香港科技大學
THE HONG KONG UNIVERSITY OF SCIENCE AND TECHNOLOGY

DESIGN & TEST
UC SANTA BARBARA

Pairing of Microring-based Silicon Photonic Transceivers for Tuning Power Optimization

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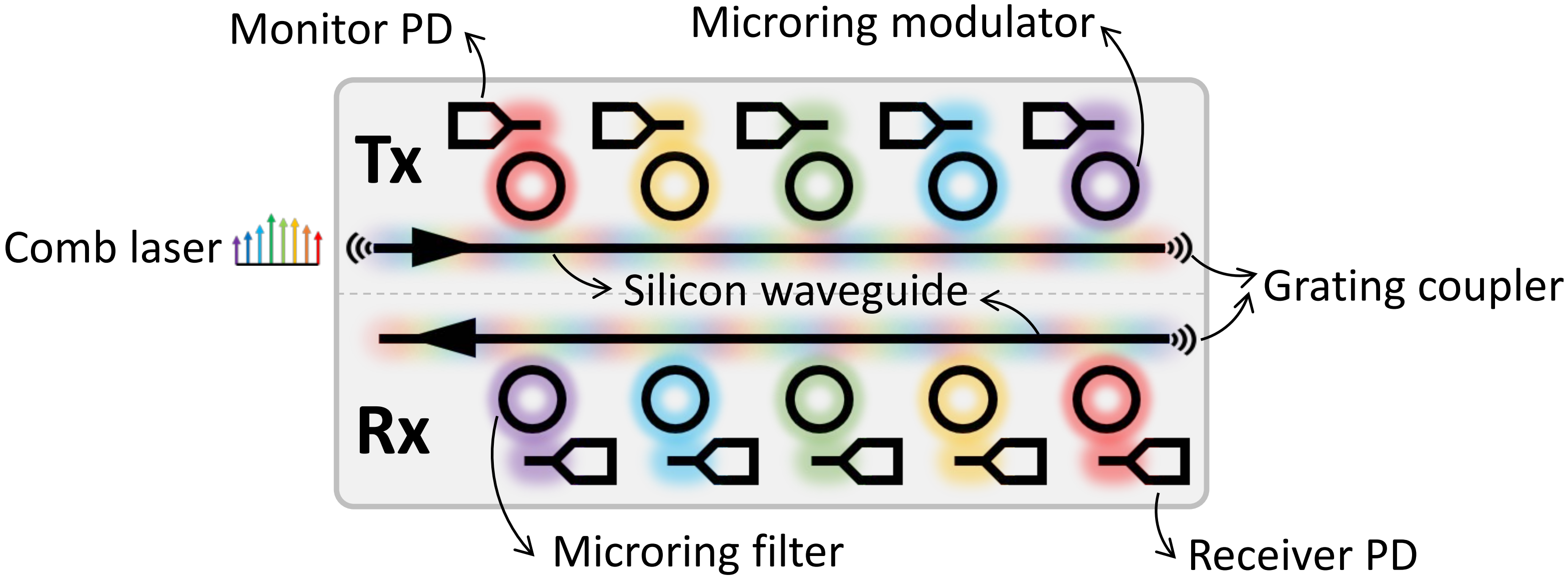
Outline

- **Background and Motivation**
- **Device Measurement and Variation Modeling**
  - Measurement of fabricated transceivers
  - Variation model for resonance wavelengths
- **Problem Formulation**
  - Separable Transceivers
  - Inseparable Transceivers
- **Algorithms and Evaluations**
- **Conclusion**

