iPRONICS
Programmable Photonics

SEMICON® EUROPA

Photonics Research Labs

UNIVERSITAT POLITÈCNICA DE VALÈNCIA

Silicon Programmable Photonics: A New Paradigm to Unleash the Power of Lighwave Chips

THE SPINOFF PRIZE
ONE TO WATCH 2020
nature research awards

José Capmany

erc

European Commission

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European Research Council
Established by the European Commission

European Innovation Council

European Innovation Council (EIC) established by the European Commission, under the Horizon Europe programme (2021-27)

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MINISTERIO DE ECONOMÍA Y COMPETITIVIDAD

CDTI Centro para el Desarrollo Tecnológico Industrial

Amadeus Capital Partners

Caixa Capital Risc

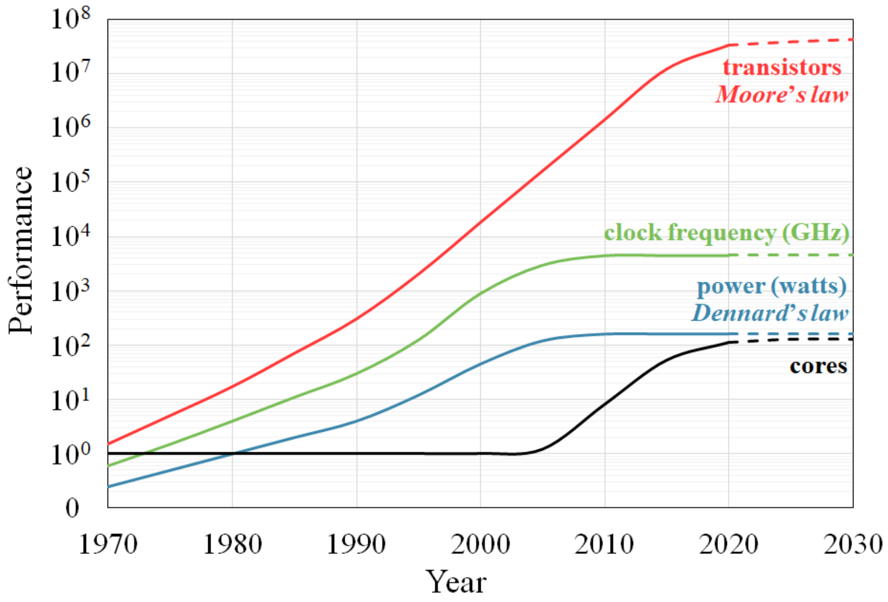
Introduction & Motivation

Houston: We have a problem!

Emerging Applications with voracious processing & bandwidth appetite!!

- 5G and Beyond
- Bio instruments
- Lab-on-a-Chip Sensors
- Internet of Things
- Autonomous driving
- Neurocomputing and Artificial Intelligence
- Hardware acceleration
- Avionics & Space
- Quantum Information

Demise of Moore and Dennard Scaling Laws



And, indeed……Data Centers

Electronics needs to team up with other technologies to meet these requirements.

A win-win solution: Electronics + Photonics

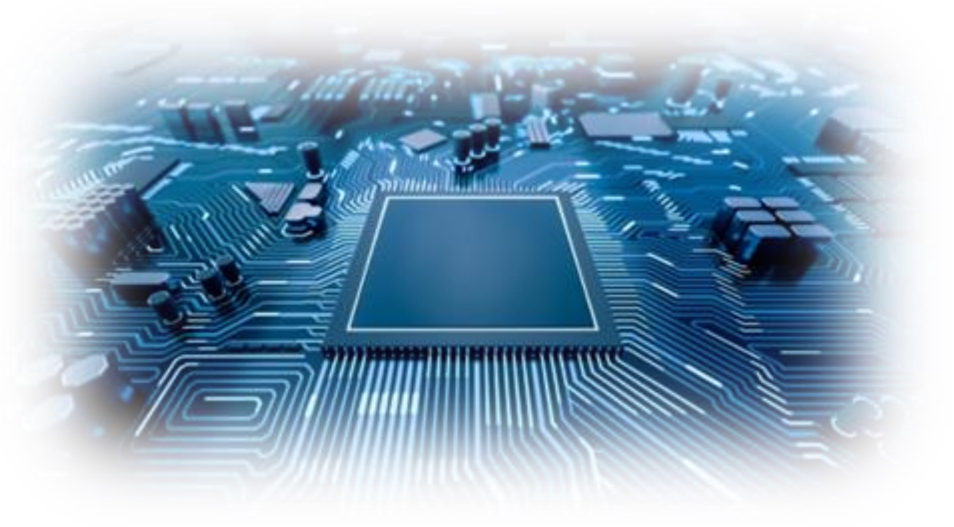
Photonics provides bandwidth, low power consumption and is complementary to Electronics.

Application-Specific Photonic Integrated Circuits are being successfully integrated into applications yet, their time-to-market and fabrication cost is many times a show stopper.

*The **time for Programmable Photonics has come!***

Solutions equivalent to FPGAs, DSPs and microprocessors will be needed.

BUT….this has already happened in the past!



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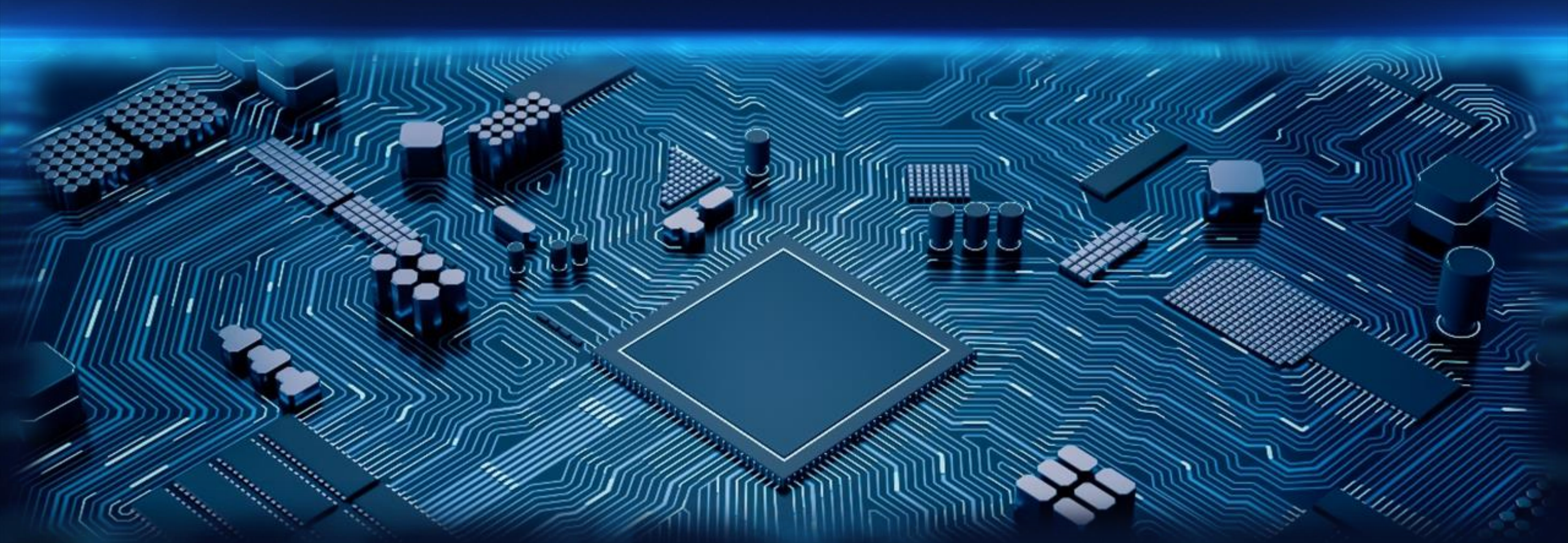


