Optical Computing Fundamentals and Applications

TuF3.4 (Invited)

2022 IEEE Photonics Conference (IPC)

Novel Technologies for Computing & High Capacity Transmission

15 November 2022

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The Annual Conference of the IEEE Photonics Society

IPC

COHERENT

Abstract

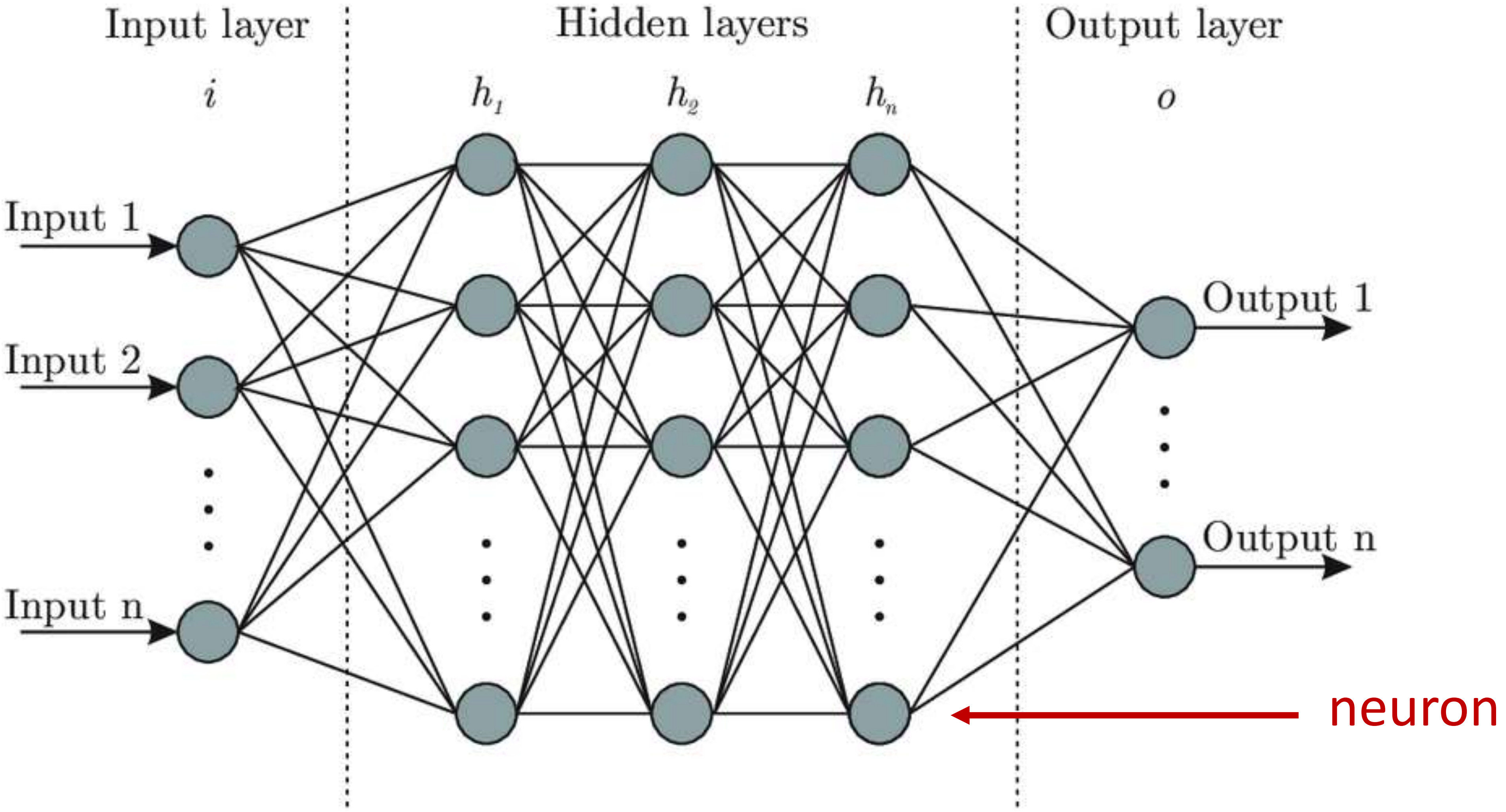
Optical computing has been proposed as a replacement for electrical computing to reduce energy use of math intensive programmable applications like machine learning. This presentation introduces optical computing in its historical context. It then shows that objective comparison requires separate calculation of data transfer and computing energy use. Detailed analysis of electrical and optical addition, multiplication and convolution shows that optical computing does not reduce energy use, in stark contrast to optical data transfer. Further, precision inherent to optical computing is of no value in general purpose applications like in the data center and is rarely, if ever, properly measured.

Outline

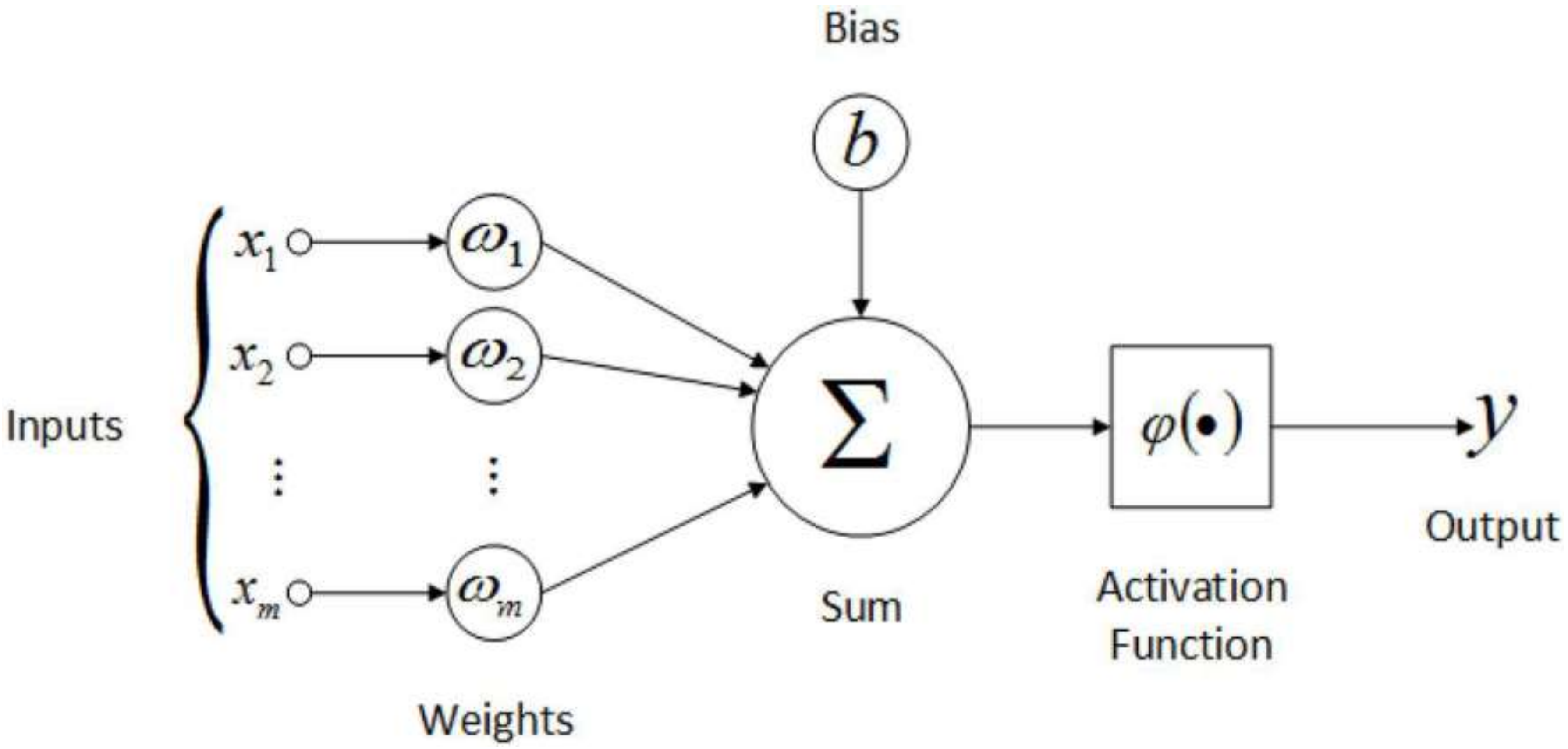
➢ Neural Networks Demystified

- Optical Computing Examples
- Addition
- Multiplication
- Convolution
- Precision
- Discussion

Inference Neural Network



Neuron


Bias
b
Inputs
x_1
x_2
x_m
ω_1
ω_2
ω_m
Weights
Σ
Sum
φ(•)
Activation
Function
y
Output

Machine Learning Terms

Machine Learning Term		Computation	
Inference			
input	inputs	x	**x**
weight	weights	w	W
Applying weights		w x	W **x**
bias	biases	b	**b**
Activation		$f(\bullet)$	
output	outputs	y	**y**
Neuron		y = *f*(**w**' **x** + b)	
Layer (except input)		**y** = *f*(W **x** + **b**)	
Training			

Machine Learning Terms and their Communication Equivalents

Machine Learning Term		Computation		Communication Term	
Inference				Signal Processing	
input	inputs	x	**x**	input	input vector
weight	weights	w	W	coefficient	coefficient matrix
Applying weights		w x	W **x**	Filtering	
bias	biases	b	**b**	threshold	threshold vector
Activation		*f*(•)		Detection	
output	outputs	y	**y**	output	output vector
Neuron		y = *f*(**w**' **x** + b)		MISO Receiver	
Layer (except input)		**y** = *f*(W **x** + **b**)		MIMO Receiver	
Training				Adaptation	

