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System boundary harmonization reveals conditional energy crossover in chip interconnects

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Abstract

Energy-per-bit comparisons between electrical and optical interconnects often mix incompatible accounting boundaries, making apparently precise crossover claims difficult to interpret. We harmonized published measurements and estimates across device, front-end, transceiver, full-link and system boundaries and examined physical reach and channel loss as candidate crossover coordinates. Package-scale electrical data did not support a transferable distance-only threshold. Within a restricted set of approximately 112-Gb/s electrical transceivers, a descriptive channel-loss relation provided an evidence-supported local coordinate: a measured 2.8-pJ/bit complete optical link crossed near 26 dB, whereas a 4.9-pJ/bit optical-I/O chiplet crossed near 41 dB. Source-removal analysis showed that these crossings remain boundary dependent. The results indicate that component-level efficiency gains translate into system advantage only when source, coupling, thermal, control and electrical-interface overheads are jointly accounted for, framing selective optoelectronic integration as a multidimensional crossover-design problem.

The energy cost of moving data is becoming a central constraint in high-performance computing and artificial-intelligence hardware. Increasing lane rates, package bandwidth density and aggregate switch capacity expose resistive loss, capacitive loading, frequency-

dependent attenuation and equalization costs in electrical links, while optical interconnects offer low propagation loss and wavelength parallelism. Recent roadmaps therefore place silicon photonics and co-packaged optics alongside advanced electrical die-to-die links rather than treating either technology as universally dominant (refs. 1-4). The practical design question is not simply whether optics is lower energy, but under which rate, reach, channel-loss, integration and thermal conditions the energy ordering changes.

That question is difficult to answer from the literature because the reported quantity 'energy per bit' does not have a single physical boundary. A modulator switching energy may describe only $CV^2/4$ in an electro-optic device; a transmitter value can include its driver but omit the laser; a transceiver value may include transmitter and receiver electronics but exclude wavelength stabilization; and a system value can additionally include host SerDes, power conversion and cooling. Values that differ by two or three orders of magnitude can therefore all be correct while describing different portions of the energy path. Recent device and integration studies explicitly acknowledge this boundary problem (refs. 1,2,5-15).

A second difficulty is that physical distance is not a sufficient coordinate for comparing contemporary electrical links. Advanced packaging, process scaling, signalling format, interconnect impedance, equalizer architecture and BER target can change energy efficiency enough that a longer package link can consume less energy per bit than a shorter link implemented in another technology. Channel insertion loss is closer to the burden that the electrical transmitter and receiver must overcome, although it too remains frequency- and implementation-dependent.

Here we perform a boundary-harmonized comparative analysis of published electrical and optical interconnect data. We separate device, front-end, transceiver, full-link and system

values; examine measured electrical energy over package-scale reach; construct a local channel-loss reference from approximately 112-Gb s⁻¹ electrical transceivers; and compare this reference with optical values whose boundaries are explicit enough to support crossover calculations. The analysis does not seek a universal crossover distance. Instead, it asks which conclusions survive when system boundary is made an explicit variable and when extrapolative crossings are rejected.

A common system boundary for heterogeneous interconnect metrics

The first result is that energy ranking depends strongly on where the accounting boundary is drawn (Fig. 1). At the device level, recent silicon modulators report intrinsic switching energies of 5.9 fJ bit⁻¹ and below 10 fJ bit⁻¹ at data rates above 100 Gb s⁻¹ (refs. 6,7). These values characterize the modulator itself and should not be interpreted as optical-link energy. Zhong et al., for example, explicitly note that intrinsic modulator power represents only a fraction of total system power (ref. 6).

Moving one boundary outward already changes the scale. A 14-nm FinFET-silicon-photonics platform reported 154 fJ bit⁻¹ for a 40-Gb s⁻¹ transmitter front end and 75 fJ bit⁻¹ for a receiver front end (ref. 8). A 25-Gb s⁻¹ 3D-integrated receiver reported 170 fJ bit⁻¹ (ref. 9). Daudlin et al. reported 50 fJ bit⁻¹ and 70 fJ bit⁻¹ for transmitter and receiver front ends, respectively, in a dense 3D-integrated photonic platform, corresponding to 120 fJ bit⁻¹ when those two front-end contributions are simply summed (ref. 5). The same study separately discusses laser and thermal-control contributions, illustrating why the 120-fJ bit⁻¹ quantity is not a complete link total.

At broader boundaries the numerical scale enters the picojoule-per-bit regime. Chang et al. reported 496 fJ bit⁻¹ for paired transmitter and receiver electronics and system-level link estimates of 1.282 pJ bit⁻¹ and 1.686 pJ bit⁻¹ under different wavelength-control

assumptions (ref. 10). Balamurugan et al. measured a complete 56-Gb s⁻¹ optical link, including a fiber-attached 3D silicon-photonics transceiver and external light engine, at 2.8 pJ bit⁻¹ (ref. 11). The TeraPHY optical-I/O chiplet reported 4.9 pJ bit⁻¹ for transmitter plus receiver operation at up to 25 Gb s⁻¹ (ref. 12), and a subsequent WDM chiplet demonstration reported 4.96-5.56 pJ bit⁻¹ for the optical Tx+Rx chiplets (ref. 13). An integrated 112-GBd CMOS-silicon-photonics transmitter further illustrates that even a sub-pJ transmitter boundary is not automatically a full-link boundary (ref. 14).

