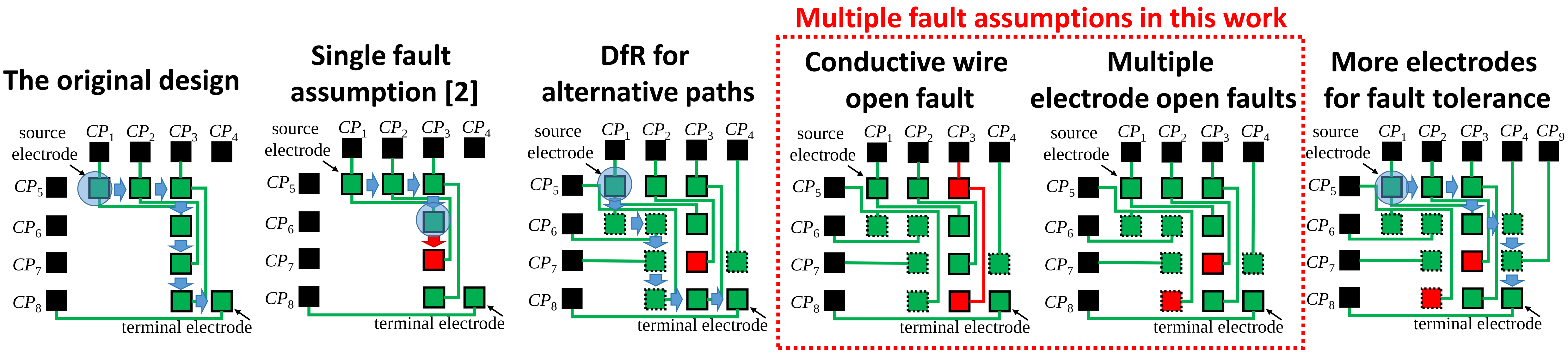
Contributions & Motivations

- A diagnosis and fault tolerance scheme for PB-DMFBs assuming multiple faults
  - Two stages for Design-for-Reliability
    - DfR design flow for PB-DMFB designs
    - On-the-fly probability-based diagnosis and fault tolerance procedure
  - The least dependence on sensors for diagnosis and fault tolerance automation



[2] J.-D. Li, et al., “Test and diagnosis of paper-based microfluidic biochips,” in Proc. IEEE VLSI Test Symposium (VTS), pp. 1-6, 2016.

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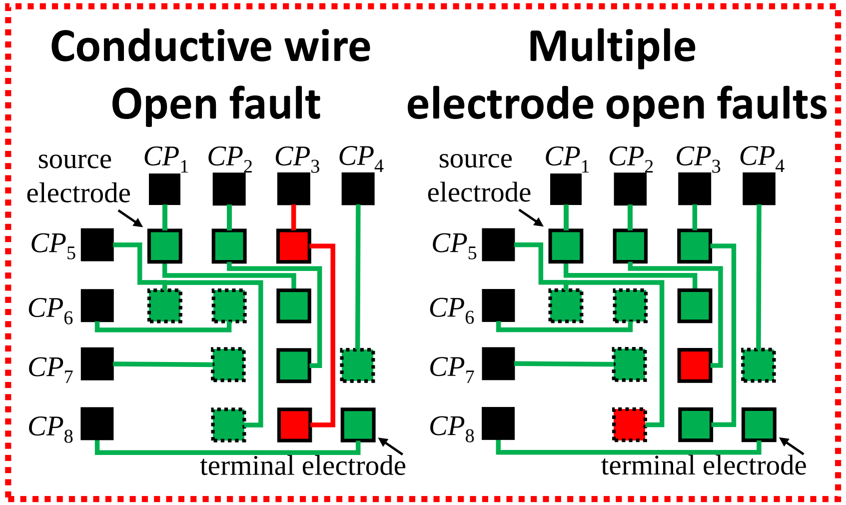
The Fault Models and Assumptions

- Electrode open fault (EOP):
  - One or more electrode open faults may occur due to the defect(s) in the PB-DMFB design
- Wire open fault (WOP):
  - One or more conductive wire open faults may occur due to the open wire routing
  - All the downstream electrodes are affected by a wire open fault
- Assumptions for cyber-physical systems
  - Sensors or smart phones to obtain the experimental data and monitor the bioassays executions
  - PB-DMFBs could be applied in resources-limited regions
  - Sensors may have limited capacity or be used for multiple diagnostics simultaneously