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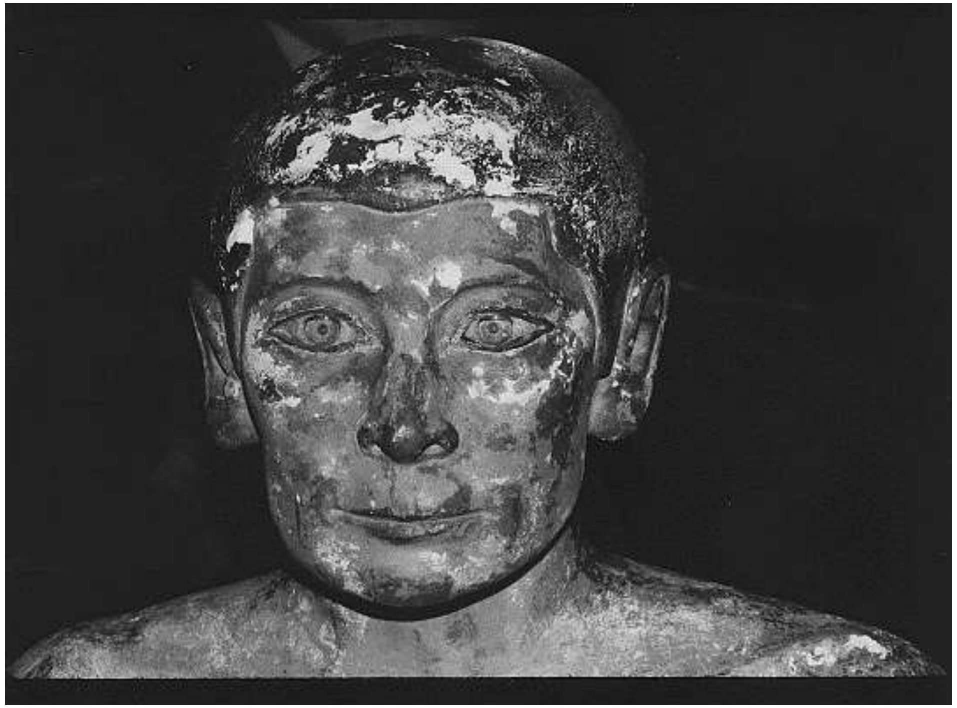
1st Optical Computing Example: 4600-year-old Egyptian Lens



- The "eyes" appear to follow the observer as they move about the statue
- On display at Louvre Museum, Paris

Widely Used Optical Computing Example: Eyeglasses

- Two lenses in a wooden frame, Italy, 1280's
- Lens processing is 2-D spatial filtering or 2-D convolution, i.e., inference
- A hypothetical electronic lens processes 24-bit RGB 512x512 pixel image at 120 frames/sec

  → ~25 trillion 8-bit Multiply-Accumulates/sec
- Zero incremental energy

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- Problem: fixed focus (fixed coefficients)
- Solution: Ben Franklin bi-focal eyeglasses
  - → 1 bit of programmability

Training

Telecom Optical Computing Example: DCF

- DCF (Dispersion Compensation Fiber) used in every Telecom link in the ’90s
- Passive, complex optical signal processing (computing)
- Zero incremental energy use (ignoring amplification for loss)
- Fixed compensation; requires a custom length spool for every link
- Dominant compensation approach despite extensive R&D into alternatives

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- Coherent DSP CMOS ASIC with adaptive equalization introduced 20 years ago
- Over time, completely replaced DCF and all other optical compensation techniques

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- Coherent DSP CMOS ASIC with adaptive equalization introduced 20 years ago
- Over time, completely replaced DCF and all other optical compensation techniques
- Same as happened to analog computing approaches in other fields; there were all replaced by digital computing

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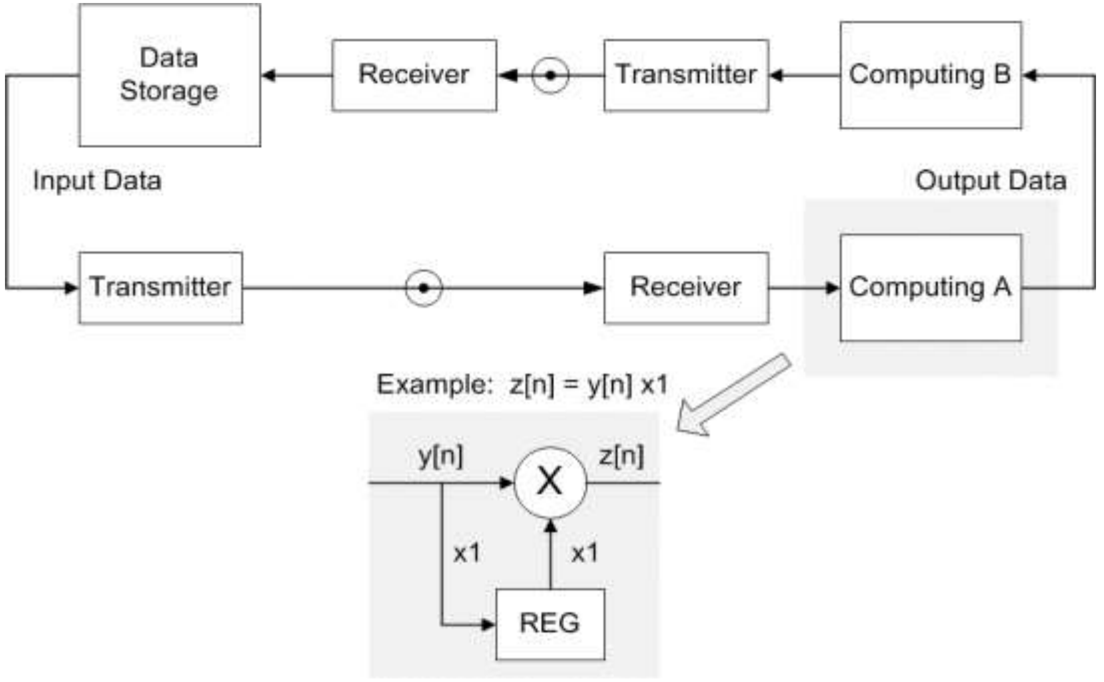
Data Transfer Compute Model Optimized for Math Operations