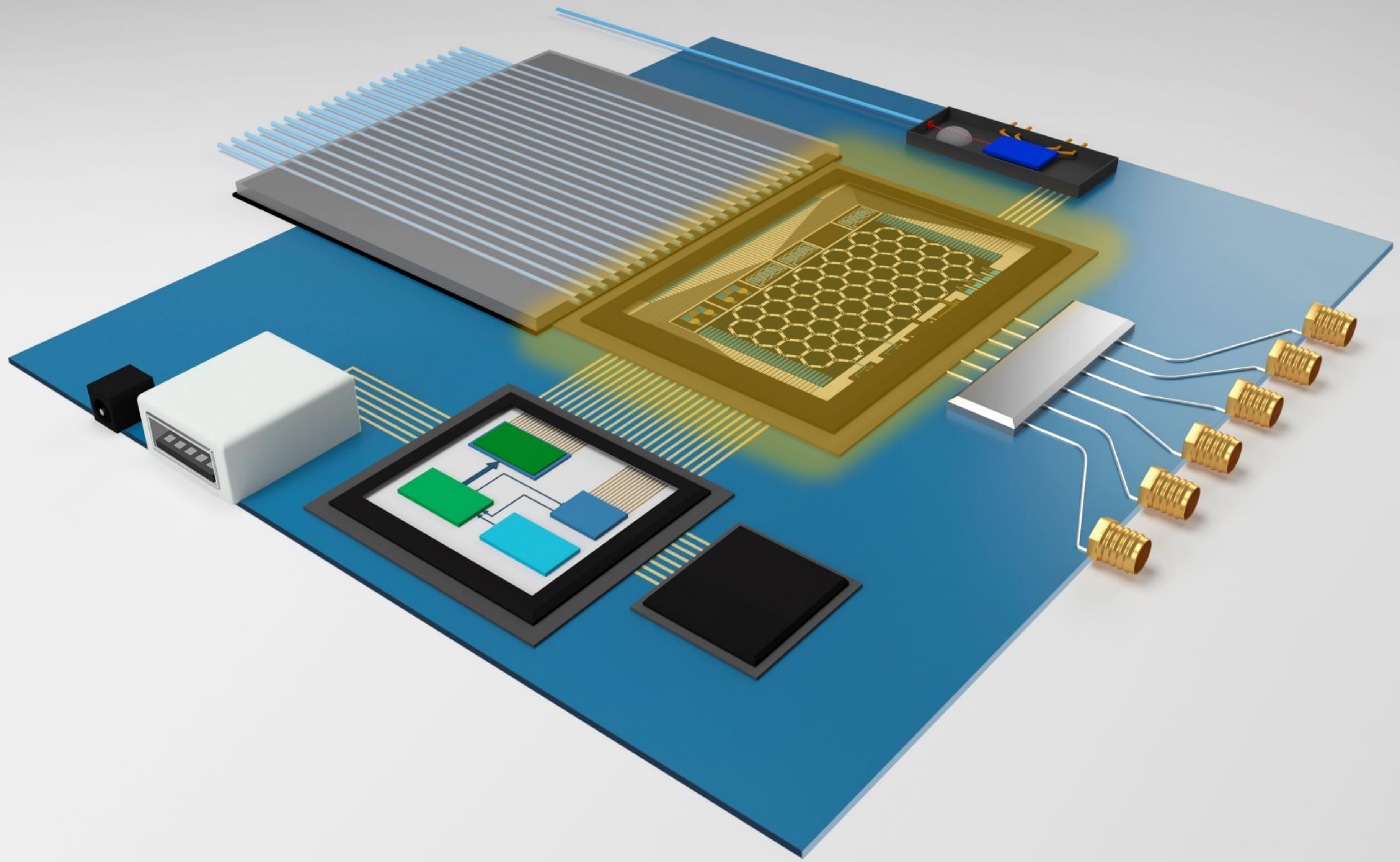
Plug & Play Programmable Processor

Multipurpose photonic processor including:

Photonic layer: a flexible optical core and IP/High performance blocks

Electronic layer: monitoring & control

Software layer: programming, optimization & interface with network control layer



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Programmable Silicon Photonic Circuits

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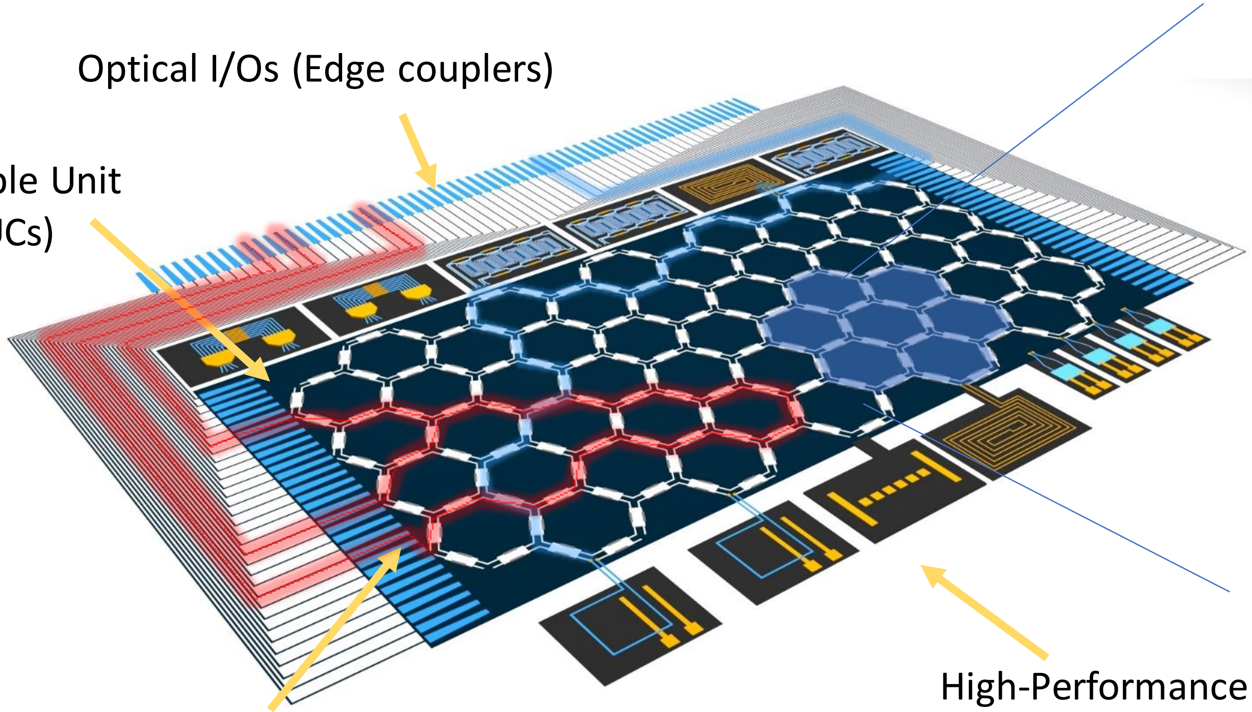
Programmable Multifuncional PICs

General-purpose photonic processor

Optical I/Os (Edge couplers)

Programmable Unit Cells (PUCs)



Reconfigurable Optical Core (Hexagonal waveguide mesh arrangement)

High-Performance Building Blocks

Tunable Coupler
Phase Shifter

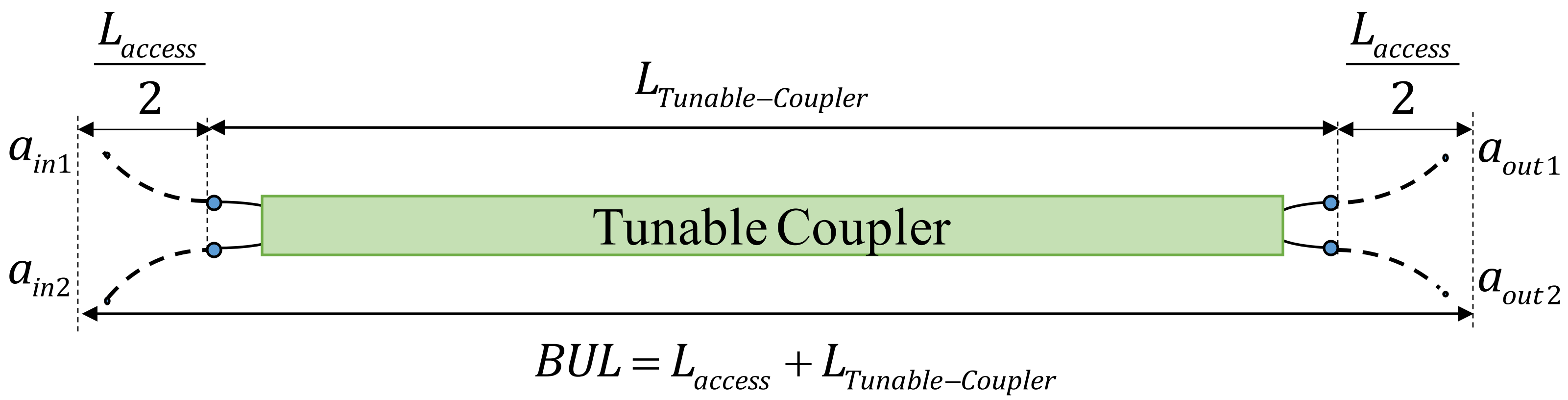
D. Pérez-López, et al, Multipurpose self-configuration of programmable photonic circuits, ***Nat. Comms***., *10.1038/s41467-020-19608-w*, *2020*

