



# **A Novel Physics-Assisted Genetic Algorithm for Decoupling Capacitor Optimization**

Presenter : Ling Zhang,

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# Self Introduction



**Ling Zhang**

**ZJU100 Young Professor**

**PhD Supervisor**

- 2011-2015: Huazhong University of S&T, B.S.
- 2015-2017: Missouri University of S&T, M.S.
- 2018-2021: Missouri University of S&T, Ph.D.
- 2021-2023: Zhejiang University, Postdoc Fellow
- 2023-Now: Zhejiang University, ZJU100 Young Professor
  
- **Research interest:** Electromagnetic compatibility, machine learning
- Has published over 100 academic papers
- **Honors & awards:**
  - ❑ 2024 IEEE Herbert K. Mertel Young Professional Award
  - ❑ 2023 APEMC Outstanding Young Scientist Award
  - ❑ 2025 ACES-China Young Scientist Award
  - ❑ 2019 & 2024 DesignCon Best Paper Award

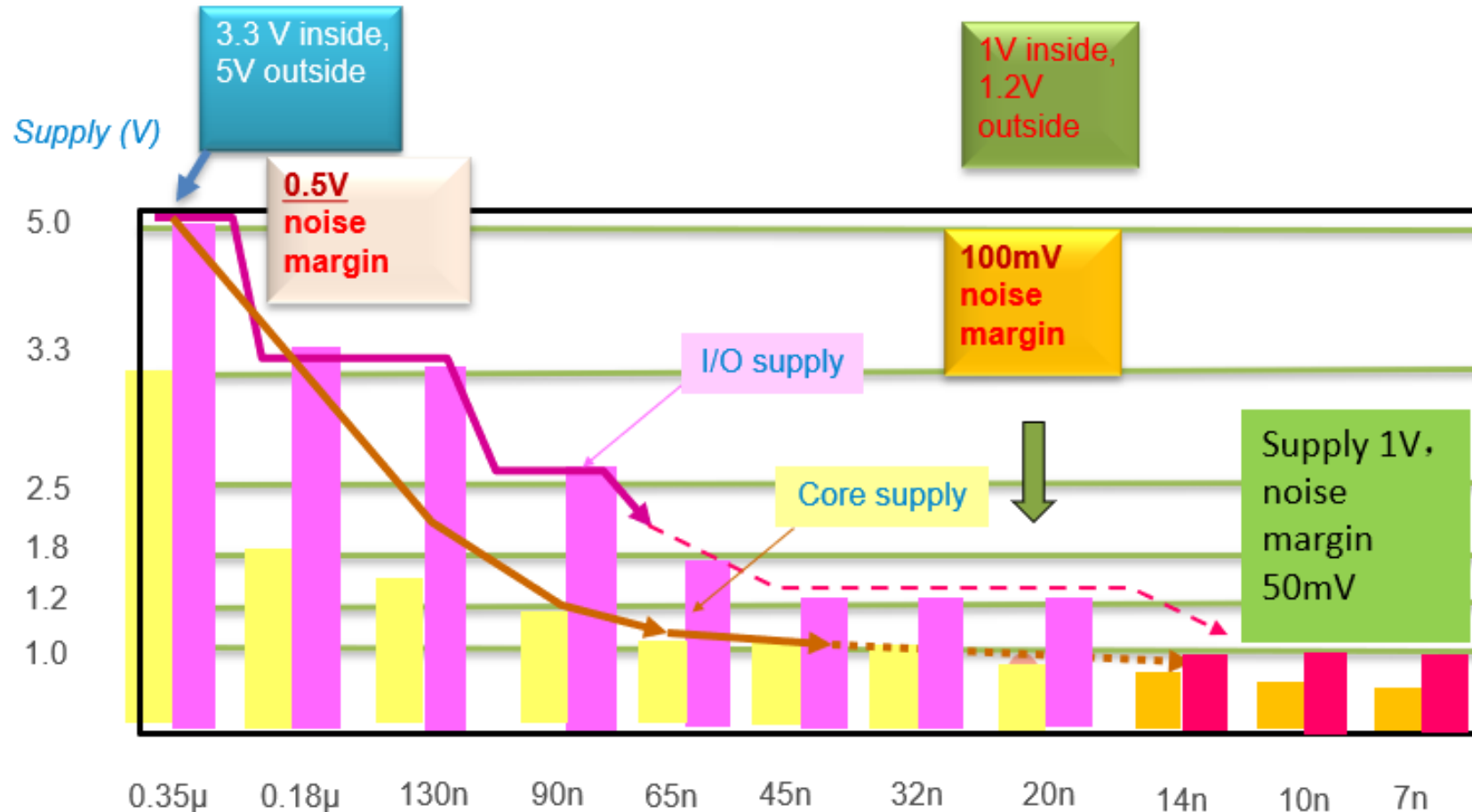
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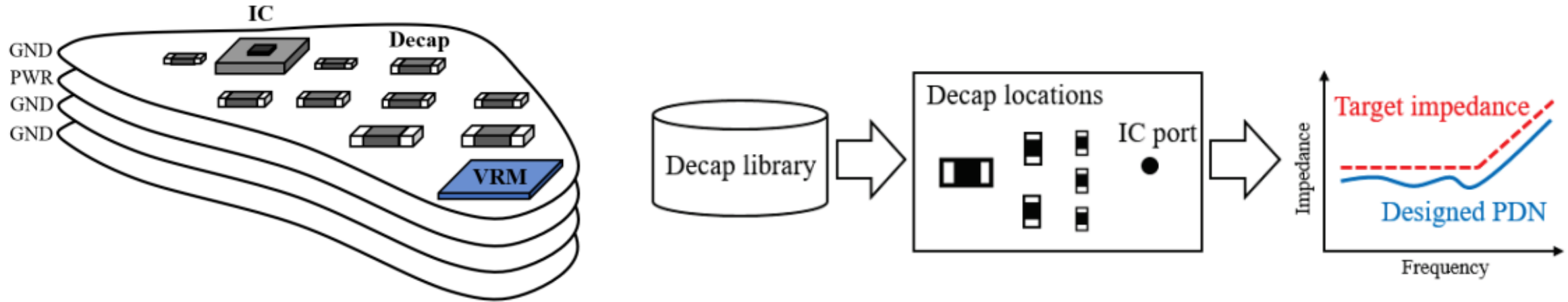
- Background
- Existing approaches for decap optimization
- Proposed method for decap optimization
- Conclusion

# Background: Power Integrity



- As the size of IC becomes smaller and smaller, the power supply voltage of ICs is also becoming lower and lower, leaving less and less margin for power supply noise.
- Therefore, power integrity of IC is more and more important.

# Decap Optimization for PDN



- To mitigate AC power supply noise in PDN, decoupling capacitors (decaps) need to be optimized to satisfy the target impedance.
- Usually, **the minimum number of decaps** is pursued to satisfy a given target impedance.
- However, **efficiently finding the optimum decap solution** is a longstanding challenge.

# Challenge of Decap Optimization



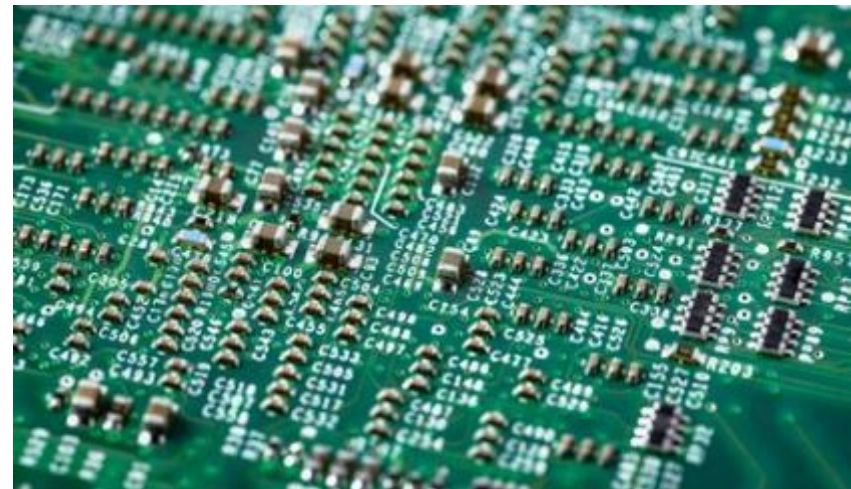
e.g., 10 decap types, 100 locations

Enormous search space:  $10^{100}$

Efficiency

Solution quality

It is hard to achieve both!