Electrical Computing w/ electrical DT

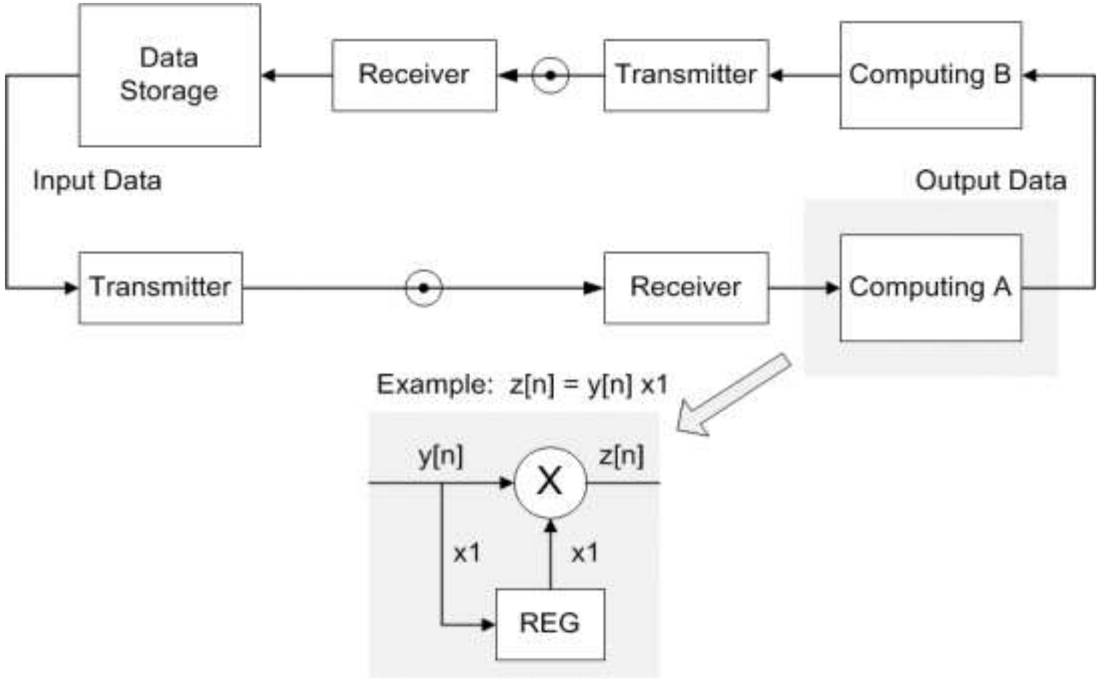


DT: Data Transfer

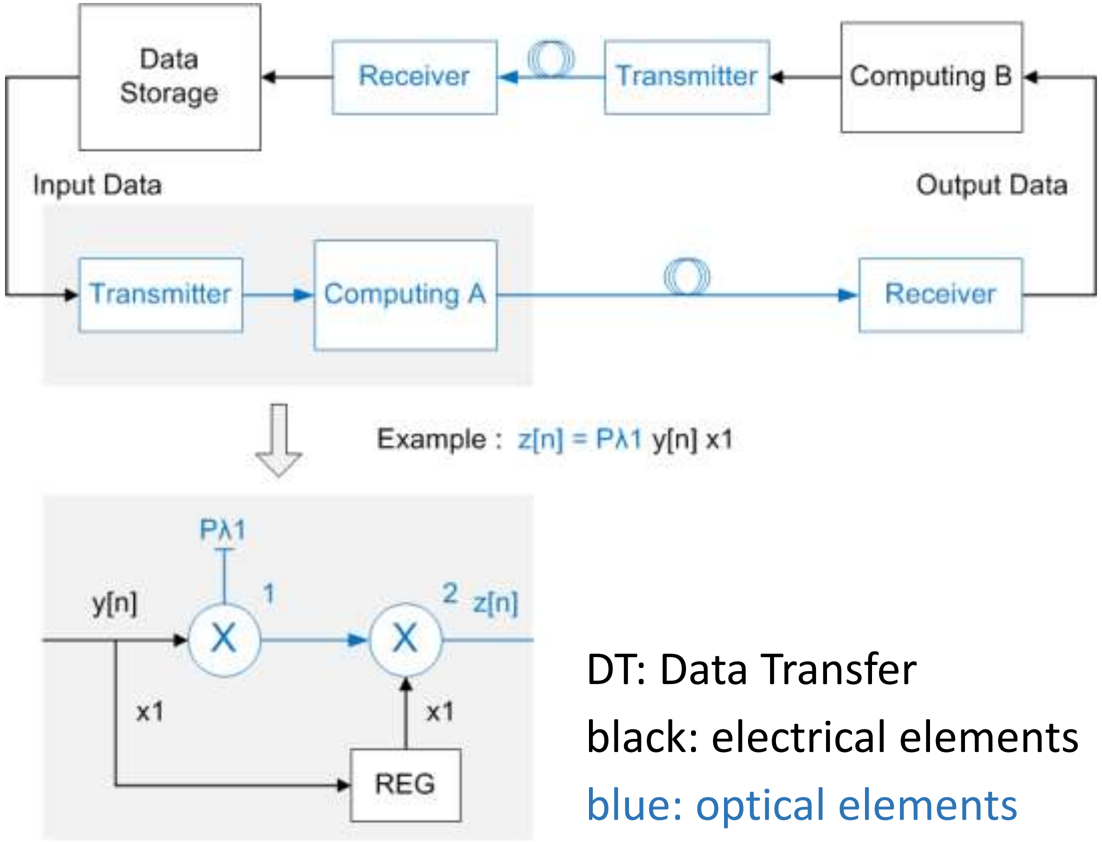
black: electrical elements

Apples-to-Oranges Energy Use Comparison Models

Electrical Computing w/ electrical DT



Optical Computing w/ optical DT



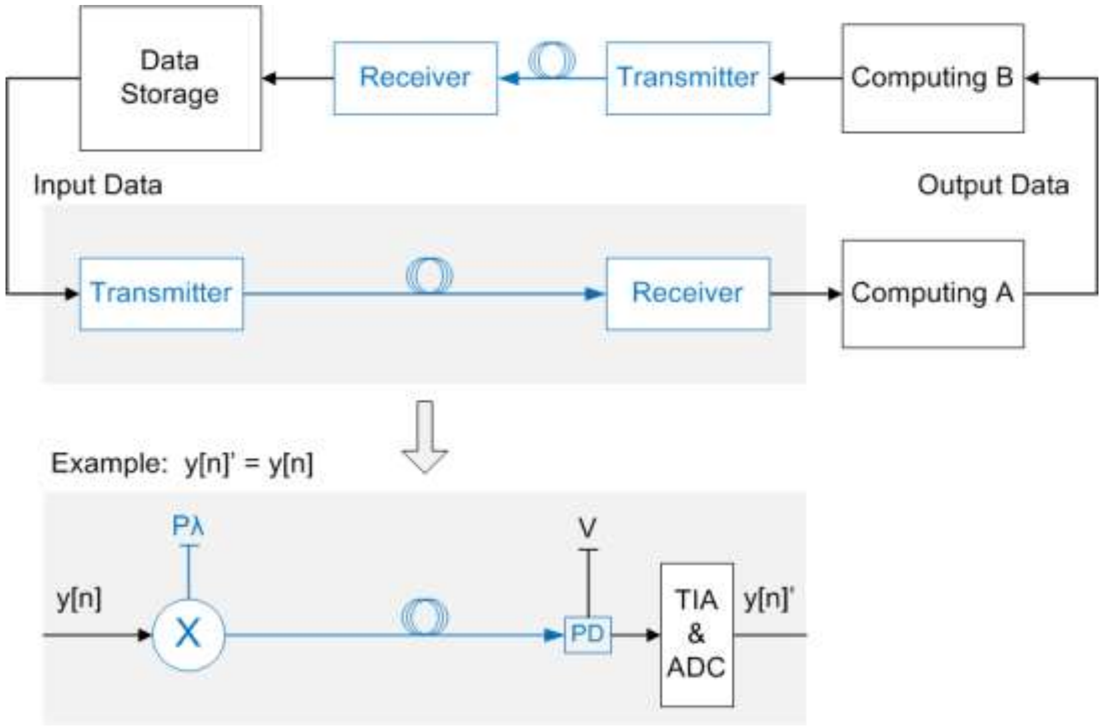
DT: Data Transfer

black: electrical elements

blue: optical elements

Data Transfer Compute Model Optimized for Math Operations

Electrical Computing w/ optical DT



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Apples-to-Apples Energy Use Comparison Models

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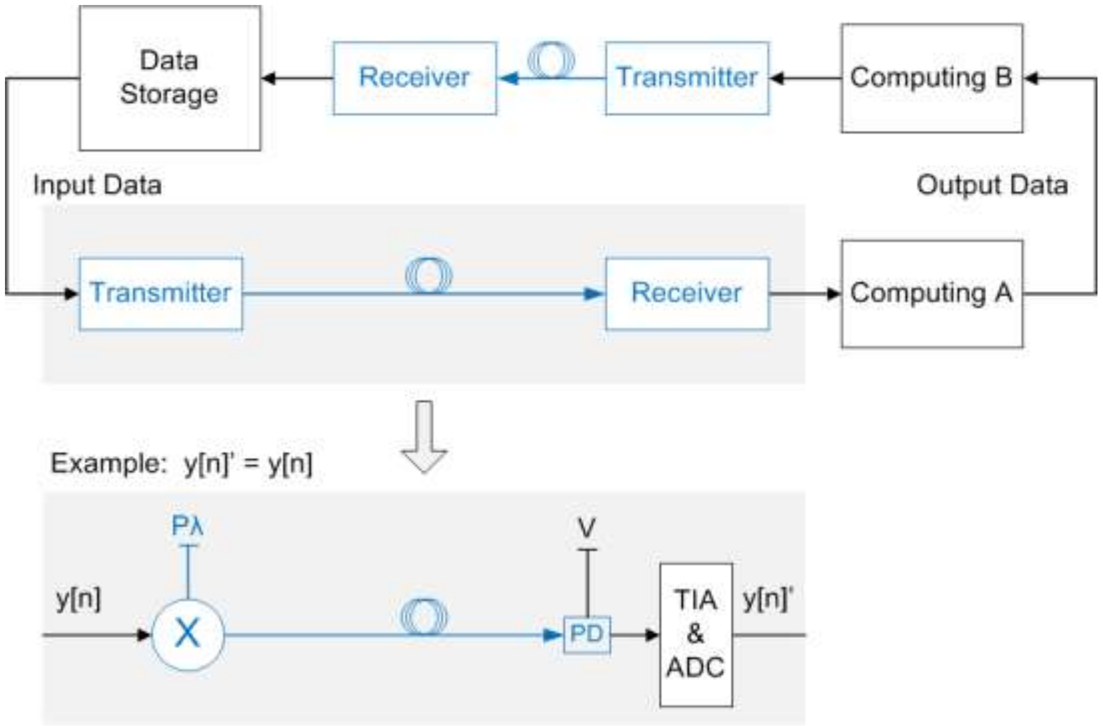
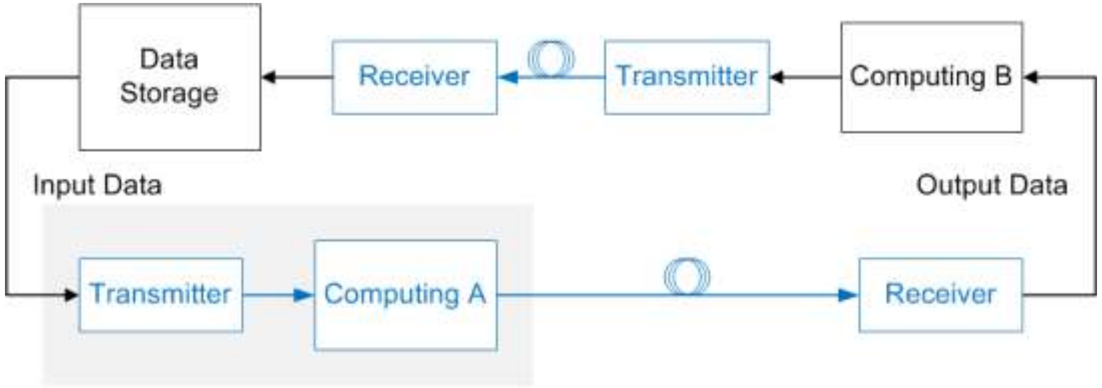
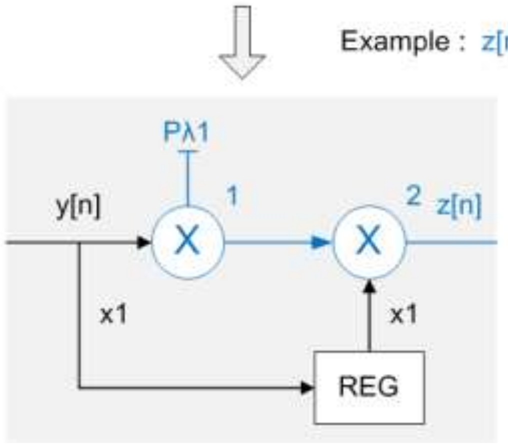