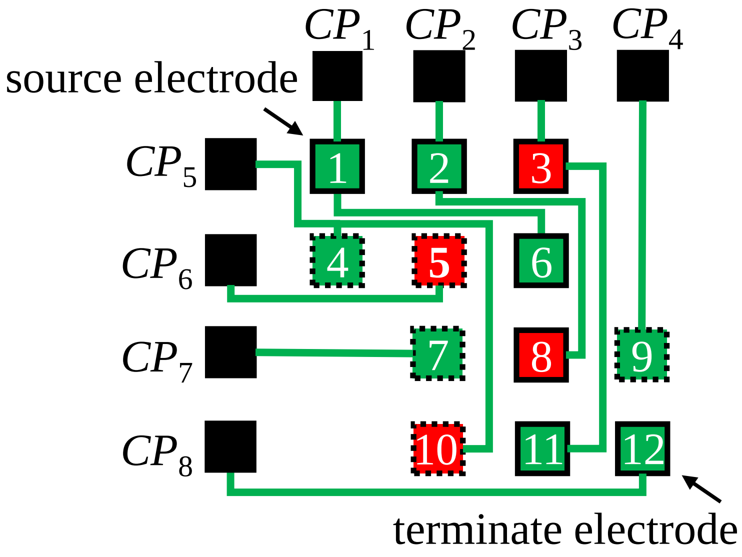
Multiple fault assumptions in this work



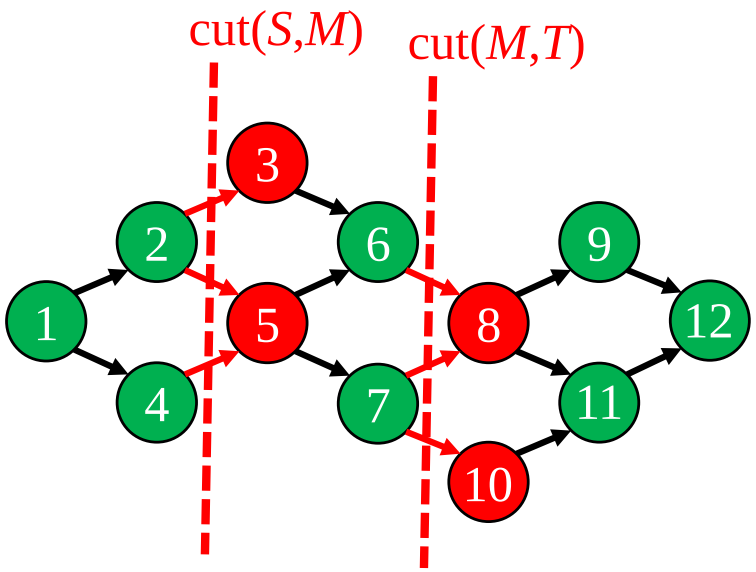
Critical Fault Sets (CFSs)

- Only faults on critical locations can disable the functionality of biochips
- The cut-set theorem can be leveraged for finding CFSs under multiple fault assumptions

PB-DMFBs with four faulty electrodes



The directed graph with the cuts



- S is the node group with the source node representing the source electrode
- T is the node group with the terminal node representing the terminal electrode
- M is the middle node group isolated by the two cuts

