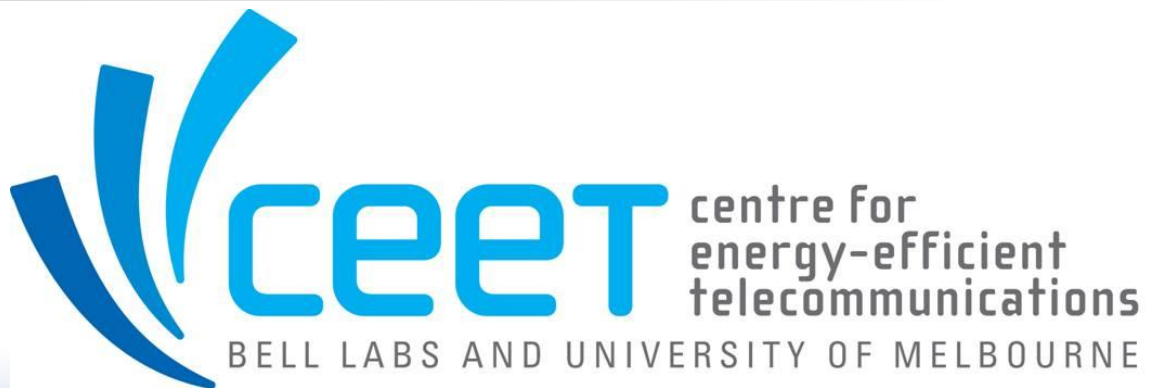


Energy Limitations on Optical Data Transport and Switching

Rod Tucker
University of Melbourne

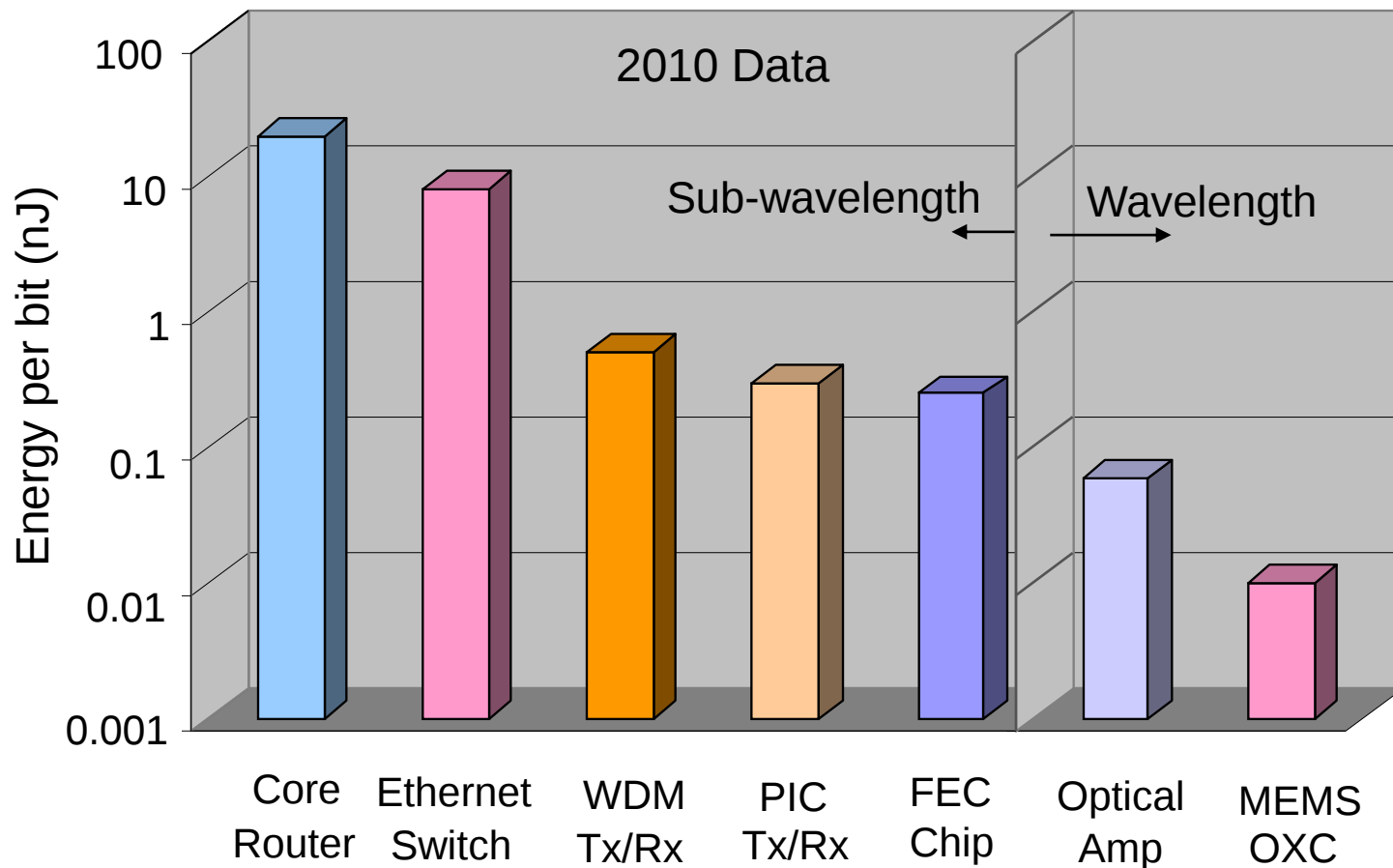


Summary

- Top-down estimate of energy consumption of the Internet
 - Projections of current trends (BAU)
 - Switches and routers
 - Optical transport
- Bottom-up estimate
 - Based on theoretical and practical lower bounds
 - Transport energy
 - Switching energy
 - Network energy
- Putting the GreenTouch factor of 1000 into context



Top-Down Analysis

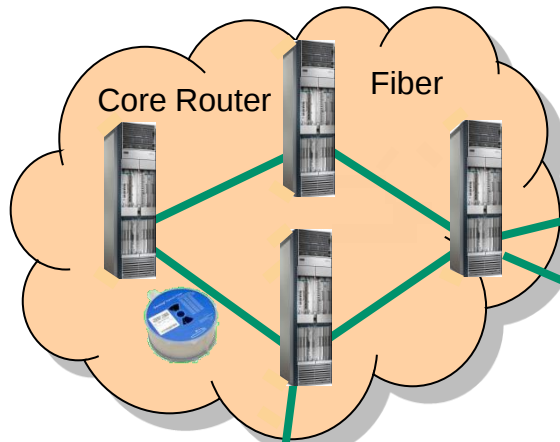


OLT:	50 nJ/b
DSL Modem:	500 nJ/b
Set-top Box:	1000 nJ/b
HD IPTV:	10,000 nJ/b

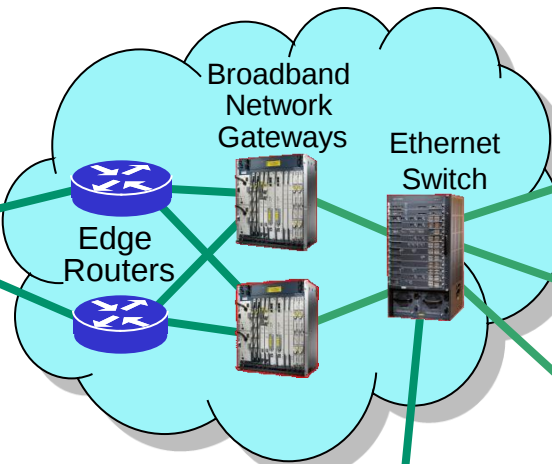
Network Energy Model

Tier 1 Network

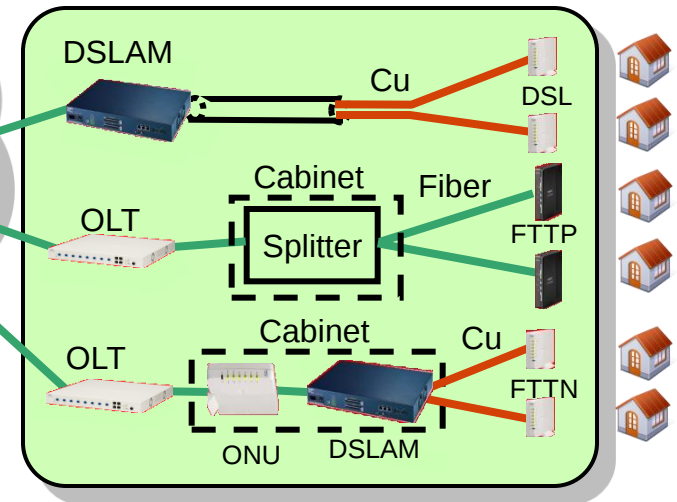
Core Network



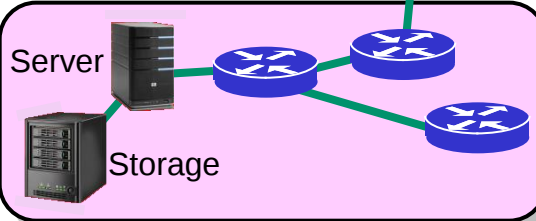
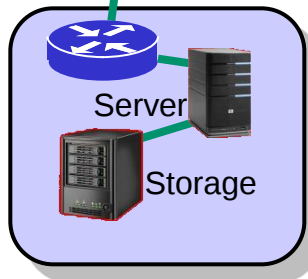
Metro/Edge Network