Optical Computing w/ optical DT



Example : z[n] = Pλ1 y[n] x1



DT: Data Transfer

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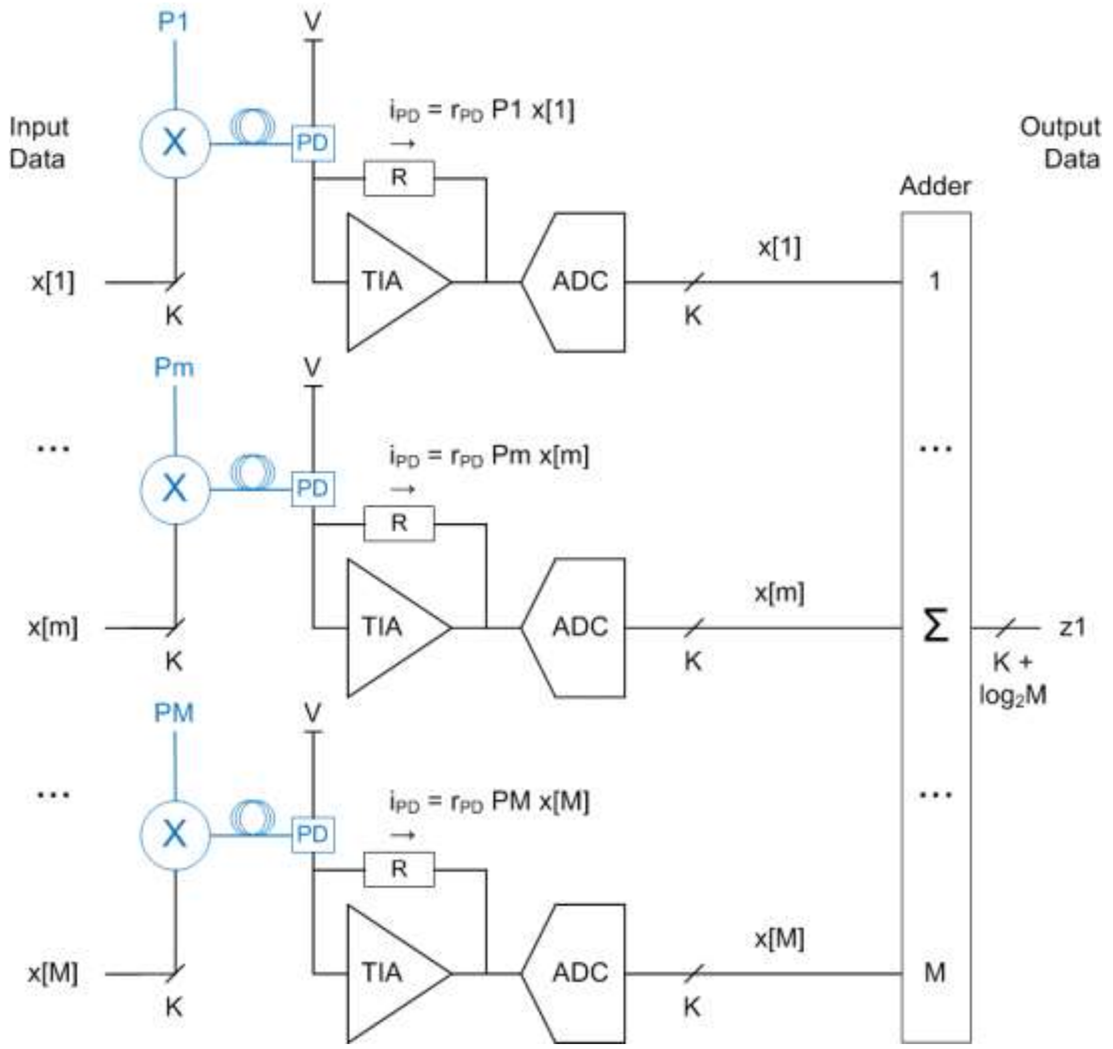
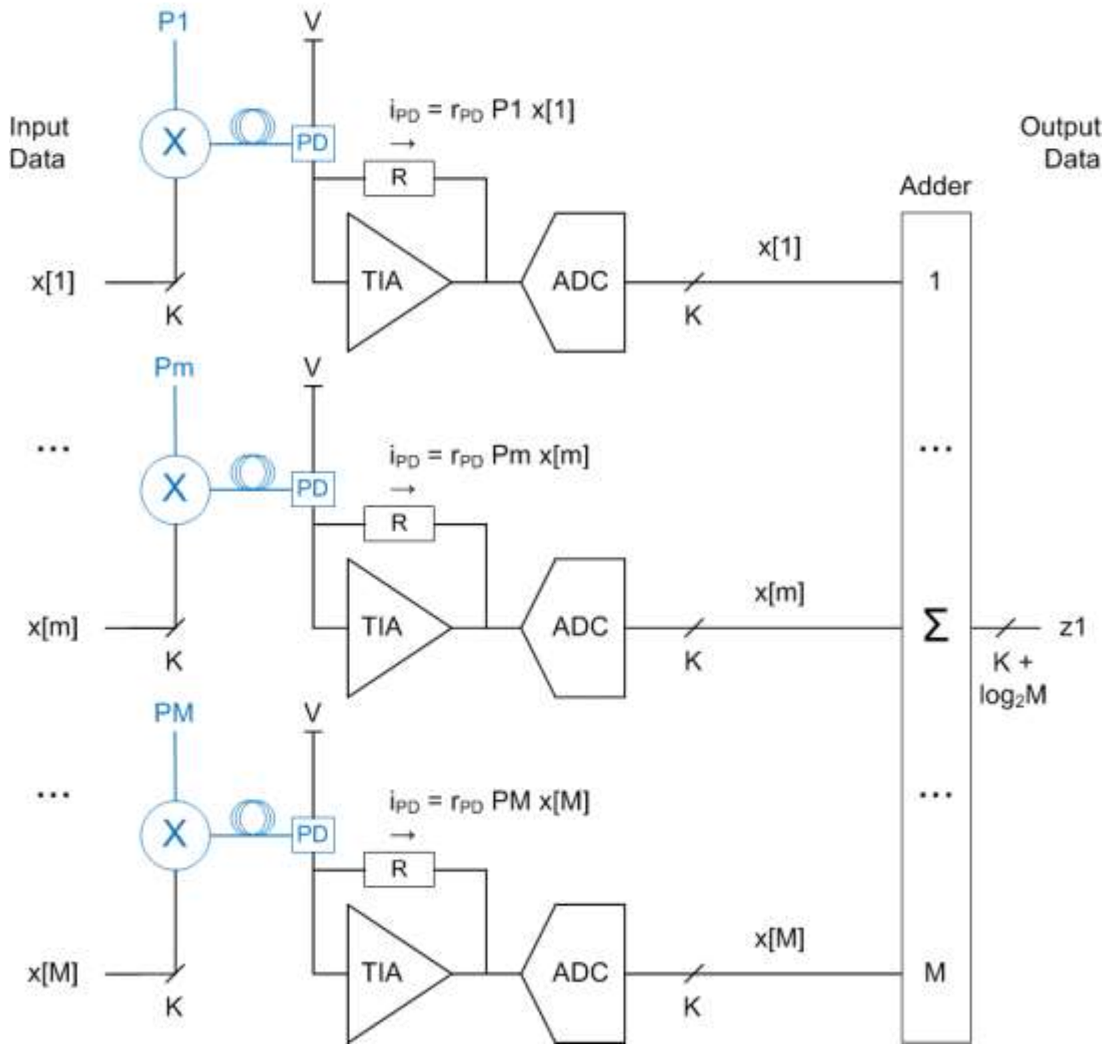
Electrical Parallel Addition (column sum) Model

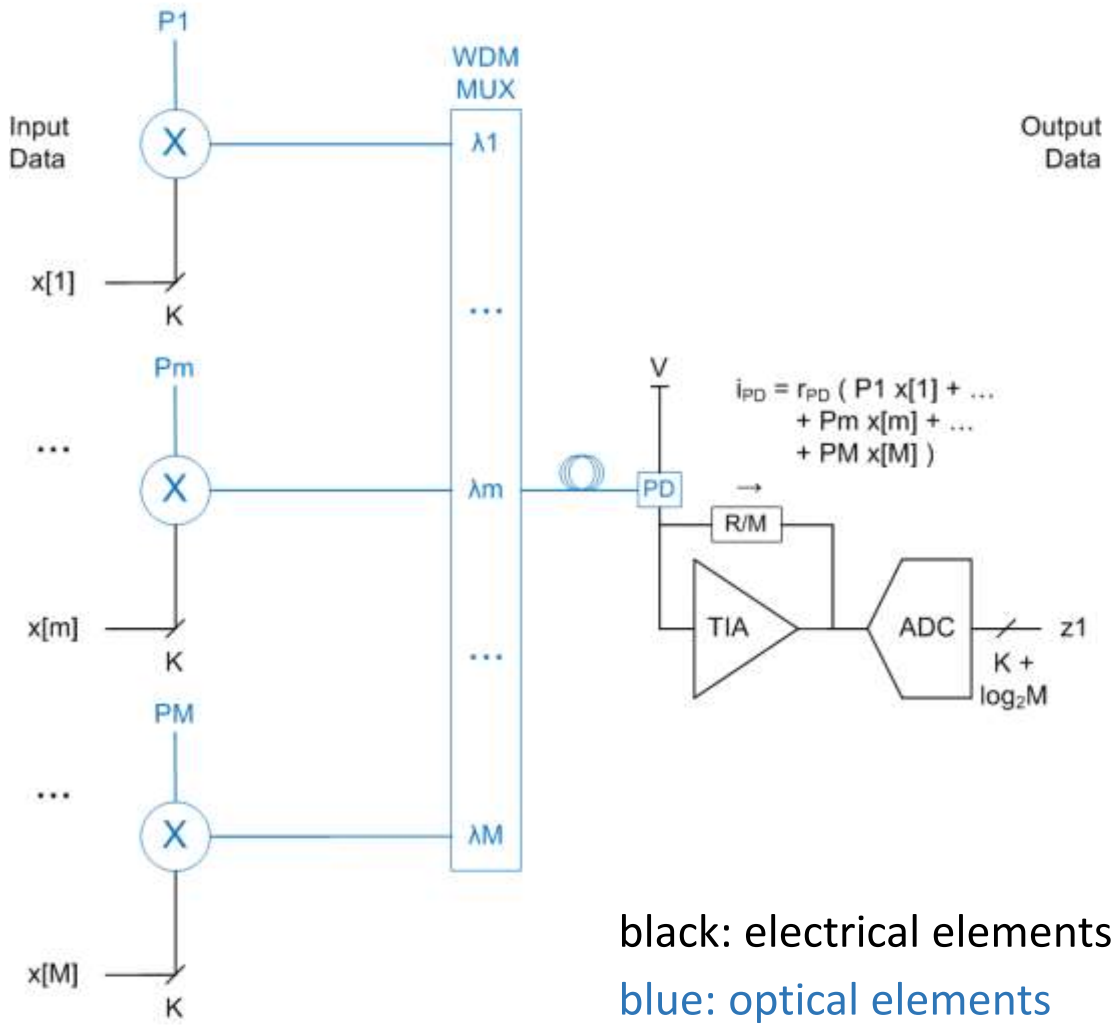


black: electrical elements

blue: optical elements

Electrical and Optical Parallel Addition (column sum) Models





black: electrical elements
blue: optical elements

CMOS Adder Energy Use

CMOS node	Delay	Energy/op (max)	Input	Rate	Energy
nm	ps	fJ	bits/op	Gops/s	fJ/bit
7	40	50	16	25	2.9
7	30	40	16	33	2.5
				average	**2.7**

Q. Xie, X. Lin, S. Chen, M. Dousti and M. Pedram, "Performance Comparisons between 7nm FinFET and Conventional Bulk CMOS Standard Cell Libraries," *IEEE Transactions on Circuits and Systems II: Express Briefs,* vol. 62, no. 8, pp. 761-765, August 2015.

A. Vatanjou, E. Lte, T. Ytterdal and S. Aunet, "Ultra-low Voltage and Energy Efficient Adders in 28nm FDSOI Exploring Poly-biasing for Device Sizing," Microprocessors & Microsystems, vol. 56, no. C, pp. 92-100, February 2018.

A. Stillmaker and B. Baas, "Scaling equations for the accurate prediction of CMOS device performance," *Integration the VLSI journal,* vol. 58, pp. 74-81, February 2017.

