A Parametric, First-Order Cost Analysis of Optical Burst Switched (OBS) Networks

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Abstract

We describe a parametric cost model appropriate for optical burst switched (OBS) networks. The model contains forty variables, and provides first-order estimates of total capital and operating expenditure costs per Kbit/s of traffic for three technology options ('legacy' SONET, dense WDM with opto-electrical conversions and edge/core routers, and OBS with edge routers and OBS edge devices) over six time intervals (initial deployment through the end of the fifth operational year). The model is used to compare estimates of OBS' cost per Kbit/s of traffic metric with other technologies over a range of network topologies, traffic loads, and multiplexing gain estimates.

1. Introduction

Optical burst switched (OBS) architectures have a number of *technical* advantages over Synchronous Optical Networks (SONET) and router-based networks utilizing wavelength division multiplexing (WDM). OBS networks are expected to exhibit higher bandwidth efficiencies for a given level of service, require significantly fewer opto-electronic (OEO) conversions, be protocol and layer transparent, achieve faster configuration and switching performance levels, and have lower operational requirements (*viz.*, space, power, cooling) due to these technical advantages.

However, it is not clear how these technical advantages might translate to *cost* advantages (*viz.*, capital and operating expenditure costs – CAPEX and OPEX, respectively). There are no operational OBS deployments to use as baselines other than a small number of laboratory and limited-reach testbeds (*e.g.*, [1]), and these proof-of-concept networks do not utilize carrier-grade networking gear. Opinions differ about OBS' potential cost advantages and bandwidth efficiencies relative to today's over-provisioned commercial carrier and ISP networks.

There are also no cost analyses of OBS known to us, though there are numerous cost models of widely deployed technologies like SONET (*e.g.*, [2, 3]), and several cost comparisons of SONET with OEO DWDM (*e.g.*, [4]). We have used these analyses and models as a blueprint for a parametric model that provides first-order estimates of OBS CAPEX and OPEX per Kbit/s of traffic from initial deployment through the end of the fifth year.

The model is *parametric* for several reasons: ***(i)*** cost estimates for some components (*e.g.*, router ports, leased fiber per mile) vary by 50-200%; ***(ii)*** technological breakthroughs (like lower-cost OEO conversions) will have a major impact on CAPEX and OPEX and need to be reassessed as they are deployed; ***(iii)*** comparisons of emerging technologies (like OBS) with widely-deployed technologies (like OEO DWDM and legacy SONET) are unconvincing unless the values of the parameters that are most advantageous to the new technology are conservative (*i.e.,* "hype-filtered"); and ***(iv)*** sensitivity analyses are straightforward when interesting parameters (*e.g.*, multiplexing gain, traffic growth rate, router port costs) can be varied over a realistic range of values as part of each analysis.

First order means ***(i)*** that the parameters and metrics are estimated (and represented) by their first moments (*e.g.*, the arithmetic mean) rather than by their distributions over time or space, and ***(ii)*** that estimates are uniform across the network's topology (*e.g.*, leased fiber costs do not vary by region, equipment costs do not vary by PoP). In other words, constitutive effects and interactions are **not** modeled. However, this does not preclude parameters for annual adjustments (*e.g.*, in traffic growth and equipment costs).

2. Cost model

2.1 Model description

This section briefly describes a parametric cost model that is appropriate for several WAN technologies, including generic OBS. The model consists of: ***(i)*** parameters for network topology (distances, link counts, points-of-presence (PoPs)), network transmission gear (optical fiber, amplifiers, regenerators, OOO-equivalent devices), core and PoP networking equipment (ADMs, OXCs, WDM terminals, routers, OBS edge devices), traffic estimates for subtending access networks, and annual traffic growth rates; ***(ii)*** CAPEX (initial estimates, annual discounts, estimates through the fifth year) and OPEX (estimates by year through the fifth year); and ***(iii)*** three technology options (legacy SONET, OEO DWDM with edge/core routers, and OBS with edge devices and core OXCs). The legacy SONET option is included so we can compare the model with a detailed SONET *vs.* OEO DWDM cost analysis by Ferreira and Cossa [4]. (Legacy SONET is SONET with little or no support for virtual concatenation, generic framing, link capacity adjustment, very high port densities, and other recent SONET/SDH enhancements.)

The model estimates: ***(i)*** traffic (Gbit/s) per POP per year; and ***(ii)*** for each technology option (legacy, DWDM, and OBS) and each year, the following: fiber equivalent miles and costs (including bi-directional and restoration paths); amplifier counts and costs; regenerator counts and costs; ADM channels and costs; OXC port counts and costs; WDM port counts and costs; edge and core router port counts and costs; OBS edge and core device counts and costs; and total CAPEX and OPEX costs per Kbit/s of traffic per year.

As noted, the cost model does **not** include a number of so-called second-order effects; *e.g.*, revenue, net present value, return on investment, gross margins, pricing discounts, depreciation, offsets, and the effects of equipment discounts and bulk rate purchases. The model is concerned *only* with first-order estimates of CAPEX and OPEX.

The model also does **not** distinguish among OBS variants. Some variants require specialized hardware or optical buffers (*e.g.*, FDLs and requisite compensation if FDLs are used), and most differ in how they reserve resources, resolve contention, and schedule and assemble bursts. As noted, OBS has not been deployed outside of laboratory or testbed settings so the actual costs and performance of the variants are unknown. Details related to channel availability, switch configuration times, scheduling complexity, blocking probability, etc. are clearly higher-order effects [5].

2.2 Model validation

We validated the model by configuring its parameters to match those in the Ferreira and Cossa ('F&C') analysis [4]. The F&C model compares legacy SONET with OEO DWDM deployments. The F&C model's topology has 9 PoPs, spans the continental US, has four full-mesh cells, and is about 61% meshed. The topology and PoP equipment configurations used in the F&C model are shown in Figure 1.