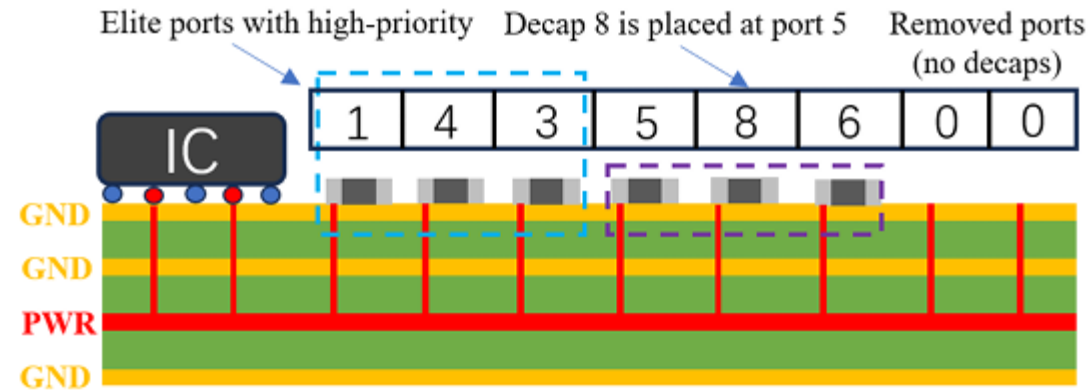
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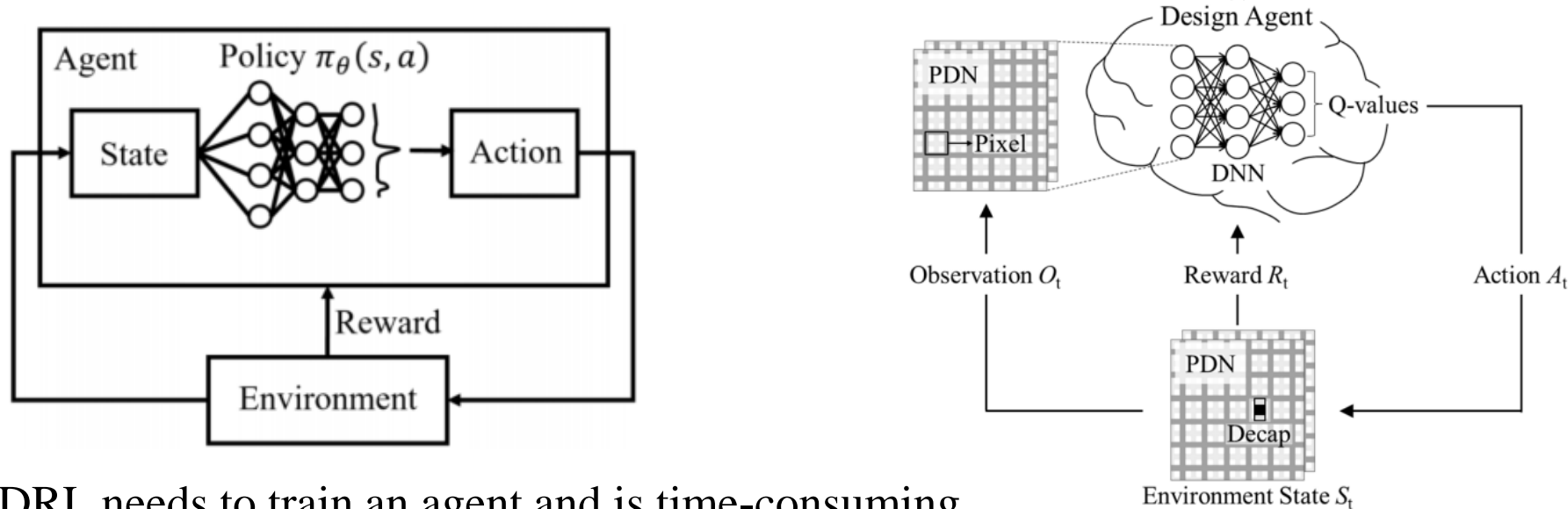
# Problem Definition for Decap Optimization



- Assume that there are  $N$  available decap locations  $L_1, L_2, \dots, L_N$
- $M$  decap types represented by  $C_1, C_2, \dots, C_M$  (0 means no decap)
- Then, the decap optimization process is minimizing the number of decaps to satisfy a target impedance

$$\begin{aligned} & \arg \min_{L_1, L_2, \dots, L_N} N_{\text{decap}} \\ & \text{s.t. } Z_{\text{pdn}}(f) \leq Z_{\text{target}}(f) \end{aligned}$$

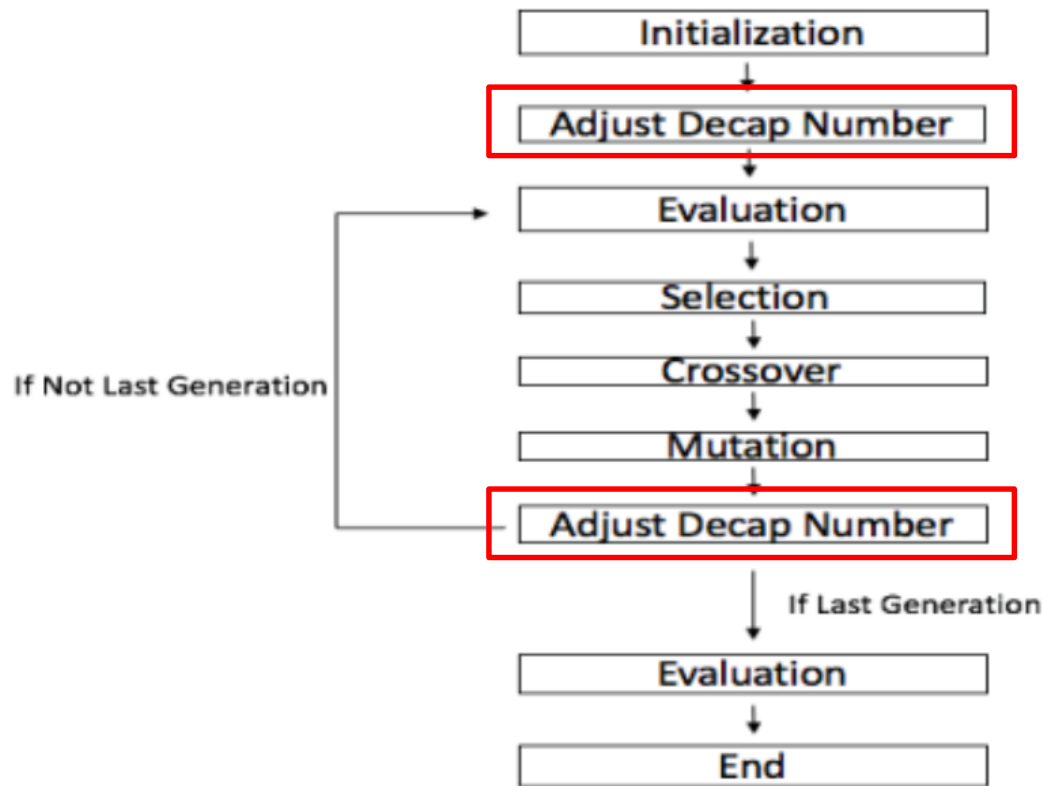
# Deep Reinforcement Learning (DRL)



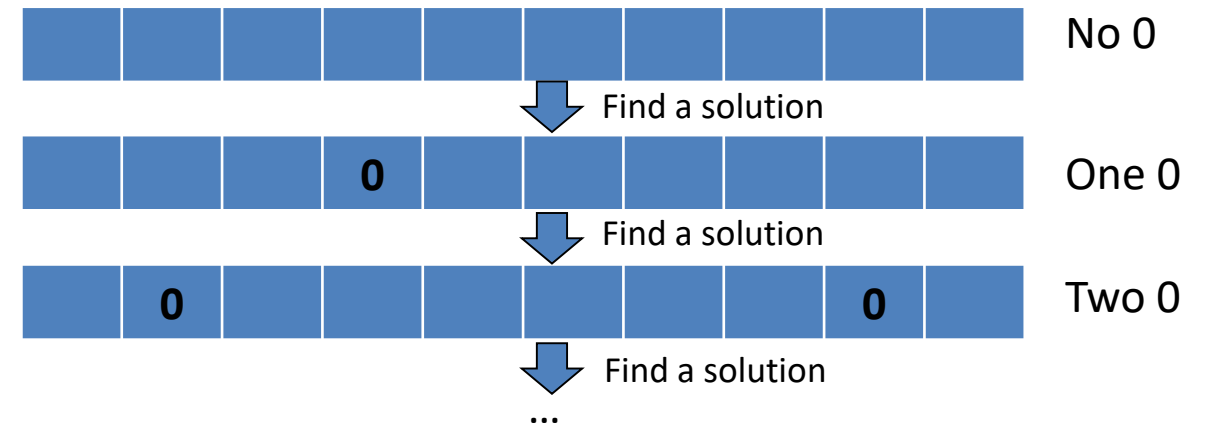
- DRL needs to train an agent and is time-consuming.
- The optimal solution cannot be guaranteed.
- The generalization performance of a trained DRL agent cannot be guaranteed to handle different PDN configurations.