Access Network

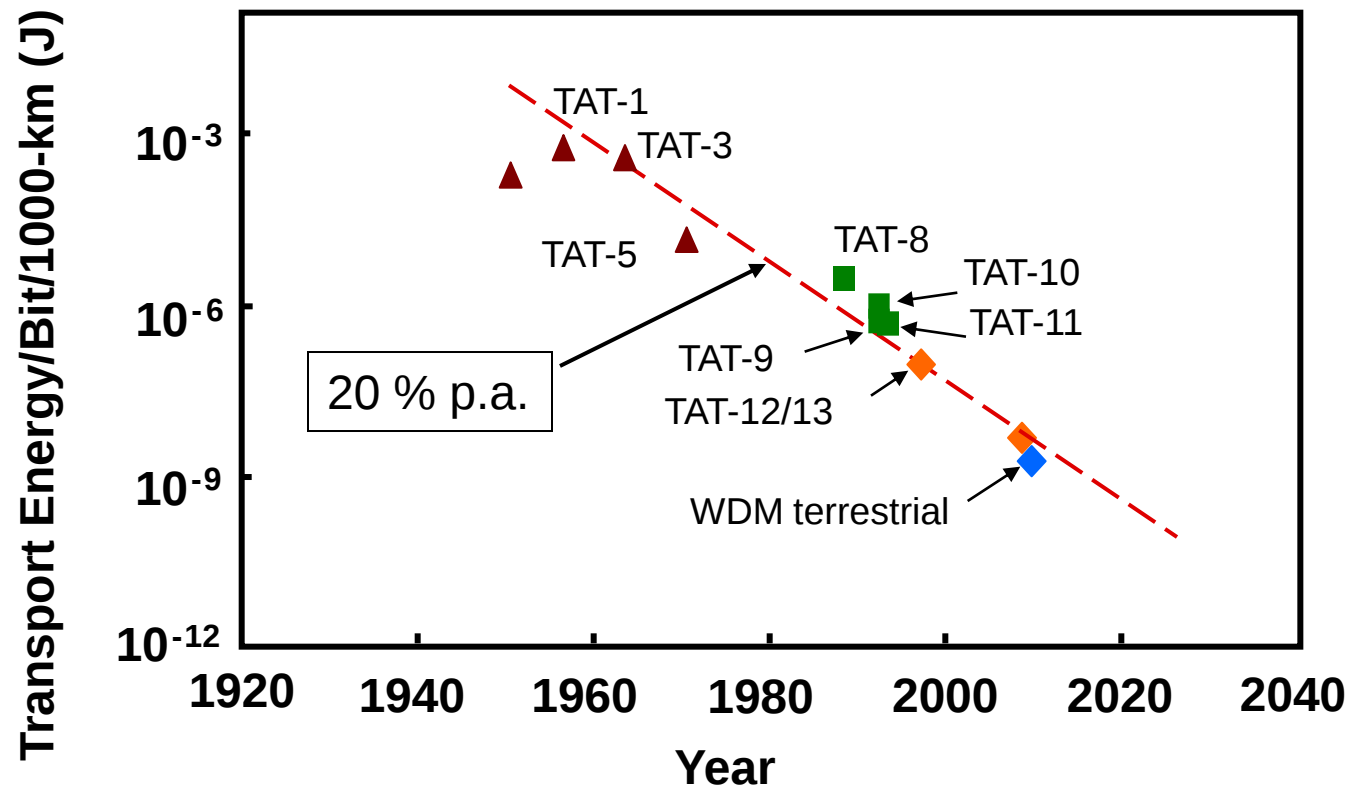


Data Center



Video Distribution Network

Efficiency Trends – Transport Systems



20% p.a. efficiency improvement in routers

(Neilson, JSTQE, 2006)

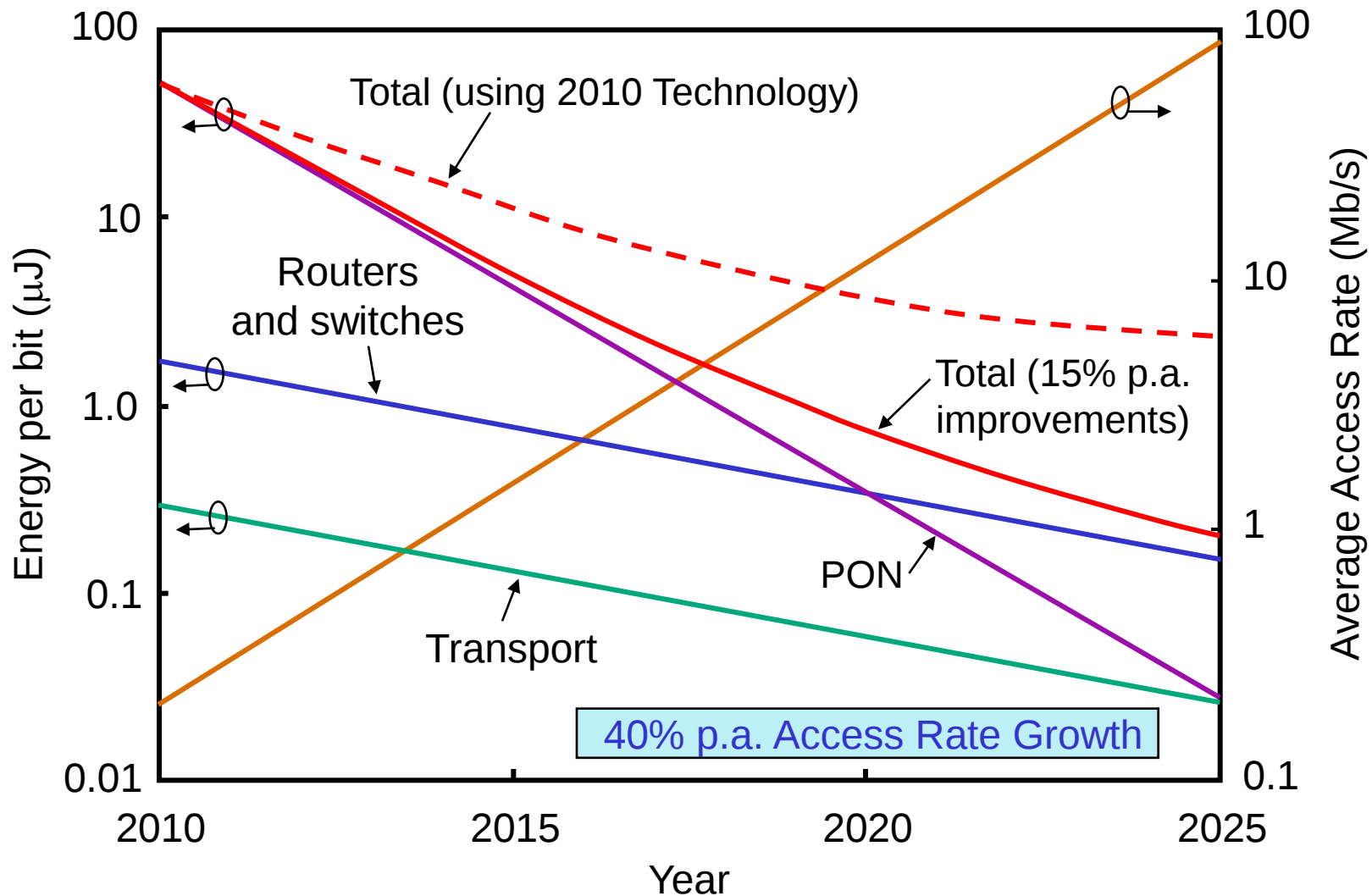
13% p.a. efficiency improvement in routers