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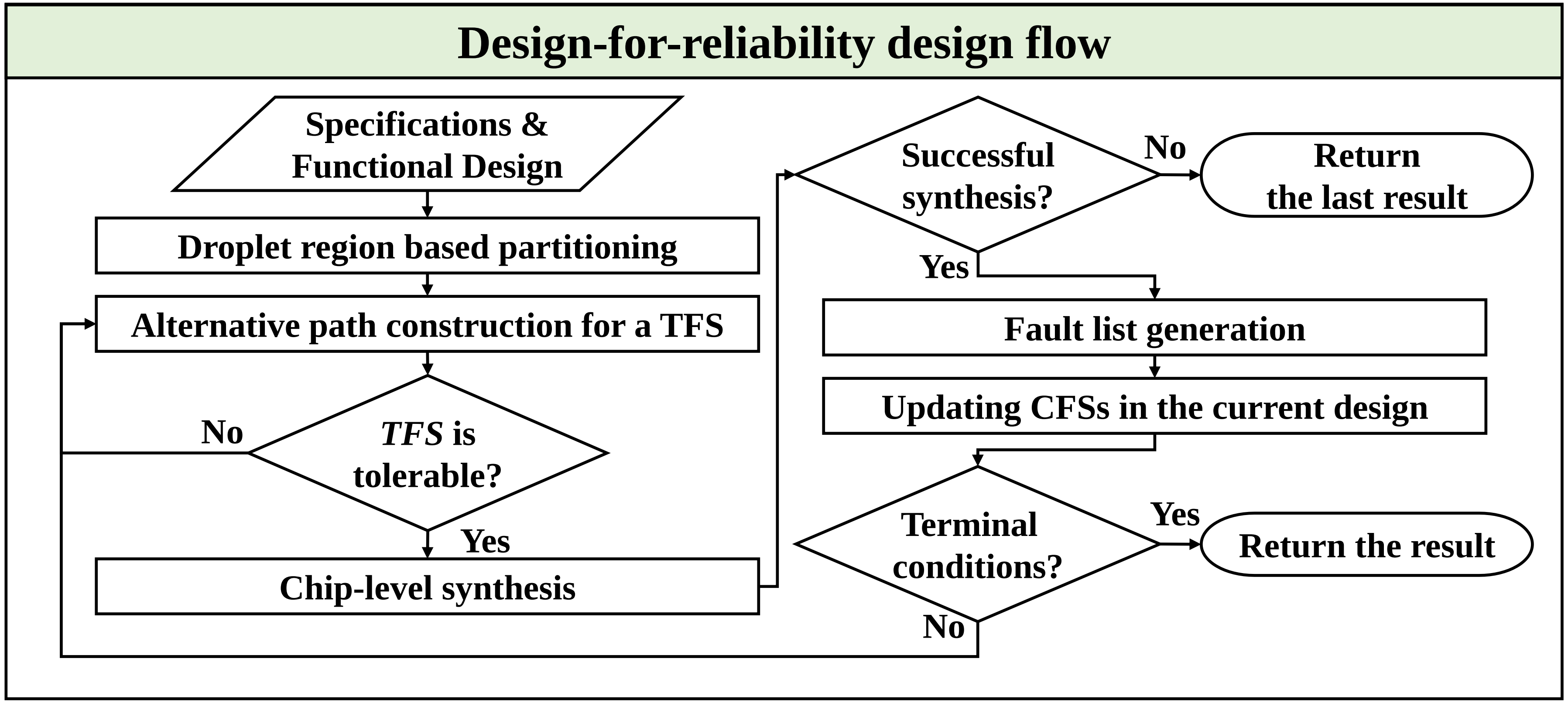
Design-for-Reliability Design Flow



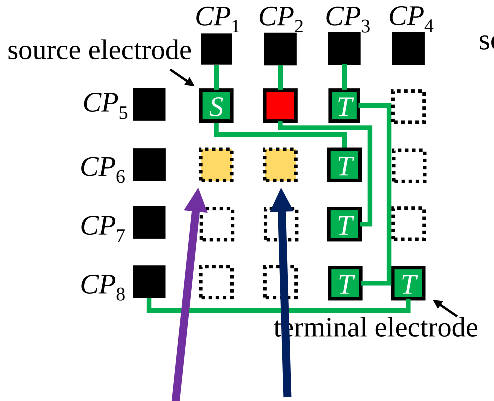
***Target fault set (TFS)**

- A droplet region consists of
  - a source electrode, a terminal electrode, and electrodes may be involved
- User-defined terminal conditions:
  - Fabrication cost (e.g., #used electrodes, wirelength)
  - #Considered Tolerated faulty electrodes (TFE)

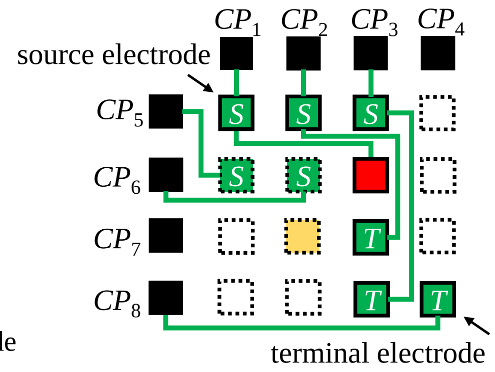
Alternative Path Construction

- The unselected electrodes can be candidate electrodes (*CE*) for alternative paths
- To have at least one valid droplet routing bypassing the faulty electrodes