- H. Park et al., “Deep Reinforcement Learning-Based Optimal Decoupling Capacitor Design Method for Silicon Interposer-Based 2.5-D/3-D ICs,” IEEE Trans. Compon. Packaging Manuf. Technol., vol. 10, no. 3, pp. 467-478, March 2020.
- H. Park et al., “Transformer Network-Based Reinforcement Learning Method for Power Distribution Network (PDN) Optimization of High Bandwidth Memory (HBM),” IEEE Trans. Microw. Theory Tech., vol. 70, no. 11, pp. 4772-4786, Nov. 2022.
- L. Zhang, L. Jiang, J. Juang, Z. Yang, E. -P. Li and C. Hwang, “Decoupling Optimization for Complex PDN Structures Using Deep Reinforcement Learning,” in IEEE Transactions on Microwave Theory and Techniques, doi: 10.1109/TMTT.2023.3248237.

# Modified Genetic Algorithm (GA)



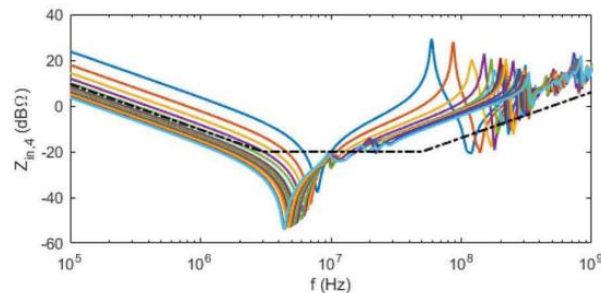
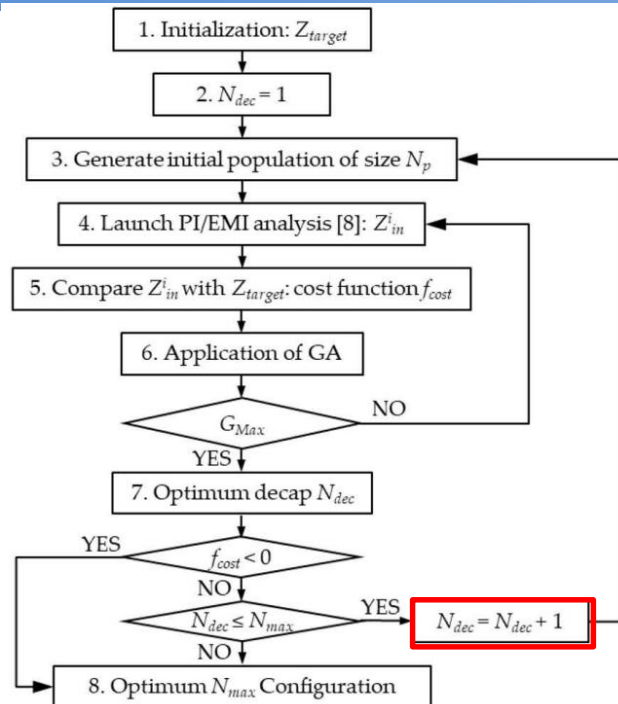
- 0 means empty and no decaps
- Guide the GA by **gradually increasing the number of 0**



- The core of this method is to better guide the algorithm towards the solutions **with fewer decaps** to narrow down the search space
- However, this algorithm still has a lot of space to be improved!

• J. Juang, et al., “A Modified Genetic Algorithm for the Selection of Decoupling Capacitors in PDN Design,” Proc. Int. Symp. IEEE Electromagn. Compat., 2021, pp. 712-717..

# Sequential Full Search



- Add decaps one by one
- In each decap selection, the combinations of **all the decaps types and decap locations** are searched once, and the best decap type and location is determined to **minimize the area above the target impedance**.
- This method is also called as “sequential full search”.
- Even though this method is efficient, **it cannot guarantee the optimal solution!**

- F. de Paulis, R. Cecchetti, C. Olivieri, and M. Buecker, “Genetic Algorithm PDN Optimization based on Minimum Number of Decoupling Capacitors Applied to Arbitrary Target Impedance,” Proc. Int. Symp. IEEE Electromagn. Compat., 2020, pp. 428-433.

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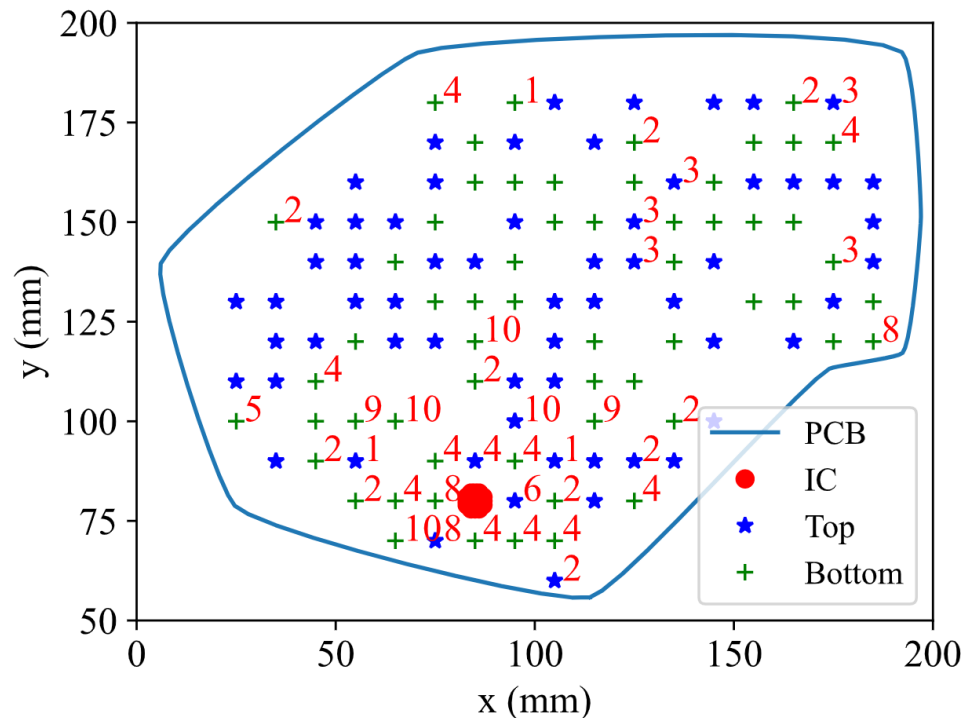


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- **Proposed method for decap optimization**
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# How to Accelerate Decap Optimization?



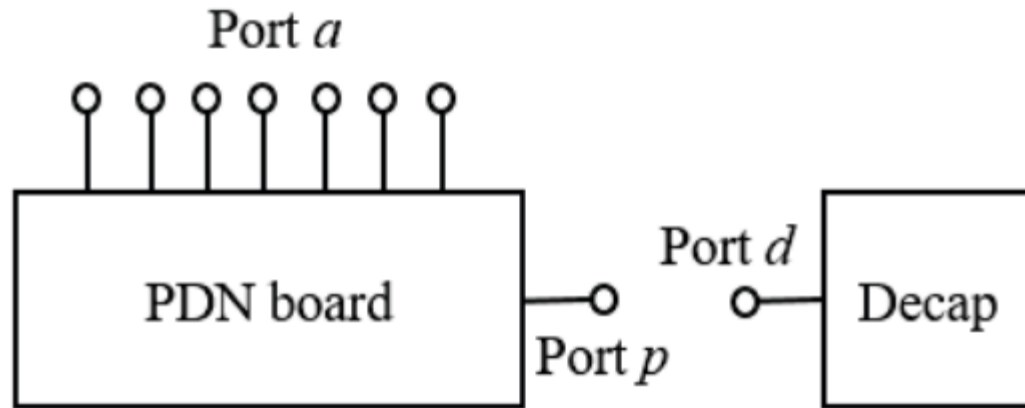
(Different decap number represents different decap types)



Many locations are not used

- The large number of decap locations is the primary reason for the difficulty in efficiently finding the optimal solution.
- Eventually, many decap locations are **actually not used**.
- Can we gradually **abandon the useless locations** during the optimization process?