D. Pérez, I. Gasulla, J. Capmany, Field-programmable photonic arrays, **Optics Express, 26, 21**, 2018.

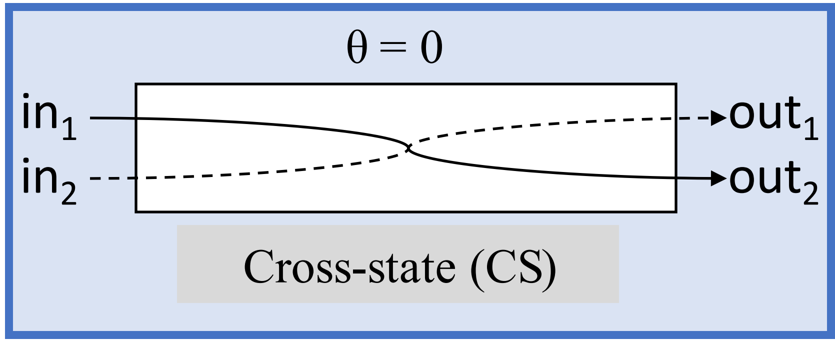
D. Pérez, "Reconfigurable lattice mesh designs for programmable photonic processors," **Opt. Express, 24, 11**, 2016

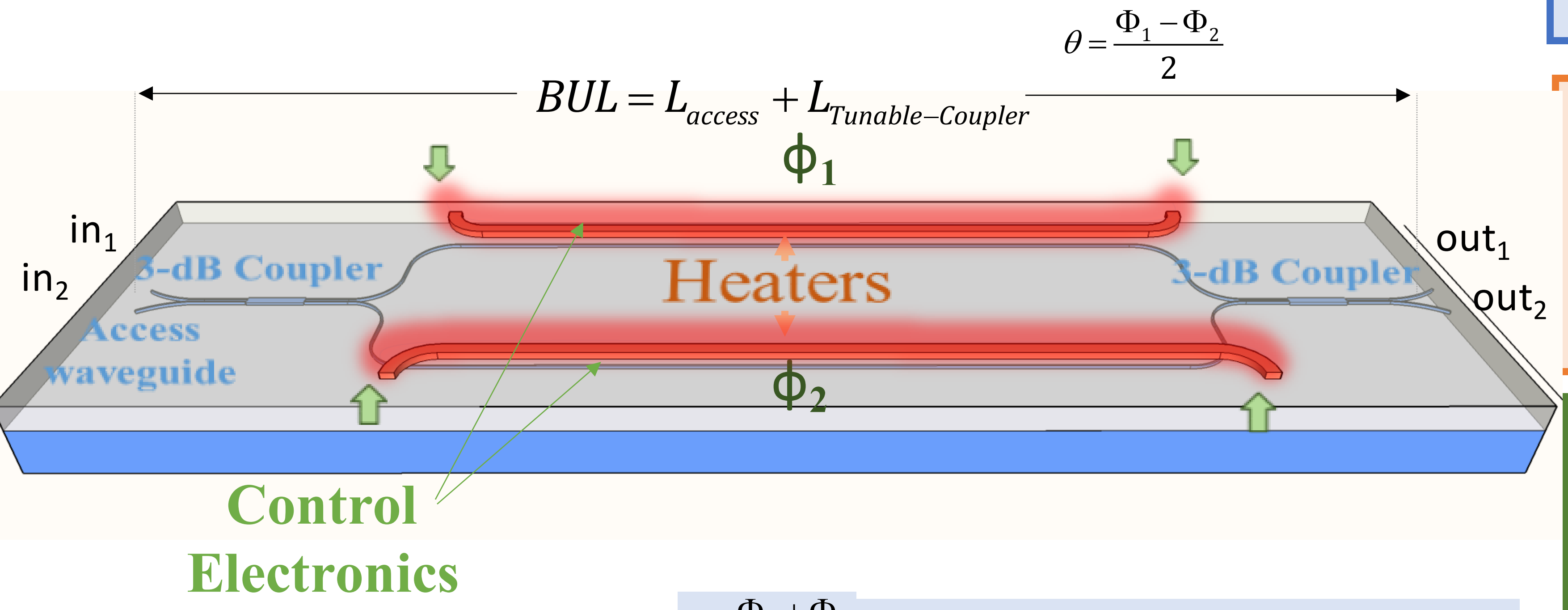
L. Zhuang, "Programmable photonic signal processor chip for radiofrequency applications," **Optica, 2, 10**, 2015

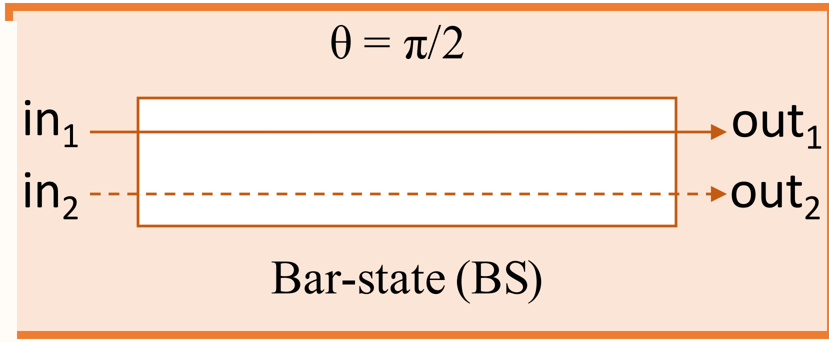
Programmable Unit Cell: How does it works?