2.2.1 Model parameters

Table 1 contains a subset of the parameters used to compare the F&C and authors' ('MCNC') models. Initial parameter values are those explicitly identified in the F&C cost analysis [4]. Six parameters specific to OBS are not included in Table 1, but will be used in subsequent analyses.

2.2.2 Results

The MCNC model provides reasonably consistent results with the F&C model for values listed in Table 1. While the results are similar (as summarized in Table 2), the F&C and MCNC models differ in several fundamental ways. As noted, the F&C model includes only legacy SONET and OEO DWDM technology options; the MCNC model includes an additional option for OBS (not shown in Table 2). The F&C model also considers estimated revenue, net present value, return on investment, gross margin, pricing minutiae, and the effects of equipment discounts and bulk rate purchases. The MCNC model is concerned only with first-order CAPEX and OPEX estimates.

3. Experiments

Following the validation step, we changed values for 14 of the model's 40 parameters to more accurately reflect estimates obtained from carriers and equipment vendors, and estimates published in the trade press. Spacing for amplifiers and regenerators was increased by about 50%. WDM network equipment and PoP equipment costs were adjusted, and more realistic OPEX multipliers were introduced. The updated values (including two OBS parameters) are summarized in Table 3.

In the remainder of this section, we describe four experiments using: ***(i)*** the F&C topology, with more realistic parameter values; ***(ii)*** an early NSF*net* topology, with more PoPs and fewer links; ***(iii)*** a realistic use-case topology with 50% more PoPs and proportionally fewer links with shorter spans [6]; and ***(iv)*** the original F&C topology with significantly shorter span distances (to emulate a coarse WDM MAN). We also performed analyses to gauge the sensitivity of certain parameters in the cost-to-bandwidth ratio computations. As noted, the comparisons involving the OBS deployment are conservative. We have purposely used parameter values **least favorable to OBS** whenever possible in each experiment, and we have varied some of them to assess their sensitivity over a realistic range of values.

Unless noted, each experiment includes a plot of the total estimated cost (CAPEX plus OPEX) per Kbit/s of traffic ("CKb") for legacy SONET (labeled "Legacy"), for routers with OEO WDM (labeled "DWDM"), and for generic OBS with edge routers and OBS edge devices (labeled "OBS") over a six year period (initial deployment through the end of the fifth year).

3.1 Experiment 1

3.1.1 Baseline

The first experiment uses the F&C topology and PoP configurations of Figure 1, the parameter values in Table 1, and the updates summarized in Table 3. Figure 2 shows the total cost per Kbit/s of traffic (CKb) for the three technology options over a six year interval. The CKb for the Legacy deployment decreases slowly over time. As traffic demand grows, the carrier must add optical fiber and SONET equipment at the edge and in the network core.

The DWDM deployment is initially more expensive than the Legacy deployment because the deployment costs of DWDM equipment are higher – OXCs are more expensive per port or channel than ADMs, PoPs require DWDM terminals and more router ports for the multiplexed traffic, and amplifiers and regenerators are considerably more expensive in DWDM networks because they support multiple wavelength channels. Carriers must purchase more capacity than they need for the initial deployment (in this example), but DWDM's CKb decreases dramatically as traffic is added because there is relatively little increase in network infrastructure costs. The increased traffic is multiplexed onto the same optical fiber by activating more wavelengths. (The model assumes 40 channels in this example.) More equipment is required at the edge to service the tributary traffic, but the edge components' costs are small relative to core network equipment. In short, the DWDM model is more scalable and thus better suited if traffic volume and growth rates are high. Note that the total traffic carried in this configuration is quite large – about 360 Gbit/s for the initial deployment. The annual traffic growth rate (50%) is conservative.

Table 2 illustrates some of the differences between initial deployments of Legacy and DWDM gear:

- Fiber is 57% of the cost of the Legacy network, but only 10% of the cost of the DWDM network.
- Network transmission equipment is 36% of the cost of the Legacy network *vs.* 16% for DWDM.
- PoP and core equipment is 7% of the cost of the Legacy network *vs.* 74% for DWDM.

The OBS deployment has an even lower CKb than the DWDM deployment in this experiment. Network and PoP equipment is more expensive for OBS, but the performance-to-cost ratio favors OBS over DWDM because OBS multiplexes traffic within wavelengths, and the multiplexing advantage of DWDM over a Legacy deployment is increased when OBS is added to DWDM. Furthermore, the gain offsets the additional cost of OBS relative to DWDM. (Note that the multiplexing gain for OBS relative to DWDM in this experiment is conservative at 1.33).

DWDM gear is more expensive than Legacy gear, but its advantage in multiplexing wavelengths dominates the CKb. Likewise, OBS' additional expense (*vs.* DWDM) is offset by its multiplexing gain. OBS and DWDM appear to be close in Figure 2. However, the DWDM CKb at the closest point – at the end of the fifth year ("6" on the abscissa) – is 1.25 larger than OBS. We shall refer to the CKb ratio as **R**, where **R** = (2.27/1.81) = 1.25 after year 5 in this experiment.

3.1.2 Sensitivity of parameters

As noted, OBS networks have not been deployed, and cost and performance estimates depend on a number of factors. To gauge which parameters are most sensitive over a reasonable range of values, we varied the default value of selected parameters as indicated in Table 4. (Recall that the CKb for OBS was 1.81 after year 5.)