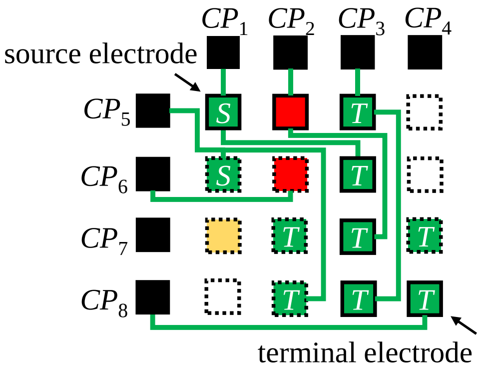
The 1st round



The 2nd round



The first TFS with multiple faults



- **Algorithm 1 - Connecting *S* and *T***
  - **Node with the most #adjacent type first**
  - **Then the order**
    - *For new TFS, S>T>FE*
    - *If no S is connected, APE>S>T*
    - *If no T is connected, APE>T>S*

- **Start from the node with the most #adjacent nodes then *S>T>FE***
- **Connecting *S* and *T* by adding node with the most #adjacent then *APE>S>T***

S/*T*: electrodes represented by *S*/*T* group *FE*: faulty electrode targeted in this round *CE*: candidate electrodes *APE*: alternative path electrodes added in this round

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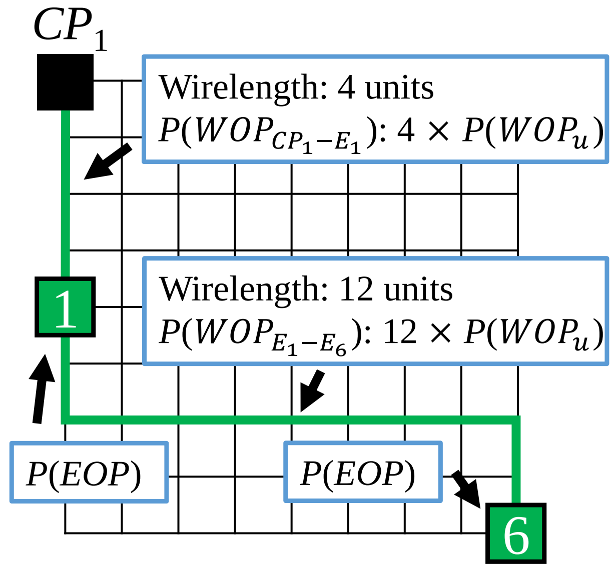
Compute the Faulty Probability

- Assume that all the electrode open faults have identical expected occurrence probability, denoted as *P*(*EOP*)
- The expected occurrence probability of a wire open fault, *P*(*WOP*), are increasing with wirelength

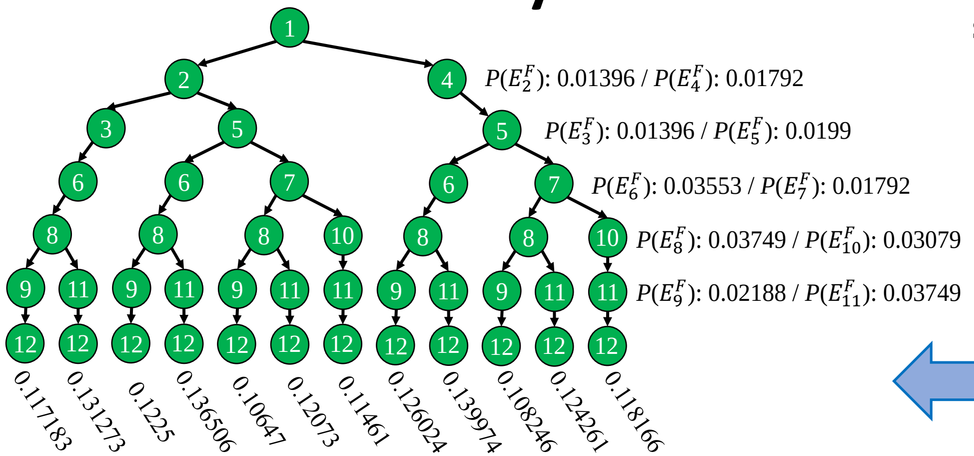
$$P(WOP) = w \times P(WOP_{\mathrm{u}})$$

- w is wirelength of the wire
- $P(WOP_{\mathrm{u}})$ is the expected probability of having a wire open fault on a wire with one unit of wirelength

