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OPTICS

Optimal Pairing and Non-Uniform Channel Alignment of Microring-based Transceivers for Comb Laser-Driven DWDM Silicon Photonics

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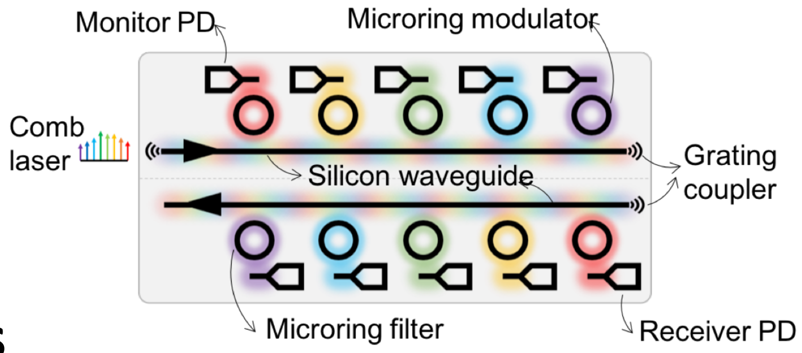
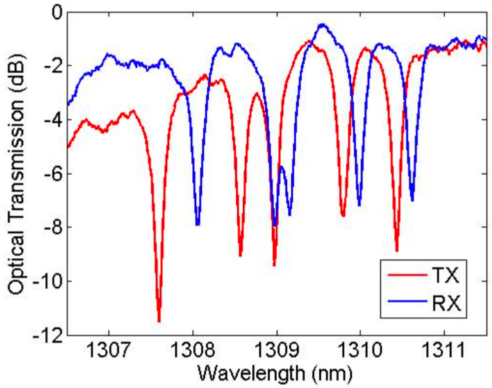
Outline

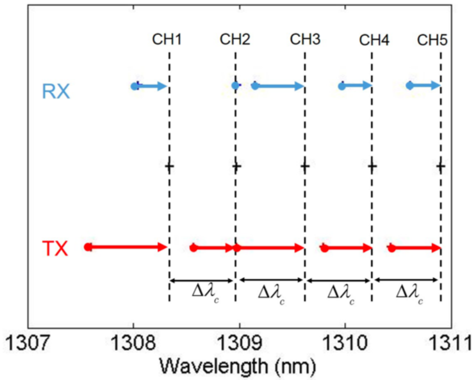
- **Background**
- **Device Measurement and Variation Modeling**
- **Technique #1: Transceiver Optimal Pairing**
- **Technique #2: Non-uniform Channel Alignment**
- **Conclusion**

Background: Microring-based DWDM

- **Microring-based optical DWDM**
  - Compact footprint of microrings
  - (De)multiplexer-free implementation
- **Microring Resonance Wavelengths**
  - Sensitive to process variations
  - Require active tuning
  - Take non-trivial tuning power





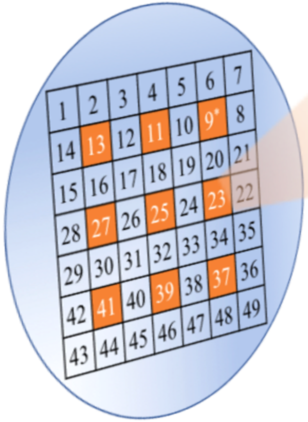


Measurement and Variation Modeling

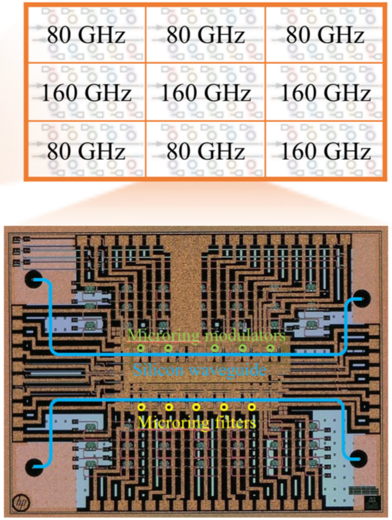
- **Nine locations measured**
  - 40 TRx with 80 GHz spacing
  - 31 TRx with 160 GHz spacing
- **Variation modeling for resonance wavelengths:**
  - Inter-transceiver global variation (GV)
  - Intra-transceiver local variation (LV)
  - Tx–Rx wavelength offset (TRxV)