Energy Use of High-speed CMOS ADCs

Output	Rate	CMOS node	Effective bits	Energy	Reference
Bits	GS/s	nm	ENOB	**fJ/bit**	
6	24	28	4.5	**210**	[32]
6	3.3	28	5.4	310	[33]
8	10	65	6.4	800	[34]
8	1	28	7.3	350	[35]
8	28	7	5.0	355	[36]

References from C. Cole, "Optical and electrical programmable computing energy use comparison," Optics Express, Vol. 29, Issue 9, pp. 13153-13170, 2021.

Electrical & Optical Addition Energy Use Comparison

- 30 Gops/sec 16-bit 7nm CMOS adder is **3/210 = 1/70** of 28 Gops/sec 8-bit 7nm CMOS ADC
- Energy use of CMOS Adder compared to ADC is insignificant, and can be ignored
- To increase ADC effective resolution by √M bits (same increase in SNR as from summing the output of M ADCs) requires M times the energy (theoretical)
- Energy use of M K-bit ADCs **equals** energy use of one (K + $\log_2 M$)-bit ADC

<u>Computing Addition optically instead of electrically does not save energy</u>

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* ADC changes required to increase resolution by 1-bit, with constant power supply voltage:

→ 4x lower ADC noise

→ 4x higher ADC signal capacitor(s) C

→ 4x higher gm to maintain constant gm/C (bandwidth)

→ 4x higher i_{drain}

→ 4x higher ADC energy use

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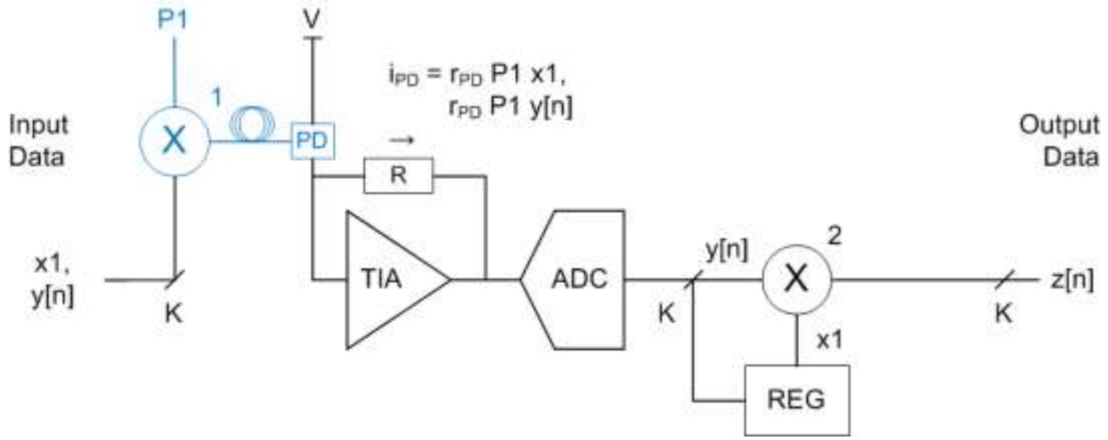
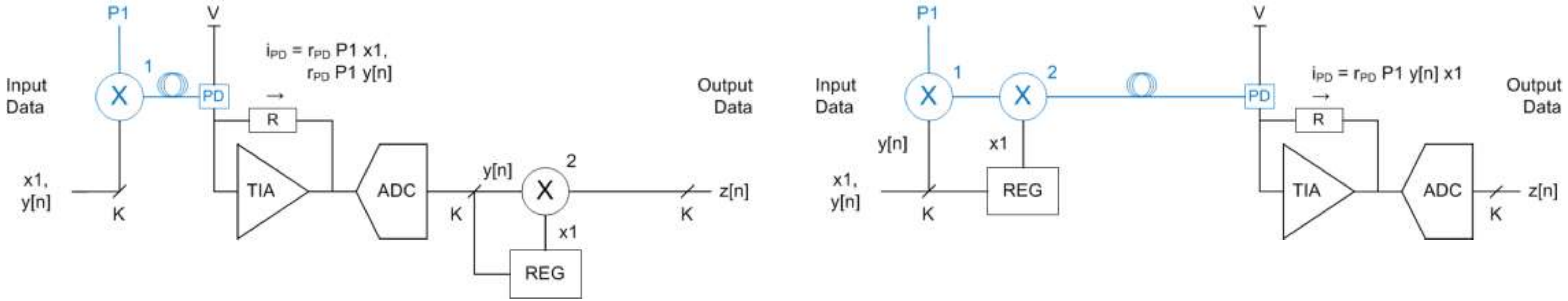
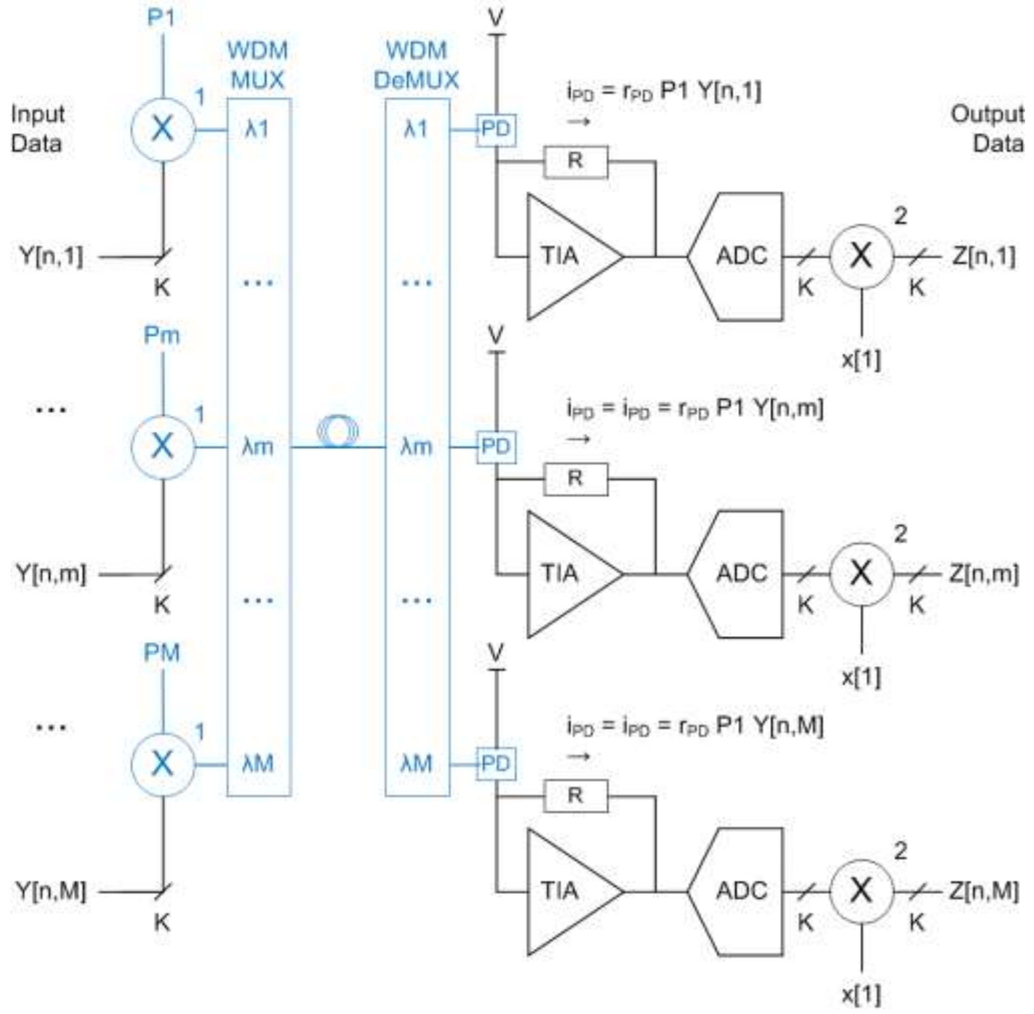
Electrical Vector Multiplication Model



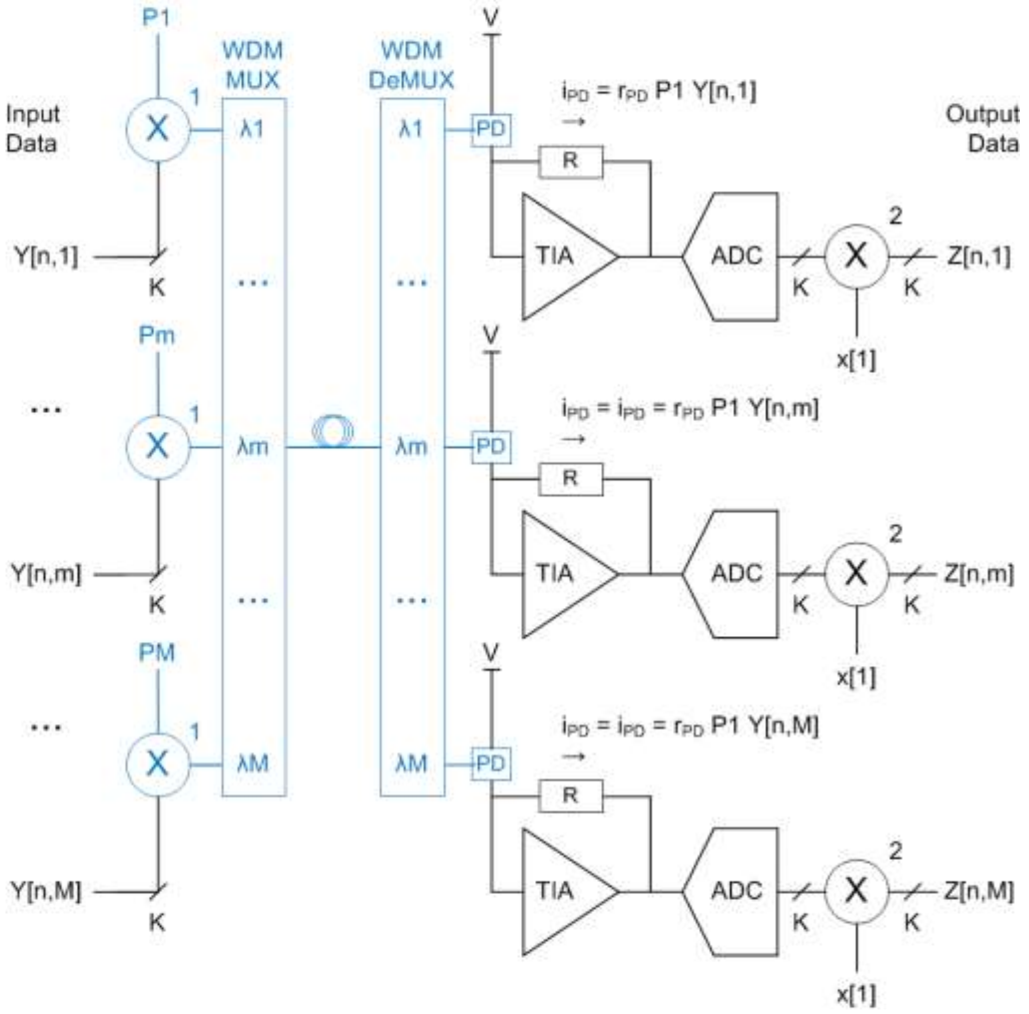
Electrical and Optical Vector Multiplication Models