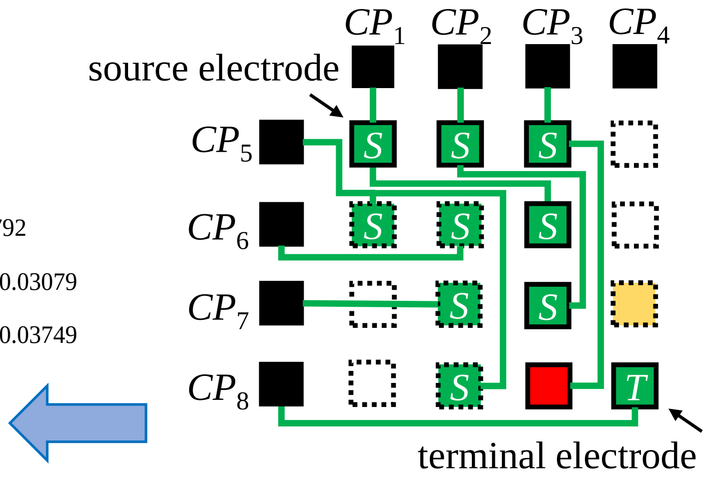
Occurrence probabilities



Occurrence probabilities of having at least one faulty electrode



PB-DMFBs with DfR

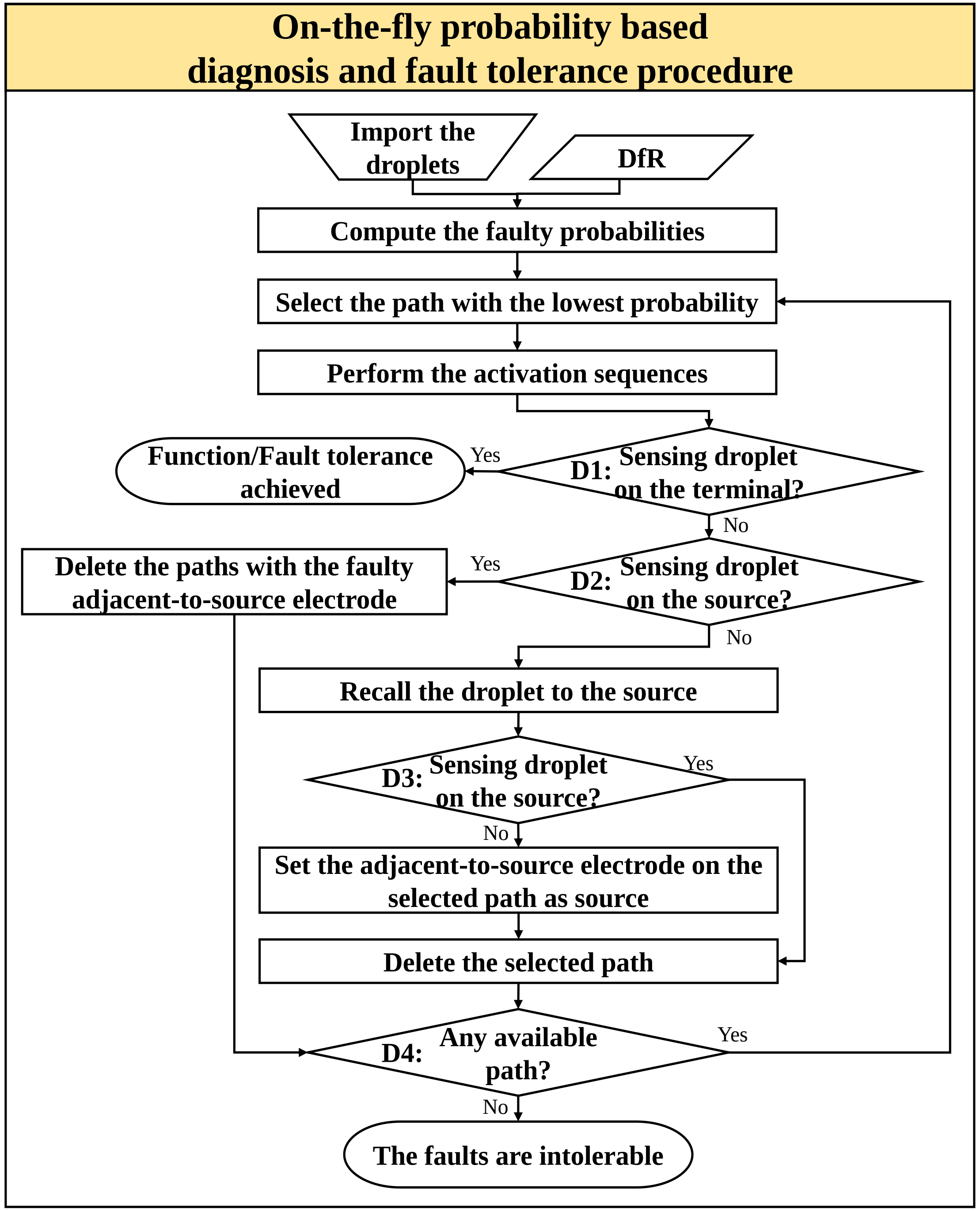


Diagnosis & Fault Tolerance Procedure

Descriptions and Countermeasures of the Conditions

D1	*D2*	*D3*	*D4*	Descriptions of the conditions	Countermeasures
Y	-	-	-	• The droplet is transported to the terminal.	• Perform the next operation in the bioassay.
N	Y	-	Y	• The droplet is on the location of source. • The adjacent-to-source electrode of the selected path is faulty.	• Delete the paths with the faulty adjacent-to-source electrode. • Select the path with the lowest probability to continue the procedure.
N	N	Y	Y	• At least one electrode on the selected path is faulty. • The source electrode is not faulty. • The adjacent-to-source electrode on the selected path is not faulty.	• Delete the selected path. • Select the path with the lowest probability to continue the procedure.
N	N	N	Y	• The source electrode is faulty. • The adjacent-to-source electrode on the selected path is not faulty. • Except the above two electrodes, at least one electrode on the selected path is faulty.	• Delete the selected path. • Set the adjacent-to-source electrode on the selected path as source. • Select the path with the lowest probability to continue the procedure.
N	Y	-	N	• At least one electrode on the selected path is faulty. • No alternative path can be used.	• Stop the bioassay, and inform the user this biochip is with failure.
N	N	X	N		

Y/N: The decision returns Yes/No. - : The procedure does not reach this decision . X: don't care.



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Experimental Results

- 7 designs with 10,000 instances to obtain the average #transportations
- *P*(*EOP*)=0.01 and *P*(WOP_u)=0.001, normal distribution

Benchmarks	Original design				Design-for-reliability								Diagnosis and fault tolerance	