Figure 2 places these values on a logarithmic energy axis while preserving the reported boundary. The apparent contradiction between femtojoule device values and picojoule link values disappears once the boundary is retained. This is the central normalization rule of the analysis: a device-only optical value is contextual evidence for technology potential, but it is not used as a primary crossover comparator against a full electrical transceiver.

Physical reach alone does not define the crossover

The same boundary discipline reveals why a universal distance threshold is not supported by present electrical data. Five measured package-scale electrical links provide clean pairs of physical reach and energy efficiency (Fig. 3). A 3-nm UCle advanced-package link operates at 0.29 pJ bit⁻¹ over an approximately 1.4-mm 2.5D CoWoS interposer, while a separate 3-nm UCle implementation reports 0.60 pJ bit⁻¹ over a 1.7-mm silicon bridge (refs. 16,17). A 28-nm simultaneous bidirectional link reports 1.21 pJ bit⁻¹ over a 3-mm channel (ref. 18). At longer package reach, a 7-nm PAM4 in-package transceiver reports 1.24 pJ bit⁻¹ at 112 Gb s⁻¹ over 20 mm (ref. 19), whereas the standard-package version of the 3-nm UCle link reaches 25 mm at 0.52 pJ bit⁻¹ (ref. 16).

If distance alone controlled energy, these five points would be expected to form a roughly increasing function $E(L)$. They do not. In particular, the 25-mm result is more energy-

efficient than several shorter links. This is not evidence that distance is irrelevant; longer channels generally increase loss and signal-integrity burden within a fixed technology. It shows instead that cross-study process node, package technology, signalling, clocking and equalization differences are large enough to dominate a one-dimensional distance trend.

Consequently, we do not fit a universal electrical energy-versus-distance law to these package data. The appropriate interpretation is conditional: physical reach is a necessary engineering variable but an insufficient common coordinate across heterogeneous implementations. This result also prevents an attractive but unsupported headline such as 'optics becomes lower energy beyond X millimetres'. A defensible crossover needs a coordinate more closely tied to the compensation burden experienced by the electrical link.

Channel loss exposes a conditional crossover regime

We therefore examined channel loss in a narrower class of high-speed electrical transceivers. Seven published operating points at approximately 112 Gb s⁻¹ were retained because their energy values represent complete or approximately complete Tx+Rx power, including analog and digital circuitry where reported, and because a channel-loss value was available (refs. 20-26). The dataset spans 20.8-48 dB and 2.29-6.51 pJ bit⁻¹. Values for which a substantial DSP contribution was explicitly excluded were kept as lower-bound sensitivity evidence rather than primary calibration points (ref. 27).

Across these seven heterogeneous points, an ordinary least-squares line gives a descriptive local relation

$$E_{elec}(A) = -0.991 + 0.144 A,$$

where E_{elec} is in pJ bit⁻¹ and A is the source-reported channel loss in dB. The coefficient of determination is $R^2 = 0.578$. We do not interpret this regression as a universal physical

law or as an inferential population model: the sample is small, process nodes and equalizer architectures differ, loss is reported under source-specific test conditions, and the measurements are not exchangeable replicates. The line is used only as a local reference over the observed 20.8-48-dB domain. A Theil-Sen sensitivity fit gives a similar point slope of 0.153 pJ bit⁻¹ dB⁻¹ but a broad slope interval, reinforcing the decision to treat the trend descriptively rather than causally.

The loss coordinate nevertheless reveals a useful conditional regime (Fig. 4). Equating the descriptive electrical line to the measured 2.8-pJ bit⁻¹ complete optical-link result of Balamurugan et al. gives a reference crossing at 26.3 dB. Leave-one-source-out refits move this value from 22.6 to 31.2 dB. Equating the line to the 4.9-pJ bit⁻¹ TeraPHY Tx+Rx chiplet metric gives a crossing at 40.9 dB, with a leave-one-source-out range of 39.0-42.9 dB. These values should be read as boundary-specific reference crossings, not universal thresholds.

The distinction between interpolation and extrapolation is important. The 1.282-pJ bit⁻¹ and 1.686-pJ bit⁻¹ system-level estimates from Chang et al. intersect the descriptive line at 15.8 dB and 18.6 dB, respectively. Both are below the minimum 20.8-dB electrical calibration point. We therefore retain these crossings only as directional evidence that reducing the complete optical-link boundary can move the crossover into a lower-loss regime; we do not report them as validated quantitative thresholds.

Optical overhead shifts the crossover boundary

Figure 5 summarizes the central sensitivity result. Changing the optical accounting boundary or overhead assumption moves the apparent electrical channel-loss crossover by more than 20 dB. The spread is much larger than the numerical precision with which

any individual source reports fJ bit-1 or pJ bit-1. Thus, system-boundary uncertainty can dominate arithmetic uncertainty.

This observation changes how device advances should be interpreted. A modulator improvement from 10 fJ bit-1 to 5 fJ bit-1 is technologically important, but if a deployed optical link remains dominated by laser electrical power, receiver electronics, thermal stabilization, wavelength locking or host-side SerDes, the system-level crossover moves much less than the device number alone suggests. Conversely, improvements in wall-plug laser efficiency, coupling loss, athermal resonator design, receiver sensitivity, co-integration and removal of electrical retiming can shift the crossover even when the intrinsic modulator energy is unchanged (refs. 1,2,5,15).