(Tamm, BLTJ, 2010)

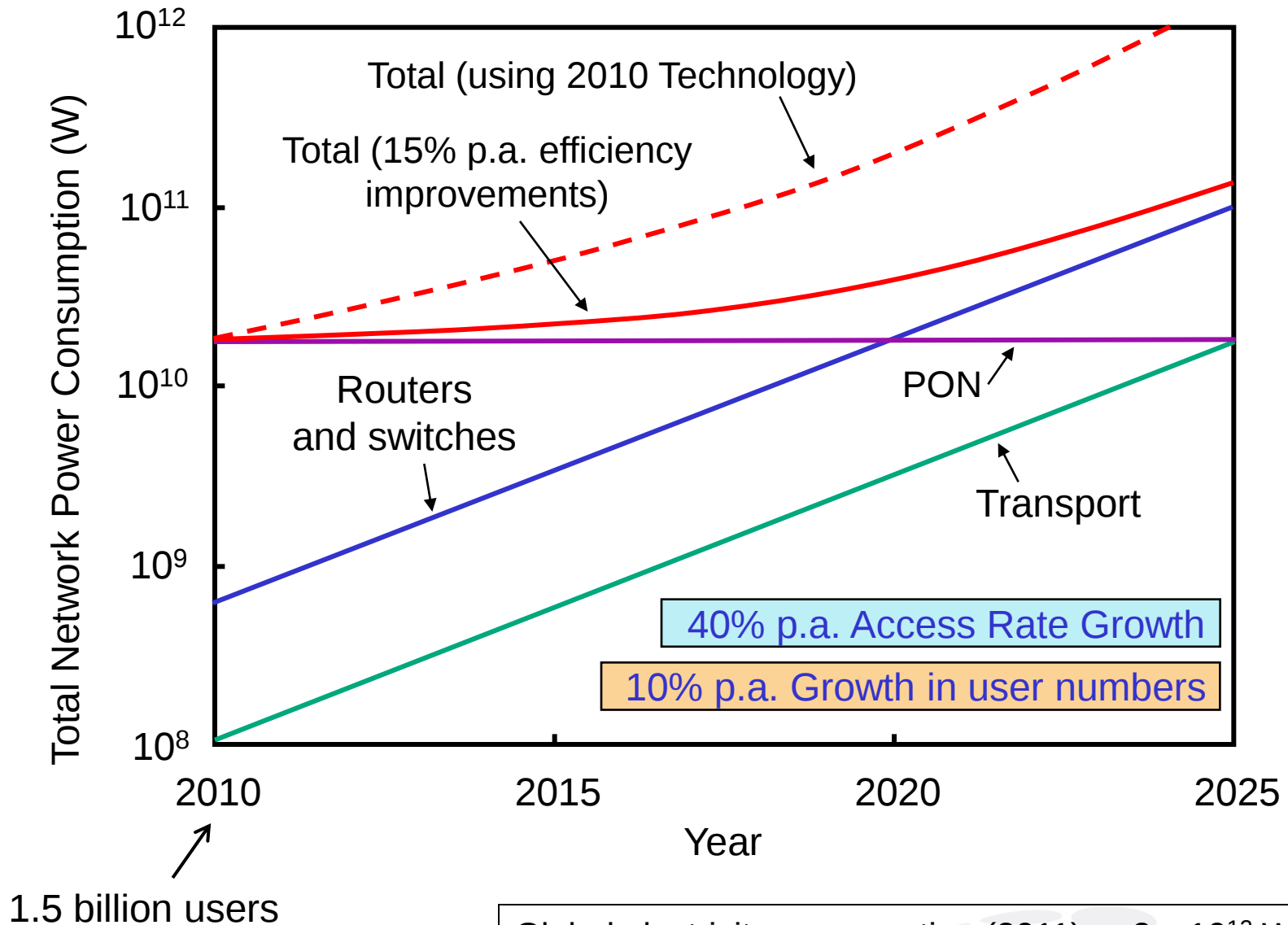
15% p.a. efficiency improvements in transport

(Han, IEEE Comms. Mag. 2010)

Top-Down Analysis



Global Network Energy Consumption

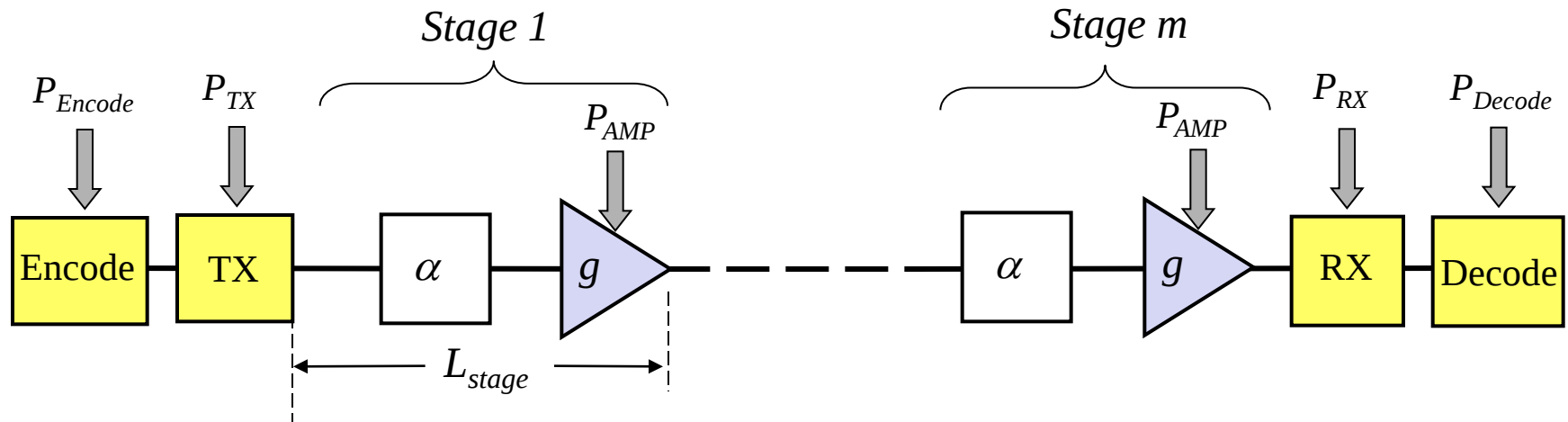


Summary

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Lower Limit on Optical Transport Energy



Total Amplifier
Energy per Bit

$$E_{AMP} = \sum \frac{P_{AMP}}{B_r} \left[\frac{SNR_{bit} m^2 e^{\alpha L_{stage}} h \nu}{\eta_{AMP}} \right]$$