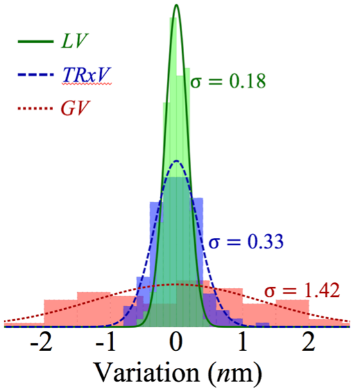
$$\lambda_{TX}(i,j) = \frac{c}{(c/\lambda_0 - (j-1)\Delta f)} + GV_i + LV_j$$

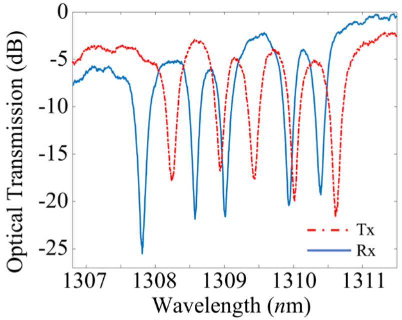
$$\lambda_{RX}(i,j') = \underbrace{\frac{c}{(c/\lambda_0 - (j'-1)\Delta f)}}_{\text{Design value}} + \underbrace{GV_i + LV_{j'} + TRxV_i}_{\text{Variation components}}$$



* Lacks Rx data



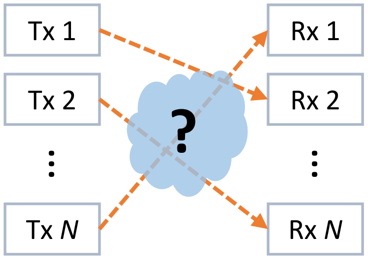




Motivation: Tuning Power Reduction

- **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.

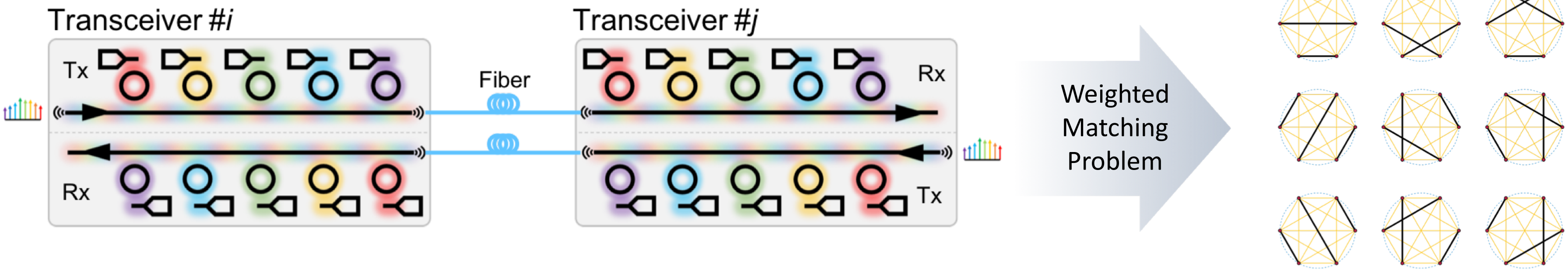
- **Technique #1: Transceiver Optimal Pairing**



Transceiver Optimal Pairing: Problem Formulation

- **Case 1: separable transceivers**

- **Case 2: inseparable transceivers**



Optimal Pairing: Separable Transceiver

- **Optimal assignment of Tx and Rx**
  - Cost matrix construction ($O(N^2)$)
  - Solve by Hungarian Algorithm ($O(N^3)$)
- **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