The same principle applies to electrical links. A channel-loss increase does not map to a fixed energy penalty independent of architecture; equalizer topology, ADC resolution, DSP activity, FFE/DFE depth, signalling format and process technology all matter. The practical crossover is therefore a surface rather than a scalar. A useful conceptual notation is $C = C(A, B, S, \Theta)$, where A is electrical channel loss, B is data rate, S denotes the system boundary and Θ collects architecture-dependent overheads such as laser, thermal, control and equalization power. The present dataset resolves only a limited slice of this higher-dimensional surface, but it is sufficient to reject a single universal distance threshold.

Implications for selective optoelectronic integration

The boundary-harmonized view suggests a selective rather than replacement-based architecture strategy. Modern package-scale electrical links can remain exceptionally efficient for short and moderate reaches, as shown by sub-pJ bit-1 UCle-class demonstrations extending to 25 mm (refs. 16,17). Optical links become increasingly

attractive where electrical attenuation and equalization burden rise, where wavelength multiplexing relaxes chip-edge bandwidth density, or where architectural changes remove energy-intensive host-side electrical stages. These advantages must be assessed against optical source, coupling, control and thermal overheads rather than against device-only numbers.

At the system level this interpretation is consistent with contemporary co-packaged-optics analyses. Evans, for example, reports that estimated CPO advantages over linear and DSP-based pluggable solutions depend strongly on which host SerDes and switch-level terms are included (ref. 28). Recent reviews similarly organize CPO performance across electrical subsystems, electro-optic and opto-electronic conversion, optical networks, thermal management and packaging (refs. 1,2). Our analysis adds a quantitative methodological point: the crossover itself is not an intrinsic constant of 'copper versus optics'. It is an outcome of the boundary and operating condition selected for comparison. This framing also identifies the most informative next measurements. Rather than reporting progressively smaller component fJ bit⁻¹ values in isolation, cross-technology comparison would benefit from paired reporting of physical reach, frequency-referenced channel loss, gross and delivered data rate, BER/FEC condition, laser-wall-plug assumptions, thermal and tuning power, and explicit inclusion of driver, receiver, clocking and DSP blocks. Such reporting would permit hierarchical or mechanism-grounded models to estimate a true multidimensional crossover surface with substantially less ambiguity.

Evidence landscape and crossover levers

A broader evidence base reinforces why the crossover should be treated as a system-design quantity rather than as a contest between isolated device efficiencies. Recent roadmaps for silicon photonics and co-packaged optics emphasize the same convergence

of bandwidth density, energy, packaging and manufacturability constraints, while also showing that the relevant accounting boundary moves outward as photonics approaches deployment (refs. 29-31). This convergence is important for interpretation: a lower modulator or detector energy can expand the optical-favourable region only if the improvement survives integration into a source-to-receiver path and does not reappear as electrical, thermal or packaging overhead elsewhere in the link.

The optical source and package are therefore first-order crossover levers. Comparisons of external and integrated light sources show that source placement changes electrical power delivery, thermal coupling, serviceability and optical-loss budgets (ref. 32). Wafer-scale and heterogeneous laser-integration approaches, including 300-mm laser attach, photonic wire bonding and micro-transfer printing, provide distinct routes for reducing coupling and assembly penalties (refs. 33-38). Broader III-V-on-silicon integration studies and heterogeneous photonic-circuit demonstrations illustrate how those choices interact with yield and electronic-photonic co-design (refs. 39,40). At larger scale, thermal coupling among laser arrays can itself become a design constraint (ref. 41). Consequently, source innovation should be evaluated through the reduction it produces in full-link energy, not only through optical output power or device efficiency.

Wavelength generation and active-device efficiency provide a second set of levers.

Integrated frequency-comb platforms can distribute a source across many wavelength channels, potentially amortizing source overhead, while high-coherence integrated lasers address a different part of the source-stability problem (refs. 42,43). At the modulation boundary, attojoule-class plasmonic IQ modulators demonstrate how far intrinsic switching energy can be reduced (ref. 44). High-bandwidth silicon modulators and electronic drive circuitry similarly show that the active electro-optic boundary continues to improve (refs.

45-47). On the receive side, very-high-bandwidth germanium and III-V photodetectors expand the feasible data-rate envelope without, by themselves, specifying the complete receiver energy (refs. 48,49). These advances are therefore best interpreted as shifts in individual terms of the system energy budget.

Passive photonics and manufacturing determine whether those component gains survive at scale. Subwavelength waveguides, couplers and grating structures can reduce footprint, polarization sensitivity and interface loss (refs. 50-52). Open-access foundry platforms increase reproducibility and cross-design comparability, while multiplexing architectures increase aggregate bandwidth per optical interface (refs. 53,54). Recent silicon-photonics syntheses and short-reach optical-I/O reviews place these device advances in a system context (refs. 55,56), and newer monolithic and heterogeneous transceiver demonstrations move the comparison boundary toward the complete communication function (refs. 57,58). Heterogeneous-integration and 3D-co-packaging studies further identify thermal paths, die placement and package assembly as variables that can either preserve or erase component-level energy gains (refs. 59,60). Together, these studies support treating crossover motion as the combined response of several coupled energy terms rather than as the consequence of a single record device metric.