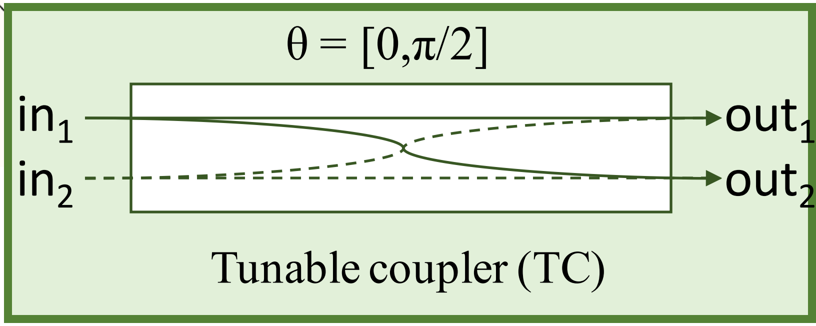


$\theta = \frac{\Phi_1 - \Phi_2}{2}$ Sets the **power division**









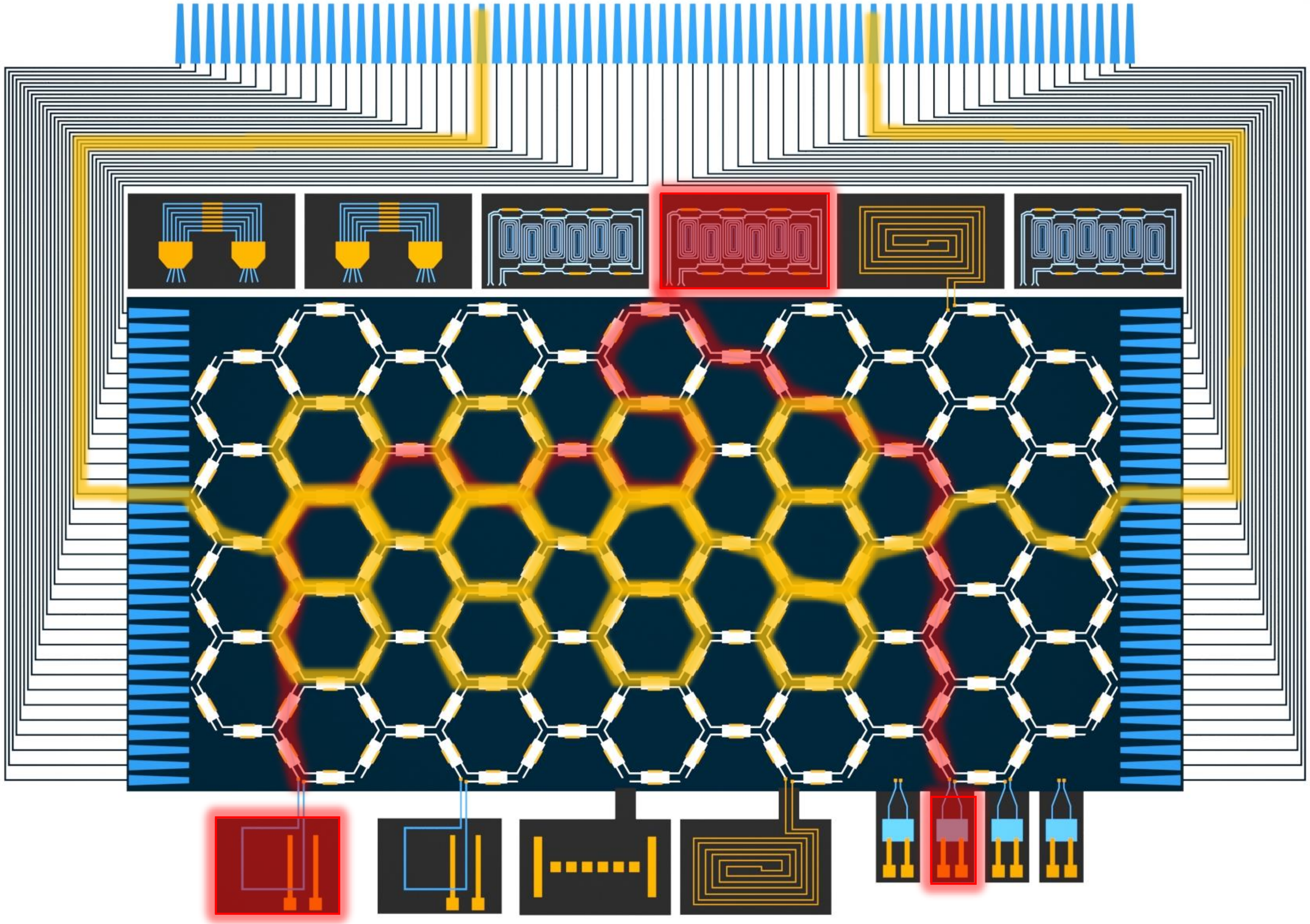
$\Delta = \frac{\Phi_1 + \Phi_2}{2}$ Sets the (independent) **phase shift**

Photonics Layer

Programmable Silicon photonics waveguide mesh

IP/High performance blocks

- Lasers
- Detectors
- Amplifiers
- WDM MUX/DEMUX
- etc



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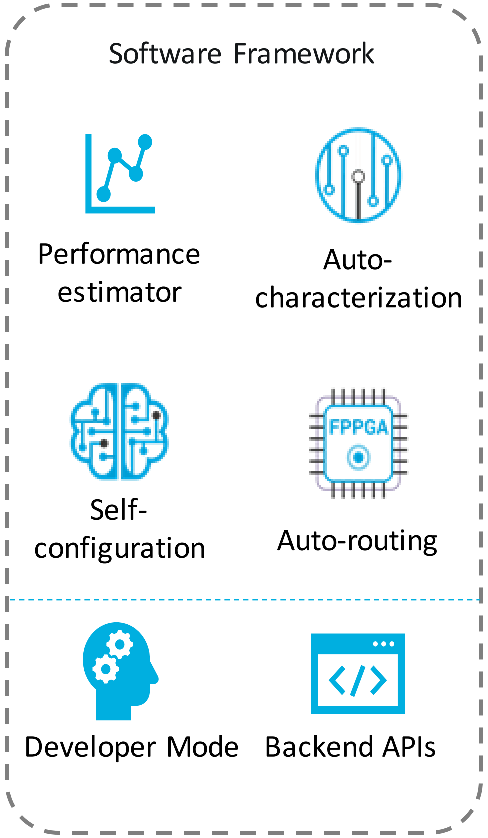
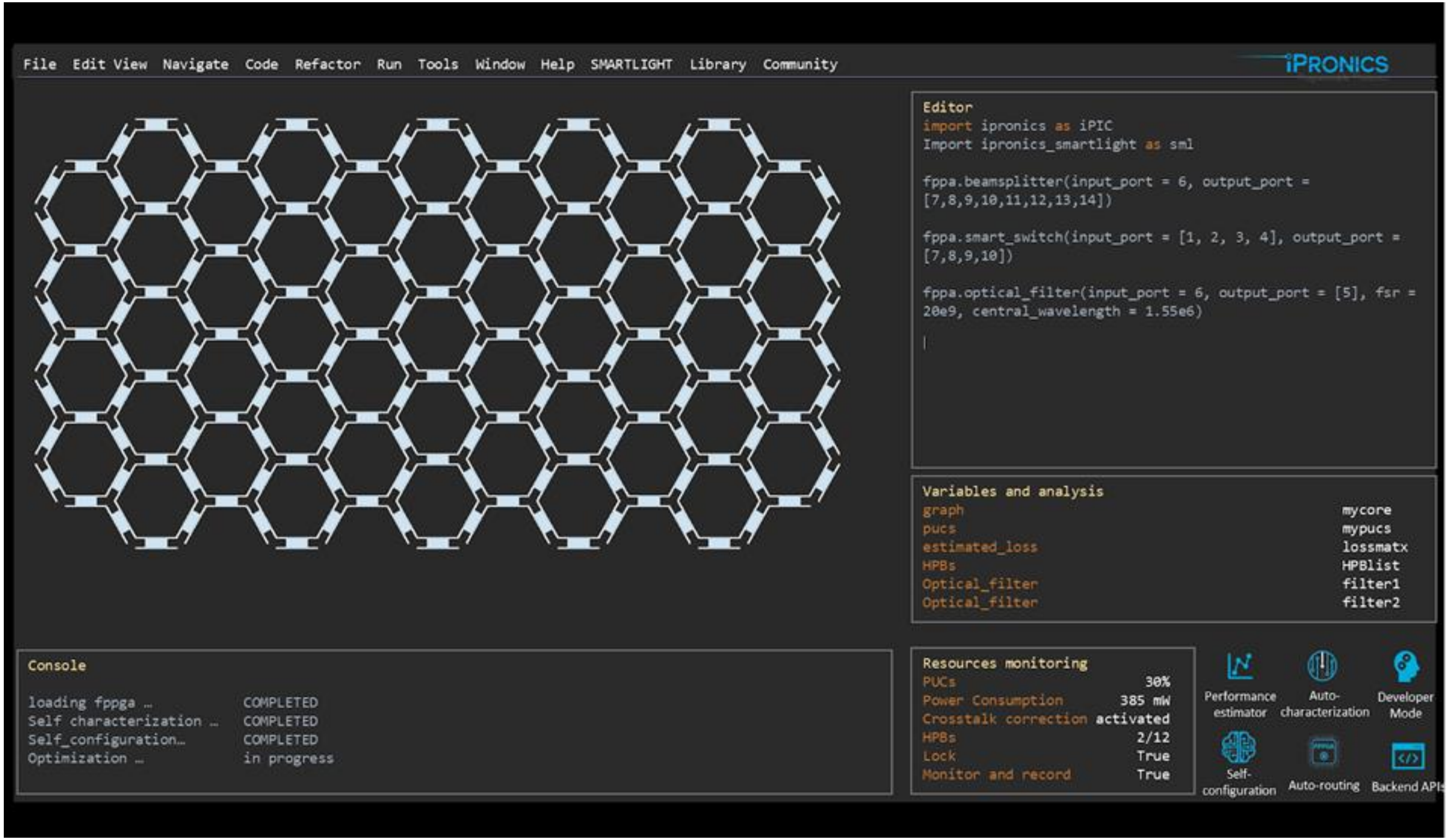
Software Layer