The most sensitive parameters over the ranges indicated for this experimental configuration are:

- Those related to traffic – traffic growth per year, and OBS' multiplexing gain. This is logical, as OBS' clear advantage is higher utilization by sub-wavelength multiplexing in networks with high traffic and moderately high growth rates. As noted, the model assumes a 50% annual traffic growth rate, while most experts use 80-100%. A higher growth rate is of great advantage to OBS relative to DWDM.
- OPEX percentage – we conservatively assumed that OBS' OPEX penalty was higher than DWDM, which is probably not realistic. A lower penalty is advantageous to OBS.
- Fiber cost per mile – but as noted, fiber costs affect non-WDM systems even more as lighting wavelengths is typically less expensive than adding fiber.
- WDM port costs – as expected (relative to Legacy gear).

The least sensitive parameters are related to transmission equipment costs, edge router port costs, and annual equipment cost reductions (*i.e.*, discounts over time). Network equipment grows slowly with moderately increasing traffic due to WDM and OBS multiplexing gain, edge router ports are relatively inexpensive, and annual discounts are small.

The surprising factors are those used to estimate OBS costs. Even if OBS equipment is quite expensive (*i.e.,* 40% of the cost of core IP routers, which is much larger than most OBS proponents expect), it makes little difference in the overall CKb. In summary, OBS' advantages over DWDM are clear in this example, and are almost certainly larger than the CKb ratio **R** = 1.25 in this example (which is based on conservative parameters).

3.2 Experiment 2

The second experiment is based on an early NSF*net* topology with more PoPs and fewer links than the F&C topology used in Experiment 1 [7]. The model has 12 PoPs, 20 wavelengths, 23% fewer links, 25% less total distance, spans the entire continental US, has no full-mesh cells, and is only about 26% meshed. The topology is shown in Figure 3. A major difference is the traffic volume – 8 Gbit/s initially, with a more realistic growth rate of 100% per year [7]. Parameter changes are summarized in Table 5.

Figure 4 shows the total cost per Kbit/s of traffic for two technology options (DWDM and OBS) over six years. Sengupta's cost model [7] estimates total DWDM CAPEX to be $858M by the end of the fifth year. The MCNC model estimates DWDM CAPEX to be $894M, which is within 4.2% of Sengupta's estimate. This is another indication that the MCNC model provides reasonable first-order estimates of CKb over time.

The CKb values in Figure 4, especially during the early years, are much higher than for the first experiment because the network is carrying far less total traffic and has enormous excess capacity. OBS and DWDM appear to be close in Figure 4. However, the CKb ratio **R** is 5.62/4.82 = 1.16 after the fifth year even when conservative OBS parameters are used. This confirms that when traffic load is low relative to capacity and there are ample wavelengths, the OBS advantage over DWDM is less pronounced – *i.e.*, sub-wavelength multiplexing is far less an issue.

If we change the OBS multiplexing gain relative to DWDM from 1.33 to 1.50 and then to 2.00 (which is still quite conservative), the OBS CKb falls from 4.82 to 4.60 and to 4.12 respectively. This increases the CKb ratio **R** from 1.16 to 1.22 to 1.36 respectively. Most OBS proponents believe that OBS will enjoy a multiplexing gain relative to DWDM of at least 2×, so the comparison is reasonable. Studies of the multiplicative factors involved in DWDM circuit switching conclude that circuits are engineered to operate at only 15% to 25% of capacity, especially in IP networks. Extra capacity is available on each link to transport bursts in these networks, so realistic estimates of the burst multiplexing gain relative to DWDM can easily extend to 5× - 6× [8].

In summary, DWDM and OBS incur larger up-front costs, and their CKb advantages are less pronounced in networks with enormous excess capacity. Even so, OBS enjoys an advantage over DWDM with the CKb ratio **R** of 1.36 at a conservative multiplexing gain of 2× and a traffic growth multiplier of 2× (100% per year). At higher multiplexing gain and realistic traffic growth rates, the CKb ratio **R** approaches 1.8 in this experiment (Figure 5). (We examine the sensitivity of the OBS multiplexing gain parameter further in Experiment 3.)

3.3 Experiment 3

3.3.1 Baseline

The third experiment is based on a use-case configuration published by the QoS Task Force [6]. The topology has 15 PoPs, 26 links, 40 wavelengths, spans 19,500 miles, is about 50% meshed, and has no explicit protection paths. The traffic volume is quite large – about 35 Gbit/s per PoP, or 525 Gbit/s total, with a conservative traffic growth rate of 50% per year. Parameter changes are summarized in Table 6.

Figure 6 shows the total cost per Kbit/s of traffic for two technology options (DWDM and OBS) over six years. The CKbs for both deployments are small because the network is carrying far more total traffic than in Experiment 2, and is running with little excess capacity. When traffic loads are high relative to capacity, the advantages of OBS and DWDM are more pronounced because the network has grown to utilize the capacity paid for up front, and the advantages of OBS relative to DWDM are more pronounced due to multiplexing gain.

The CKb ratio **R** after the fifth year is 0.95/0.63 = 1.51 even with a conservative traffic growth rate of 50% and a very conservative OBS multiplexing gain of 2. As noted, many believe that OBS will enjoy a multiplexing gain of at least 4 and perhaps 5-6, so **R** = 1.51 is almost certainly understated.

3.3.2 Sensitivity to multiplexing gain

Figure 7 (left) shows how OBS' CKb (ordinate) improves relative to DWDM's CKb as the OBS multiplexing gain (abscissa) increases, and Figure 7 (right) shows how the CKb ratio **R** (ordinate) increases as the OBS multiplexing gain (abscissa) increases in this example. The rate of increase is largest between multiplexing gains of 1.11 and 5.00. *E.g.*, if OBS has a multiplexing gain of 5, the DWDM CKb is twice the OBS CKb. Carriers typically expect a CKb advantage of at least 20% (**R** = 1.20) before considering a new technology, which is achieved in this example at a multiplexing gain of 1.33 . (The shaded column in the Figure 7's table reflects values shown in Figure 6.)