Technology levers that move the crossover surface

The same framework allows individual technology programmes to be interpreted by the direction in which they are expected to move the crossover surface. For light generation, hybrid and heterogeneous III-V/silicon sources span precise flip-chip attachment, CMOS-compatible laser integration and directly modulated heterogeneous lasers (refs. 61-63). Fully integrated optical-network demonstrations show how source and circuit choices interact at architecture scale (ref. 64), while quantum-dot approaches pursue reduced

defect sensitivity and improved temperature robustness on silicon (refs. 65-71). These routes are not equivalent in the energy model: they change wall-plug efficiency, coupling loss, thermal-control power, wavelength-control requirements and manufacturability in different combinations. A useful roadmap metric is therefore not simply 'laser efficiency' but the change in complete-link energy after the source is integrated under a stated thermal and yield assumption.

Integration density and modulation speed provide another coupled lever. Terabit-class co-packaged photonic engines demonstrate the value of moving optical conversion closer to switching silicon (ref. 72), whereas high-symbol-rate microring and dual-drive modulators push the active device boundary toward higher lane rates (refs. 73,74). The passive network that connects these devices is equally consequential. Ultra-low-loss silicon-nitride and multimode waveguides can reduce transport penalties (refs. 75,76), while compact edge and grating couplers target fiber-chip interface loss and packaging tolerance (refs. 77-81). A component improvement that saves tens of femtojoules per bit can therefore be neutralized by a few decibels of additional coupling loss if the source power must be increased to maintain the same receiver operating point.

Receiver and wavelength-routing technologies likewise alter different terms of the crossover equation. High-bandwidth germanium photodiodes, light-trapping structures, silicon reflectors and gain-peaked receivers extend optical bandwidth and sensitivity (refs. 82-86). Microring filters and thermally tunable higher-order resonators enable dense wavelength routing but introduce control and tuning considerations (refs. 87-89). Arrayed-waveguide gratings and hybrid multiplexers provide alternative scaling routes for many-channel links (refs. 90-92). The system implication is that wavelength-density gains should

be assessed together with the static and dynamic control energy required to hold the multiplexed link inside its operating window.

Electrical technology is not a stationary baseline. Recent wireline and chiplet transceivers continue to reduce energy while tolerating substantial channel loss or high bandwidth density (refs. 93-98). This continuing improvement explains why a crossover inferred from a fixed generation of copper links should not be extrapolated indefinitely. Historical WDM silicon-photonics arrays already showed that transmitter and receiver component energies could enter the sub-pJ-per-bit regime while excluding some source and tuning costs (ref. 99), and monolithic processors communicating directly with light demonstrated the architectural possibility of eliminating conventional off-chip electrical interfaces (ref. 100). The competitive boundary therefore co-evolves: optical integration moves one side of the surface while electrical process, equalization and packaging advances move the other. The appropriate research target is the rate at which a technology changes the boundary-matched system energy under comparable throughput, reach, error-rate and thermal conditions.

Conclusions

System-boundary harmonization changes the interpretation of published interconnect energy values. Device-only optical measurements in the few-femtojoule-per-bit range and complete optical links in the picojoule-per-bit range are not competing estimates of the same quantity; they occupy different boundaries. Likewise, modern electrical package links do not follow a universal cross-study energy-versus-distance curve.

Within a restricted approximately 112-Gb s⁻¹ electrical dataset, channel loss provides a more informative local coordinate. A descriptive fit gives boundary-specific crossings near 26 dB for a measured 2.8-pJ bit⁻¹ complete optical link and near 41 dB for a 4.9-pJ bit⁻¹

Tx+Rx optical-I/O chiplet metric, with leave-one-source-out ranges that quantify source sensitivity. Lower optical-link estimates cross outside the observed electrical domain and therefore remain extrapolative.

These findings support a conditional design principle: electrical and optical interconnects should be selected through a common system boundary and an operating-condition-aware energy model, not through a universal distance rule or isolated device metric. Selective optoelectronic integration is consequently best viewed as a quantitative crossover-design problem.

Methods

Evidence discovery and eligibility

We performed a targeted comparative evidence synthesis rather than a formal systematic review. Literature discovery emphasized primary journal articles, publisher pages and official conference materials reporting energy efficiency for electrical or optical chip, package or data-centre interconnects. Searches were iteratively expanded from recent Nature-family and IEEE reviews to the underlying primary demonstrations. The evidence table was frozen for this draft on 11 October 2026. A source was eligible for quantitative use when its reported or derivable energy metric could be assigned to an explicit system boundary and accompanied by at least one operating descriptor such as data rate, physical reach or channel loss. Review and roadmap values were retained for context or external validation but were not treated as primary measured calibration points.

Evidence classes and system boundaries

Each value was classified as measured, derived from measured power, reported estimate, roadmap target or scenario-only. Boundaries were classified as device, front end,

transceiver, full link or system. Device includes an isolated modulator or photodetector; front end includes the local driver/modulator or photodiode/receiver electronics; transceiver includes Tx and Rx electronics; full link adds source and path-dependent terms when explicitly included; system can additionally include host SerDes, switch, power-delivery or cooling overhead. Primary crossover calculations used only values whose boundaries could be compared without knowingly substituting a device-only optical number for a full electrical transceiver number.