	Size	*#E*	*#CP*	*WL*	*#DR*	*T.C.*	*#E*	*#CP*	*WL*	*#FE* = 1	*#FE* = 2	*#FE* = 3	Proposed	Random
amino-acid-1	6x8	20	12	208	6	*#TFE*=1	32	18	324	100%	97.85%	92.74%	3.3726	3.589
						#TFE=2	36	22	358	100%	99.37%	97.59%	2.098	4.4795
amino-acid-2	6x8	24	16	224	6	*#TFE*=1	36	22	332	100%	99.05%	96.81%	3.5269	4.0032
						#TFE=2	40	26	380	100%	99.49%	98.24%	3.4051	4.2413
protein-1	13x13	34	18	320	8	*#TFE*=1	60	34	744	100%	96.04%	88.14%	5.258	5.6362
						#TFE=2	76	42	764	100%	98.95%	96.78%	5.4269	5.4961
protein-2	13x13	51	30	688	15	C.L.S.	75	38	949	86.67%	66.31%	45.34%	5.1594	5.2999

- For most cases, the proposed method achieves
  - 100% for single fault tolerance
  - 96.04-99.49% for fault sets with two
  - 88.14-98.24% for three
- The proposed procedure can consume less time to achieve diagnosis and fault tolerance

- *#E* = #used electrodes
- *#CP* = #used control ports
- *WL* = wirelength
- *#DR* = #partitioned droplet regions
- *T.C.* = terminal conditions of DfR design flow
- *#TFE* = #considered tolerable faulty electrodes
- C.L.S. = the design flow returned the last available result due to the capacity of Chip-Level Synthesis tools
- *#FE* = 1: fault coverage for #faulty electrode = 1
- The last two column = averaged transportations used among partitioned regions

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Conclusion

- A diagnosis and fault tolerance scheme for PB-DMFBs assuming multiple faults
  - Two stages for Design-for-Reliability
    - DfR design flow for PB-DMFB designs
      - Experimental Results show that for the most cases, the DfR provides fault tolerance
    - On-the-fly probability-based diagnosis and fault tolerance procedure
      - Consume less time to achieve diagnosis and fault tolerance

  - The least dependence on sensors for diagnosis and fault tolerance automation
    - The procedure only monitoring the locations of source and terminal electrodes (D1-D3)

Thank you very much!