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# Throughput-Cost Analysis of Optical Flow Switching

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**Abstract:** In this paper, we employ a cost model embodying major sources of capital expenditure (CapEx) to compare the throughput-cost tradeoff offered by Optical Flow Switching to that of more traditional optical network architectures.

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## 1. Introduction

In our previous work [1-3], we presented the Optical Flow Switching (OFS) architecture as a key enabler of scalable future optical networks, and carried out a simple throughput-cost comparison to other optical network architectures. In this paper, we substantially refine our analysis in the following two ways: i) We formulate a more comprehensive cost model, employing additional source of CapEx; ii) We optimize the physical layers of the architectures that we compare, in order to obtain a “best-case” scenario for each architecture. Our major conclusion is that *OFS is the most cost-scalable architecture of all*, in that its asymptotic normalized cost is several times lower than that of competing architectures.

## 2. Architectures considered

### A. OFS

In OFS, users request end-to-end lightpaths for long-duration (i.e., greater than 100 ms) transactions. In order to schedule data transmission across the wide-area network (WAN), users communicate via an electronic control plane with the scheduling processors assigned to their respective MANs. These scheduling processors, in turn, coordinate transmission of data across the WAN in an electronic control plane. This is in contrast to Optical Burst Switching (OBS), where access to network resources occurs in a random-access fashion. In OFS, it is assumed that the smallest granularity of bandwidth that can be reserved across the core is a wavelength. In the event that several single users have transactions which are not sufficiently large to warrant their own wavelength channels, they may multiplex their data for transmission across the WAN via dynamic broadcast group formation. Motivated by the minimization of network management and switch complexity in the network core, transactions are serviced as indivisible entities. That is, data cells comprising a flow of the entire transaction traverse the network contiguously in time, along the same wavelength channel (assuming no wavelength conversion), and along the same spatial network path. This is in contrast to packet switched networks, where transactions are broken up into constituent cells, and these cells are switched and routed through the network independently. Note that in OFS networks, unlike packet switched networks, all queuing of data occurs at the end users, thereby obviating the need for buffering in the network core. A core node is thus equipped with a bufferless optical cross-connect (OXC). OFS is a centralized transport architecture in that coordination is required for logical topology reconfiguration. However, OFS traffic in the core will likely be sufficiently aggregated and intense to warrant a quasi-static logical topology that changes on coarse time scales (minutes to hours).

### B. EPS and OCS/EPS

The two traditional optical network architectures that we compare OFS to are electronic packet switching (EPS) and optical circuit switching (OCS/EPS). EPS networks employ fiber for transport between nodes in the MAN and WAN, and electronic aggregation, routing, and switching at nodes. In the access, passive optical networks (PONs) with optical-electronic-optical (OEO) conversions at the head-end are employed. We define OCS/EPS to be identical to EPS in the access and MAN, but employing optical circuits between WAN edge routers with optical bypass via OXCs at intermediate nodes.

### C. Hybrid architectures

In our study, we also investigate the throughput-cost tradeoffs offered by hybrid architectures – architectures comprising two or more of the aforementioned homogeneous network architectures. We point out that the EPS-OCS/EPS hybrid architecture resembles the Generalized Multiprotocol Label Switching (GMPLS) architecture.

### 3. Model

#### A. Topology and traffic assumptions

In our cost study, we assume that all of the architectures considered operate on the same WAN fiber plant topology: a 60 node network introduced in [4] as a representative US carrier backbone network. The assumption of a pre-existing fiber plant is reasonable for countries, such as the US, which have established telecommunication infrastructures. Assuming the same fiber plant for all architectures is reasonable since the layout of the fiber plant is governed more by right-of-way and geographic considerations than the detailed network architecture. The sets of WAN node pair traffic demands that we consider are uniformly scaled versions of the set employed in [4]. This traffic set reflects actual US backbone network traffic, and is therefore not uniform all-to-all in nature.