Unit normalization

Energy values were converted to pJ bit⁻¹. When a source reported total power P and data rate R rather than energy efficiency, energy per bit was calculated as $E = P/R$. With P in mW and R in Gb s⁻¹, the numerical result is directly in pJ bit⁻¹ because $1 \text{ mW} / 1 \text{ Gb s}^{-1} = 1 \text{ pJ bit}^{-1}$. Derived values were used only when the power and rate referred to the same operating point. Values described as 'less than' a limit were treated as bounds in contextual plots rather than exact calibration observations.

Physical-reach analysis

The package-reach plot used five measured electrical observations with explicit physical length and energy efficiency: 1.4 mm/0.29 pJ bit⁻¹ (UCIe advanced package), 1.7 mm/0.60 pJ bit⁻¹, 3 mm/1.21 pJ bit⁻¹, 20 mm/1.24 pJ bit⁻¹, and 25 mm/0.52 pJ bit⁻¹. Because these observations span process nodes, signalling schemes and package implementations, no universal distance regression was fitted. The plot is used to test whether a monotonic cross-study relation is supported by the observed evidence.

Electrical channel-loss analysis

The primary loss-energy subset contained seven approximately 112-Gb s⁻¹ electrical operating points with complete or approximately complete Tx+Rx power: 20.8 dB/2.29 pJ bit⁻¹, 35 dB/2.50 pJ bit⁻¹, 40 dB/4.48 pJ bit⁻¹, 41.5 dB/6.51 pJ bit⁻¹, 43.9 dB/6.16 pJ bit⁻¹, 45 dB/6.00 pJ bit⁻¹ and 48 dB/4.63 pJ bit⁻¹. A simple ordinary least-squares line $E = \beta_0 + \beta_1 A$ was used solely as a local descriptive reference. The fitted coefficients were $\beta_0 = -0.9906$ pJ bit⁻¹ and $\beta_1 = 0.14408$ pJ bit⁻¹ dB⁻¹, with $R^2 = 0.578$. A Theil-Sen slope estimate of 0.153 pJ bit⁻¹ dB⁻¹ was calculated as a robust sensitivity check. Inferential P values are not used to support the scientific claim because the observations are heterogeneous literature points rather than random independent samples from a common population.

Crossover calculation and source sensitivity

For an optical energy level E_{opt} , the descriptive crossing was calculated from $A^* = (E_{opt} - \beta_0)/\beta_1$. A crossing was considered quantitatively interpretable only when A^* lay inside the observed electrical domain of 20.8-48 dB. Source sensitivity was evaluated by repeating the electrical fit after leaving out one primary electrical source at a time and recalculating A^* . The minimum and maximum leave-one-source-out values are reported as a source-sensitivity range; they are not confidence intervals. Optical scenarios were 1.282 and 1.686 pJ bit⁻¹ from Chang et al., the measured 2.8-pJ bit⁻¹ complete link from Balamurugan et al., and the measured 4.9-pJ bit⁻¹ TeraPHY Tx+Rx chiplet metric.

Limitations

The primary electrical loss analysis contains only seven observations and mixes process nodes, circuit architectures, BER targets and test conditions. Channel loss is used as

reported by each source, generally near the relevant Nyquist frequency, and is not converted into physical distance. Optical boundary completeness also varies: in particular, a Tx+Rx chiplet metric may not include all laser, tuning and facility-level overheads. The fitted line is therefore neither a mechanistic law nor a predictive model outside the observed domain. Reporting and source-availability bias remain possible. The analysis supports conditional crossover reasoning and boundary harmonization; it does not establish universal superiority of optical or electrical interconnects.

Computational and language-model assistance

Calculations, leave-one-source-out refits and figures were generated in Python using NumPy, pandas, SciPy and Matplotlib. Large-language-model tools were used for literature-discovery assistance, code drafting, consistency checks and language editing. Numerical values retained in the primary analysis were checked against primary papers, publisher pages, official conference materials or source-linked comparison tables where accessible. Boundary classification, inclusion and exclusion decisions, calculations and scientific interpretation remain the responsibility of the authors. No language model is listed as an author.

Data availability

All numerical inputs in this draft were transcribed or derived from the published sources cited in the manuscript. The harmonized evidence tables used to generate Figs. 2-5 accompany the working draft as CSV files. A version-controlled archival deposit with source-location metadata should be created before submission.

Code availability

Python scripts used for normalization, regression, leave-one-source-out analysis and figure generation accompany the working draft. An archival repository and persistent identifier should be created before submission.

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Key contribution: architectural demonstration of a processor communicating directly through integrated photonics.

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Author contributions

Draft allocation: T.F. conceived the study, developed the methodology and analysis, curated the evidence, generated the visualizations and drafted the manuscript. H.F. contributed to validation and data curation. Final CRediT assignments should be confirmed by all authors before submission.