Again, we see that DWDM and OBS incur large up-front costs (relative to a Legacy network), but their CKb advantages are significant in networks with relatively little excess capacity. OBS enjoys a CKb that is half that of DWDM at a multiplexing gain of about 5 (in this example).

3.4 Experiment 4

3.4.1 Baseline

The fourth experiment is based on the F&C topology of Figure 1, but scaled down to distances typically found in US metropolitan area networks (MAN) that deploy coarse WDM (CWDM) gear. The topology is the same as in Experiment 1, but has 1,000 miles of optical fiber, OC-48 links (2.4 Gbit/s), 8 wavelengths, less expensive routers, and one-tenth the tributary traffic – about 4 Gbit/s per PoP rather than 40 Gbit/s. We also assume a modest multiplexing gain for OBS of 1.33 and no discount for CWDM gear relative to DWDM initially. (CWDM gear is typically one-third to one-half the cost of DWDM gear per wavelength.) Changes summarized in Table 7.

Figure 8 shows the total cost per Kbit/s of traffic for three options (Legacy, DWDM – actually CWDM in this example despite the label, and OBS) over six years. The Legacy and OBS CKbs are within 10% after the end of the fifth year, with OBS overtaking Legacy SONET only after year 5. CWDM is characteristically larger than OBS.

The model has not been validated against a CWDM cost model, so it is not clear whether the CKbs are realistic for Legacy gear. But the advantages of OBS would indeed be smaller relative to SONET in short-reach MANs. If NG SONET or RPR is used, the OBS advantage may disappear entirely because of their higher bandwidth efficiencies. If Ethernet is used, it almost certainly has a lower CKb than NG SONET and OBS because of its low cost (in part due to its lack of carrier-class adornments).

Next, we performed three variations of Experiment 4 by ***(i)*** varying the actual distance, ***(ii)*** increasing the OBS multiplexing gain while varying the distance, and ***(iii)*** increasing the CWDM adjustment factor (*i.e.*, the cost advantage of CWDM relative to DWDM) while varying the distance.

3.4.2 Sensitivity to distance

Varying distances from 1,000 to 5,000 miles (without changing any other parameters) produces the results of Figure 9. After the fifth year and at distances of 2,000 miles and above, CWDM and OBS provide a superior CKb (in this example) as they do not require additional network gear and fiber. The Legacy network's infrastructure costs grow linearly as more network gear and fiber are added, as expected. The difference between CWDM and OBS varies little with distance.

Metropolitan area networks in the US connect 11 PoPs on average and have interPoP span lengths of no more than 70-100 Km, so the majority of MANs have total distances no greater than 1,000 miles. Shorter distances clearly favor the Legacy technology in this example. If optical fiber is expensive or scarce, CWDM is the clear choice because less fiber is required to accommodate demand due to multiplexing. The same argument can be made for OBS relative to CWDM. However, CWDM and OBS may not be clear winners relative to SONET in MANs because of their significantly higher up-front costs.

3.4.3 Sensitivity to distance and multiplexing gain

Increasing the multiplexing gain to 5 (from 2) and varying the distances from 1,000 to 5,000 miles produces the results of Figure 10 (at the end of the fifth year). As expected, OBS' advantage increases with multiplexing gain. The OBS curve drops relative to Figure 9.

3.4.4 Sensitivity to the CWDM adjustment factor

CWDM is significantly less expensive than DWDM. Increasing the CWDM to DWDM cost advantage from parity to 2 : 1, applying a conservative multiplexing gain of 2, and varying the distances from 1,000 to 5,000 miles produces the results of Figure 11 after the fifth year. As expected, OBS' advantage increases if CWDM's cost relative to DWDM is reduced. The OBS and CWDM curves drop relative to Figure 9. (OBS gain is again 2.)

These results suggest that OBS is not a clear winner at total network circumferences below 1,000 miles because Legacy gear's CKb increases nearly linearly with distance, and the crossover point is about 1,000 miles in this conservative model. Many US MANs have circumferences of less than 1,000 total miles. The advantages of CWDM and OBS clearly increase with distance, the advantage of OBS relative to CWDM increases with multiplexing gain, and the advantage of CWDM and OBS relative to Legacy gear increases with decreasing CWDM cost (relative to DWDM).

The MCNC model was validated only against longer distance models, so these conclusions may not accurately reflect the costs of deploying OBS over CWDM in metro-sized networks. A more careful analysis is also required because the MCNC model is more conservative than the F&C model (Table 2), and the OBS multiplexing gain is quite conservative. As noted, NG SONET or RPR or Ethernet are almost certainly be more realistic technologies for MAN comparisons than legacy SONET.

4. Conclusions

DWDM's advantage in total estimated cost (CAPEX plus OPEX) per Kbit/s of traffic *vs.* a legacy SONET deployment increases when OBS' sub-wavelength multiplexing capability is added. OBS multiplexing gain offsets the additional cost of OBS relative to DWDM even at very conservative traffic growth rates. Parameters related to traffic – annual traffic growth rate and OBS' multiplexing gain – appear to be most influential, while parameters related to transmission and network equipment costs appear to be least influential. The advantages of DWDM and OBS are marginal in networks with excess capacity, but are far more pronounced when traffic load is high relative to capacity. Finally, OBS may not a clear winner in MANs because the crossover point is about 1,000 miles when conservative OBS parameters are used.