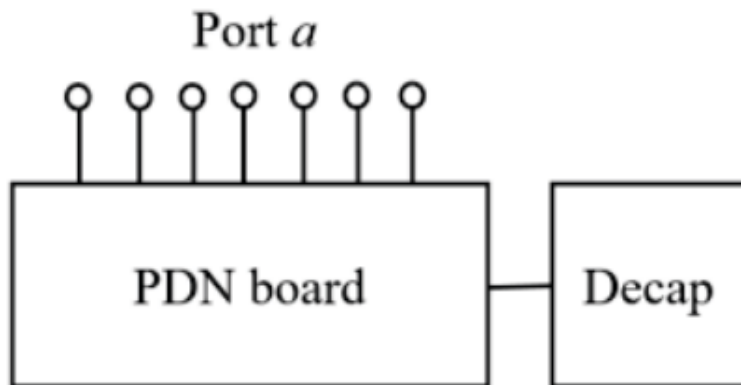
# Impedance Calculation



$$\begin{cases} \begin{bmatrix} U_a \\ U_p \end{bmatrix} = \begin{bmatrix} Z_{aa} & Z_{ap} \\ Z_{pa} & Z_{pp} \end{bmatrix} \cdot \begin{bmatrix} I_a \\ I_p \end{bmatrix} \\ U_d = Z_{dd} \cdot I_d \end{cases} \quad \begin{cases} U_p = U_d \\ I_p = -I_d \end{cases}$$



$$U_a = \left[ Z_{aa} - Z_{ap} (Z_{pp} + Z_{dd})^{-1} Z_{pa} \right] \cdot I_a$$



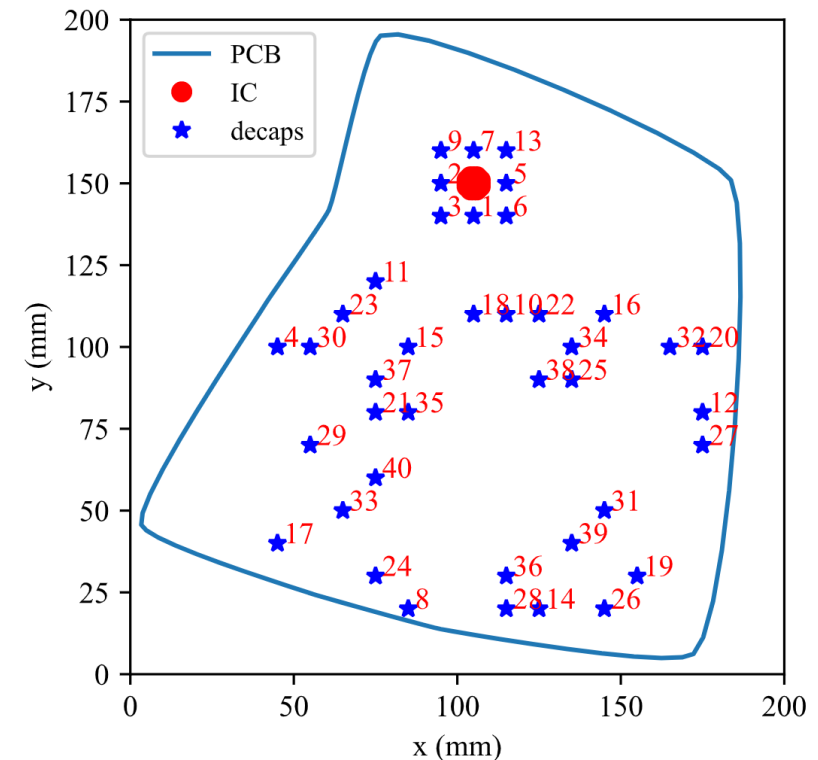
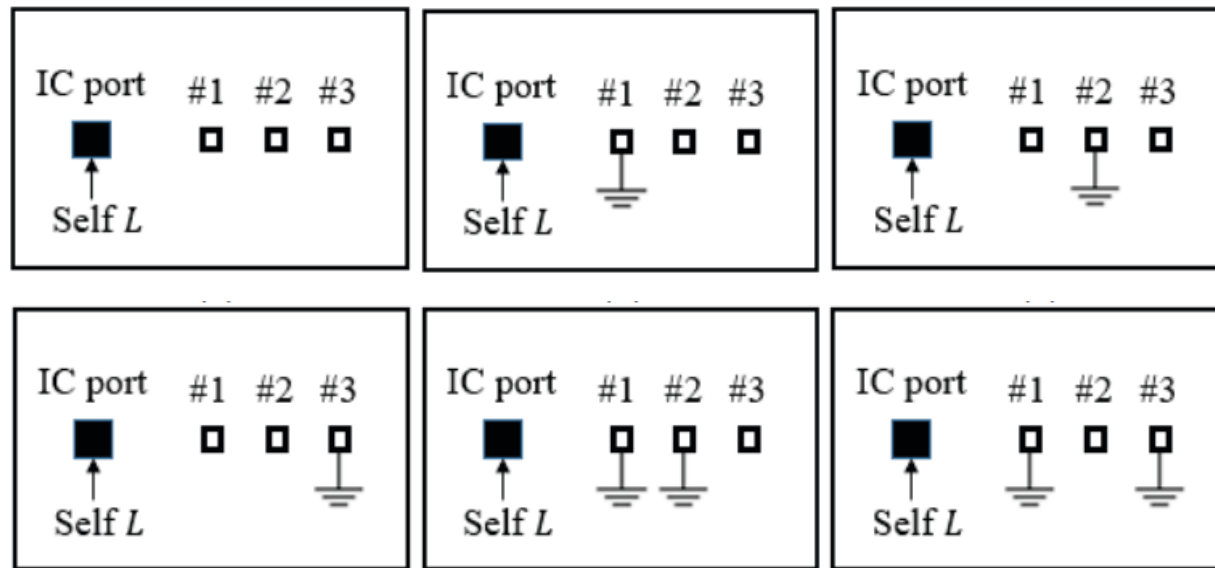
- The impedance after adding decaps is calculated by cascading Z-parameters.

- L. Zhang, W. Huang, J. Juang, H. Lin, B. -C. Tseng and C. Hwang, "An Enhanced Deep Reinforcement Learning Algorithm for Decoupling Capacitor Selection in Power Distribution Network Design," 2020 IEEE International Symposium on Electromagnetic Compatibility & Signal/Power Integrity (EMCSI), Reno, NV, USA, 2020, pp. 245-250.

# Proposed Method – Step 1

## Step 1 – Port prioritization

Shorting the decap ports progressively and **prioritize the locations from the inductance** looking into the IC port.



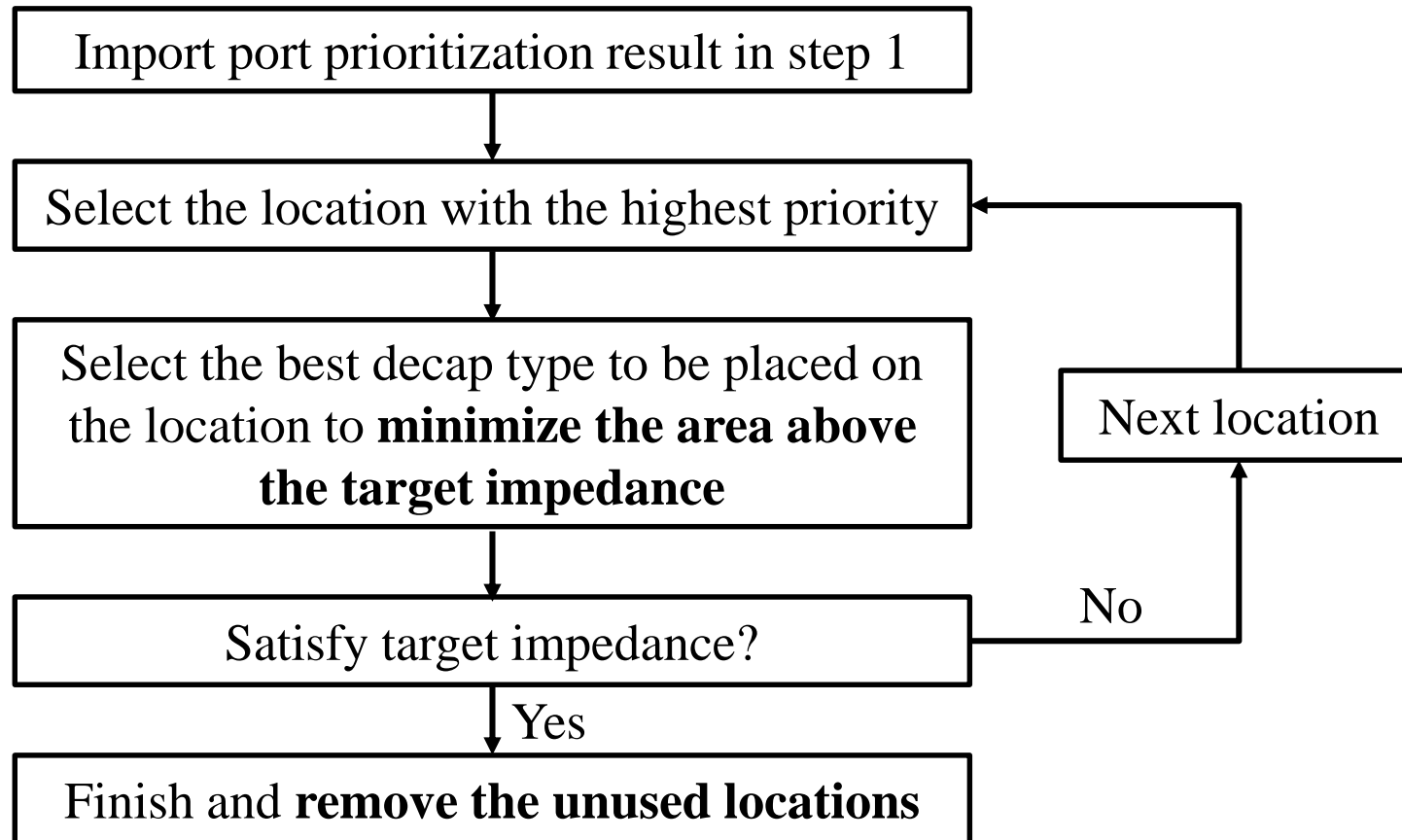
- Smaller number means higher priority.