Amplifier
Efficiency

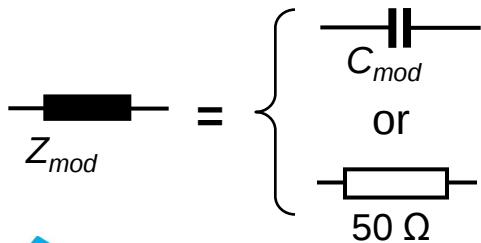
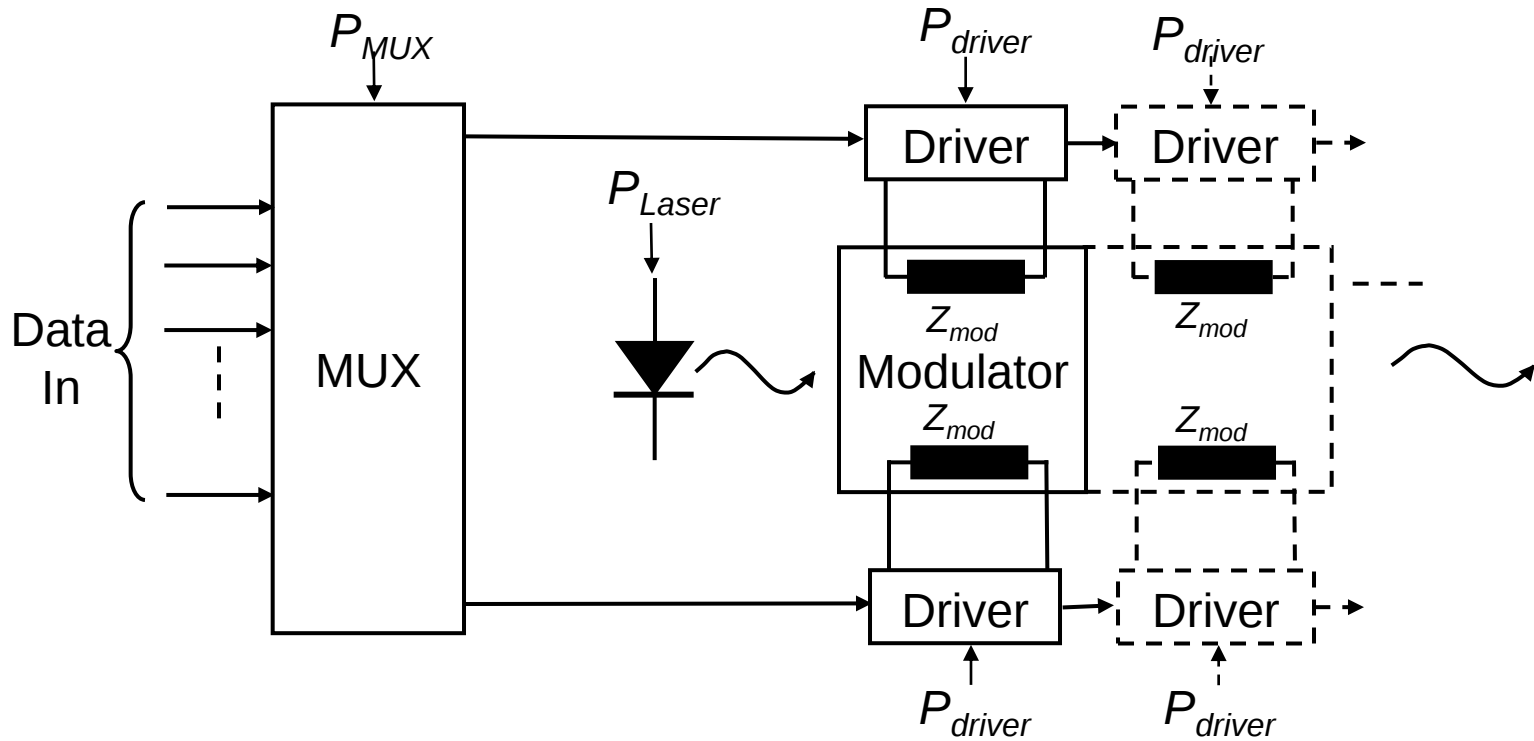
Total TX/RX
Energy per Bit