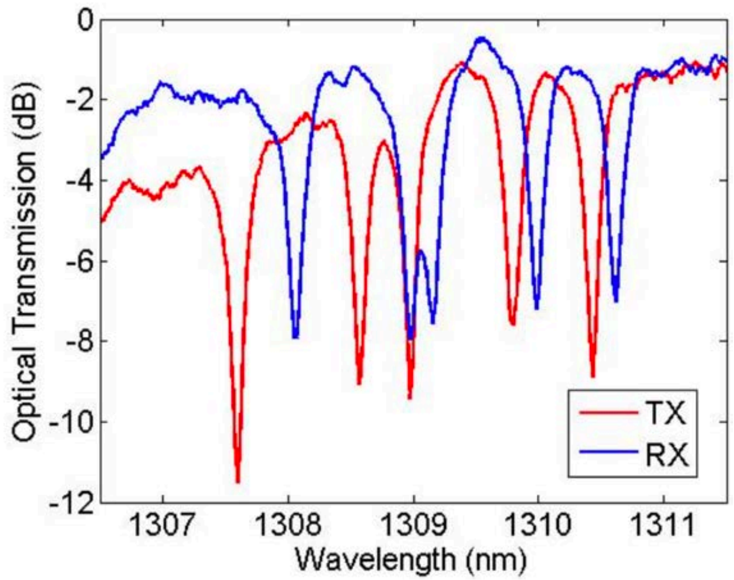
Background: Microring-based WDM

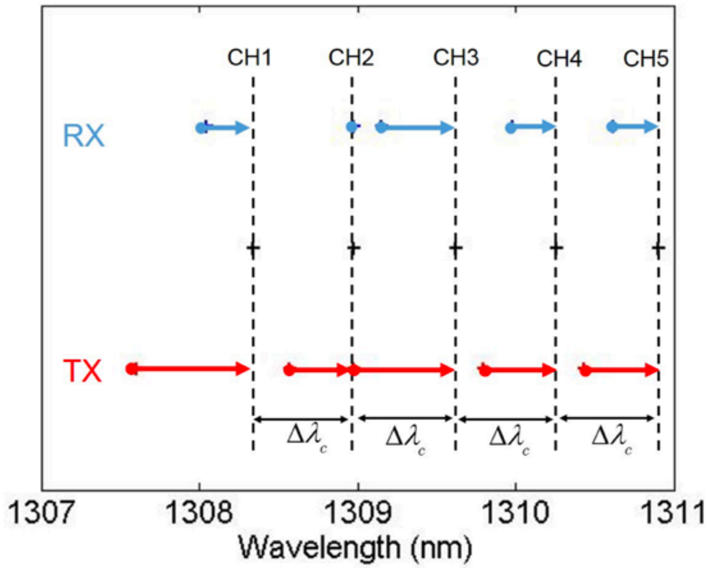
- **Optical interconnects** to solve communication bottleneck in HPC
- **Silicon photonics** as a scalable solution by taking advantage of CMOS-compatible integration
- **Microring-based TRx** considered promising due to its compact footprint and (de)multiplexer-free WDM implementation



Background: Microring Variations and Tuning

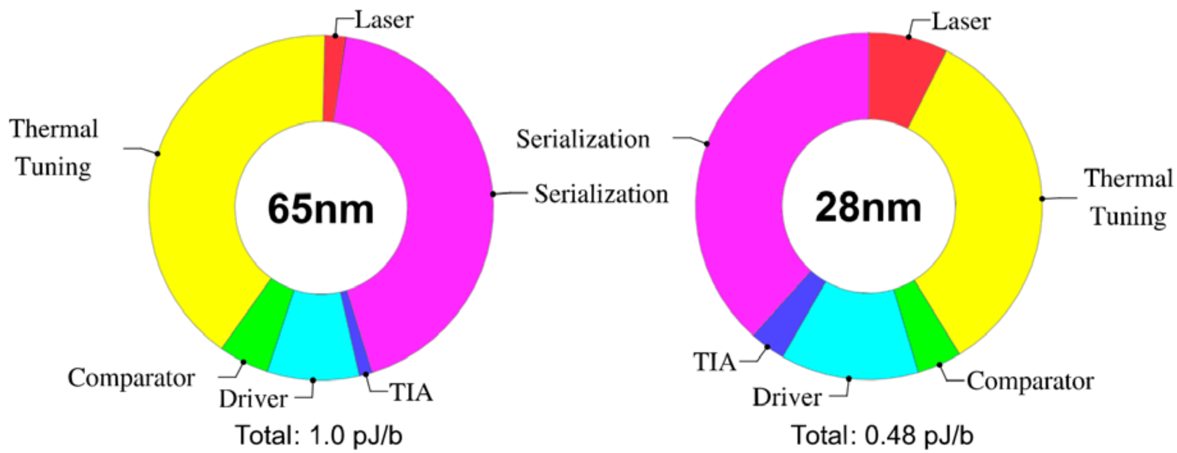
- **Microring resonators** are highly sensitive to process variations
- **Geometry inaccuracies** could lead to wavelength variations as large as 10 nm at wafer scale
- **Resonance wavelengths** of microrings need to be tuned to align with corresponding carrier wavelengths