In the metro-area, unlike in the wide-area, we do not assume a fixed fiber plant topology over which all architectures operate. Instead, we analytically optimized the fiber topology in accordance with the switching and fiber deployment costs particular to each architecture. Our rationale for this is that the metro-area is undergoing significant development with MANs requiring significant expenditures to augment existing fiber plant topologies. We restrict our consideration of fiber plant topologies to those that are based upon regular graphs with nodal symmetry, since such topologies are reasonable models of real MANs and are more analytically tractable. We found that the family of Generalized Moore Graphs minimizes [5] cost, albeit with different dimensions for different architectures. With respect to traffic in the MAN, we assume that intra-MAN traffic is uniform all-to-all, whereas inter-MAN traffic is uniform all-to-one (and one-to-all) to (from) the gateway node of the MAN.

In the access, we employ PONs with remotely pumped erbium-doped fiber, which support a large number of end-users economically. Our design for EPS and OCS/EPS employs an optical line terminal (OLT) at the head-end, whereas our OFS PON connects to the MAN passively and transparently. With respect to individual end-user data rate requirements, we consider both homogeneous and heterogeneous requirements.

#### B. Cost model

Our cost model focuses CapEx costs and neglects ongoing OpEx costs, which constitute a significant portion of a network's cost. The significance of OpEx notwithstanding, carriers tend to evaluate network design alternatives based upon CapEx, owing to the difficulty in forecasting the wide range of OpEx costs. Interestingly, the number of OEO conversions in a network, a CapEx component captured in our cost model, has been shown to be a rough indicator for a network's OpEx, since the electronics in these conversions consume a major portion of the costs related to power, required office space, and maintenance [4,6]. A potential shortcoming of this cost model –in addition to the omission of OpEx –is the possible neglect of significant sources of cost which are roughly constant across architectures, resulting in an overemphasis of the cost differences among architectures. The CapEx cost components included are: fiber, switching/routing, amplification, dispersion compensation, regeneration, and transceivers. We account for cost differences arising from varying optical reach and line-rate. We assume 40 Gbps line-rate throughout, except for PONs in EPS and OCS/EPS, for which a 10 Gbps line-rate is assumed.

### 4. Results

In Fig. 1, we indicate the minimum-cost architecture as a function of number of end-users per MAN and average end-user data rate; and in Fig. 2, we depict a horizontal cross-section of Fig. 1 at a MAN population of  $10^6$  end-users. When aggregate traffic is low, EPS is seen to be the most sensible architecture. Electronic switches and routers, to be sure, are less economically scalable technologies than OXCs, but they operate at finer data granularities than OXC. Thus, when aggregate traffic is low, it is wasteful to provision entire wavelength-granular OXC ports that are poorly utilized – which is why EPS is the minimum-cost architecture in this regime of operation. However, when traffic increases, optical switching in the WAN is sensible, rendering OCS/EPS the minimum-cost architecture. As aggregate traffic grows even larger, optical switching in the MAN and at the access boundary is most economical, rendering OFS the minimum-cost architecture.

In Fig. 3, we indicate the minimum-cost hybrid architecture as a function of the number of end-users per MAN and average end-user data rate. As in Fig. 1, when aggregate traffic is relatively low, the homogeneous EPS architecture is optimal for the reasons discussed above. However, as aggregate traffic increases, we find that hybrid architectures become preferable to homogeneous architectures. Specifically, we find that with increasing traffic, OCS/EPS, and subsequently OFS, become components of the minimum-cost hybrid architecture. In Fig. 4, we depict a horizontal cross-section of the minimum-cost hybrid architecture in Fig. 3 at a MAN population of  $10^6$  end-users. The black curve, which represents the normalized cost of the entire hybrid architecture, is essentially a weighted average of the three colored subarchitecture curves. At low average end-user data rates the (black) hybrid architecture curve follows the (blue) EPS curve, and for high average end-user data rates the hybrid architecture curve follows the (red) OFS curve, indicating the dominance of these architectures at these two extremes.