Some applications of Programmable Photonics

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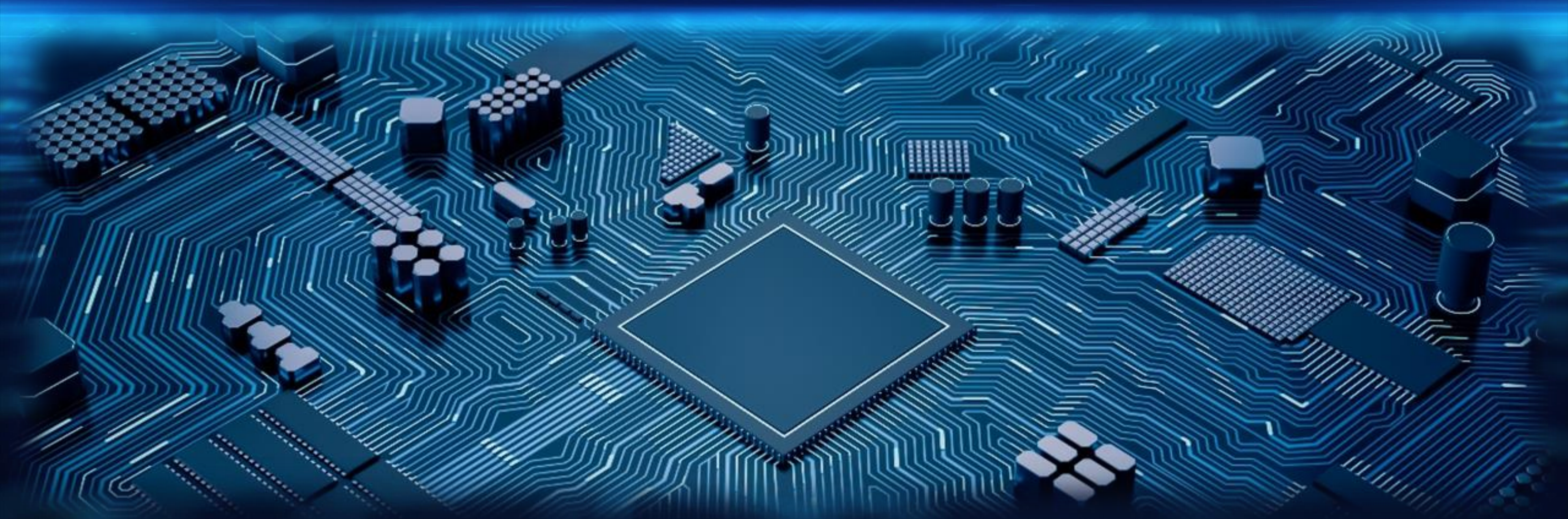


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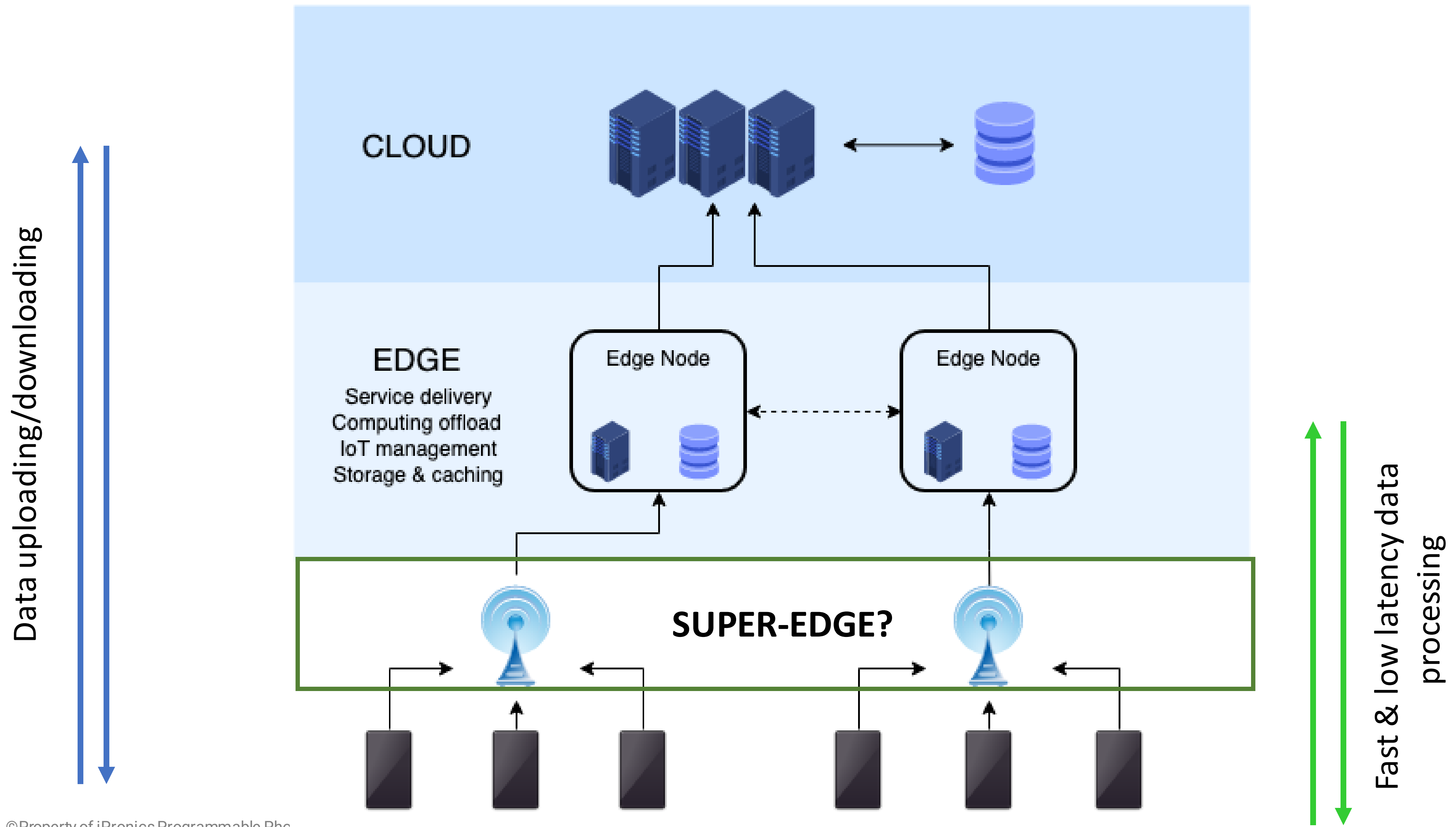
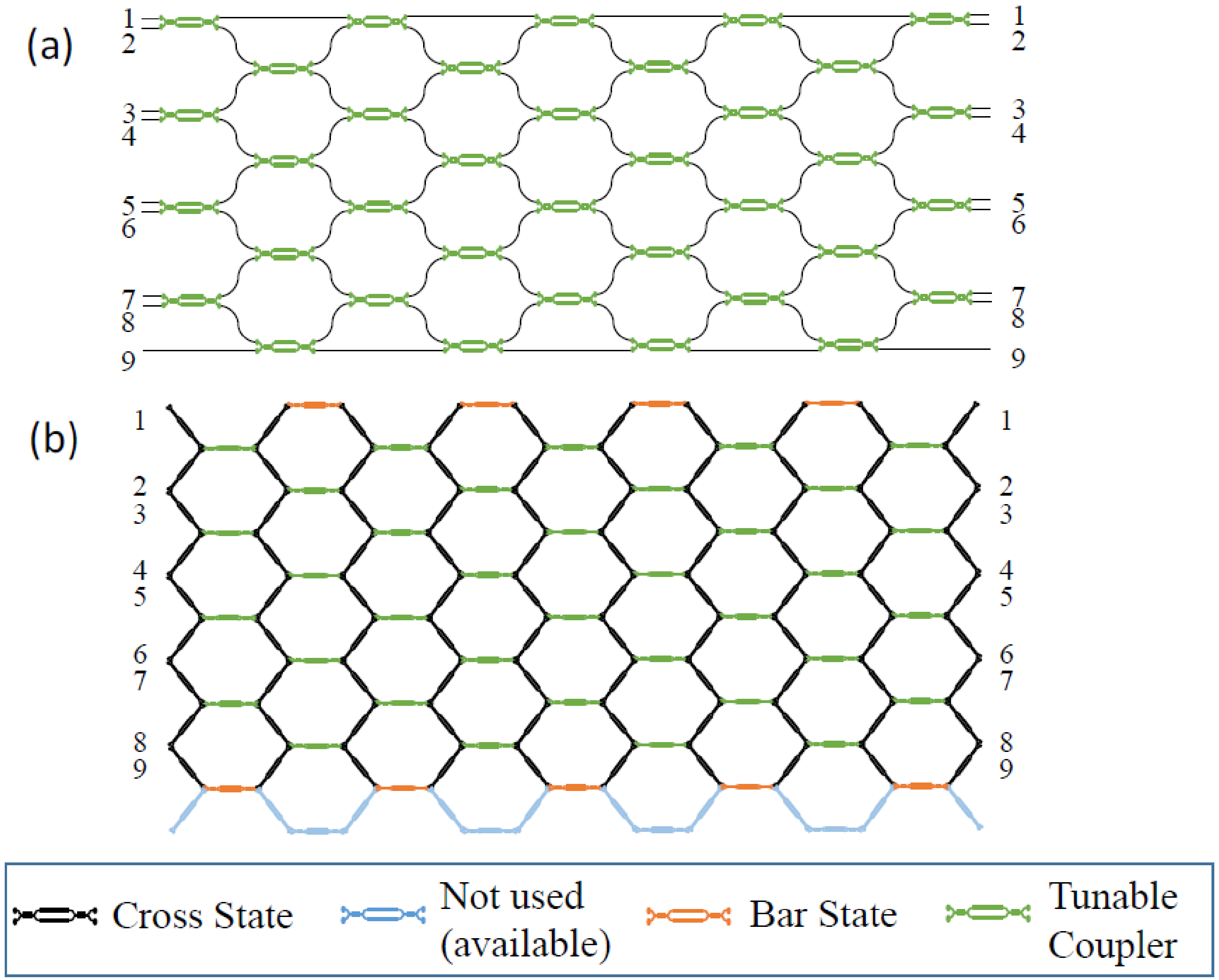
Data Centers: *Device →BTS →Edge →Cloud*