Motivation

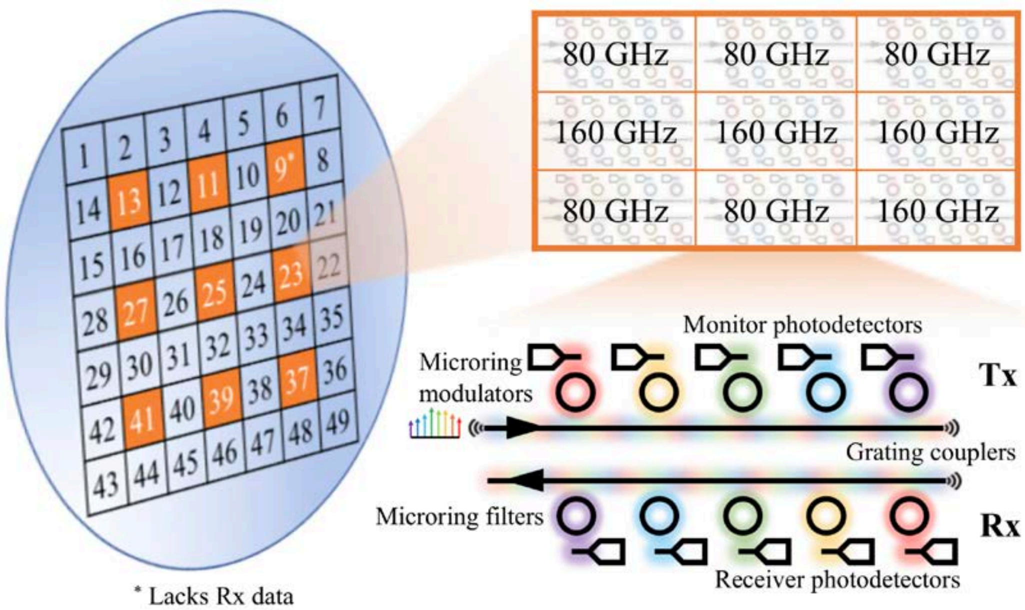
- **Wavelengths tuning power** takes a non-trivial portion of the total power budget
- **Existing solutions** to tuning power mitigation target on individual transceivers
- **In the presence of multiple devices**, different Tx – Rx pairing results in different tuning power
- **Optimal pairing** exists which minimize the average tuning power

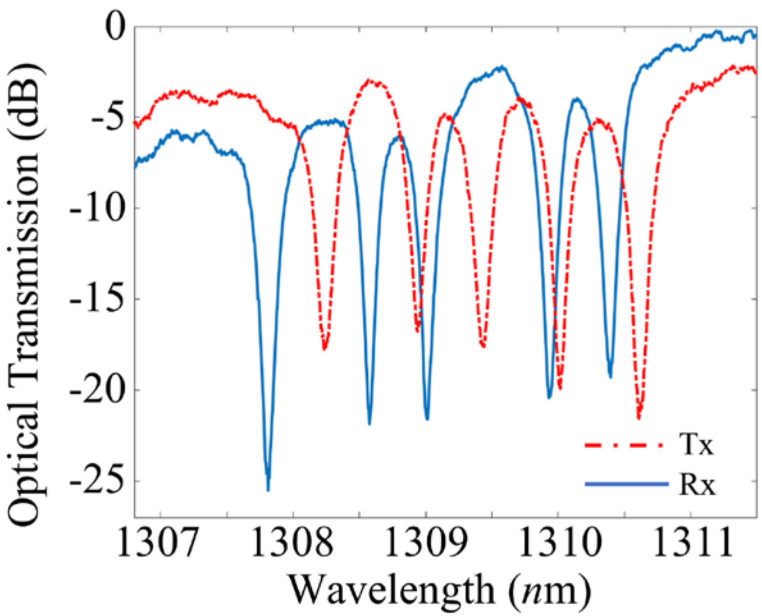


Polster et al, IEEE Trans. on VLSI Systems, 2016

Device Measurement

- **Nine representative locations measured**
  - 40 TRx with 80 GHz spacing
  - 31 TRx with 160 GHz spacing