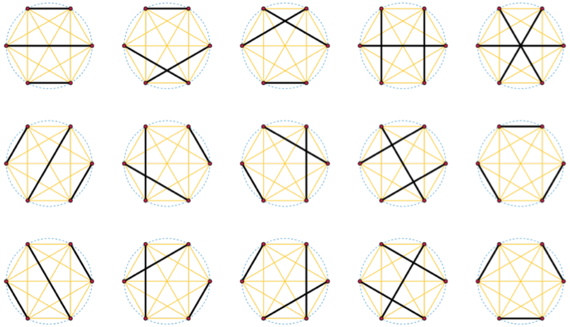
- **Evaluation on Synthetic data**

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

Optimal Pairing: Inseparable Transceiver

- **Minimum-weight matching of TRx**
  - Even # of TRx: perfect matching
  - Odd # of TRx: maximal matching
  - O*(N!!)* solution space where *N!! = N(N-2)(N-4)…*



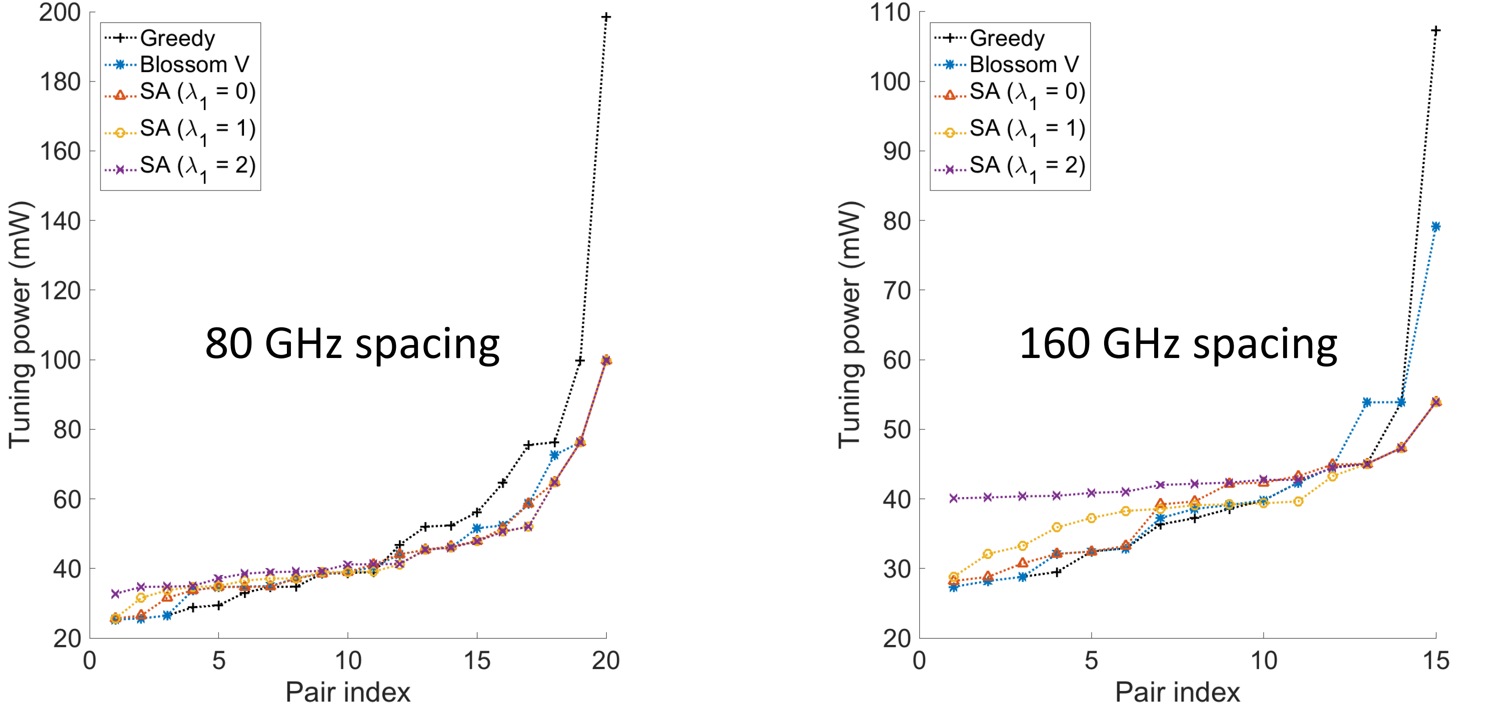
- **Blossom V Algorithm***
  - Solves min-weight perfect matching in $O(V^2E) = O(N^4)$
  - Does not apply to min-weight maximal matching
- **Our simulated annealing-based algorithm**
  - Cost function: $E = \mu\left(\vec{A}\right) + \lambda \cdot \sigma\left(\vec{A}\right)$