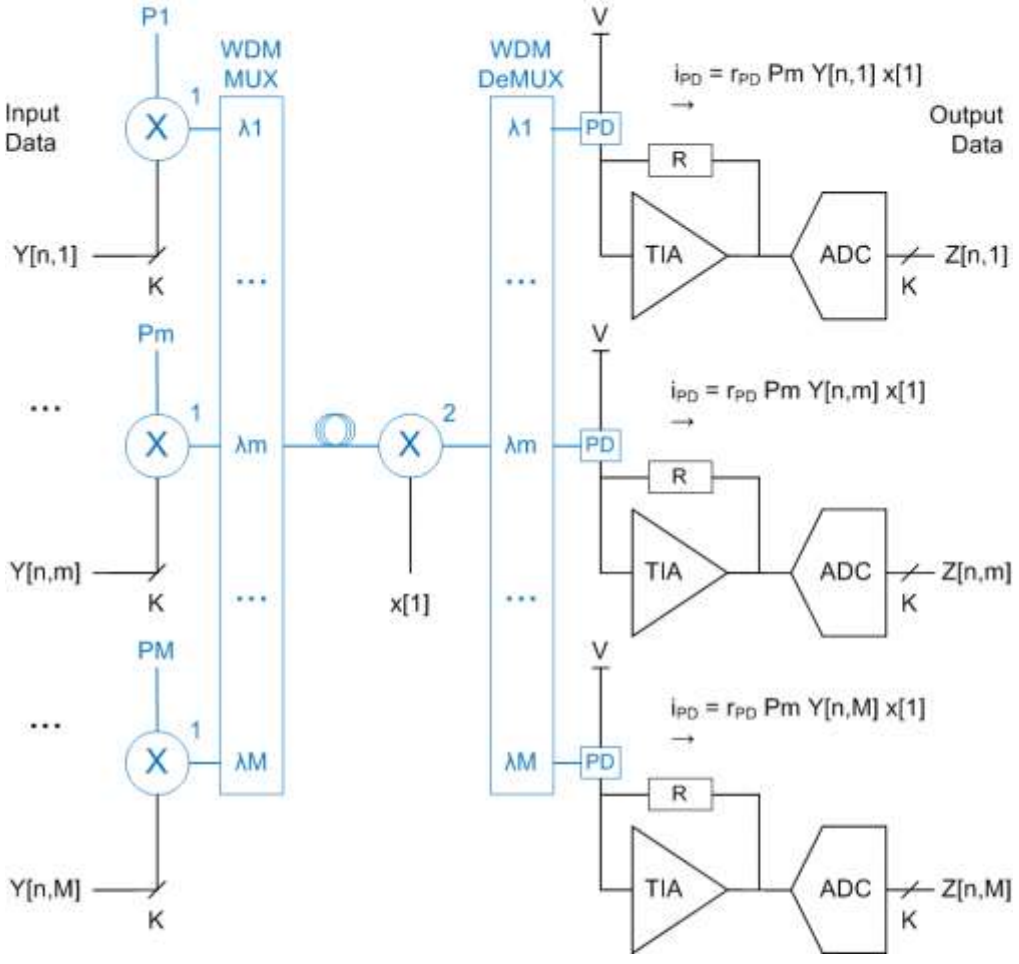


Electrical Parallel Vector Multiplication Model



Electrical and Optical Parallel Vector Multiplication Models





Energy Use of CMOS 16-bit Multipliers

CMOS node	Delay	Energy/op (max)	Input	Rate	Energy
nm	ps	fJ	bits/op	Gops/s	fJ/bit
7	58	296	16	17.5	19
7	40	310	16	25	19

Q. Xie, X. Lin, S. Chen, M. Dousti and M. Pedram, "Performance Comparisons between 7nm FinFET and Conventional Bulk CMOS Standard Cell Libraries," *IEEE Transactions on Circuits and Systems II: Express Briefs,* vol. 62, no. 8, pp. 761-765, August 2015.

D. Baran, M. Aktan, and V. Oklobdzija, "Energy Efficient Implementation of Parallel CMOS Multipliers with Improved Compressors," in ACM/IEEE International Symposium on Low-Power Electronics and Design (ISLPED), pp. 147–152, August 2010.

A. Stillmaker and B. Baas, "Scaling equations for the accurate prediction of CMOS device performance," *Integration the VLSI journal,* vol. 58, pp. 74-81, February 2017.

Electrical & Optical Multiplication Energy Use Comparison

- 25 Gops/sec 16-bit 7nm CMOS multiplier is **19/210 = 1/11** of 28 Gops/sec 8-bit 7nm CMOS ADC
- Energy use of CMOS Multiplier compared to CMOS ADC is insignificant, and can be ignored
- Electrical and Optical Multiplication models have the same ADC energy use

<u>Computing Multiplication optically instead of electrically does not save energy</u>