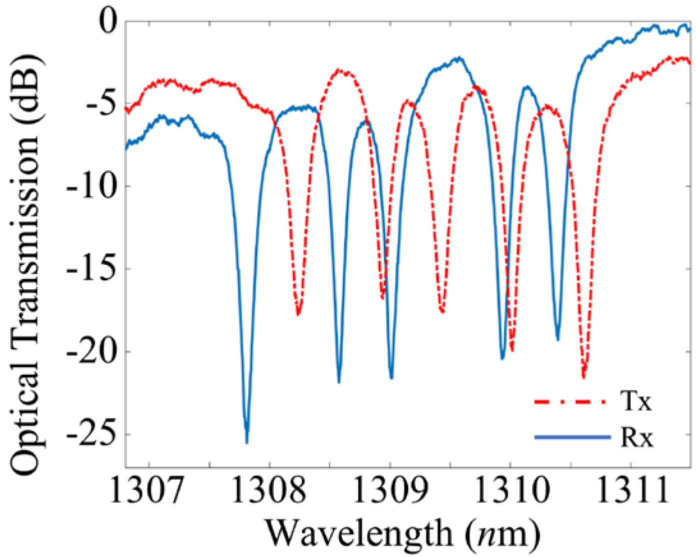


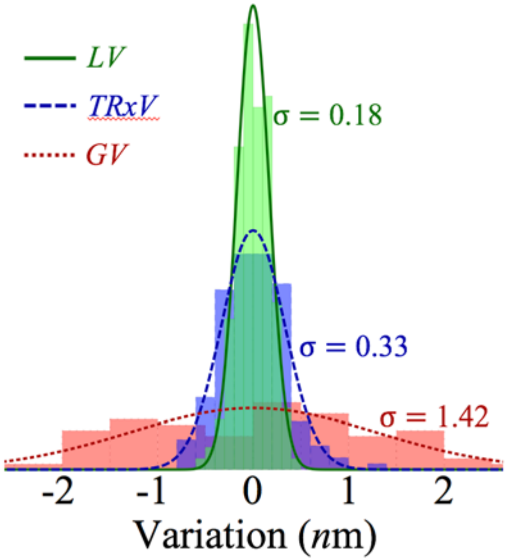
Variation Modeling

- **Variation components of resonance wavelengths:**
  - Global variation *(GV)* across different TRx
  - Local variation *(LV)* across different microrings within a TRx
  - Tx – Rx wavelength offset (*TRxV*) within a TRx

$$\lambda_{TX}(i,j) = \lambda_0 + GV_i + (j-1)\Delta\lambda_c + LV_j$$

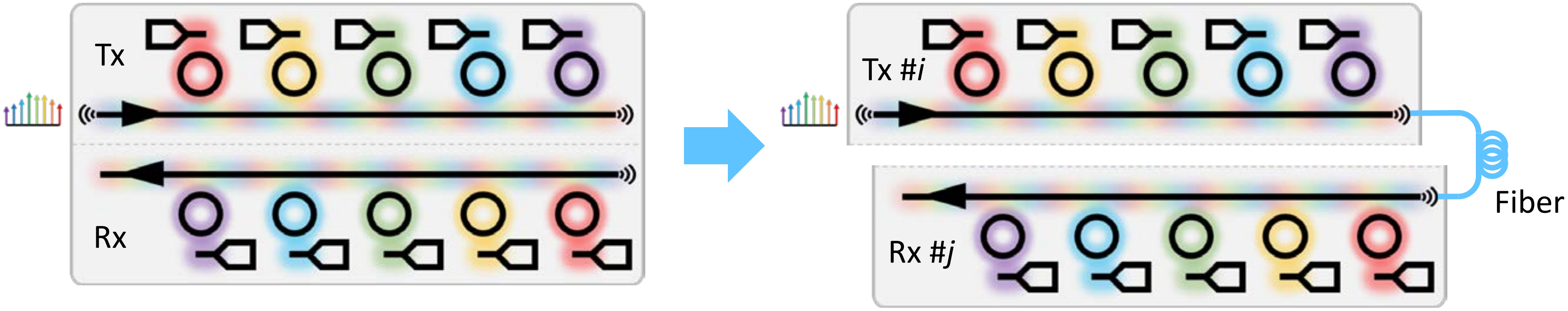
$$\lambda_{RX}(i,j) = \lambda_0 + GV_i + (j-1)\Delta\lambda_c + LV_j + TRxV_i$$