- L. Zhang, W. Huang, J. Juang, H. Lin, B. -C. Tseng and C. Hwang, “An Enhanced Deep Reinforcement Learning Algorithm for Decoupling Capacitor Selection in Power Distribution Network Design,” 2020 IEEE International Symposium on Electromagnetic Compatibility & Signal/Power Integrity (EMCSI), Reno, NV, USA, 2020, pp. 245-250.

# Proposed Method – Step 2



## Step 2 – Determine initial solution

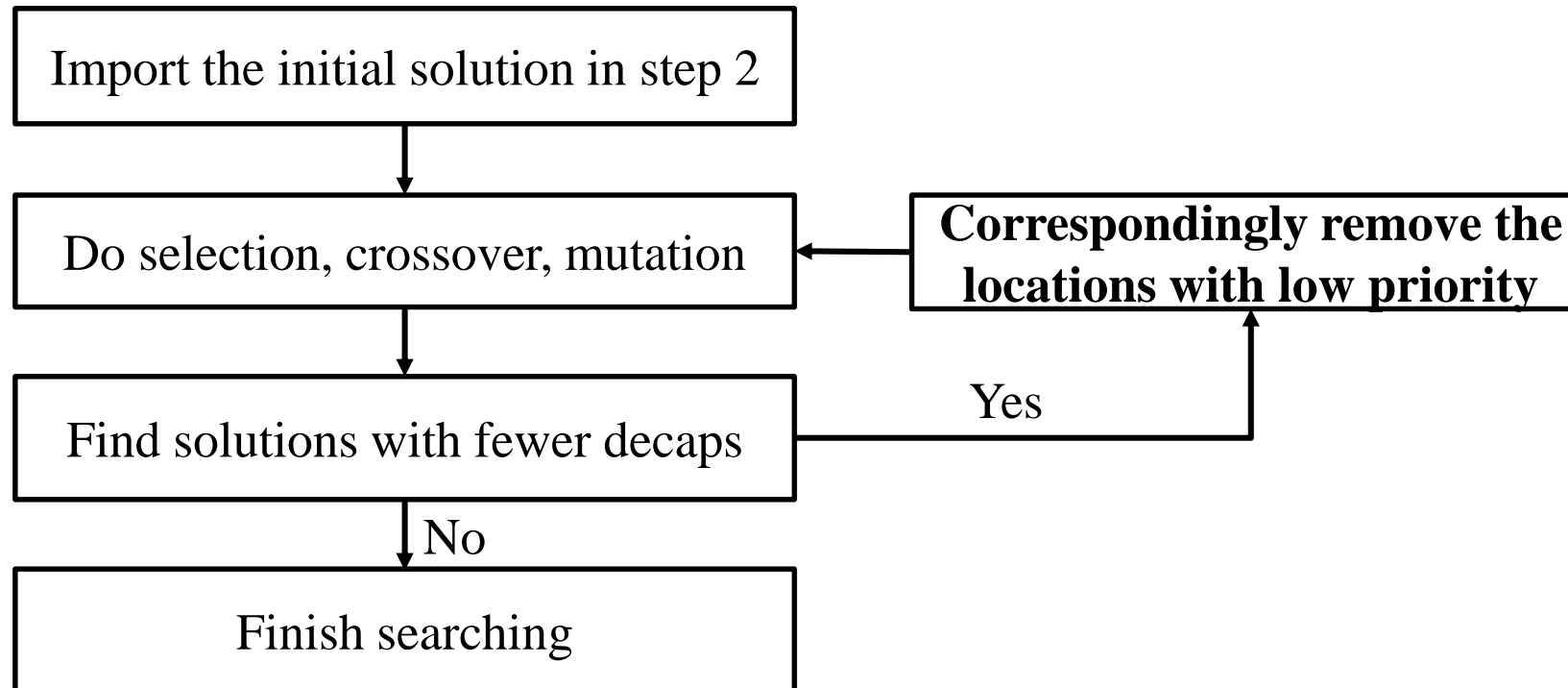


- Decaps are added one by one onto the prioritized locations until the target impedance is satisfied.
- An initial solution can be determined efficiently.
- The unused locations can be removed to narrow down the search space.

# Proposed Method – Step 3



## Step 3 – Port Removal

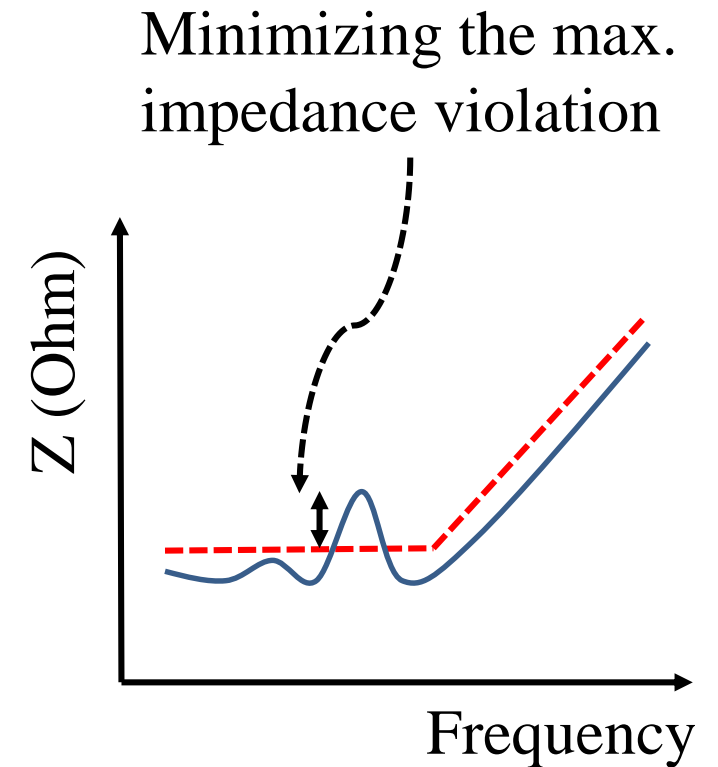


- By gradually remove the low-priority locations during the optimization process, the search space is narrowed down, and the convergence is further accelerated!
- The selection, crossover, and mutation are the same with the modified GA.

# Cost Function

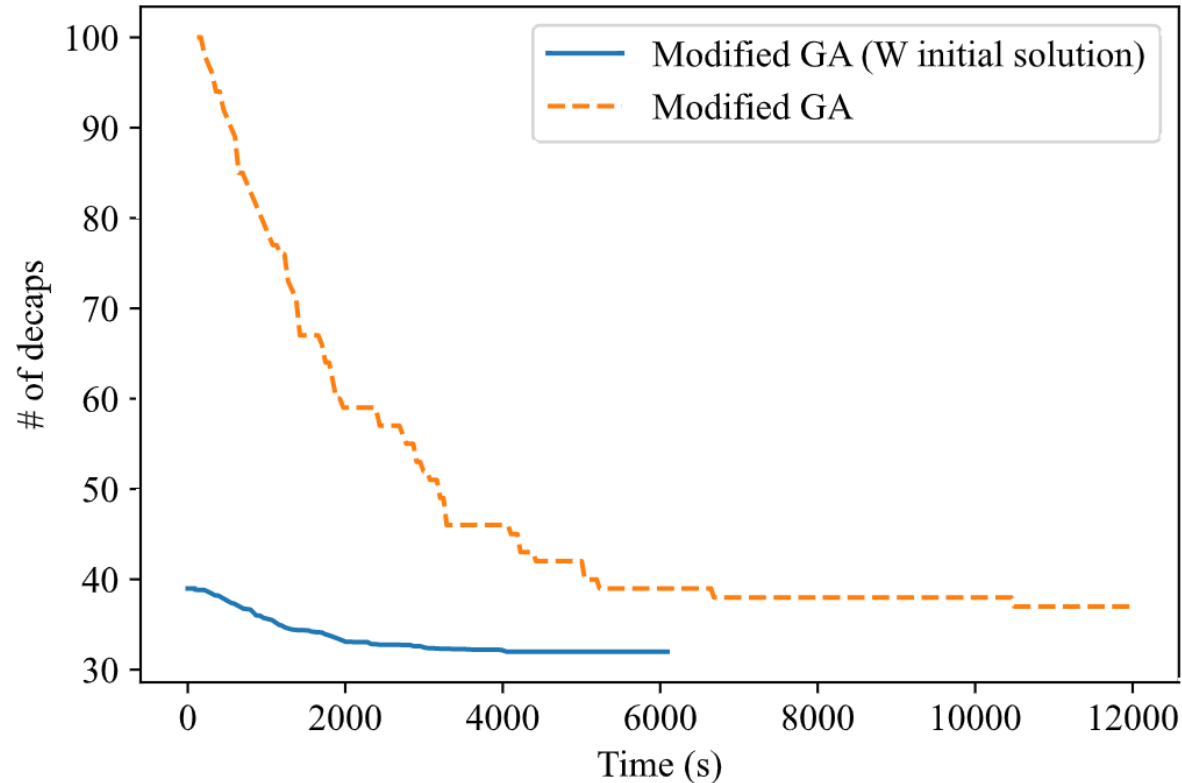
$$f_{obj} = \begin{cases} \{N_d, \text{if } \forall f : Z_{pdn}(f) \leq Z_{target}(f)\} \\ \left\{ \begin{aligned} &N + \max[Z_{pdn}(f) - Z_{target}(f), 0], \\ &\text{if } \exists f : Z_{pdn}(f) > Z_{target}(f) \end{aligned} \right\} \end{cases}$$

- If the target impedance can be satisfied, the cost function is to minimize the number of decaps.
- If the target impedance cannot be satisfied, the cost function is to minimize the maximum impedance violation.