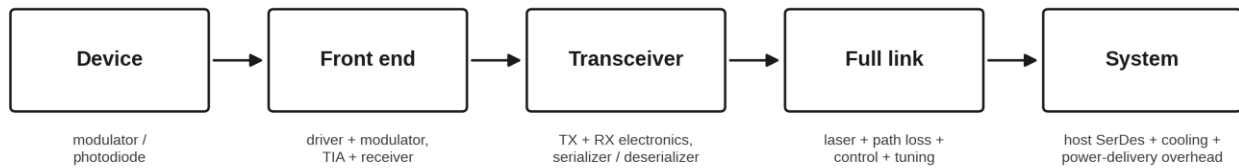
Competing interests

Competing-interests declaration to be confirmed before submission.

Table 1 | Representative evidence anchors used to define comparison boundaries

Domain	Source / operating point	Reported metric	Boundary	Role in analysis
Electrical reach	Melek et al. 2026 UCIe-AP	1.4 mm; 0.29 pJ bit-1	Advanced-package link	Reach-energy evidence
Electrical reach	Poon et al. 2022	20 mm; 1.24 pJ bit-1 at 112 Gb s-1	In-package Tx+Rx	Reach-energy evidence
Electrical reach	Melek et al. 2026 UCIe-SP	25 mm; 0.52 pJ bit-1	Standard-package link	Reach-energy evidence
Electrical loss	Ye et al. 2023	20.8 dB; 2.29 pJ bit-1	Full Tx+Rx	Primary loss fit
Electrical loss	Zhang et al. 2024	43.9 dB; 6.16 pJ bit-1	Full Tx+Rx	Primary loss fit
Electrical loss	Park et al. 2024	48 dB; 4.63 pJ bit-1	Full Tx+Rx, analog+digital	Primary loss fit
Optical	Chang et al. 2023	1.282 / 1.686 pJ bit-1	Full-link estimates	Directional crossing; extrapolative
Optical	Balamurugan et al. 2026	2.8 pJ bit-1	Measured complete optical link	Primary boundary-matched comparator
Optical	Sun et al. 2020 TeraPHY	4.9 pJ bit-1	Tx+Rx optical-I/O chiplet	Boundary-sensitive comparator

Energy metrics are comparable only after the system boundary is matched



Primary comparison: harmonized transceiver/full-link values; device-only values are contextual.

Figure 1 | System-boundary hierarchy for interconnect energy comparison. Reported energy metrics are comparable only after the accounting boundary is matched. Device-only values are retained as technology context, whereas the primary comparison emphasizes transceiver and full-link boundaries. EO, electro-optic; OE, opto-electronic; TIA, transimpedance amplifier; SerDes, serializer/deserializer.

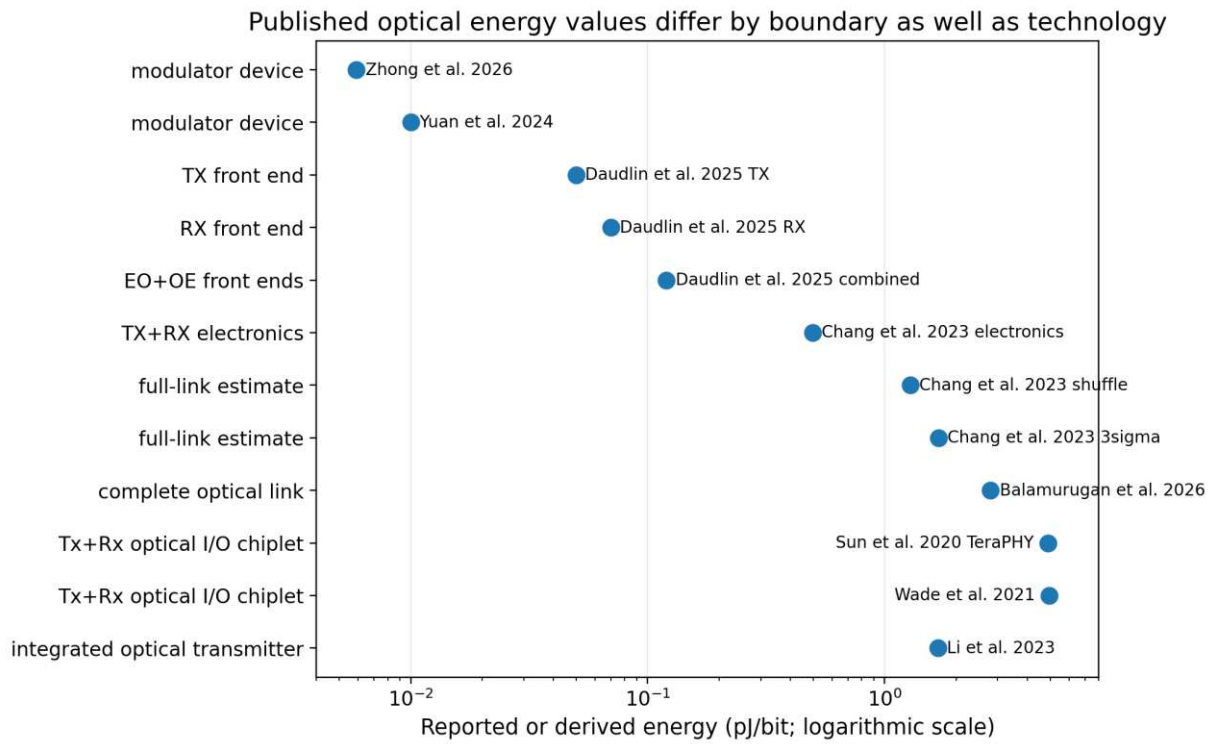


Figure 2 | Optical energy values span orders of magnitude because the system boundary changes. Representative optical values are shown on a logarithmic energy axis with their reported boundaries retained. Few-fJ bit-1 modulator values, front-end values and pJ bit-1 complete-link or chiplet values should not be interpreted as estimates of the same quantity.