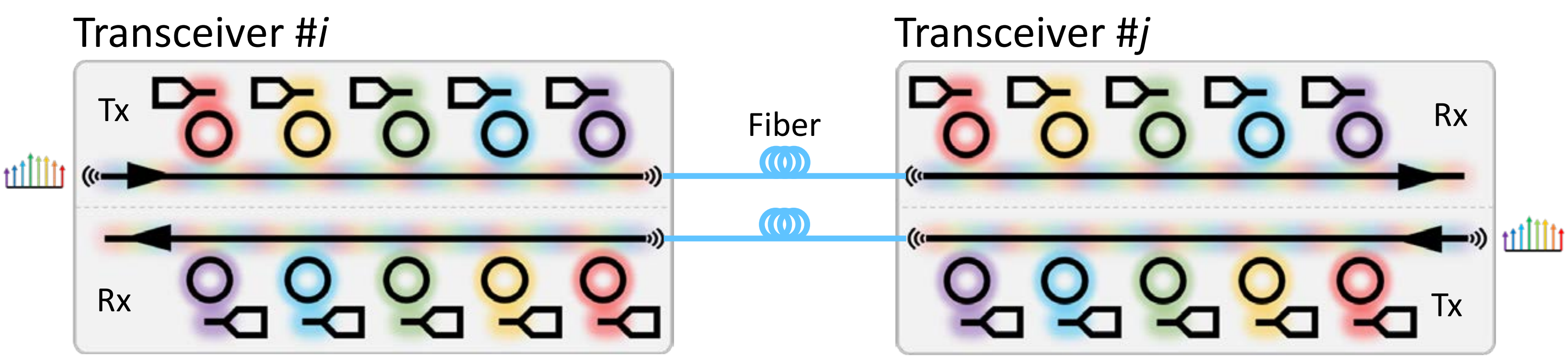


Problem Formulation: Two Cases

- **Case 1: separable transceivers**



- **Case 2: inseparable transceivers**

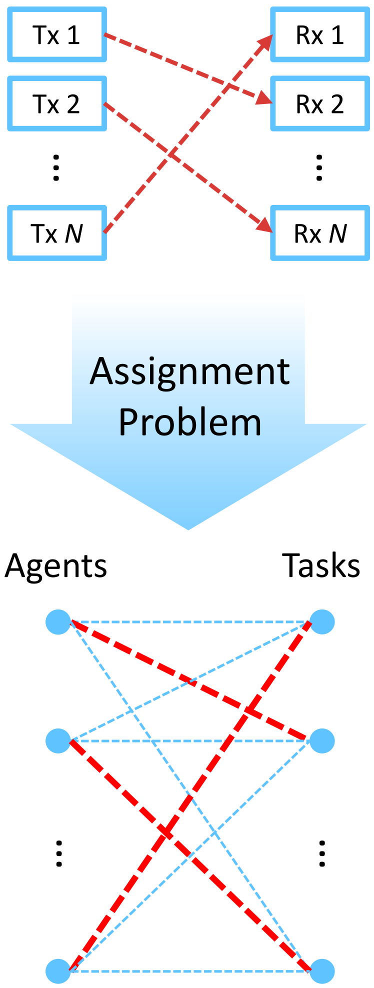


Separable Transceivers: Assignment Problem

- **Optimal assignment of Tx and Rx**
  - Cost matrix construction (O(N^2))

	Tx #1	Tx #2	…	Tx #*N*
Rx #1	c_{11}	c_{12}	…	c_{1N}
Rx #2	c_{21}	c_{22}	…	c_{2N}
…	…	…	…	…
Rx #*N*	c_{N1}	c_{N2}	…	c_{NN}

  - Solved by Hungarian Algorithm (O(N^3))



Separable Transceivers: Evaluation

- **Evaluation on measurement data**

Channel Spacing	Avg. Tuning Power (mW)*		Power Saving (%)
	Local Assignment	Optimal Assignment	
80 GHz	25.7	24.1	6.2
160 GHz	24.7	21.3	13.8