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

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

Optimal Pairing: Inseparable Transceiver (cont.)

- **Evaluation on measurement data***



*Assuming 0.15 nm/mW tuning efficiency

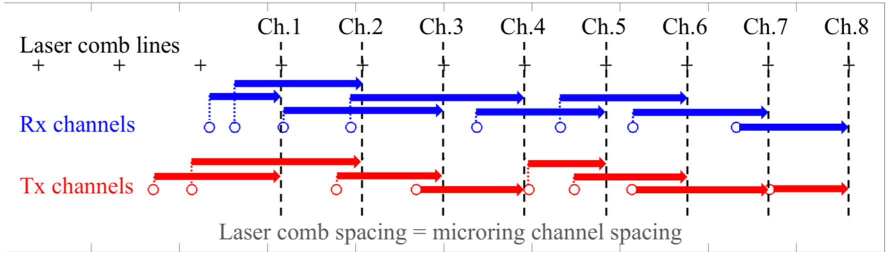
Optimal Pairing: Inseparable Transceiver (cont.)

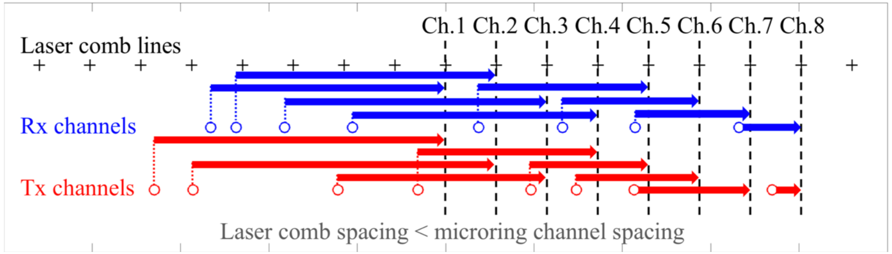
- **Evaluation on synthetic data**

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

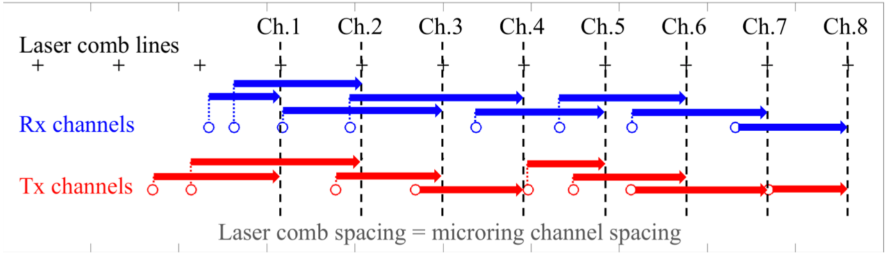
Motivation: System Energy Efficiency

- **Previous technique only considered microring tuning power**
- **Laser comb spacing usually assumed equal to microring channel spacing**
  - **Consecutive comb lines can be used**
  - **Maximum spectrum efficiency**
- **Is the assumption mandatory?**