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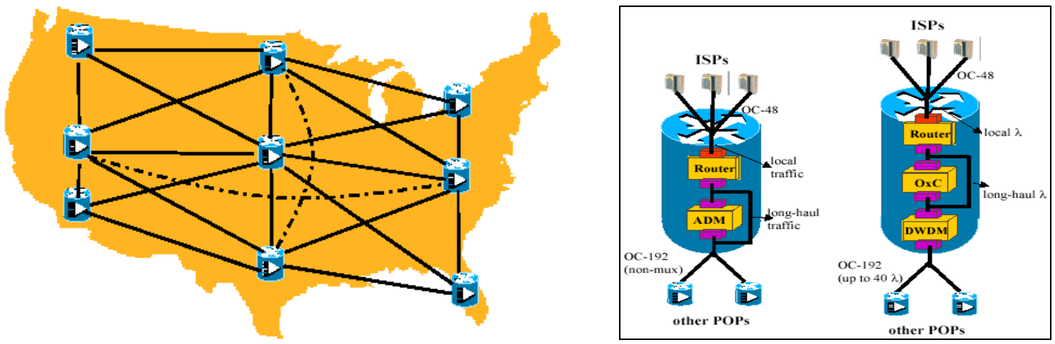

Figure 1. Topology (left, from [4]), and two PoP configurations (right, from [4]) used in the F&C model [4].

Table 1. Selected parameters and values used to compare the F&C and the MCNC models.

Topology		**Transmission gear**		**Tributary traffic per PoP**	
Actual distance (miles)	23,000	Legacy amplifier cost ($M)	0.080	Residential (Gbit/s)	1.7680
Link count	22	Legacy amplifier spacing (miles)	31	Business (Gbit/s)	28.8000
Link rate (Gbit/s)	9.6	WDM amplifier cost ($M)	0.240	Other traffic (Gbit/s)	9.4356
WDM bi-directional multiplier	2	WDM amplifier spacing (miles)	40	Annual growth multiplier	1.25
Legacy bi-directional multiplier	2	Legacy regen cost ($M)	0.080	**PoP and core equipment**	
WDM protection multiplier	2	Legacy regen spacing (miles)	155	OXC port cost ($M)	0.075
Legacy protection multiplier	2	WDM regen cost ($M)	0.320	WDM port cost ($M)	0.156
PoPs		WDM regen spacing (miles)	200	ADM channel cost ($M)	0.040
Number of PoPs	9	Annual cost multiplier	0.90	Router OC-48 port cost ($M)	0.080
Fiber		**OPEX**		Router OC-48 port factor	0.925
Cost per mile ($M)	0.0048	Legacy base multiplier	0.01	Router OC-192 port cost ($M)	0.300
Wavelength capacity (WDM)	40	WDM base multiplier	0.05	Router OC-192 port factor	0.76
				In/out multiplier for ports	2
				Annual cost multiplier	0.90

Table 2. Comparison of F&C and MCNC models with initial parameter values.

Cost Components	**Legacy SONET**			**OEO DWDM**		
	F&C	**MCNC**	**Δ**	**F&C**	**MCNC**	**Δ**
Fiber ($M)	1,881	1,840	-2.1 %	440	442	0.5 %
Amplifiers ($M)	990	989	-0.1 %	572	552	-3.5 %
Regenerators ($M)	198	198	0.0 %	132	147	-3.8 %
ADMs ($M)	33	29	-12.1 %	0	0	0 %
OXCs ($M)	0	0	0 %	528	528	0 %
WDM terminals ($M)	0	0	0 %	1,100	1,100	0 %
Routers ($M)	198	194	-2.0 %	1,628	1,632	0.2 %
Total ($M)	3,300	3,250	-1.5 %	4,400	4,401	0.0 %
CAPEX per Kbit/s of traffic – initial deployment	9.1	9.0	-1.1 %	12.2	12.2	0.0 %
CAPEX per Kbit/s of traffic – end of fifth year	6.9	7.4	7.2 %	4.0	4.0	0.0 %

Table 3. Original and updated parameters used in Experiment 1.

Parameter	**Value**		**Parameter**	**Value**	
	Original	**Updated**		**Original**	**Updated**
Legacy amplifier spacing (miles)	31	44	OXC port cost ($M)	0.075	0.078
Legacy regen spacing (miles)	155	220	Router OC-48 port cost ($M)	0.080	0.065
WDM amplifier cost ($M)	0.240	0.135	Router OC-192 port cost ($M)	0.300	0.250
WDM amplifier spacing (miles)	40	62	Legacy OPEX base multiplier	0.01	0.20
WDM regen cost ($M)	0.320	0.621	WDM OPEX base multiplier	0.05	0.10
WDM regen spacing (miles)	200	310	OBS OPEX base multiplier	--	0.15
Annual traffic growth multiplier	1.25	1.50	Multiplexing gain for OBS	--	1.33

Deployment	Legacy	DWDM	OBS
Initial CKb	9.56	11.72	8.17
CKb (1)	9.80	8.53	6.17
CKb (2)	9.54	6.18	4.60
CKb (3)	9.08	4.44	3.39
CKb (4)	8.56	3.18	2.48
CKb (5)	8.05	2.27	1.81

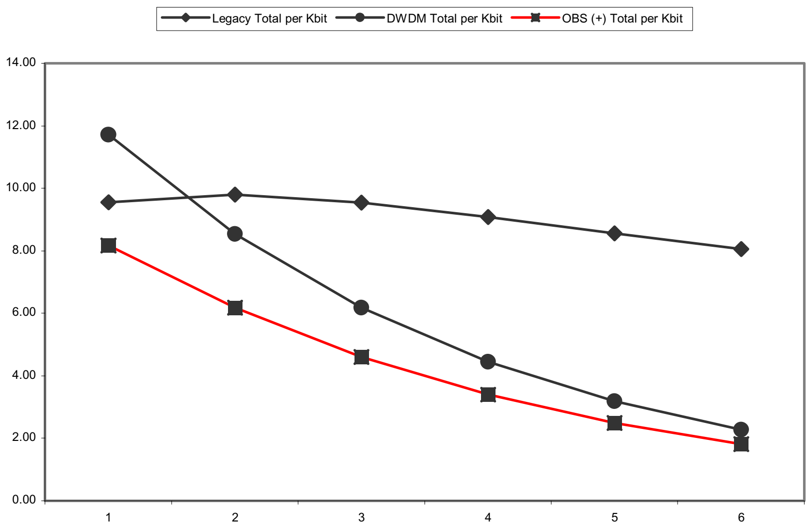

Figure 2. Total cost per Kbit/s of bandwidth by period; *1* is initial deployment, *6* is end of year 5.