$$E_{TX/RX} = \frac{P_{Encode} + P_{TX} + P_{RX} + P_{Decode}}{B_r}$$

← Dominates

Bit Rate

Optical Transmitter



Lumped modulator

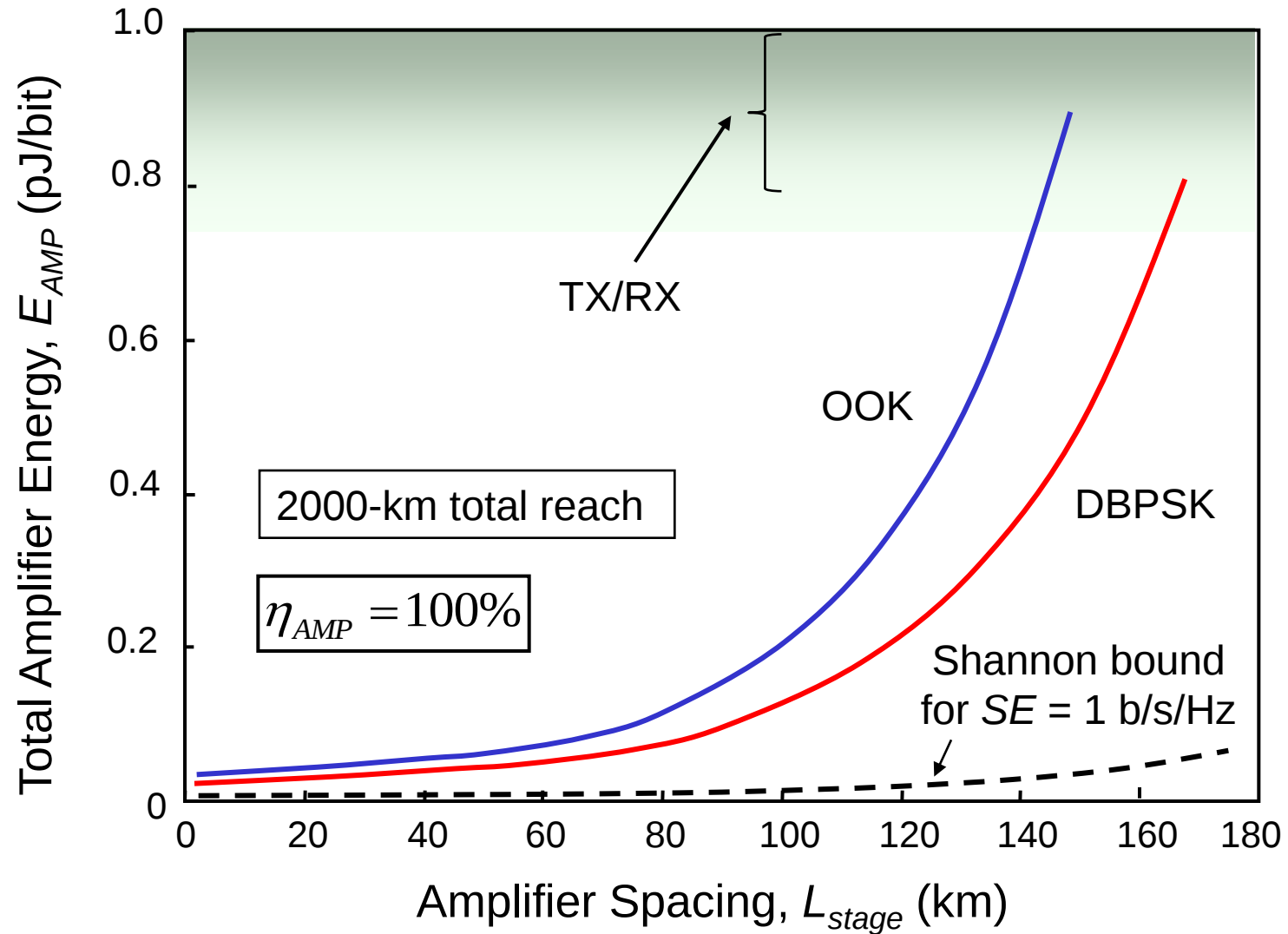
Distributed modulator

$$E = \frac{1}{2} C_{mod} V_{mod}^2$$

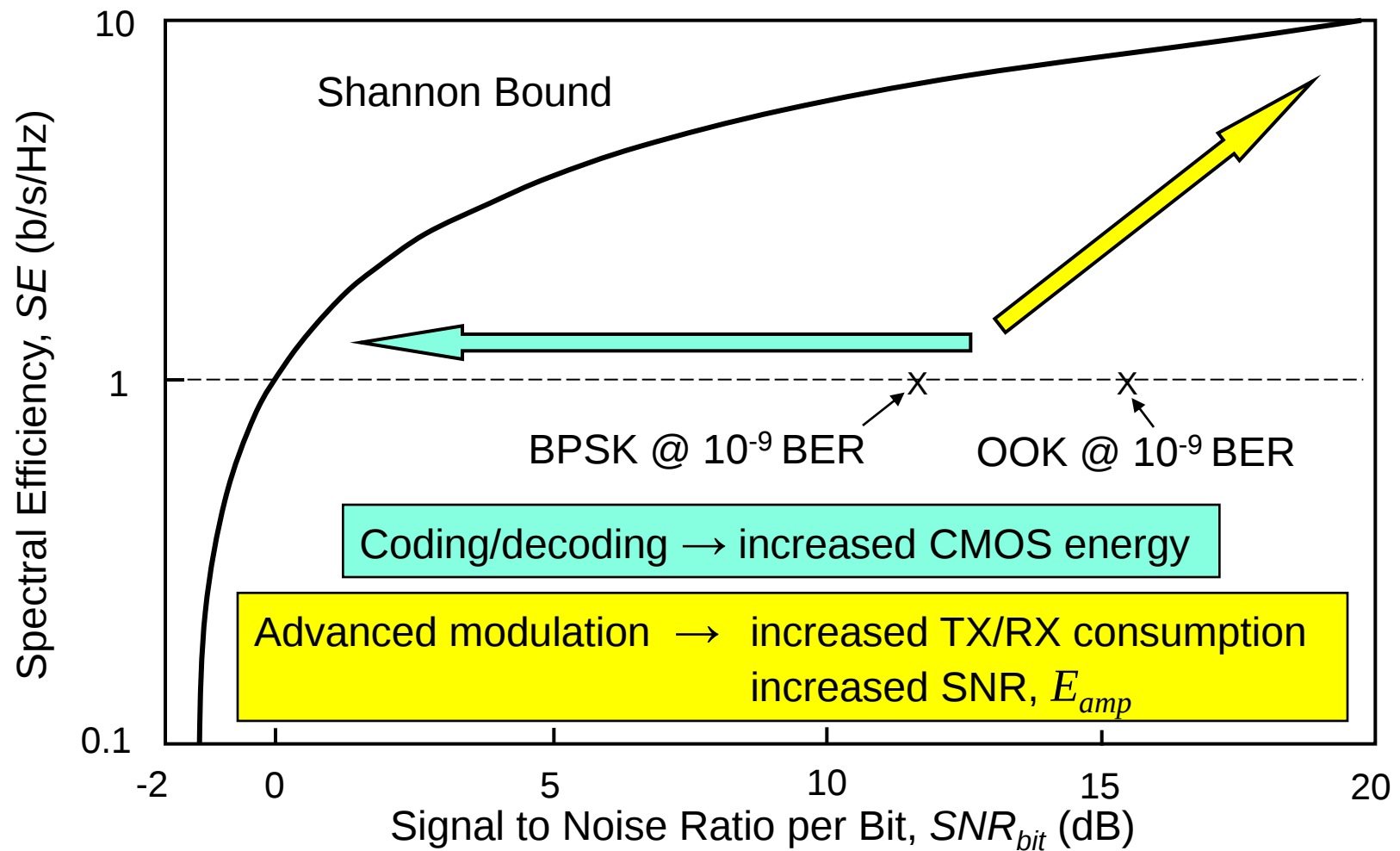
$$E = \frac{V_{mod}^2}{50 B_r}$$