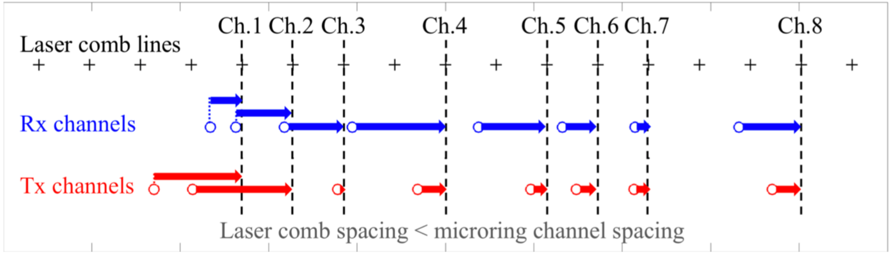




Tuning Power/Laser Power Trade-off



Consecutive channel alignment

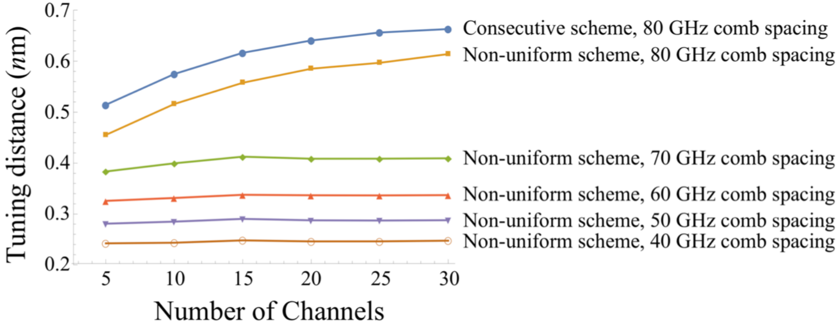


Non-uniform channel alignment

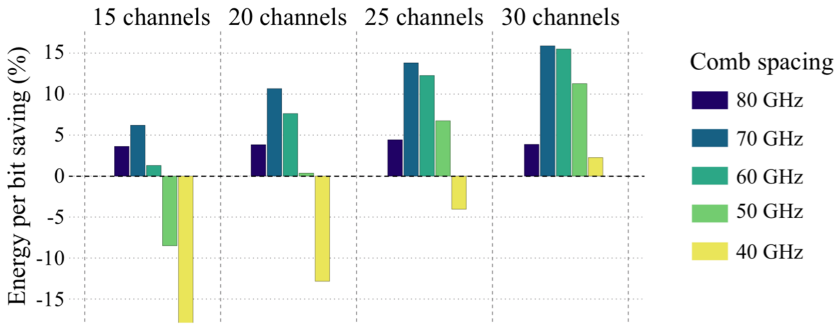
- **Technique #2: non-uniform channel alignment**
  - **Add laser comb spacing into design space**
  - **Align each microring channel to the next available comb line**
  - **Explore tuning/laser power trade-off for best overall energy efficiency**