Table 4. Sensitivity analysis; rows in descending order by Δ CKb.

Parameter	Default Value	Low Range	High Range	OBS CKb at Low	OBS CKb at High	Δ
Traffic growth per year	1.50	1.80	1.20	0.75	5.44	4.69
OBS multiplexing gain	1.33	3.33	1.00	1.20	2.14	0.94
OPEX percentage of CAPEX	0.15	0.10	0.20	1.52	2.09	0.57
Fiber cost per mile ($M)	0.0048	0.0024	0.0096	1.65	2.11	0.46
WDM port cost ($M)	0.156	0.100	0.200	1.56	2.00	0.44
OXC port cost ($M)	0.078	0.040	0.120	1.65	1.98	0.33
WDM port cost increase due to OBS	1.20	1.00	1.50	1.69	1.98	0.29
OBS edge device cost relative to routers	0.2	0.1	0.4	1.71	1.99	0.28
OXC port cost increase due to OBS	1.10	1.00	1.50	1.78	1.92	0.14
WDM amplifier spacing (miles)	62	82	42	1.77	1.87	0.10
WDM regen spacing (miles)	310	400	200	1.78	1.88	0.10
WDM regen cost ($M)	0.621	0.400	0.800	1.76	1.84	0.08
WDM amplifier cost ($M)	0.135	0.100	0.170	1.77	1.84	0.07
Router OC-48 port cost ($M)	0.065	0.040	0.100	1.79	1.83	0.04
Annual PoP equipment cost multiplier	0.90	0.80	1.00	1.79	1.83	0.04
Annual network equipment cost multiplier	0.90	0.80	1.00	1.81	1.81	0.00

Table 5. Updated parameters used in Experiment 2.

Actual distance (miles)	17,000
Link count	17
WDM protection multiplier	1
Number of PoPs	12
OXC port cost ($M)	0.085
Traffic per PoP (Gbit/s)	0.667
Annual traffic growth multiplier	2
Wavelength capacity (WDM)	20

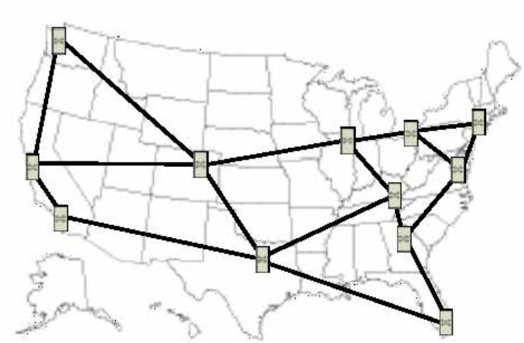

Figure 3. Topology used in Experiment 2 (from [7]).

Deployment	DWDM	OBS
Initial CKb	122.99	92.71
CKb (1)	67.11	52.43
CKb (2)	36.37	29.26
CKb (3)	19.60	16.16
CKb (4)	10.52	8.85
CKb (5)	5.62	4.82

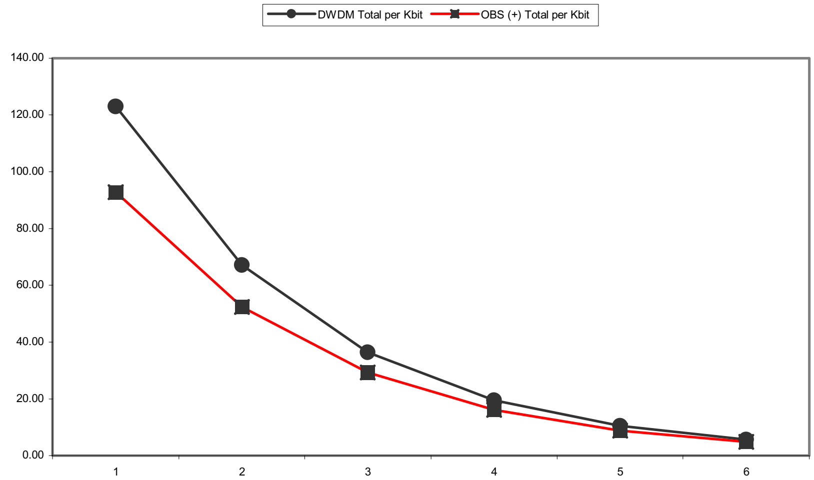

Figure 4. Total cost per Kbit/s of bandwidth by period.

Table 6. Updated parameters used in Experiment 3.

Actual distance (miles)	19,500
Link count	26
WDM protection multiplier	1
Number of PoPs	15
Traffic per PoP (Gbit/s)	35.0
Annual traffic growth multiplier	1.5
Wavelength capacity (WDM)	40

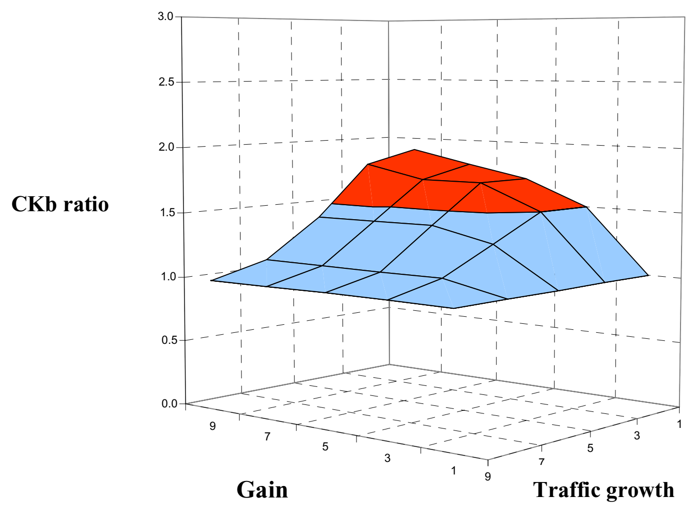

Figure 5. CKb ratio R × gain × traffic growth rate.