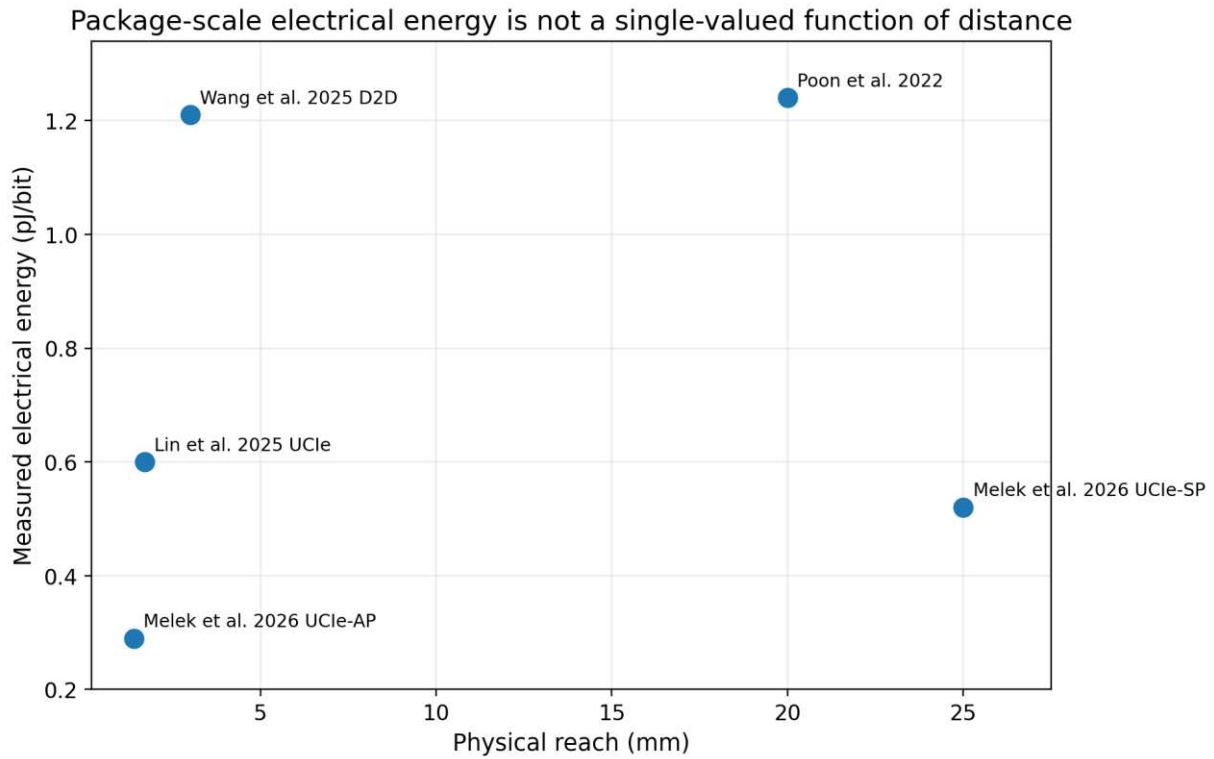


Figure 3 | Physical reach alone does not define electrical-link energy across heterogeneous implementations. Five measured package-scale electrical links show a non-monotonic cross-study relationship between physical reach and energy efficiency. Process node, packaging, signalling and equalization differ across studies; the panel is therefore descriptive and no distance-only regression is fitted.