# Power of Initial Solution

- Board #1 with 100 ports



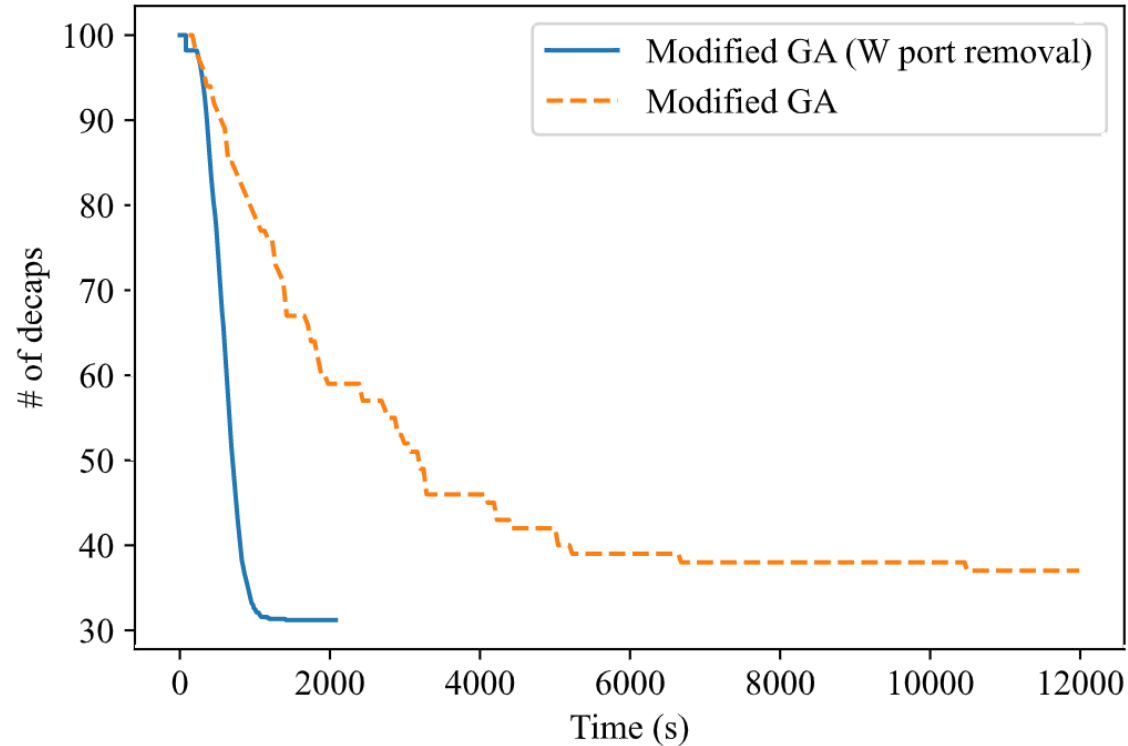
- Without initial solution, the modified GA can only find 37 decaps after 12,000 seconds.
- But after feeding the initial solution to the algorithm, it can **find 31 decaps in only 3000 seconds!**

- **Modified GA:** J. Juang, et al., “A Modified Genetic Algorithm for the Selection of Decoupling Capacitors in PDN Design,” Proc. Int. Symp. IEEE Electromagn. Compat., 2021, pp. 712-717..

# Power of Port Removal



- Board #1 with 100 ports

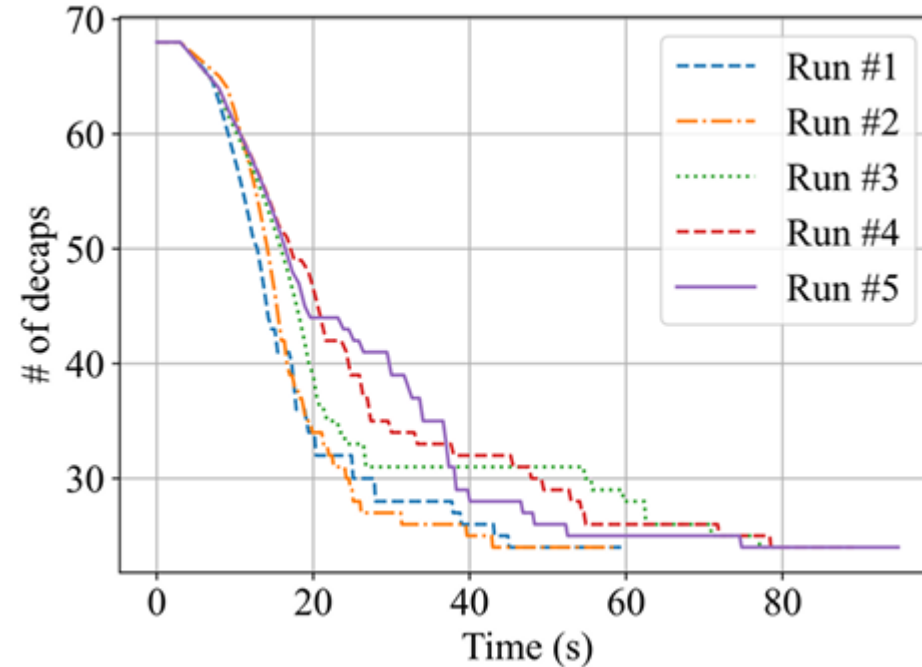
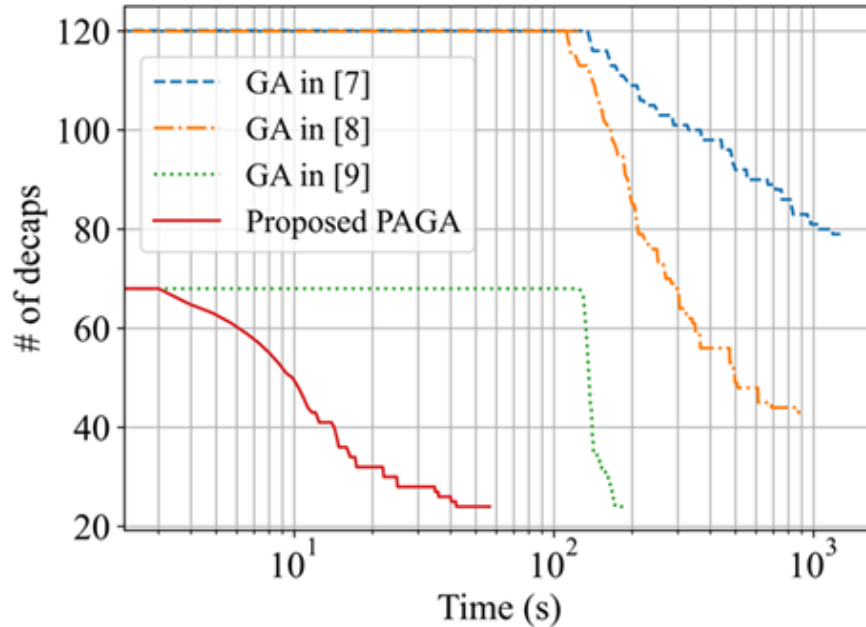


- Without port removal, the modified GA can only find 37 decaps after 12,000 seconds.
- But after adding port removal to the algorithm, it can **find 31 decaps in only 1000 seconds!**

- **Modified GA:** J. Juang, et al., “A Modified Genetic Algorithm for the Selection of Decoupling Capacitors in PDN Design,” Proc. Int. Symp. IEEE Electromagn. Compat., 2021, pp. 712-717..

# Overall Performance

- Board #2 with 120 ports



- After combining the initial solution and port removal, the proposed method shows an overwhelming advantage over the other GA methods.
- Also, the proposed method has excellent repeatability.

[7] Z. Xu, Z. Wang, Y. Sun, C. Hwang, H. Delingette, and J. Fan, "Jitter aware economic PDN optimization with a genetic algorithm," IEEE Trans. Microw. Theory Techn., vol. 69, no. 8, pp. 3715–3725, Aug. 2021

[8] J. Juang et al., "A modified genetic algorithm for the selection of decoupling capacitors in PDN design," in Proc. Int. Symp. IEEE Electromagn. Compat., Jun. 2021, pp. 712–717.