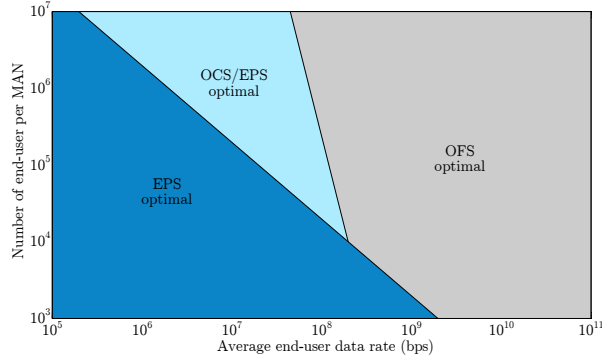


Fig. 1: Minimum-cost homogeneous architecture as a function of MAN size and average end-user data rate

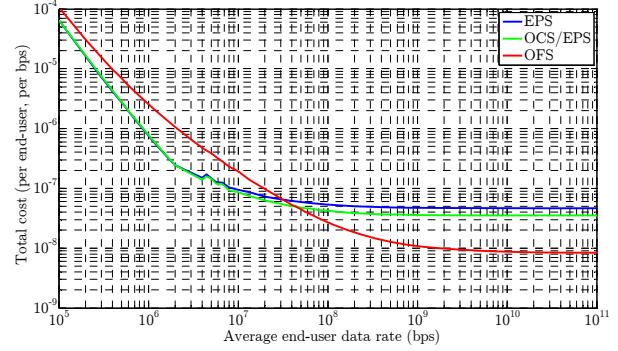


Fig. 2: Normalized network cost vs. average end-user data rate. Each MAN has  $10^6$  end-users.

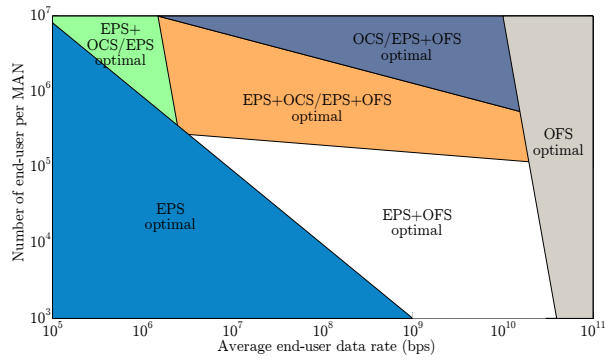


Fig. 3: Minimum-cost hybrid architecture as a function of MAN size and end-user average data rate

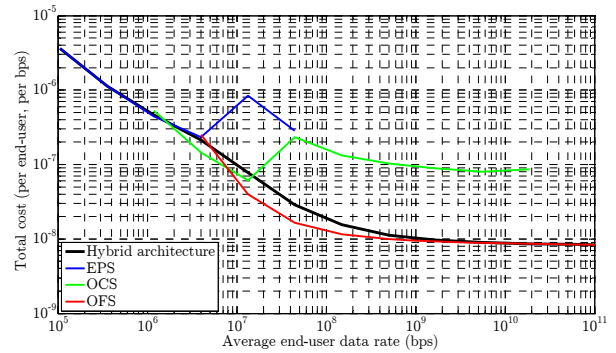


Fig. 4: Normalized cost components of minimum-cost hybrid architecture / fraction of traffic vs. average end-user data rate. Each MAN has  $10^6$  end-users.

## 5. Conclusions

Our main conclusion is that *OFS is the most cost-scalable architecture of all*, in that it is most economically attractive homogeneous architecture, and a critical component of hybrid architectures, when aggregate traffic is large. The work in this paper may be extended along various directions. With respect to cost, the most salient limitation of our work was the omission of OpEx. With respect to performance, a natural extension would be the inclusion of delay constraints. Lastly, the work in this paper could be broadened to include additional architectures.

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