White Paper

Powering Costs as Fiber Goes Deeper Into the Loop

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Powering Costs as Fiber Goes Deeper Into the Loop

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Abstract

As digital loop carrier (DLC) architectures carry fiber deeper and deeper into the local loop to satisfy ever-increasing bandwidth demands, techniques and costs for powering these architectures are sometimes ignored. Here, we examine the costs associated with delivering power to nodes where optical-to-electric conversions (O/Es) occur, sometimes referred to as optical network units (ONUs), as different quantities of ONUs are powered from a single power node. The conclusions show that with larger ONUs, which serve greater numbers of customers, ten-year ownership costs for network powering increase when more than ten ONUs are powered from a single power node. Smaller-sized ONUs are different: greater quantities of smaller ONUs may be powered out of a single power node without increasing ten-year operating costs. Finally, when the power supply status monitoring costs are not divided among many ONUs., such as when powering a small quantity, or even one, from a single power node, ownership costs rise.

1. Introduction

Digital loop carrier (DLC) architectures are carrying fiber deeper and deeper into the local loop to satisfy ever-increasing consumer demand for bandwidth. Deeper fiber can also allow separation (grooming) of traditional circuit-switched and packet-switched traffic before this traffic can burden network switches and routers [1]. Powering of these fiber-based architectures and the maintenance and ongoing service costs associated with powering are often overlooked or neglected. Until computers, televisions, telephones, and other interactive appliances are equipped with fiber-optic interfaces, then somewhere within the local loop, whether at an optical network unit (ONU), residential gateway, curbside enclosure, or somewhere in between, a conversion between optical and electric signals is needed. These conversions between optical and electrical signals, sometimes referred to as O/E conversions, consume minor or even insignificant power. More significant electrical power is demanded by the transmission of these electrical signals over the remaining wireline portion of the local loop to the telephone, television, or other communication appliance.

Paralleling the transmission architecture is the powering architecture. Just as fiber can be extended to different depths within the local loop, so too can electric power. Traditionally, all powering of the local loop took place in the conditioned environment of the central office (CO), as did the switching functions. Network transmission architectures have evolved and migrated switching and processing functions out of the CO into the outside plant (OSP), such as with DLC. Powering has also migrated from the CO to the OSP. This paper addresses the costs of powering as powering architectures reach different depths within the local loop. Other papers have analyzed powering costs with different architectures [2], but here, powering is examined for DLC as the ratio of ONUs to power node changes. Home-based powering [3] defines one extreme in local-loop powering architectures; the other extreme uses traditional powering from the CO.

Among factors which affect the initial or capital costs are the expenses of redundancy in the power supply, status monitoring of the power supply and battery plant. Operating costs are examined with respect to energy losses in transmitting the power from the power node to the loads, and the costs of maintenance of the power nodes.

Given that some quantity of ONUs are needed in a deployment, this paper examines the costs of powering these ONUs with different powering architectures. One architecture, local powering. places the power processing at each ONU. An alternative architecture, referred to as network powering, uses a power node to provide dc power to a multitude of ONUs over copper twisted pairs. These power nodes can serve different quantities of ONUs. A large power node can serve more ONUs, but at the expense of more transmission losses, as the distance among ONUs and the power node are larger. For smaller power nodes, the ONU to power node distance is shorter, but greater quantities of these smaller power nodes are needed.

Among the advantages offered by network powering over powering at each ONU are:

- Status monitoring in numerous locations is complex and expensive. Network powering produces fewer locations which must be provisioned with status monitoring.

- Status monitoring of a power supply at an ONU occupies a single plain ordinary telephone service (POTS) at each ONU. Using network powering with a power node for every five ONUs, as an example, consumes a single POTS line for each five ONUs.
- Service costs with numerous powering locations are significant. Network powering reduces the number of service locations.
- As the number of powering locations increases, service and maintenance become more complicated and expensive, and preventive maintenance less likely.
- A power supply which powers larger quantities of traffic can utilize traffic statistics to reduce battery backup power requirements.
- Network powering produces fewer battery sites to service and maintain.
- Network powering can produce lower deployment costs. Network powering requires one utility connection at the power node which serves multiple ONUs, rather than needing a utility drop at each ONU.
- Lower operating expenses.
- Higher reliability. Redundancy costs can be spread over a quantity of ONUs. With a power supply at each ONU, each ONU requires a redundant power source which can double the cost of powering.
- Additional powering options become economically feasible. Energy storage alternatives, such as fuel cells, or engine generators, are more easily added with network powering.