Some basic functionalities



Can implement any arbitrary complex-valued NxN Matrix transformation through the emulation of a multiport interfeoremter.

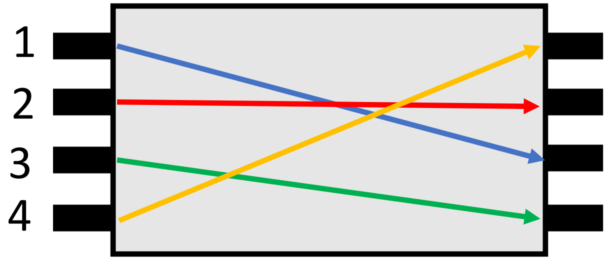
This includes:

a) Pure switching
b) Switching+Multicasting
c) Broadcasting
d) Complex interconnection maps
e) Matrix-vector multiplication
f) DFT

Data Centers: Versatile interconnection

Case 1: Match 1-2-1

Inputs* Outputs



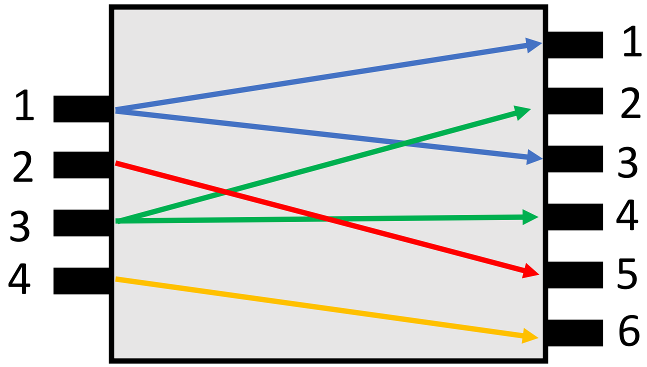
Equivalent Matrix:

$$M = \begin{pmatrix} 0 & 0 & 0 & 1 \\ 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{pmatrix}$$

Matrix dimensions: m × m

Case 2: Multicasting

Inputs Outputs



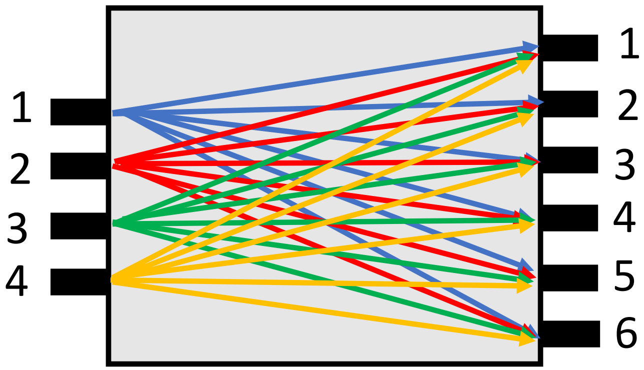
Equivalent Matrix:

$$\begin{pmatrix} 1/2 & 0 & 0 & 0 \\ 0 & 0 & 1/2 & 0 \\ \vdots & & & \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

Matrix dimensions: m × n

Case 3: Power divider

Inputs Outputs



Equivalent Matrix:

$$M = \begin{pmatrix} 1/6 & 1/6 & 1/6 & 1/6 \\ 1/6 & 1/6 & 1/6 & 1/6 \\ 1/6 & 1/6 & 1/6 & 1/6 \\ 1/6 & 1/6 & 1/6 & 1/6 \\ 1/6 & 1/6 & 1/6 & 1/6 \\ 1/6 & 1/6 & 1/6 & 1/6 \end{pmatrix}$$

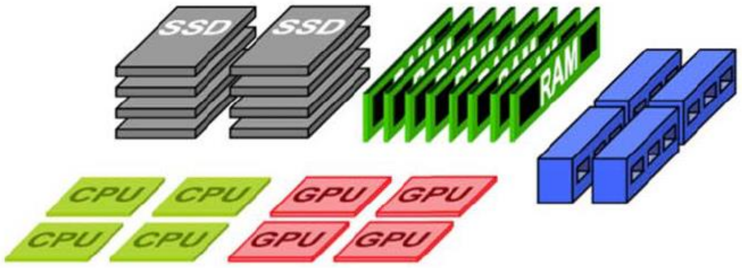
Matrix dimensions: m × n

Or a combination of the 3 cases!