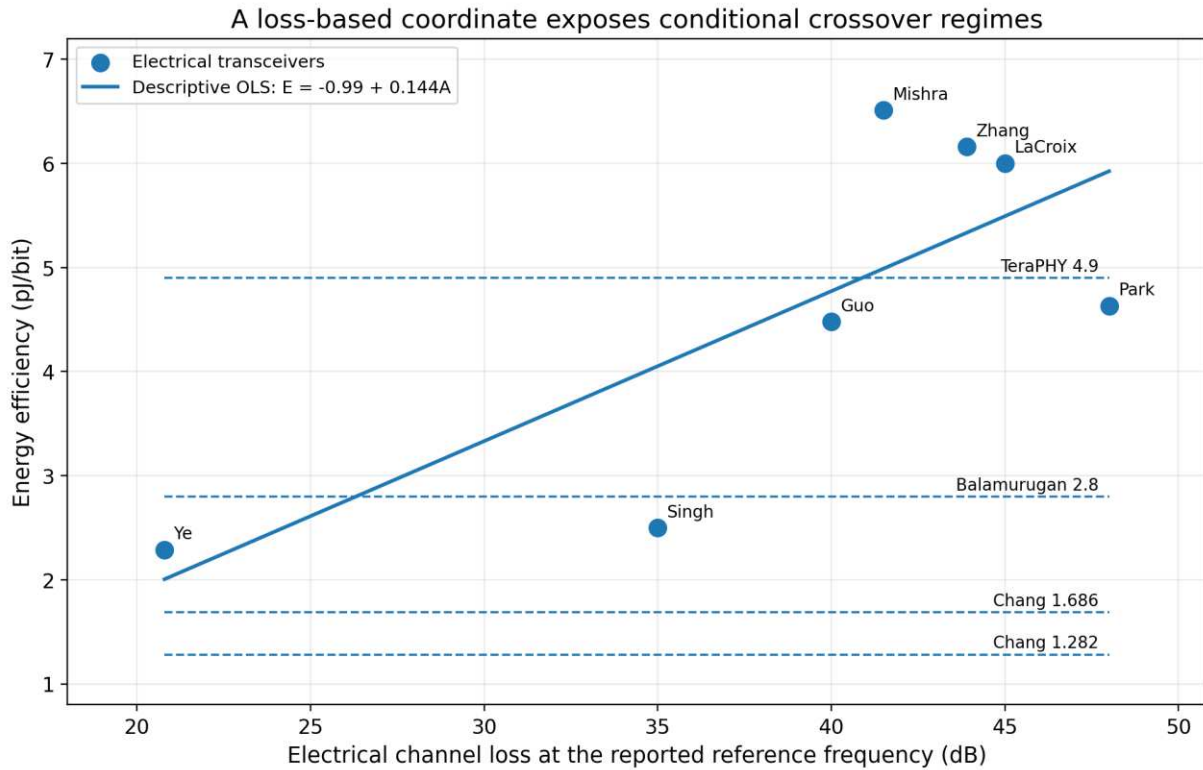


Figure 4 | A channel-loss coordinate exposes conditional crossover regimes in approximately 112-Gb s⁻¹ electrical links. Points show the seven primary electrical observations. The line is an ordinary least-squares descriptive local reference over the observed 20.8-48-dB domain, not a universal law. Horizontal lines show selected optical energy levels. Crossings outside the electrical domain are treated as extrapolative.

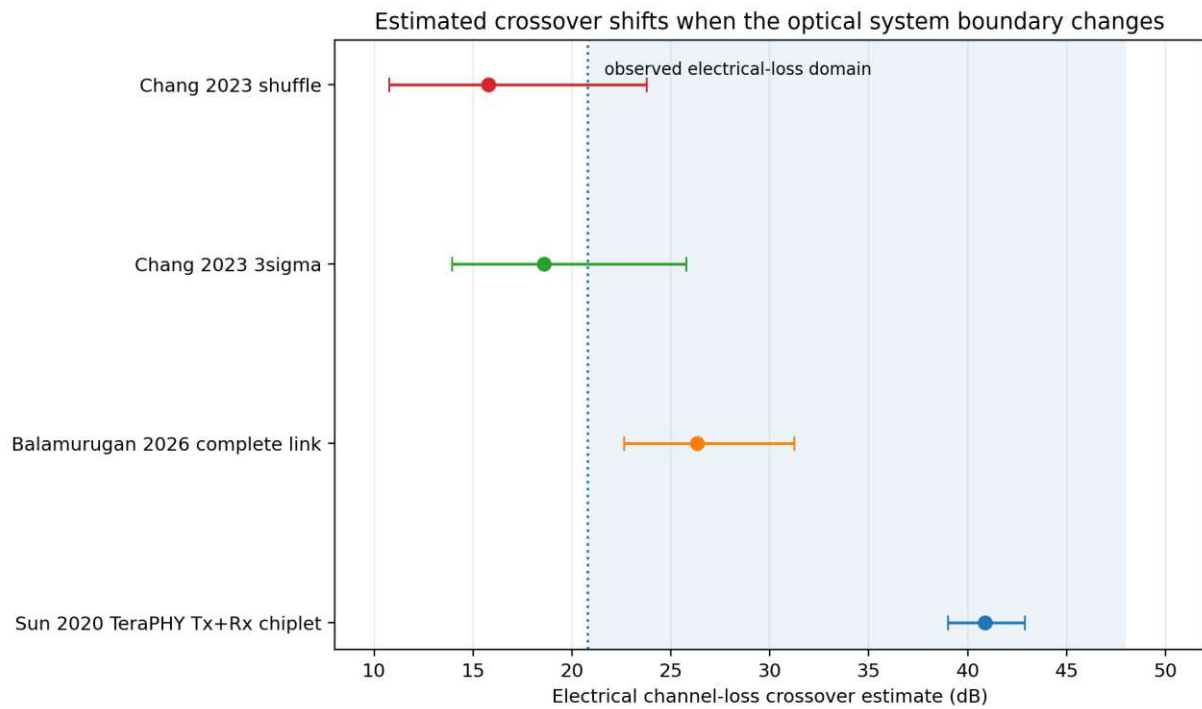


Figure 5 | Estimated crossover changes when the optical system boundary changes. Points are crossover locations from the full seven-point electrical descriptive fit; bars are minima and maxima from leave-one-source-out refits. The shaded region marks the observed 20.8-48-dB electrical-loss domain. Chang scenarios cross partly or wholly outside this domain and are therefore directional only; Balamurugan and TeraPHY comparisons are interpolative within the primary domain.