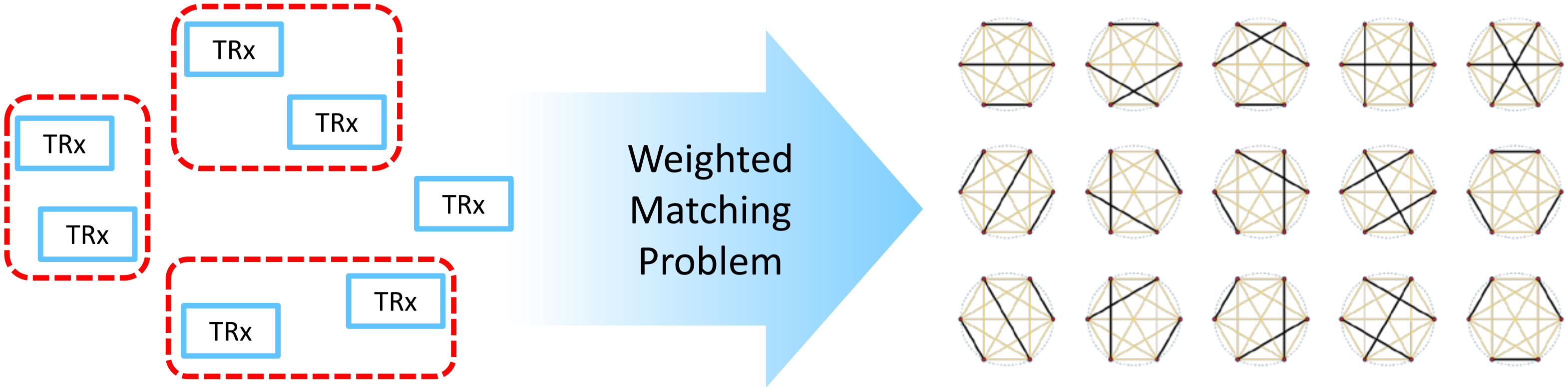
- **Evaluation on synthetic data**

Channel Spacing	# of Tx and Rx	Power Saving (%)	Exe. Time (s)
80 GHz	40	11.2	0.02
80 GHz	400	23.2	2.6
80 GHz	1000	25.8	26.8
80 GHz	1500	26.6	89.5
160 GHz	31	14.4	0.01
160 GHz	301	27.1	1.4
160 GHz	1001	29.8	28.3
160 GHz	1501	30.6	94.0

*Assuming 0.15 nm/mW tuning efficiency

Inseparable Transceivers: Matching Problem

- **Minimum-weight maximal matching of TRx**



Even # of TRx: perfect matching. Odd # of TRx: maximal matching.

- O*(N!!)* solution space where *N!! = N(N-2)(N-4)…*
- Blossom V Algorithm*
  - Solves min-weight perfect matching in $O(V^2E) = O(N^4)$
  - Does not apply to min-weight **maximal** matching

*V. Kolmogorov, *Mathematical Programming Computation, 2009*

Inseparable Transceivers: Proposed Algorithm

- **Simulated annealing-based algorithm**

Cost matrix construction (O(N^2));
Greedy pairing as initial state (O(N^3));
while temp > finalTemp **do**
    Randomly shuffle two pairs of TRx;
    if $\Delta E < 0$ **then**
        Accept new matching;
    else
        Accept new matching
            with prob. of $\exp\left(-\Delta E / kT\right)$;
    end
    temp = temp × coolingRate;
end
Return the matching with minimum cost;