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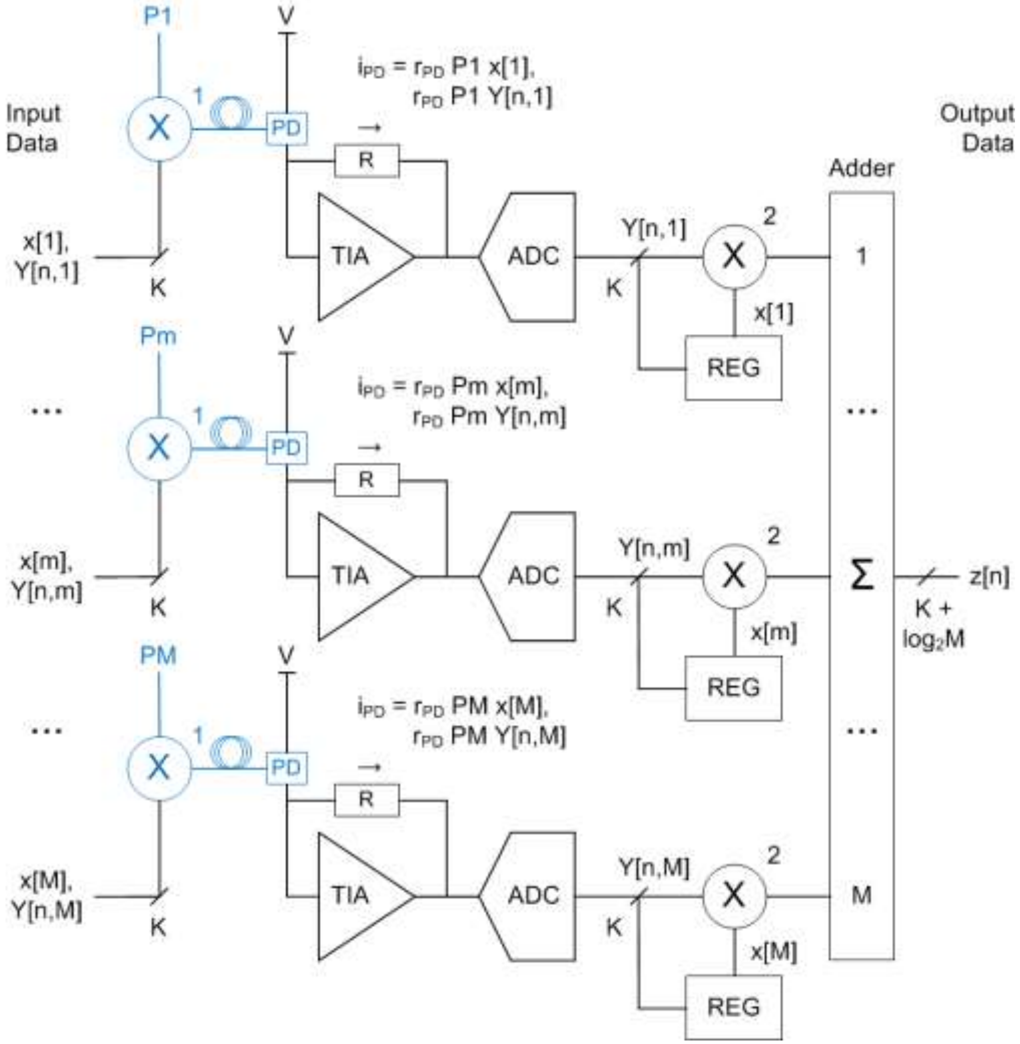
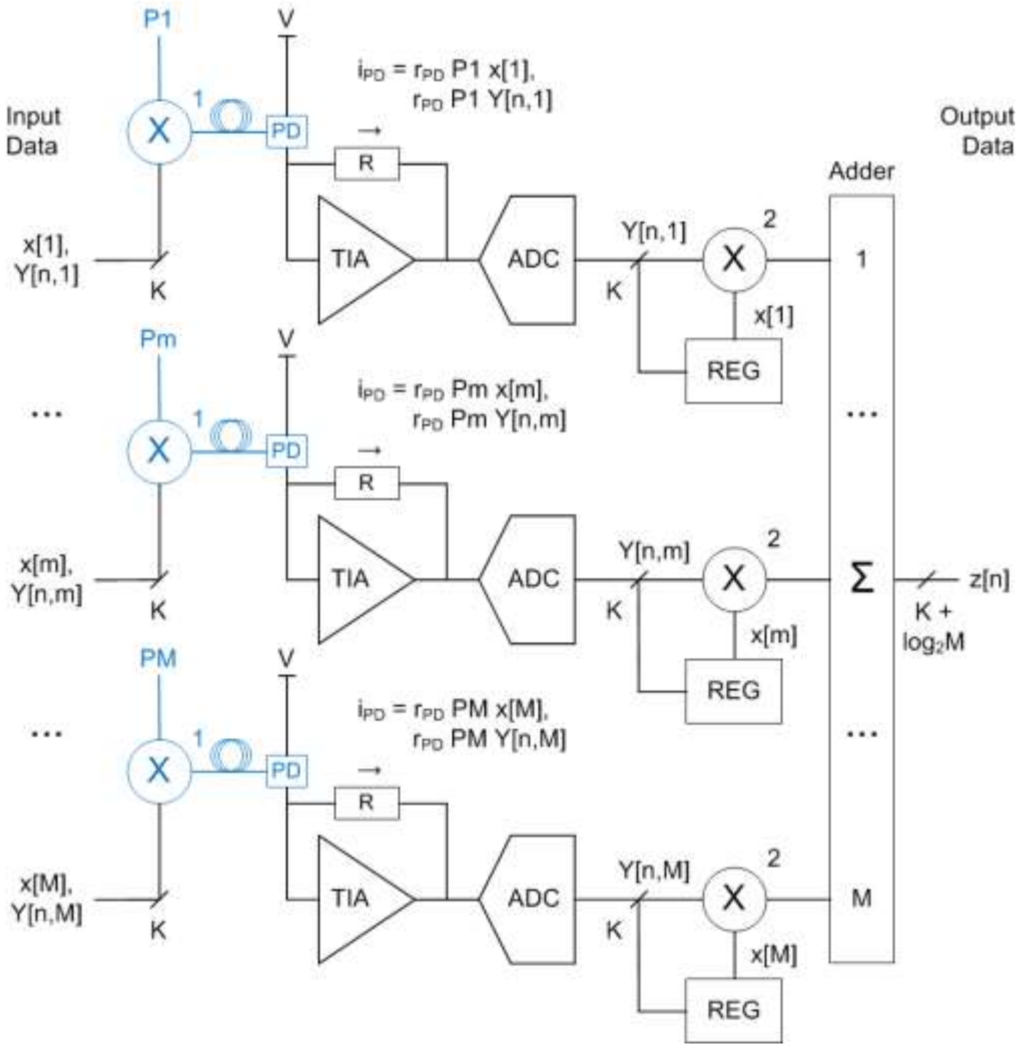
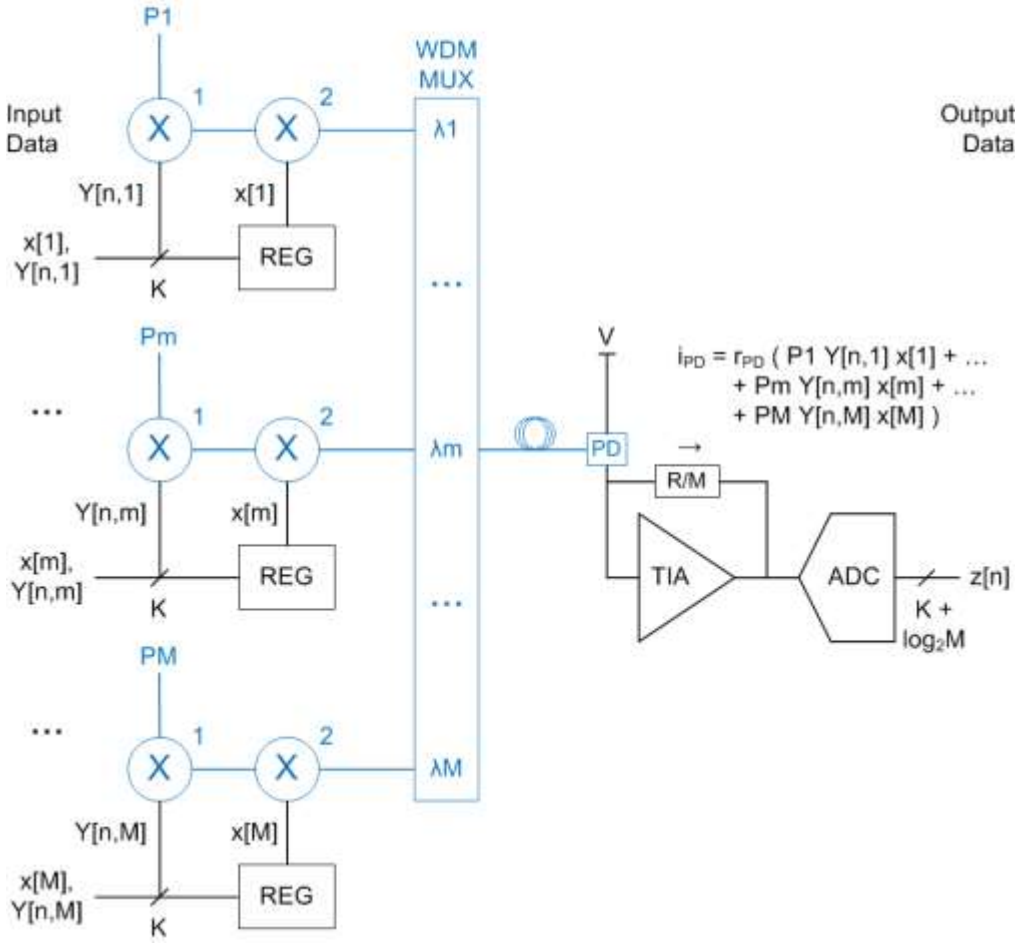
Electrical Matrix Vector Product Computation Model



Electrical & Optical Matrix Vector Product Computation Models





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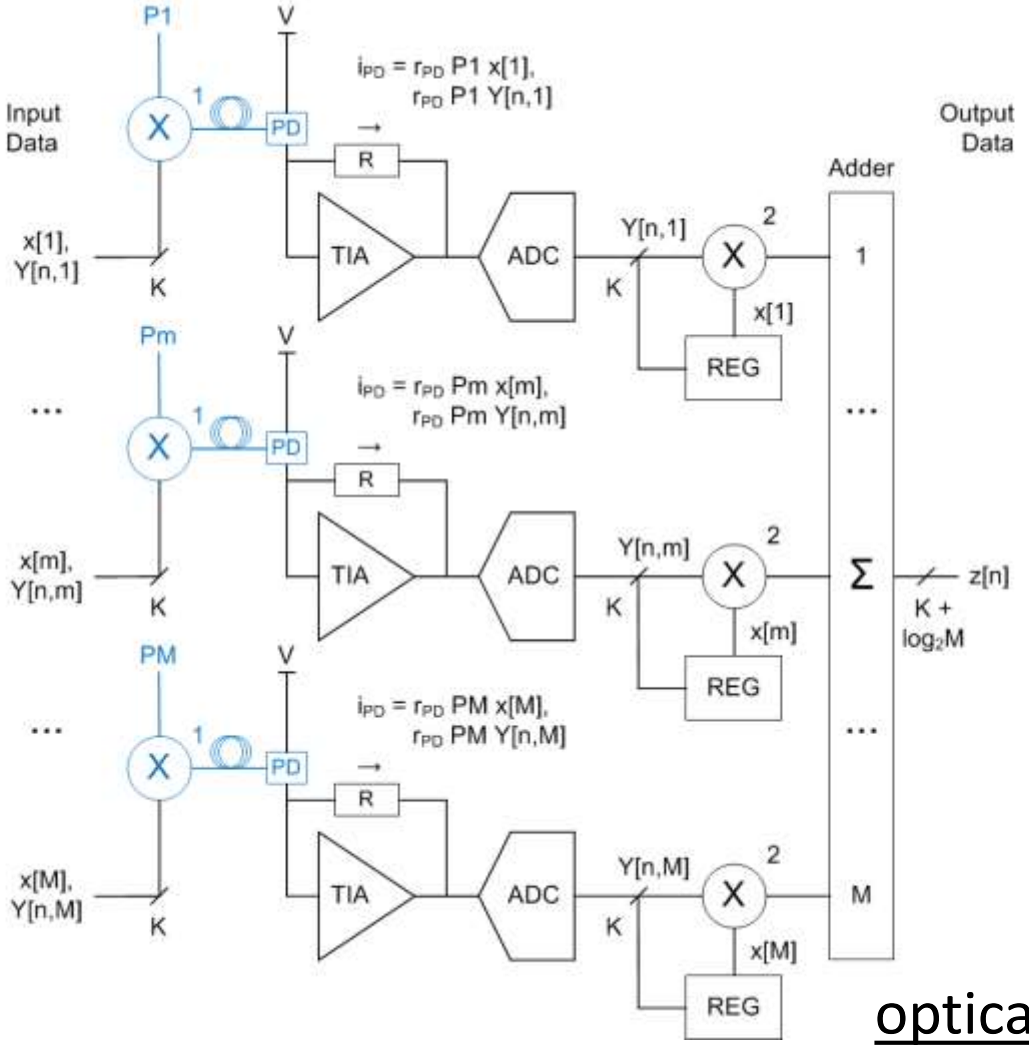