2. Status Monitoring

Battery plants must have the capacity to support loads for the requisite eight hours. Furthermore, battery plants are expensive and the finite life expectancy of the battery plant is reduced rather dramatically as temperature increases. For these reasons, battery plants of any size located in the OSP require status monitoring. If, however, the eight-hour requirement for backup power is moderated or removed, the cost of status monitoring of the battery plant and battery-plant environment must be justified by the offset in the maintenance costs. Presently, in the regulatory environment where eight-hour backup is an absolute requirement, monitoring of the battery plant is needed to ensure the eight-hour capacity.

Status Monitoring Costs

Initial	Annual Operating
$750	$300

Table 1. Assumed costs for status monitoring.

2.1 Capital Costs

Initial expenditures for status monitoring arise from the capital costs of the hardware needed to acquire the data to be monitored, along with the transceiver which modulates and demodulates data onto some communications path to the network operations center (NOC). Operating and capital costs associated with the NOC, such as the personnel who operate the NOC, are not considered here because it is assumed that these NOC costs are fixed, and are independent of the quantity of power nodes which are monitored.

Based on a casual survey of several manufacturers of power nodes, as well as vendors of status monitoring equipment, the hardware costs for status monitoring are nominally $750. This hardware is capable of monitoring the battery voltage, as well as any major and minor alarms associated with the power node. This $750 status monitoring cost also includes the cost of the transceiver or modem which modulates the data for in-band transmission to the NOC.

2.2 Operating Costs

Unlike the NOC costs which are relatively independent of the quantity of power supplies which must be monitored, transmission of data between the power node and the NOC has an ongoing cost which varies with the number of monitoring sites. To approximate the costs associated with transmission of the data from the power node to the NOC, it is assumed this data path displaces a single plain ordinary telephone service (POTS) line. An estimate of the yearly value of this POTS line is $300 [4]. Table 1 summarizes the initial and operating costs associated with status monitoring.

2.3 Status Monitoring Costs

At one extreme, only a single ONU is served from a

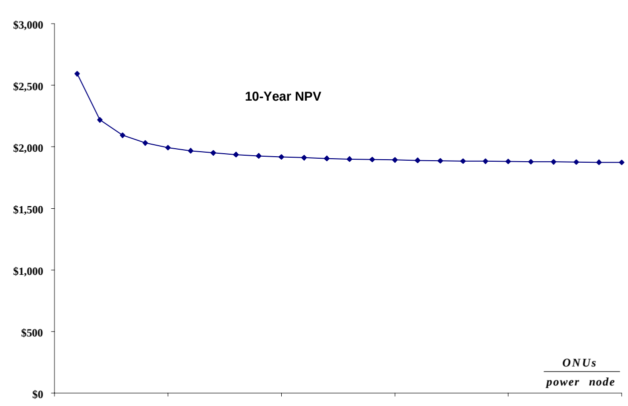

Figure 1. Costs of status monitoring as the number of power supplies served from a single power node varies.

power node; at this extreme, there is a one-to-one mapping between the number of power nodes and the number of ONUs. Since each ONU power node requires status monitoring, this extreme is the most expensive architecture, as seen in Fig. 1. As the quantities of ONUs hosted by a single power node increases, the costs of status monitoring each ONU decreases. A power node dedicated to a single O/E conversion, such as with a fiber to the home (FTTH) architecture with a power supply at each residence, produces significant expenses for status monitoring. In consideration of these status monitoring expenses, a more reasonable, lower-cost alternative to a power supply at each residence is a power node which serves three or four residences, a deployment architecture referred to as FTTH/power to the curb (FTTH/PTTC).