[9] L. Zhang et al., "A physics-based genetic algorithm for decap optimization in power distribution networks," in Proc. IEEE Symp. Electromagn. Compat. Signal/Power Integrity (EMC+SIPI), Jul. 2023, pp. 698–703.

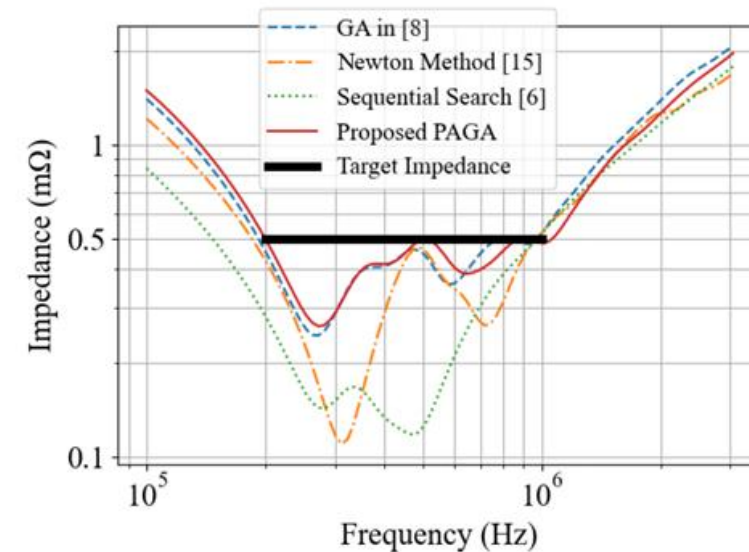
# Comparison with Other Methods



- Board #2 with 120 ports

OPTIMIZATION RESULT COMPARISON—CASE 1

Methods	Time (s)	Decaps Number
GA in [7]	1266	79
GA in [8]	887	43
GA in [9]	187	24
Sequential search method [6]	\	61
Sorting search method [16]	\	No Sol.
Newton- Hessian method [15]	\	101
Proposed PAGA	61	24



- The proposed method can converge to the optimal solution efficiently.

[6] F. de Paulis et al., "Genetic algorithm PDN optimization based on minimum number of decoupling capacitors applied to arbitrary target impedance," in Proc. IEEE Int. Symp. Electromagn. Compat. Signal/Power Integrity (EMCSI), Jul. 2020, pp. 428–433.

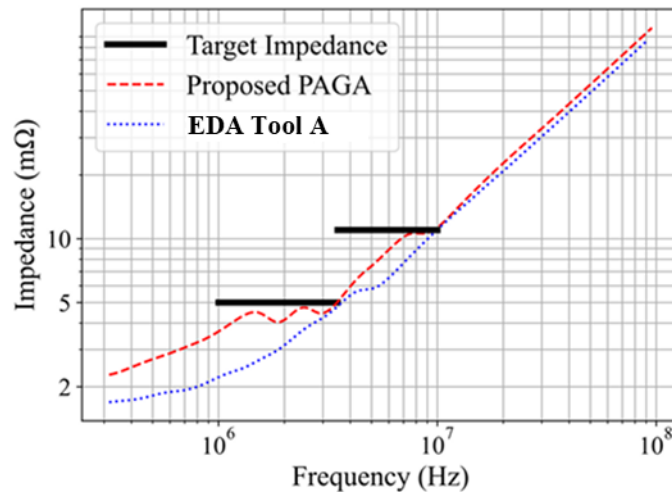
[15] J. Wang, Z. Xu, X. Chu, J. Lu, B. Ravelo, and J. Fan, "Multiport PDN optimization with the Newton–Hessian minimization method," IEEE Trans. Microw. Theory Techn., vol. 69, no. 4, pp. 2098–2109, Apr. 2021.

[16] K. Koo, G. R. Luevano, T. Wang, S. Özbayat, T. Michalka, and J. L. Drewniak, "Fast algorithm for minimizing the number of decap in power distribution networks," IEEE Trans. Electromagn. Compat., vol. 60, no. 3, pp. 725–732, Jun. 2018..

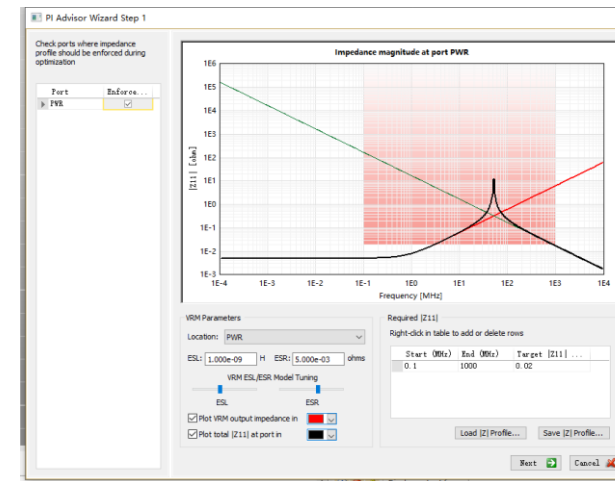
# Comparison with Commercial Tool

- Board #3 with 123 ports (a real-product design)

Impedance result



EDA Tool A



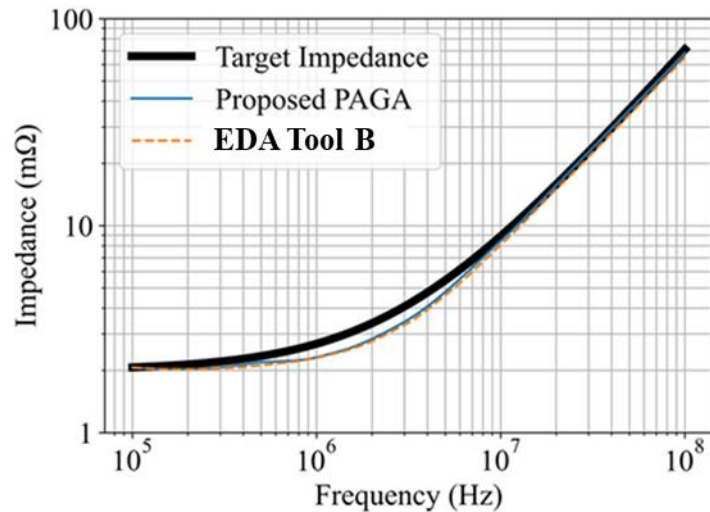
1 <sup>st</sup> Board	GA in [7]	595	78
	GA in [8]	441	32
	GA in [9]	140	10
	EDA Tool A	57	34
	Proposed PAGA	18	10

- For a real board with 123 ports, EDA Tool A took about **1 mins to find 34 decaps.**
- However, our proposed method only took about **18 seconds to find 10 decaps!**

# Comparison with Commercial Tool

- Board #4 with 68 ports (a real-product design)

Impedance result



EDA Tool B

Scheme ID	Cost	Number	Number of Capa	Area	Impedance M
Original Scheme	99	99	1	79200	270.898
Scheme 1	50	50	8	177800	16.8945
Scheme 2	51	51	9	177600	16.8939
Scheme 3	52	52	10	179400	16.8903
Scheme 4	53	53	9	180000	16.8825
Scheme 5	54	54	9	180800	16.8798
Scheme 6	55	55	8	182600	16.8787
Scheme 7	56	56	9	184600	16.877
Scheme 8	57	57	9	184200	16.8737
Scheme 9	58	58	10	183800	16.8693
Scheme 10	59	59	10	185600	16.8648
Scheme 11	61	61	10	192800	16.8641
Scheme 12	62	62	10	191200	16.8624

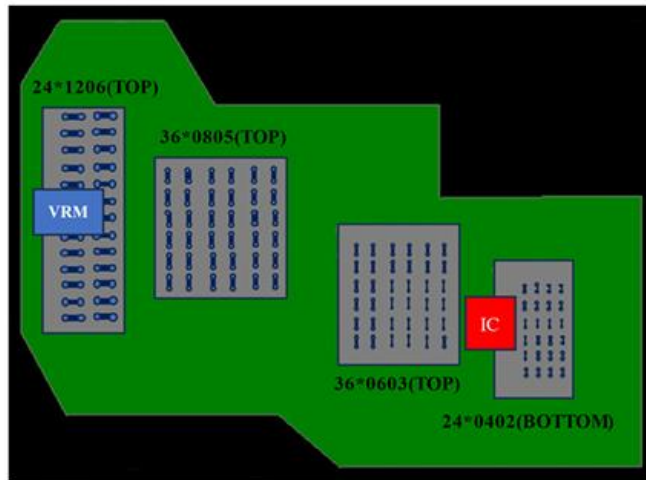
2 <sup>nd</sup> Board	GA in[7]	188	37
	GA in [8]	161	32
	GA in [9]	55	29
	EDA Tool B	52	34
	Proposed PAGA	31	29

