Evolution of Photonic Infrastructure in the IOWN Concept: Architecture, Experimental Results and Real-Time Applications

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EXTENDED ABSTRACT

Wide-area cyber-physical systems (CPS), distributed artificial intelligence, and digital twins require communication networks that provide deterministic latency, bounded jitter, long-term synchronization stability, and scalable energy efficiency. Conventional electronic packet-switched networks are inherently limited by buffering and contention, which introduce latency dispersion and cumulative jitter. This work evaluates how photonic networking under the Innovative Optical and Wireless Network (IOWN) concept modifies these constraints at the system level.

The results compare a conventional electronic packet-switched network with an All-Photonics Network (APN)-like architecture using a behavioral simulation model focused on application-visible performance. The analysis emphasizes latency distributions, temporal stability, and energy scaling rather than average throughput.

Latency determinism is illustrated in Fig. 1, which shows end-to-end latency probability distributions. The electronic network exhibits a wide distribution with a pronounced long tail, where rare queuing events cause the p99 latency to significantly exceed the mean. In contrast, the photonic network produces a sharply concentrated distribution near the propagation delay, with negligible dispersion. The p99 latency nearly coincides with the mean, indicating near-deterministic timing. This result demonstrates that photonic networking removes architectural sources of latency variability, leaving physical propagation as the dominant contributor.

Long-term temporal stability is shown in Fig. 2, which presents synchronization error over extended time horizons. In the electronic network, synchronization error grows unboundedly due to the accumulation of low-frequency jitter components, exhibiting random-walk-like drift. Such behavior limits scalability of tightly coordinated CPS and distributed AI workloads. In contrast, the photonic network maintains bounded synchronization error that fluctuates around zero, preserving clock coherence across geographically distributed nodes.

Fig. 2 also highlights energy scaling behavior. Electronic network energy per bit increases with distance due to repeated electronic processing at intermediate nodes, whereas photonic networking achieves near distance-independent energy consumption by preserving transmission in the optical domain. As a result, photonic transport simultaneously provides deterministic latency, synchronization stability, and scalable energy efficiency.

The combined results in Fig. 1 and Fig. 2 confirm that photonic networking under the IOWN concept represents a qualitative shift rather than an incremental improvement, enabling wide-area realtime operation limited primarily by physical propagation rather than architectural overhead.

The demonstrated elimination of latency tails and bounded synchronization drift directly supports wide-area realtime CPS, distributed AI inference, and digital twin platforms. These application-driven results confirm the practical relevance of IOWN beyond architectural exploration.

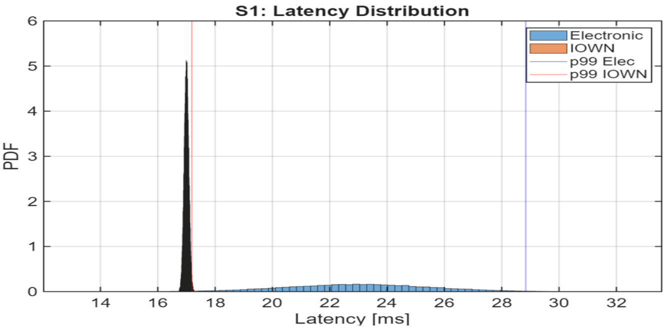

Fig. 1. End-to-end latency distribution for electronic and photonic (IOWN/APN-like) networks.

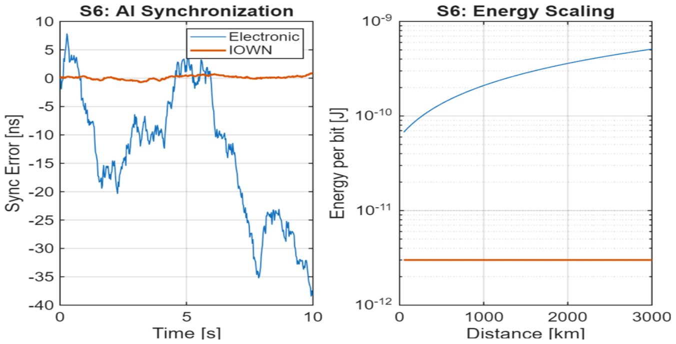

Fig. 2. (Left) Long-term synchronization error for distributed AI workloads. (Right) Energy consumption per bit versus distance.