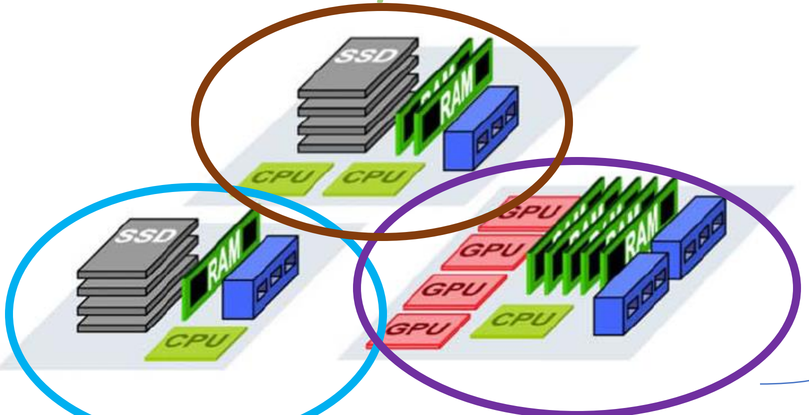
*Target dimension: 16 × 16 system

Cloud DCI: Dynamic resource sharing

Disaggregated Rack

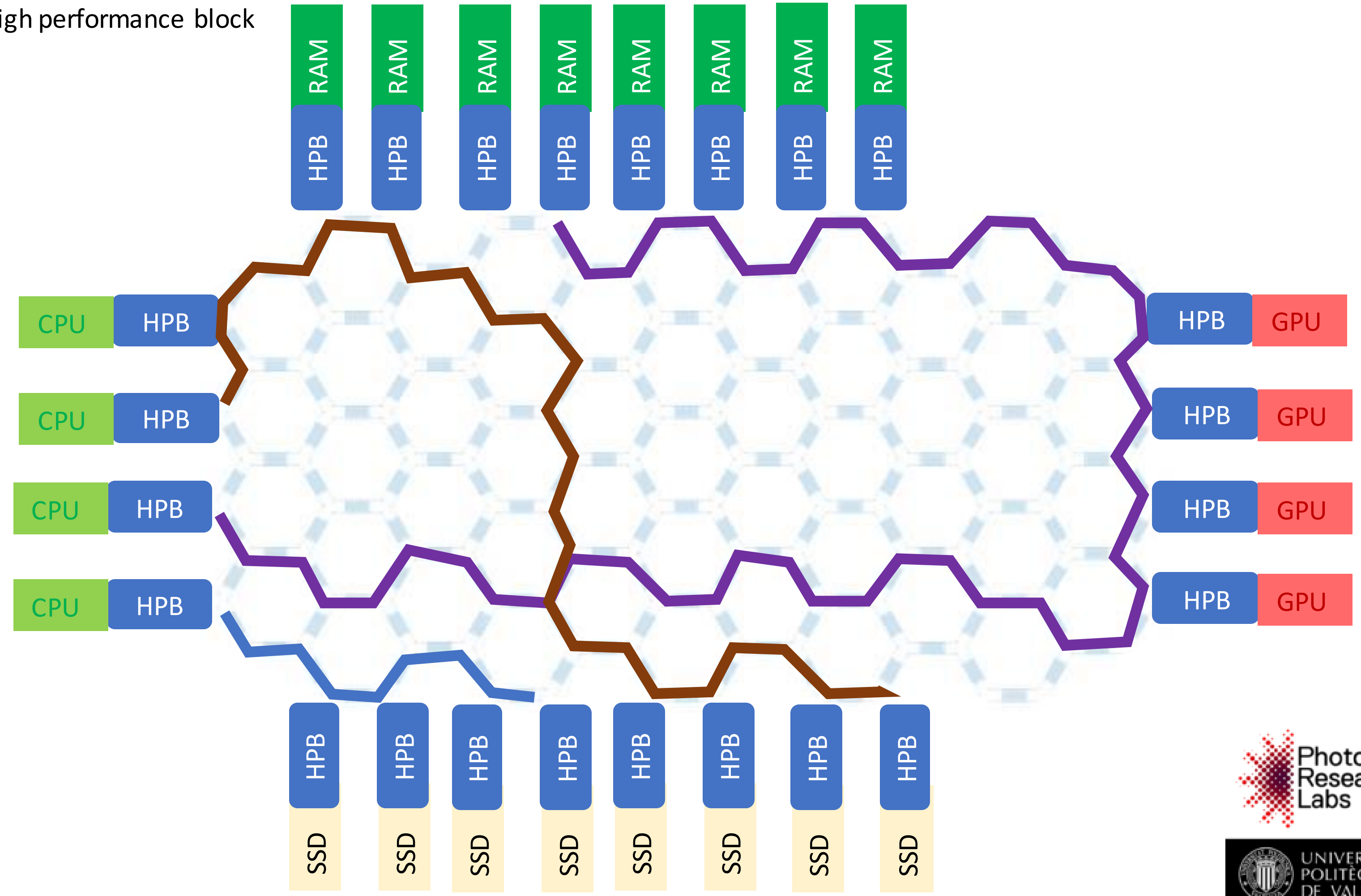


Pool and Compose



CPU: Central Processing Unit
SSU: Solid State Drive
GPU: Graphics Processing Unit
RAM: Random Access Memory
HPB: High performance block

Resources connected to plug and play processor via I/O (fiber) ports



Edge Data Centers

- Low latency Matrix-vector computing
- DFT based processing

Chiplet interconnection

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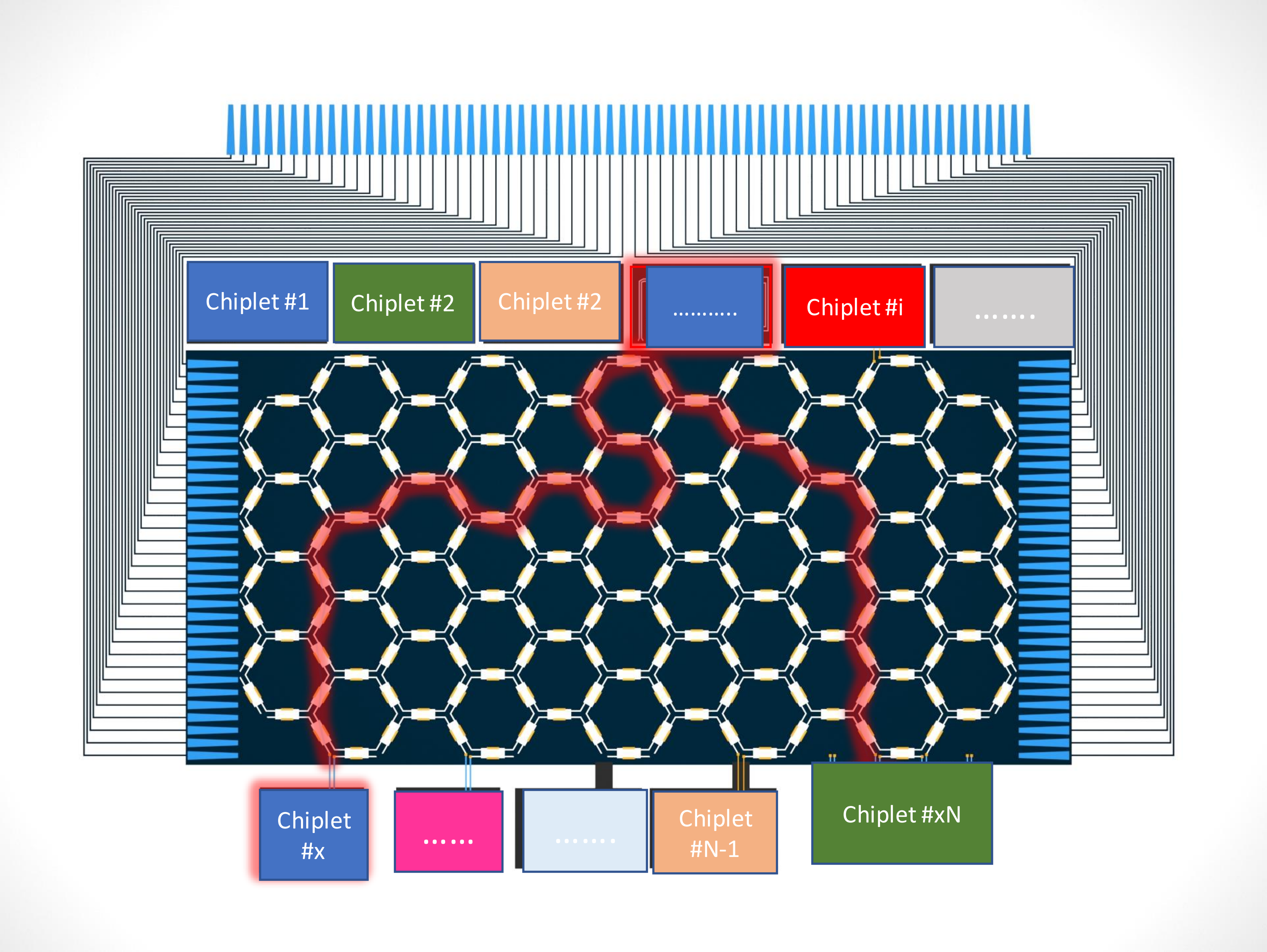
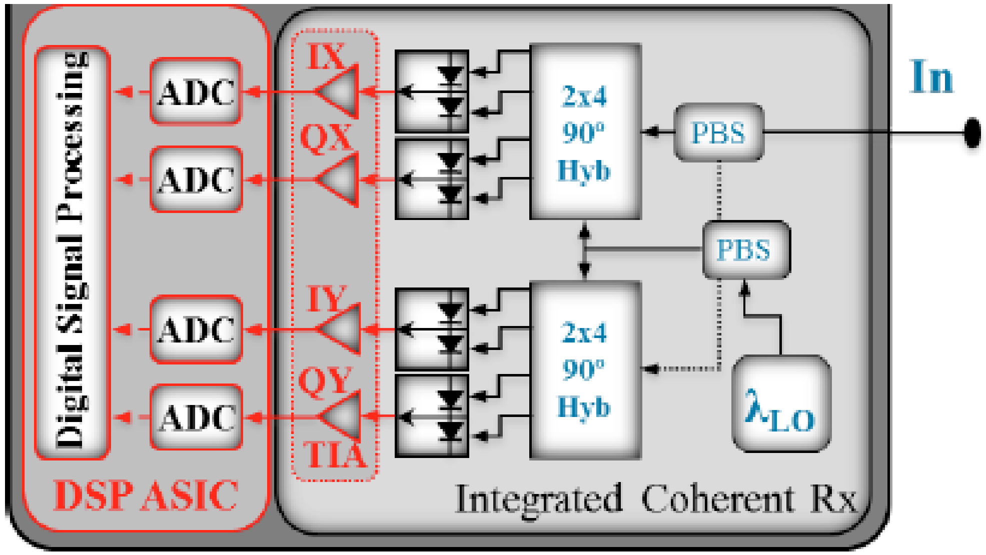
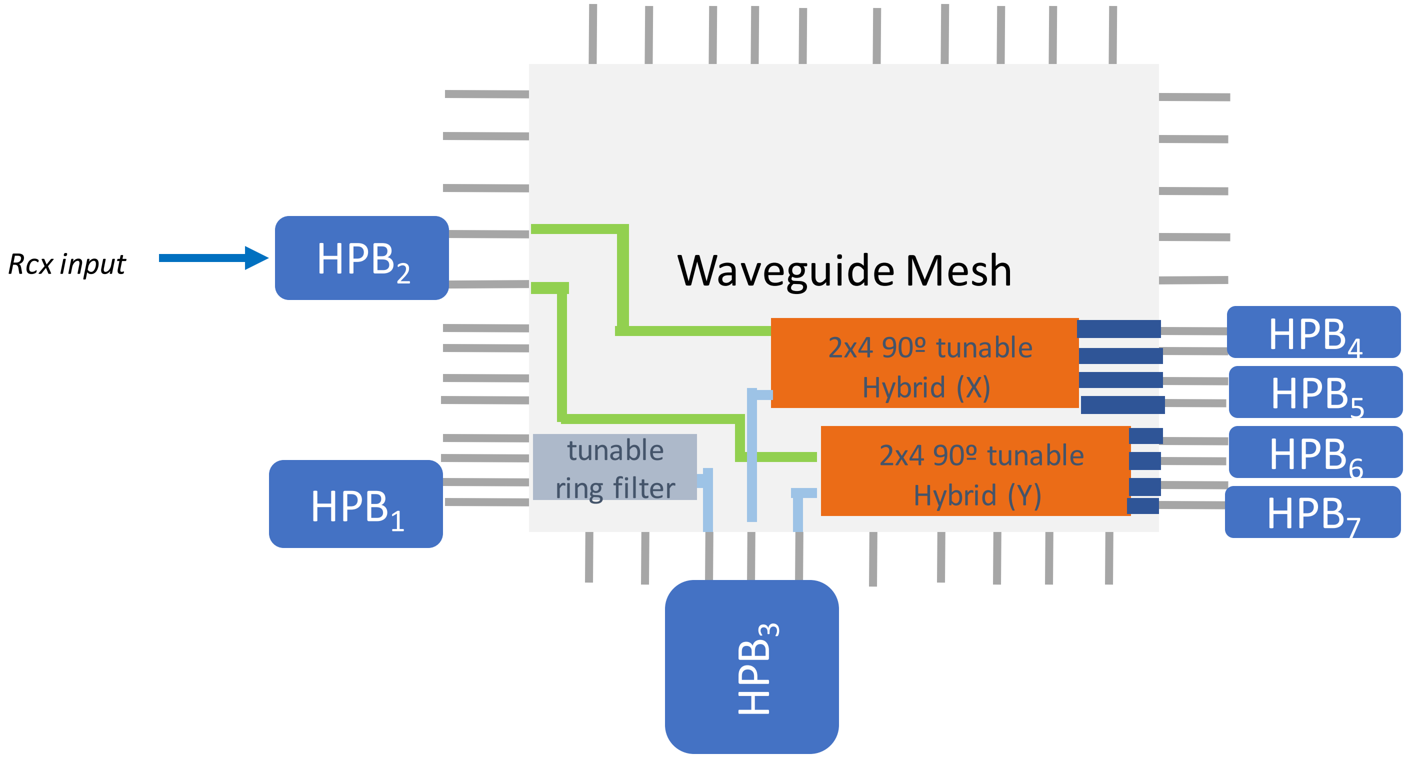
Chiplets connected to plug and play processor via internal ports