Non-uniform Channel Alignment

- **Average tuning distance per microring[1]**



- **Saving on system energy per bit[1,2,3]**

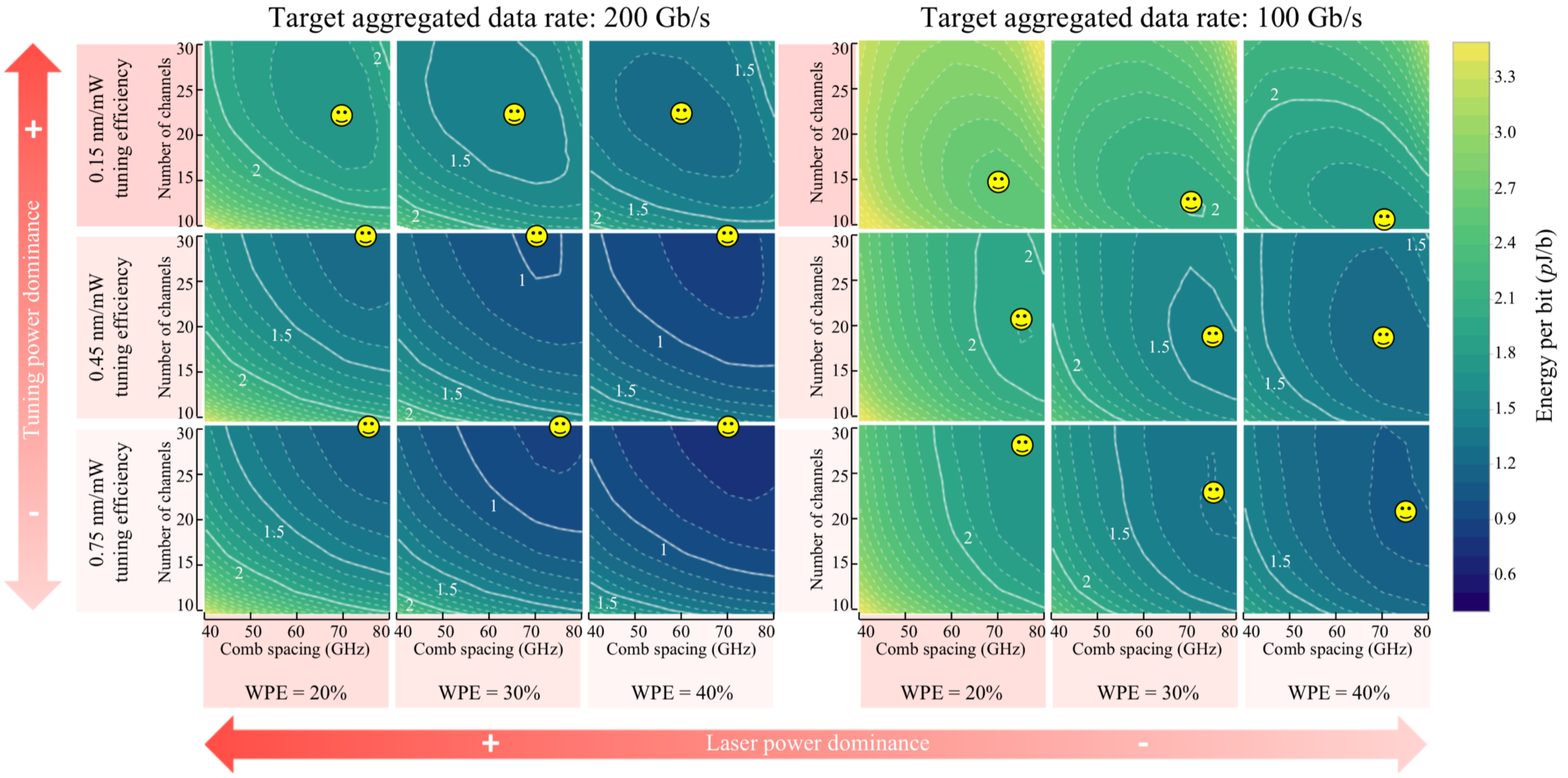


- Always reduces the average tuning distance compared to the consecutive scheme.
- Eliminates the channel count dependency of the tuning distance with denser comb lines.

- For larger channel counts, denser comb lines can be used without compromising the overall energy efficiency.
- The biggest energy per bit saving does not require aggressively dense comb lines.

[1]Based on synthetic wavelengths of transceivers with 80 GHz channel spacing.
[2]Power penalty models of the transceiver link taken from M. Bahadori *et al.*, 2017 and Polster et al., 2017.
[3]10 Gbps per channel data rate, 0.15 nm/mW tuning efficiency and 20% laser WPE assumed.

Case Study for Design Space Exploration



Conclusion

- **Transceiver Optimal Pairing**
  - Formulated the TRx pairing of as assignment and matching problems.
  - Optimization algorithms on either case for tuning power minimization.
  - Can be applied on top of any previously proposed techniques which target on individual transceivers.
- **Non-uniform Channel Alignment**
  - Significantly reduce the microring tuning power.
  - Improve overall energy efficiency despite some overhead in laser power.
  - Expand the design space by one additional dimension.
  - Provide guidelines on energy-efficient design of future DWDM silicon photonic transceivers.