Deployment	DWDM	OBS
Initial CKb	4.84	2.79
CKb (1)	3.53	2.11
CKb (2)	2.56	1.58
CKb (3)	1.85	1.17
CKb (4)	1.33	0.86
CKb (5)	0.95	0.63

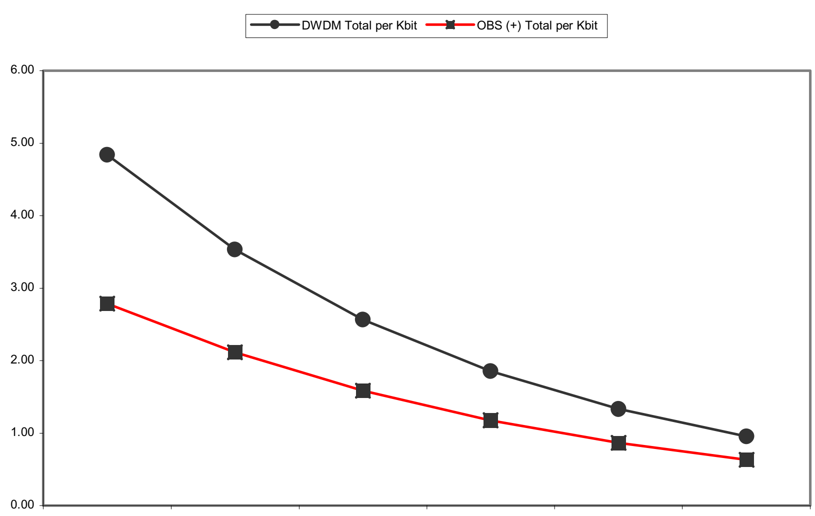

Figure 6. Total cost per Kbit/s of bandwidth by period.

DWDM CKb	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95
OBS CKb	0.85	0.77	0.72	0.63	0.58	0.53	0.47	0.42	0.39
CKbs ratio R	1.12	1.23	1.32	1.51	1.64	1.79	2.02	2.26	2.44
OBS multiplexing gain	1.11	1.33	1.49	2.00	2.50	3.33	5.00	10.00	20.00

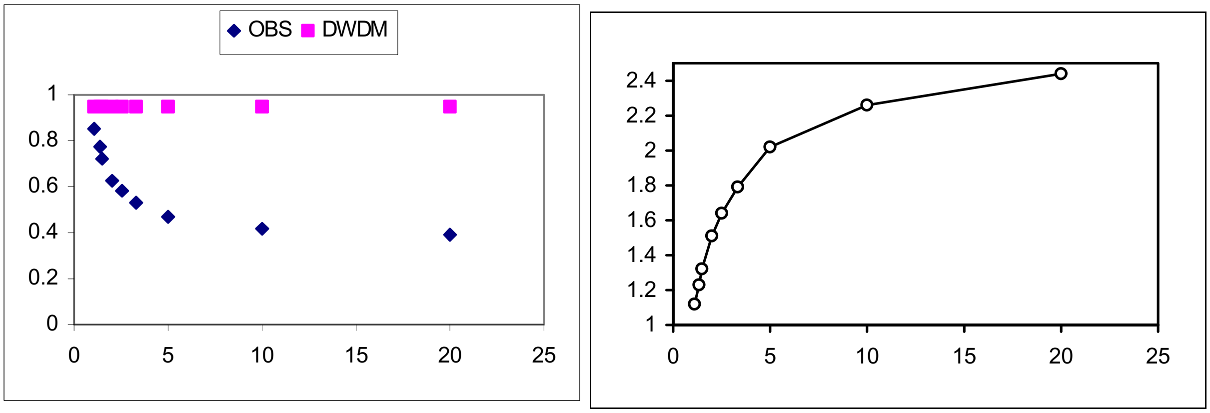

Figure 7. CKb for OBS and DWDM (left), and CKb ratio **R** (right) for multiplexing gains between 1.11 and 20.

Table 7. Updated parameters used in Experiment 4.

Actual distance (miles)	1,000		Traffic per PoP (Gbit/s)	4.0
Link rate (Gbit/s)	2.4		Wavelength capacity (WDM)	8
Router cost adjustment	0.5		Multiplexing gain for OBS	1.33
CWDM discount adjustment	1.00			

Deployment	Legacy	CWDM	OBS
Initial CKb	2.50	13.37	7.81
CKb (1)	2.52	9.73	5.90
CKb (2)	2.41	7.04	4.40
CKb (3)	2.25	5.07	3.24
CKb (4)	2.08	3.63	2.37
CKb (5)	1.92	2.59	1.73

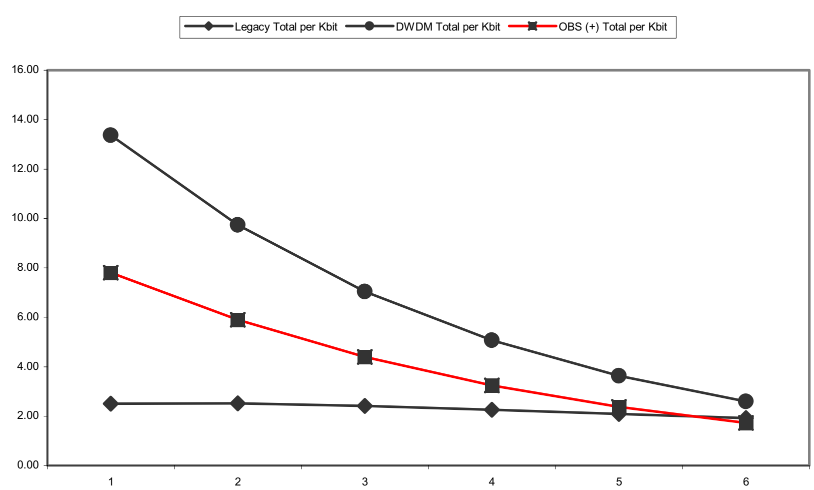

Figure 8. Total cost per Kbit/s of bandwidth by period.