Intelligent Transceivers



Integrated Coherent Receiver



HPB_1 Local Oscillator laser

HPB_2 PBS+Polarization rotator

HPB_3 PBS

HPB_{4-7} Balanced detectors

Tunable ring laser: *allows the tailoring of local oscillator laser linewidth to different values*

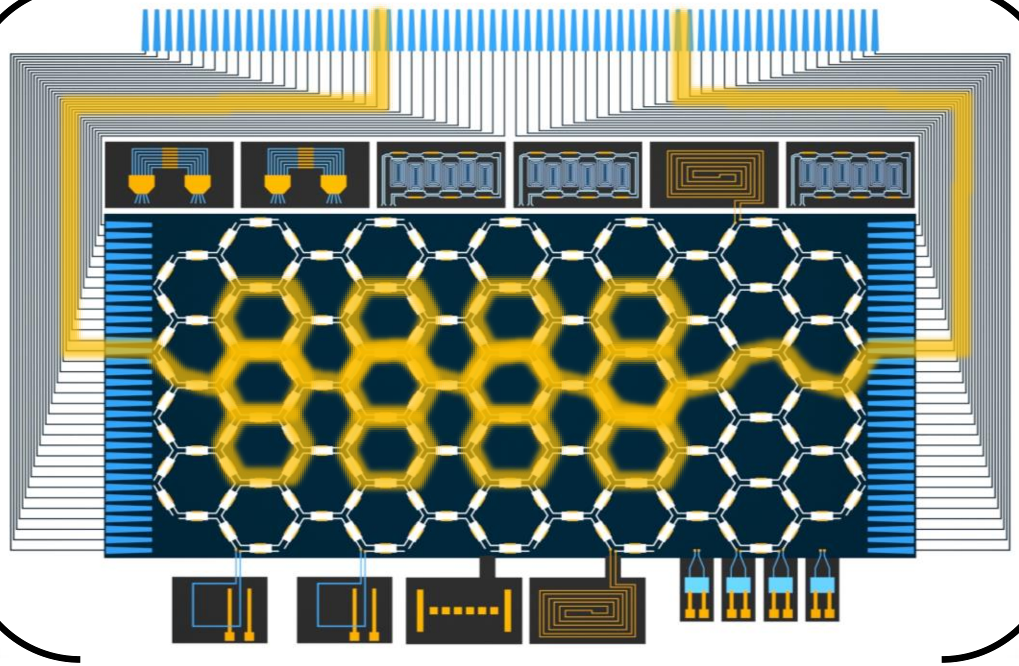
2x4 90º tunable Hybrids: *Allow 90º hybrid operation with exact balanced splitting by reconfiguration*

Reconfigurable connections before Balanced detector: *Allow exact power splitting adjustment between the two inputs to the balanced receiver or correct unbalanced electrical power response*

Applications in Edge DCI: MVM processing

Matrix M

$$\begin{pmatrix} O_1 \\ O_2 \\ \vdots \\ O_N \end{pmatrix} =$$



$$\begin{pmatrix} I_1 \\ I_2 \\ \vdots \\ I_N \end{pmatrix}$$

- Parallelized matrix vector multiplication
- Feedforward/feedbackward propagation – allows backpropagation
- Arbitrary unitary matrices can be programmed

Summary & Conclusions

Adding Extra Flexibility to Coherent Transceivers

- **Programmable Integrated Photonics** is going to happen!. It shares commonalities with integrated Electronics. Yet it is completely different

- In particular we have focused on the **General Programmable Plug and Play Photonic Processor**, introducing the hardware and software tier structure and providing some proof-of-concepts experimental examples.

- **The range of applications is huge!** programmable photonics can bring very flexible solutions to:
  - Switching and resource interconnection and pooling in Data Centers
  - Chiplet interconnections
  - Flexible transceiver architectures
  - Harwdware acceleration (via matrix-vector multiplication)