- For a real board with 68 ports, EDA Tool B took about **1 mins to find 34 decaps.**
- However, our proposed method only took about **31 seconds to find 29 decaps!**

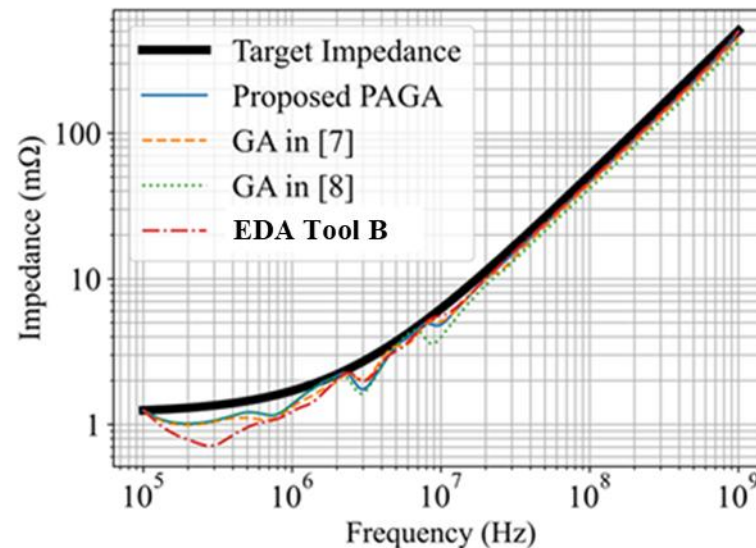
# Package Size Constraint

- Board #5 with 120 ports (with package size constraint)

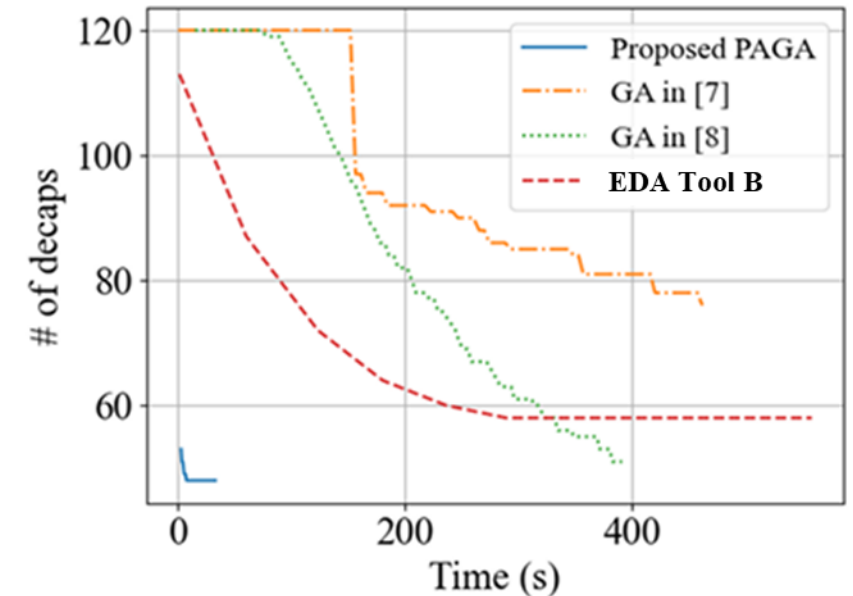
Board layout



Impedance result



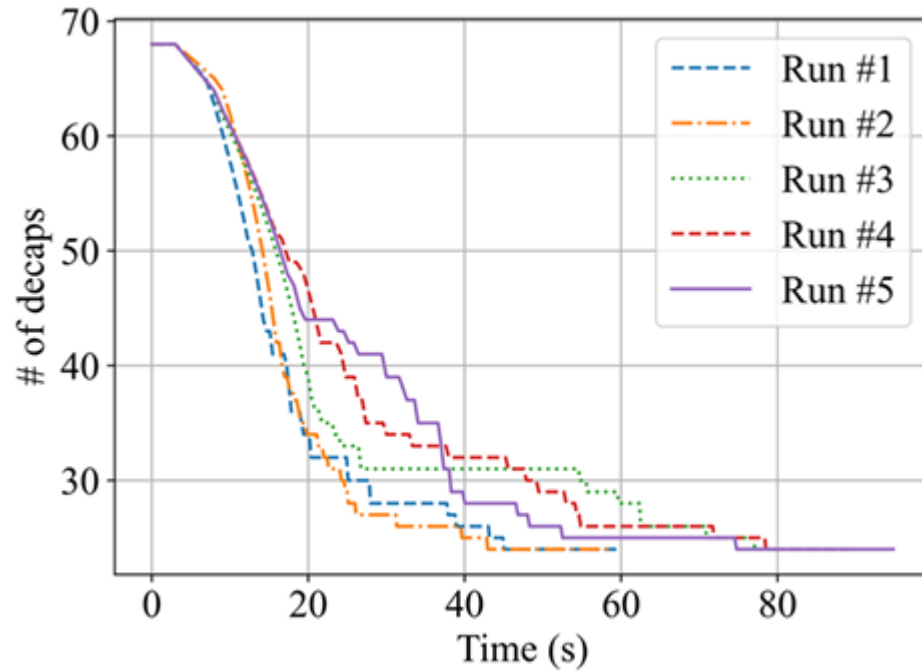
Convergence process



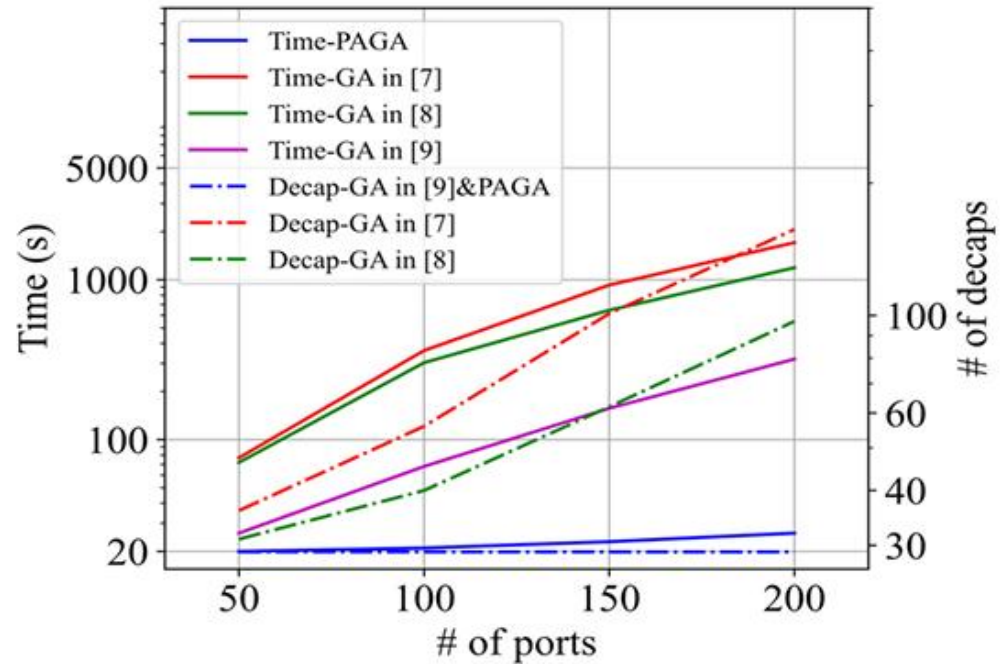
- The proposed PAGA can also tackle the decap optimization scenarios with decap size constraints!

# Robustness Validation

Repeatability  
(5 independent runs for the same case)



Scalability  
(Time and decap numbers when candidate locations increase)



- the proposed PAGA can maintain high time efficiency in large-scale problems!

# Conclusion

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- The proposed method is much more efficient than the state-of-the-art approaches in finding the optimal decap solutions!
- The proposed method can serve as a very powerful algorithm in EDA tool development for power integrity!



# Future Work

- The proposed method still needs the simulated S-parameters including the IC ports and decap ports.
- However, when the number of candidate decap locations becomes extremely large in pre-layout design, simulating and exporting the S-parameters may be very challenging.
- Therefore, our future work will address this problem and **avoid the simulation of S-parameters** in decap optimization.

# Publications



- L. Jiang, L. Zhang et al., "A Novel Physics-Assisted Genetic Algorithm for Decoupling Capacitor Optimization," in IEEE Transactions on Microwave Theory and Techniques, vol. 72, no. 8, pp. 4498-4507, Aug. 2024.
- L. Zhang, L. Jiang, J. Juang, Z. Yang, E. -P. Li and C. Hwang, "Decoupling Optimization for Complex PDN Structures Using Deep Reinforcement Learning," in IEEE Transactions on Microwave Theory and Techniques, vol. 71, no. 9, pp. 3773-3783, Sept. 2023.
- L. Zhang et al., "Efficient DC and AC Impedance Calculation for Arbitrary-Shape and Multilayer PDN Using Boundary Integration," in IEEE Transactions on Signal and Power Integrity, vol. 1, pp. 1-11, 2022.