~ 1 pJ

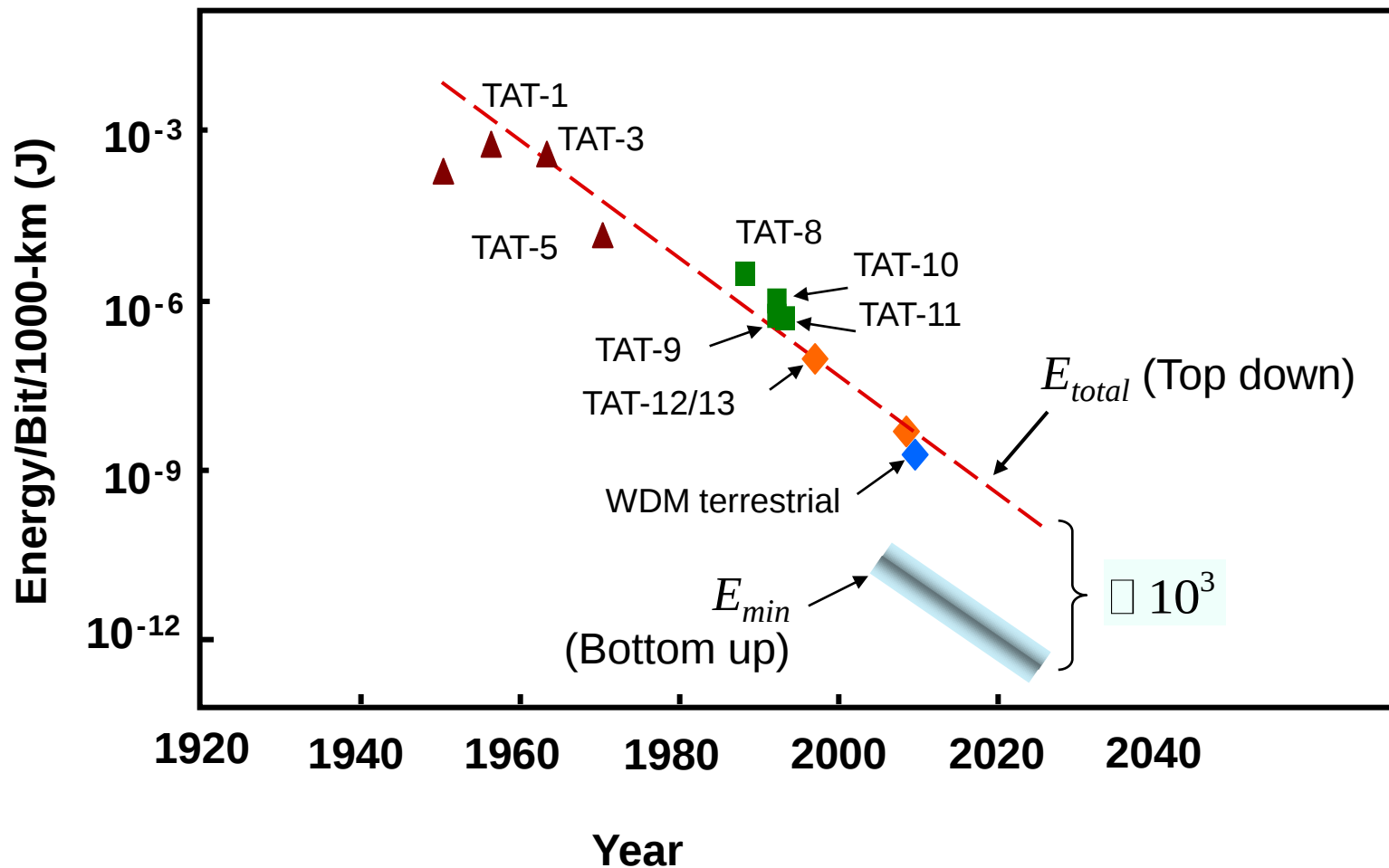
Lower Limit on Transport Energy per Bit



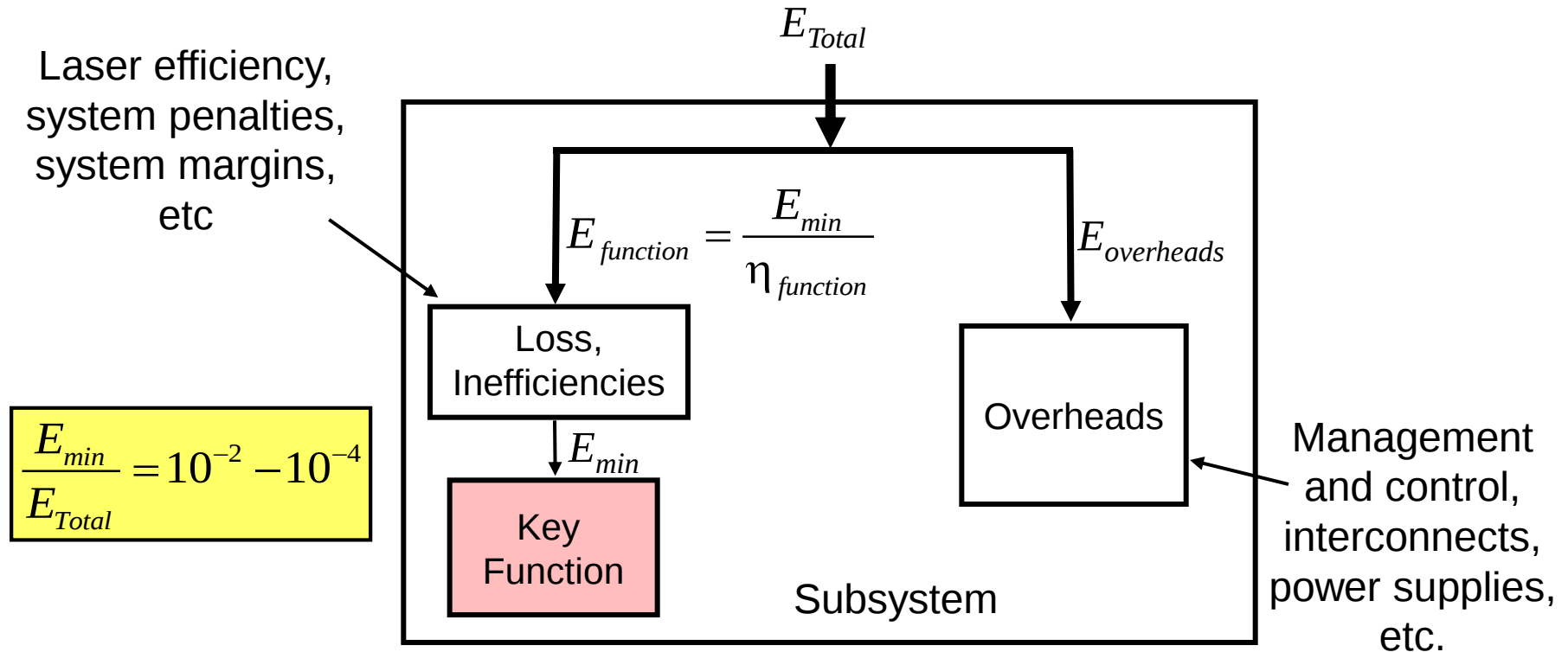
Shannon Bound



Energy per Bit per 1000-km



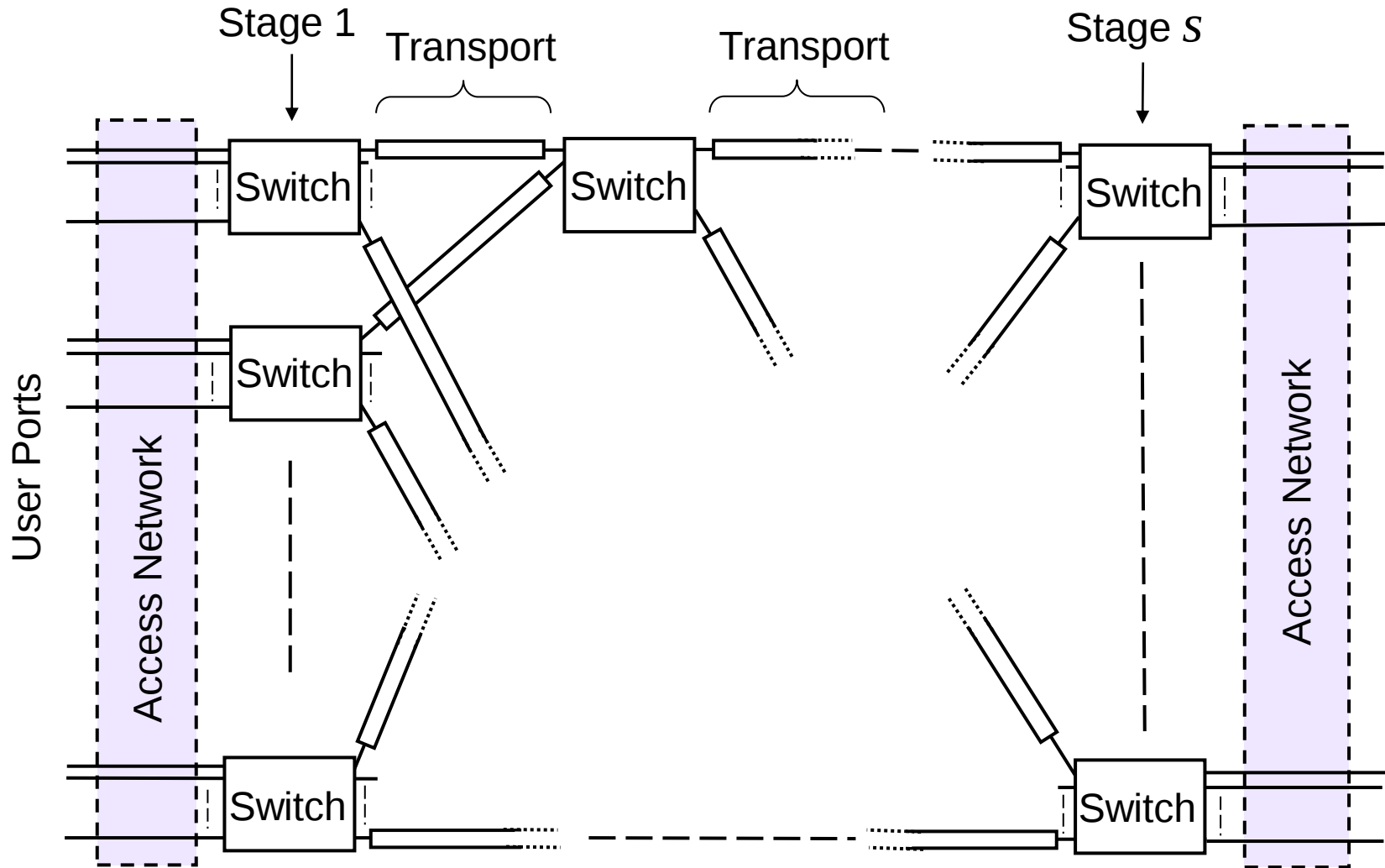
Loss/Efficiencies and Energy Overheads



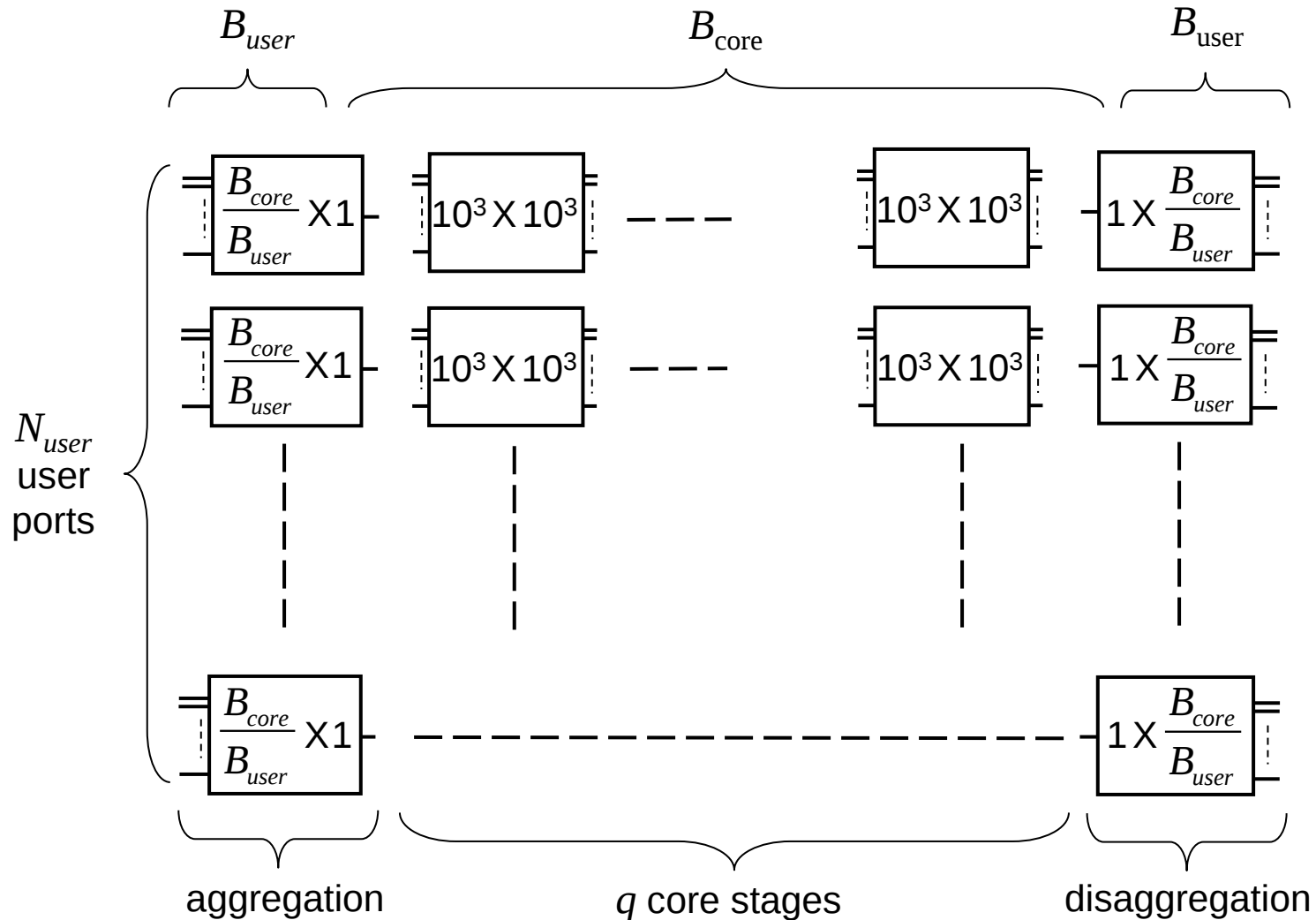
Key Conclusion:

Minimizing E_{min} is not necessarily the best strategy for minimizing E_{Total}

Network Energy



Switching Energy

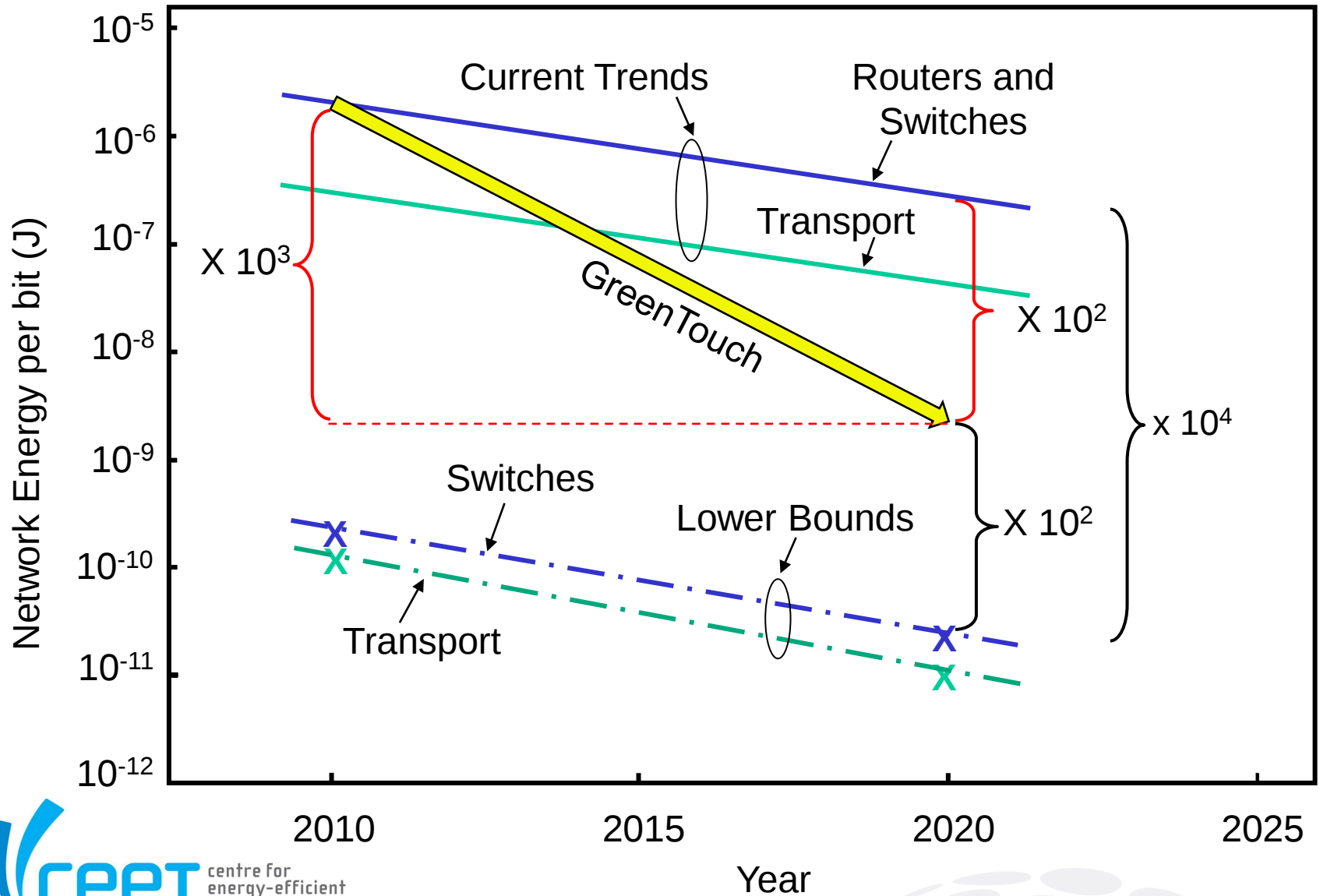


Switch Energies per Bit

Technology			Energy per Bit			
			2010-era technology		Target	
			2 x 2 Switch	10 ³ x 10 ³ Switch	2 x 2 Switch	10 ³ x 10 ³ Switch
O/O/O	E-O	Lumped	20 fJ	-	20 fJ	-
		TW	1.8 pJ	-	1 pJ	20 pJ
	SOA Gate Array		8 pJ	-	4 pJ	75 pJ
O/E/O	Wavelength-routed		-	-	-	10 pJ
	CMOS		200 fJ	4 pJ	20 fJ	400 fJ
			(+ 70 pJ)	(+70 pJ)	(+ 6 pJ)	(+ 6 pJ)