$$E = \mu\left(\vec{A}\right) + \lambda \cdot \sigma\left(\vec{A}\right)$$

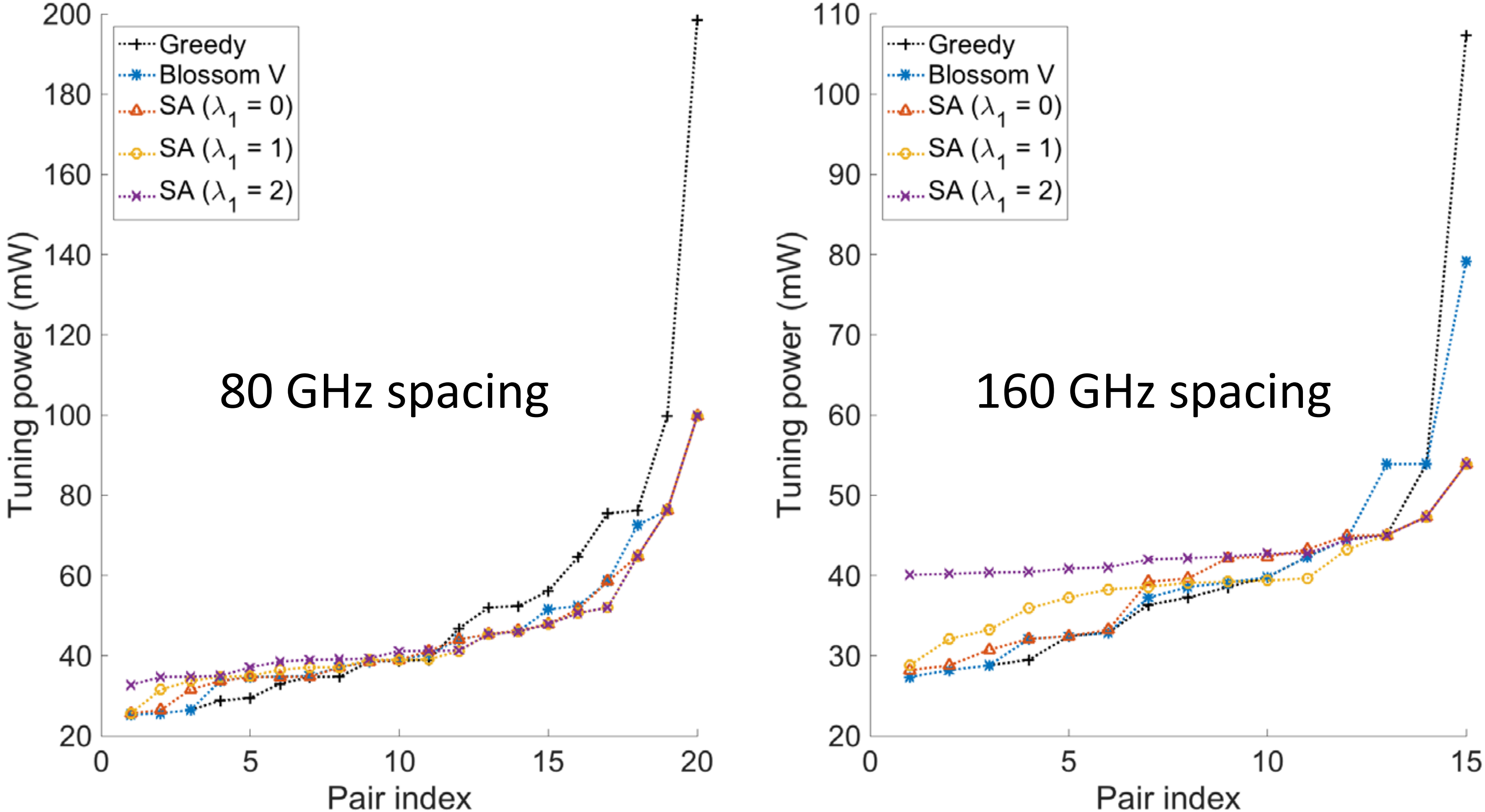
$\vec{A}$: tuning cost vector of current matching

$\lambda = 0$: only optimize for avg. tuning cost

$\lambda > 0$: optimize for avg. tuning cost **and** tuning cost uniformity

Inseparable Transceivers: Evaluation

- **Evaluation on measurement data***



*Assuming 0.15 nm/mW tuning efficiency

Inseparable Transceivers: Evaluation

- **Evaluation on synthetic data***

Channel Spacing	# of TRx	Power Saving (%)	Std. Reduction (%)	Exe. Time (s)
80 GHz	40	66.1	81.7	0.44
80 GHz	400	72.7	90.3	4.24
80 GHz	1000	75.4	77.1	18.25
80 GHz	1500	77.1	83.8	42.89
160 GHz	31	60.8	78.8	0.37
160 GHz	301	66.3	87.1	2.99
160 GHz	1001	72.9	84.0	18.27
160 GHz	1501	73.5	80.7	42.97

*Assuming 0.15 nm/mW tuning efficiency, $\lambda = 1$

Conclusion

- Formulated the optimal pairing of TRx as assignment and matching problems depending on application scenarios.
- Applied optimization algorithms on either case for tuning power minimization.
- Optimal pairing techniques evaluated on both measurement and synthetic data.
- Greater power saving can be achieved when more devices are available for pairing.
- Our techniques can be applied on top of any previously proposed techniques which target on individual transceivers.
- The execution time is acceptable as a one-time cost in the production stage.

Q & A

- **Thank you!**

Questions?