Total distance	Legacy	CWDM	OBS
1,000	1.92	2.59	1.73
2,000	3.25	2.80	1.98
3,000	4.59	3.01	2.23
4,000	5.92	3.22	2.47
5,000	7.25	3.43	2.72

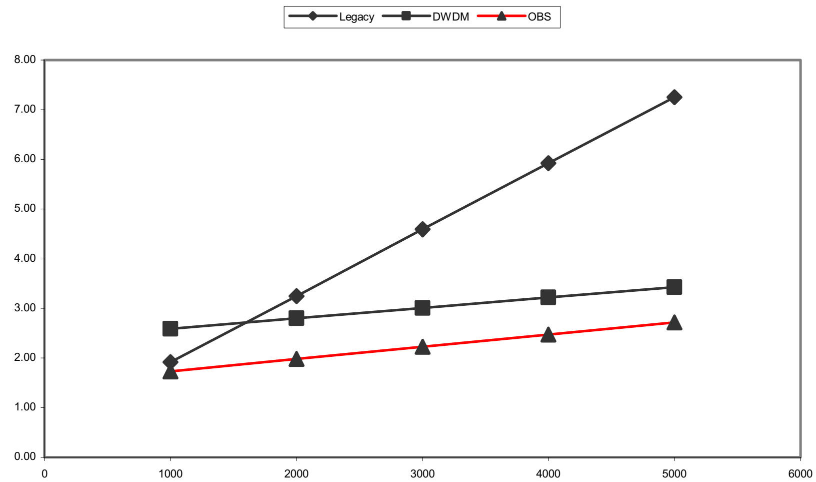

Figure 9. Total cost per Kbit/s of bandwidth by distance after end of year 5 with multiplexing gain of 2.

Total distance	Legacy	CWDM	OBS
1,000	1.92	2.59	0.92
2,000	3.25	2.80	1.17
3,000	4.59	3.01	1.42
4,000	5.92	3.22	1.67
5,000	7.25	3.43	1.92

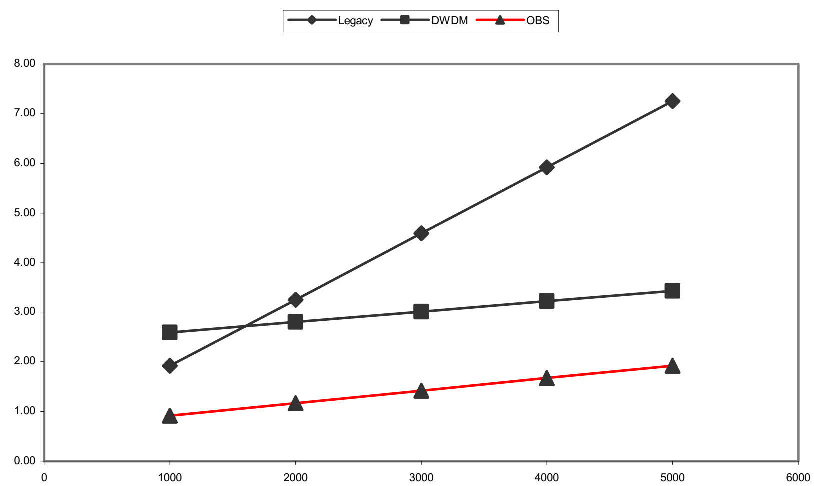

Figure 10. Total cost per Kbit/s of bandwidth by distance after end of year 5 with multiplexing gain of 5.

Total distance	Legacy	DWDM	OBS
1,000	1.92	1.94	1.27
2,000	3.25	2.15	1.52
3,000	4.59	2.36	1.77
4,000	5.92	2.57	2.02
5,000	7.25	2.78	2.27

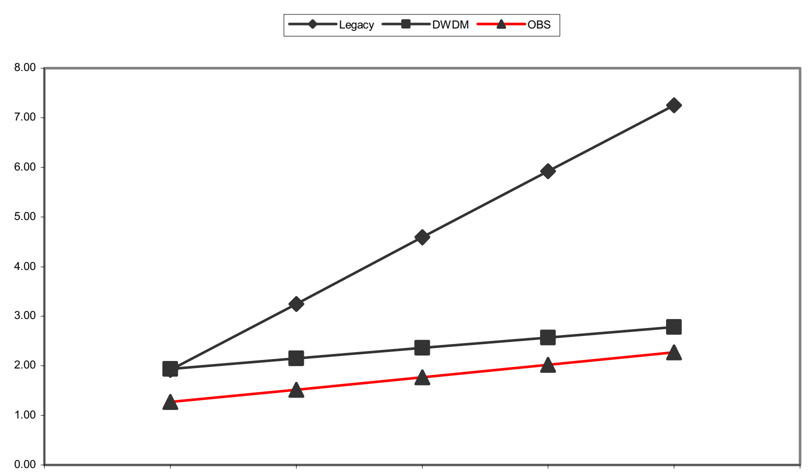

Figure 11. Total cost per Kbit/s of bandwidth by distance after end of year 5 with multiplexing gain of 2 and CWDM factor of 50%.