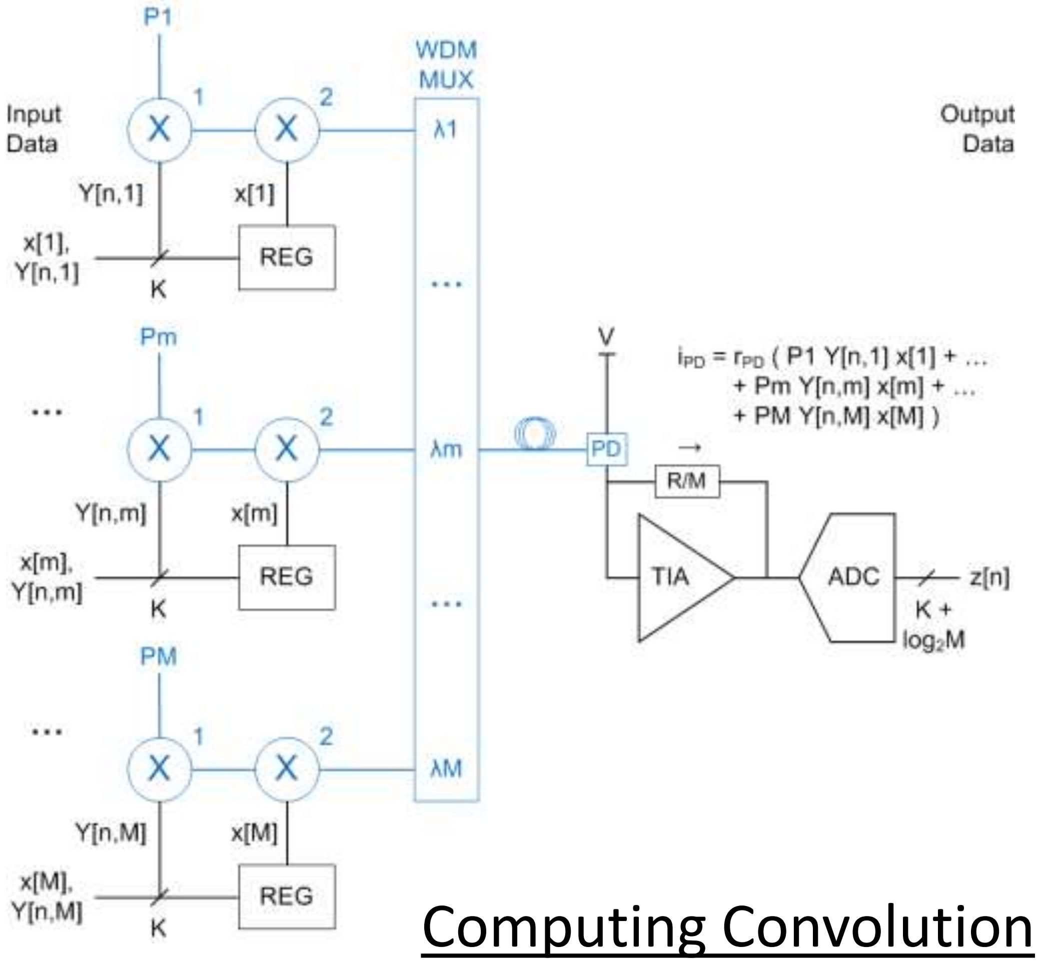

<u>Computing Convolution</u>

<u>optically instead of electrically does not save energy</u>

Optical Datacom Filter CMOS Computing Example: Fast FFE

- FFE (Feed Forward Equalizer) processing is convolution
- Same processing as applying weights in a neuron (inference)
- Used in high volume 56 Gb/sec and 112 Gb/sec per lane PHY (CDR) optical receivers
- Architecture: ADC + CMOS DSP with only CTLE analog pre-compensation
- Optical receiver FFE is the perfect problem for optical computing:
  - high bit rate
  - low precision
  - low number of coefficients
  - digital to optical & optical to digital conversion already in place
  - zero incremental energy use
- Yet all optical receivers use CMOS DSP FFEs, and none use optical computing

CMOS Multiplier and FFE MAC Energy Use

MAC Type	CMOS node	Delay	Energy/op (max)	Input	Rate	Energy
	nm	ps	fJ	bits/op	Gops/s	fJ/bit
Adder & Multiplier	7	58	367	16	17.5	23
FFE	7	11	159	8	90	**20**

Q. Xie, X. Lin, S. Chen, M. Dousti and M. Pedram, "Performance Comparisons between 7nm FinFET and Conventional Bulk CMOS Standard Cell Libraries," *IEEE Transactions on Circuits and Systems II: Express Briefs,* vol. 62, no. 8, pp. 761-765, August 2015.

C. Menolfi, M. Braendli, P. Francese, T. Morf, A. Cevrero, M. Kossel, L. Kull, D. Luu, I. Ozkaya and T. Toifl, "A 112Gb/s 2.6pJ/b 8-tap FFE PAM-4 SST TX in 14nm CMOS," in IEEE International Solid-State Circuits Conference Digest of Technical Papers, pp. 104-105, February 2018.

A. Stillmaker and B. Baas, "Scaling equations for the accurate prediction of CMOS device performance," *Integration the VLSI journal,* vol. 58, pp. 74-81, February 2017.

Why All Optical Receivers use CMOS DSP FFEs

- 7nm CMOS 90 Gops/sec 8-bit MAC is **20/210 = 1/10** of 28 Gops/sec 8-bit 7nm CMOS ADC
- Programmability, testability, repeatability and manufacturability are critical in commercial products
- If **20 fJ/bit** 7nm CMOS MAC energy use is too high, wait a few years:
  - core digital logic energy use is dropping with each node shrink
  - 3nm CMOS will be < **8 fJ/bit**
  - in contrast, I/O and analog circuit energy use is plateauing with node shrinks

<u>Computing Convolution optically instead of electrically does not save energy</u>

A. Stillmaker and B. Baas, "Scaling equations for the accurate prediction of CMOS device performance," *Integration the VLSI journal,* vol. 58, pp. 74-81, February 2017.

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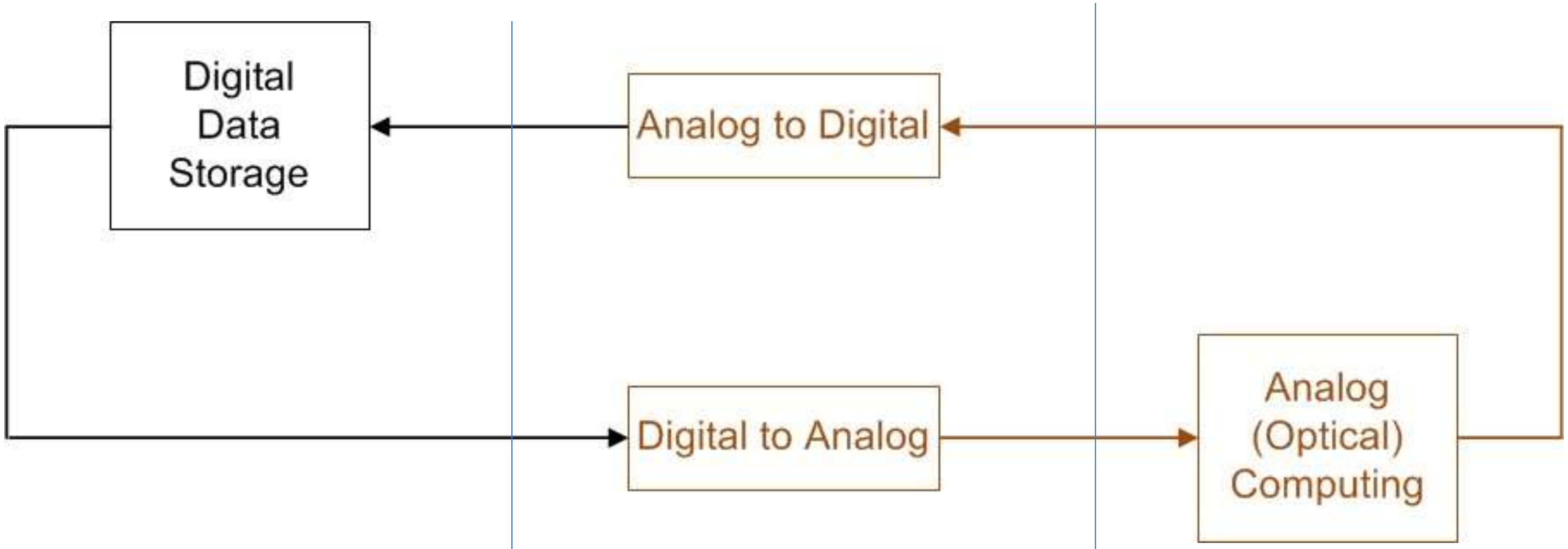
ML in the Datacenter

- The trend in machine learning is towards greater scale, complexity and programmability
- Model size increases are orders of magnitude to be meaningful.
- Optical computing precision and complexity scale poorly making them not useful in datacenters, resulting in zero deployment
- Web2.0 datacenter operators are not interested in low-resolution ML computing
  - TPUs and GPUs have 8-bit integer modes; they are rarely used
- There is interest in FP8 (Floating Point 8) for some ML applications
  - Two orders of magnitude greater dynamic range than practical optical precision
- Bigger problem is that precision of optical computing systems is rarely measured

Generic Model of Mixed Signal Computing System



determine energy use and computation speed

does not determine energy use and speed

- ENOB (effective number of bits) is a fundamental figure of merit of mixed systems
- ENOB has been measured for decades, for example using test tones and FFT processing to determine SNR (ENOB = $(SNR_{dB} – 1.76)/6.02$)

Optical Computing Precision Characterization

- Optical Computing results rarely, if ever, include measurement of underlying precision
- Instead, they
  - quote the precision of ADC and DAC components, which is not system precision,
  - run ML models and use convergence results to conclude that the unknown and unmeasured underlying precision is good enough for the application
- Treating a system as a block box with underlying parameters unknown is not modern engineering; it’s pre 19th Century craftsmanship
- Performance claims for an Optical Computing system, without fully analyzed and measured ENOB, have no justification

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Optical Pre-processing

- Optical Computing is very effective as pre-processing before O-to-E conversion
  - Eyeglasses
  - Digital camera front-end
  - LIDAR
  - FSO Beamformer
  - Microscopy
- Implementations are highly domain specific; there are no generic solutions
- Optical pre-processing is a great area for research and development

General Purpose Optical Computing

- Publications mostly compare optical computing using optical data transfer, to electrical computing using electrical data transfer, and incorrectly attribute low energy use to computing even though it's insignificant
- Total optical or electrical programmable computing energy use is dominated by data transfer and conversion to and from digital memory; computing is negligible in comparison
- Systems rarely have measured ENOB, therefore their performance claims are unsupported

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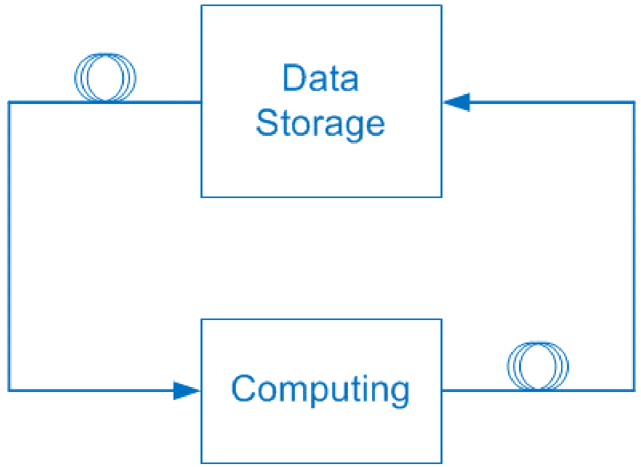
- Total optical or electrical programmable computing energy use is dominated by data transfer and conversion to and from digital memory; computing is negligible in comparison
- Systems rarely have measured ENOB, therefore their performance claims are unsupported
- General purpose optical computing has no advantages, and its many disadvantages result in no commercial use
- It should be avoided in research and development

There is Hope for General Purpose Optical Computing



blue: optical elements

It just needs dense optical RAM.

Optical Computing Fundamentals and Applications

Thank you