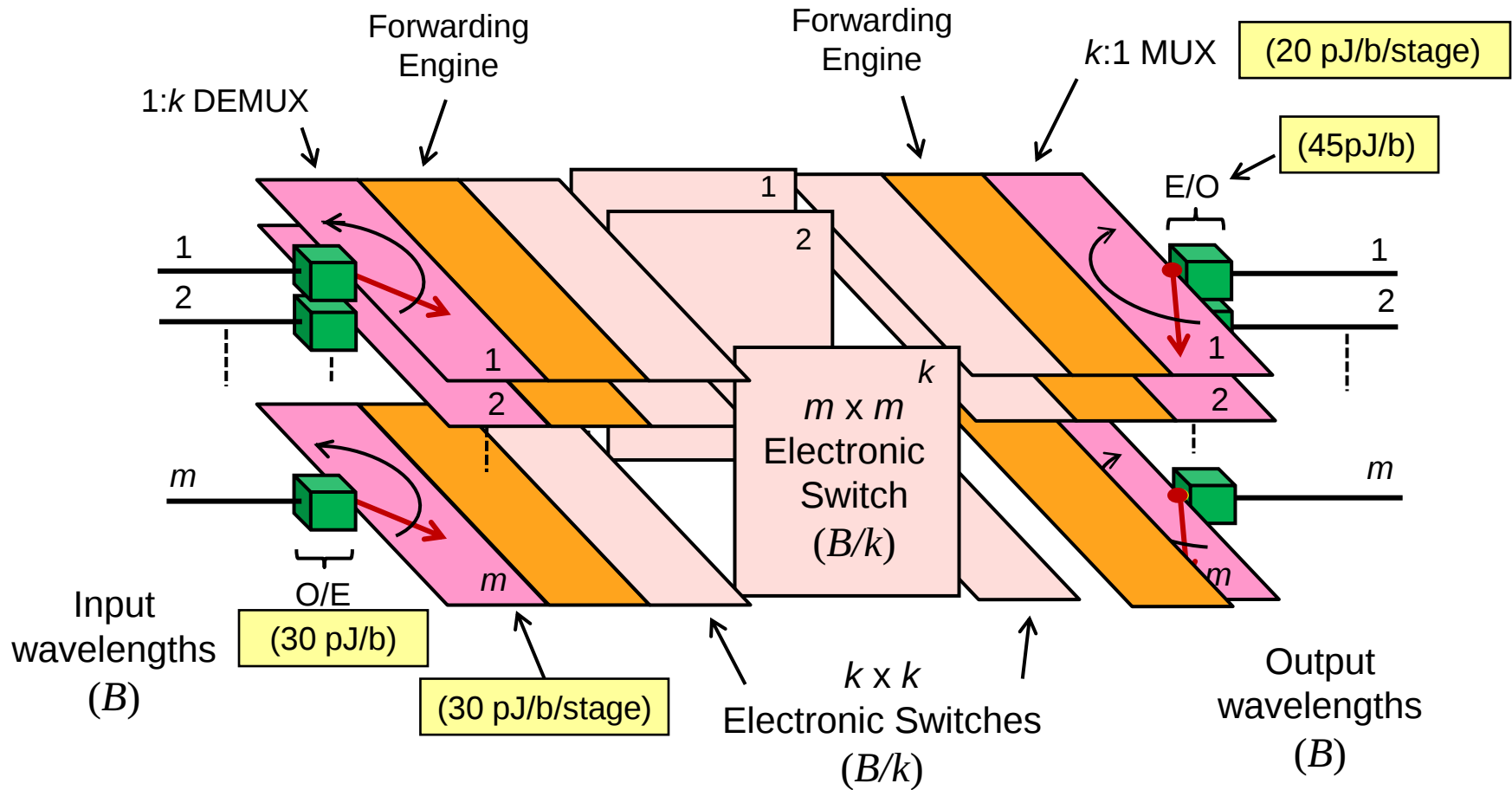
O/E Converters
MUX/DEMUX

Energy Improvements

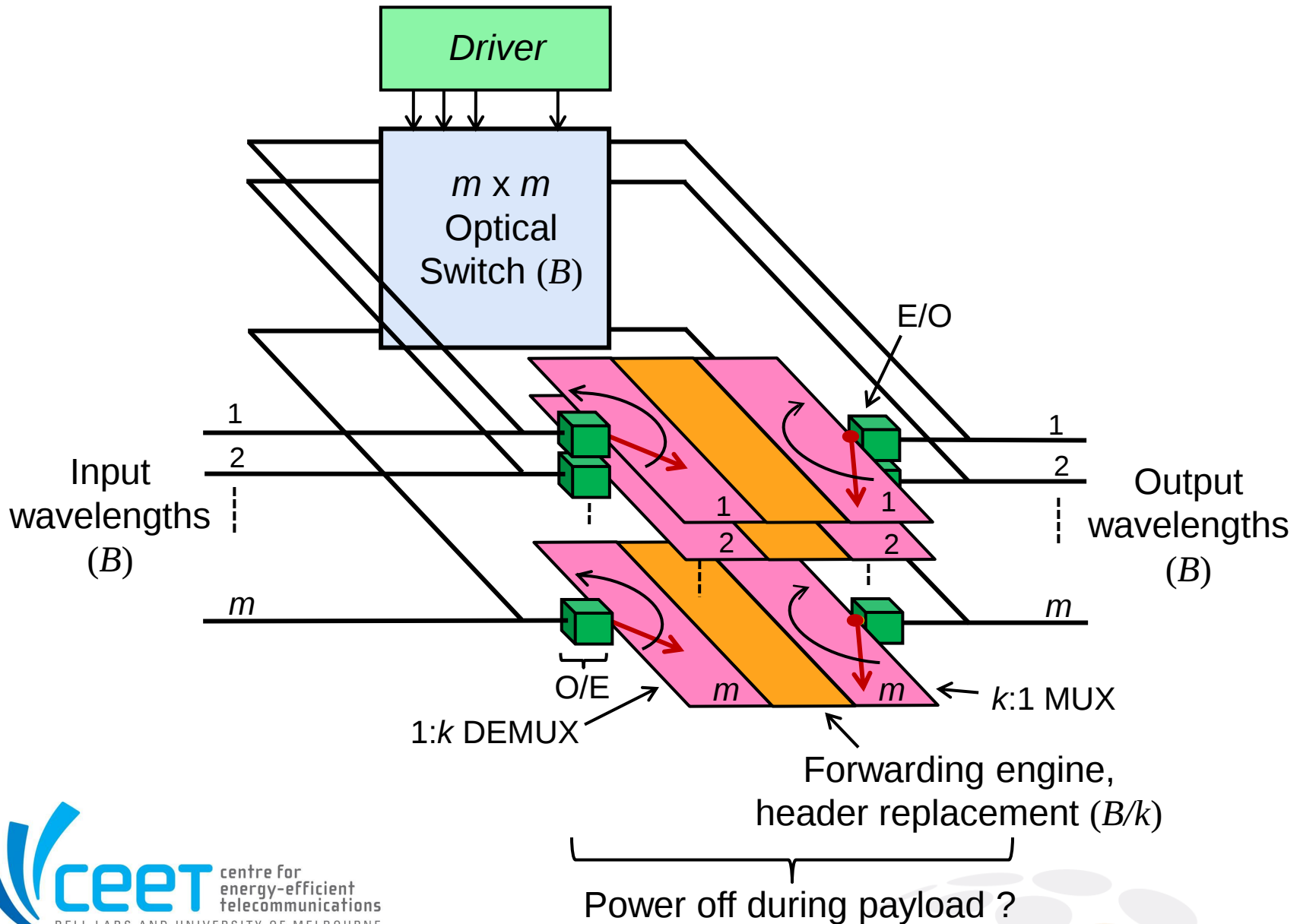


Packet Switching

Electronic Packet Switch - No buffers

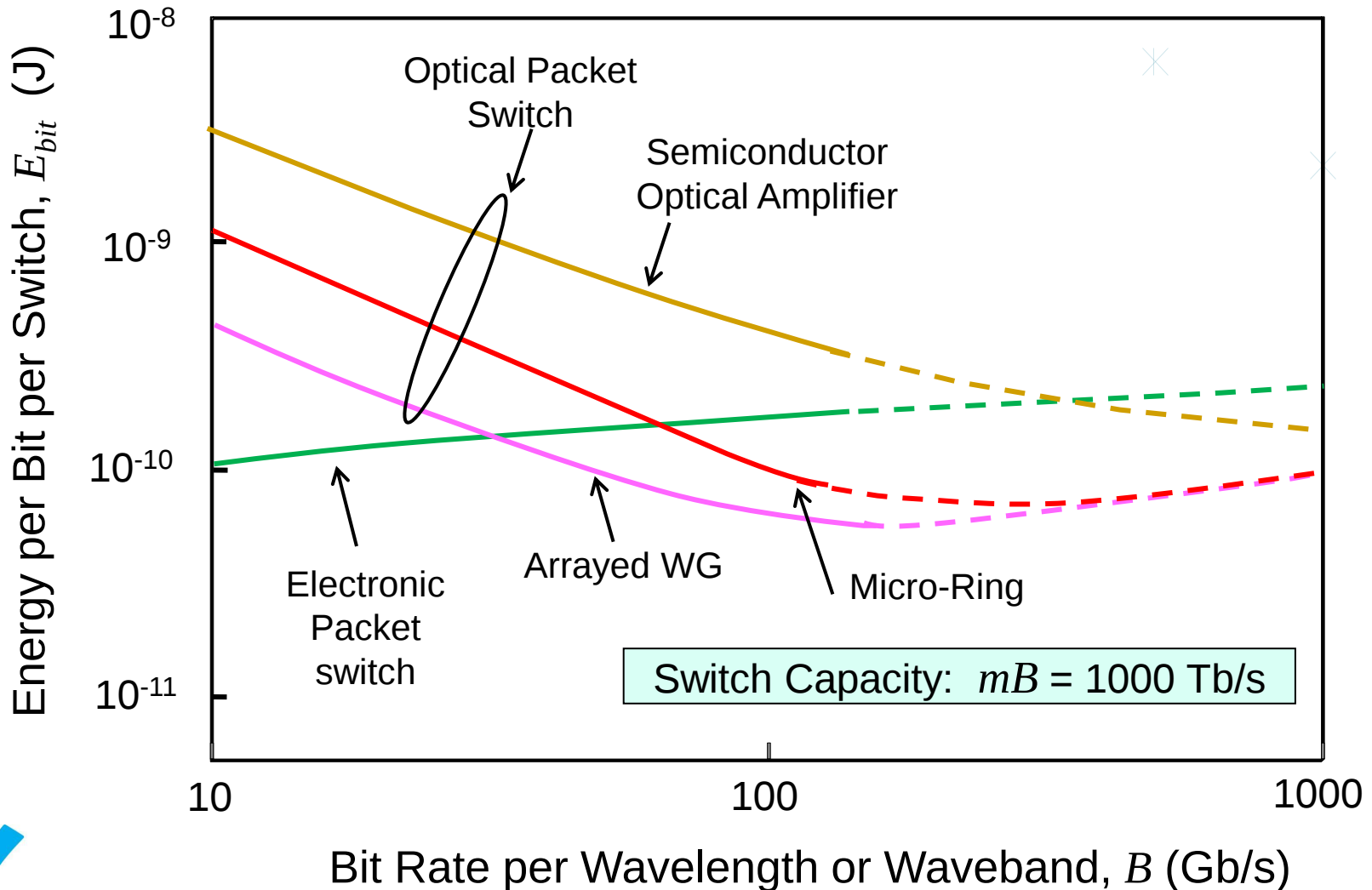


Optical Packet Switch



Lower Bound on Energy in Packet Switching

Excludes Forwarding Engine



Conclusions

- Top-down and bottom-up estimates of energy differ by $\sim 10^4$
- Theoretical limits on optical transmission are well defined
- Not so for networks
- Optical packet switching offers no clear advantage over electronic packet switching