3. Transmission Losses

As the distance between the power node and the ONU grows farther, power losses dissipated in the resistance of the twisted pair(s) carrying the power between the power node and the ONU also increase. Here a technique for assessing different deployment architectures relative to these transmission losses is discussed and presented. As the quantity of ONUs hosted by a power node increases, the proximity of the power node and ONU also varies; with a power node or power supply located at each ONU, there is no distance between the power source and ONU load. Conversely, a power node serving larger quantities of ONUs is typically be located farther away from ONUs than a power node hosting a smaller quantity of ONUs. The distance between the power node and the ONUs impacts costs in several ways. Though installation expenses are not discussed here, because they vary so widely from deployments in dense, urban cities, to rural and semi-rural business parks, the initial costs of trenching or aerial installations can be significant. However, the incremental costs, specifically associated with powering can be low if the are the twisted pairs carrying the power are collocated with the fiber feeding each ONU. For instance, if the power node is collocated with the remote terminal (RT), the fiber lines feeding each ONU can be routed with the twisted pairs carrying power to the ONUs. Costs which are discussed here, are the transmission losses between the power node and ONU.

Transmission losses in general are reduced by increasing the voltage at which power is transmitted. However in

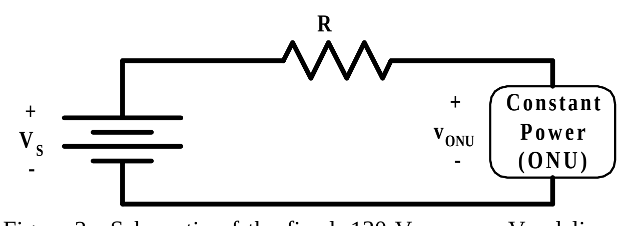

Figure 2. Schematic of the fixed, 130-V source , V_S, delivery power to a constant-power ONU through a copper twisted pair with a resistance R.

fiber-fed applications, the National Electric Code (NEC) with Bellcore TA-1500, limit the transmission voltage to an absolute maximum of 140V, with a nominal output voltage of 130V.

3.1 Loss Calculations

Using Fig. 2, calculations of efficiency and power loss in the copper twisted pair(s) are computed. A fixed source voltage V_S exists with a constant power ONU load of P_{ONU}. Current in the loop of Fig. 2 is calculated as

$$i = \frac{P_{ONU}}{V_{ONU}} \tag{1}$$

Applying Kirchhoff's voltage law to the loop in Fig. 1,

$$v_{ONU} = V_S - i\,R \tag{2}$$

Or, using (1) to express the current in (2), and rearranging

$$v_{ONU}^{\;2} - v_{ONU}\,V_S + P_{ONU}\,R = 0 \tag{3}$$

Though two roots to this quadratic equation exist, circuit analysis, either through small-signal stability analysis of the operating point, or from graphical analysis with load lines, shows that only the larger root of (3) is stable. Thus, solving (3) for the stable, larger root,

$$v_{ONU} = \frac{1 + \left(1 - \frac{4\,P_{ONU}\,R}{V_S^{\;2}}\right)^{1/2}}{2} V_S \tag{4}$$

Most often, to avoid undesired operation at a low-voltage disconnect (LVD) [5], the ONU power supply has a LVD of 65V which is approximately one-half the 130V supply voltage. This 65V LVD does not affect the maximum power which can be transferred to the ONU, since the maximum power transfer theorem shows that the maximum power is transferred to the ONU when the voltage at the ONU load is one half of the source voltage. This is also apparent from (4) as the ONU voltage v_{ONU} becomes less than one-half the supply voltage, the argument of the square root becomes negative, and thus v_{ONU} assumes an imaginary component..

Using (4) to express the ONU voltage v_{ONU}, the efficiency η of the power transmission between the power node and ONU load can be expressed as

$$\eta = \frac{1 + \left(1 - \frac{4\,P_{ONU}\,R}{V_S^{\;2}}\right)^{1/2}}{2} \tag{5}$$

As expected, this transmission efficiency rises as the source voltage V_S is increased, and also is more efficient as the resistance is smaller or as the ONU power is lower. Equation (5) is plotted in Fig. 3 with the loop resistance R as the variable, and with ONU power P_{ONU} as a parameter. Longer loops, with larger resistance have less efficiency. The lowest efficiency is 50 percent, which is the case when the ONU voltage is one half the source voltage.

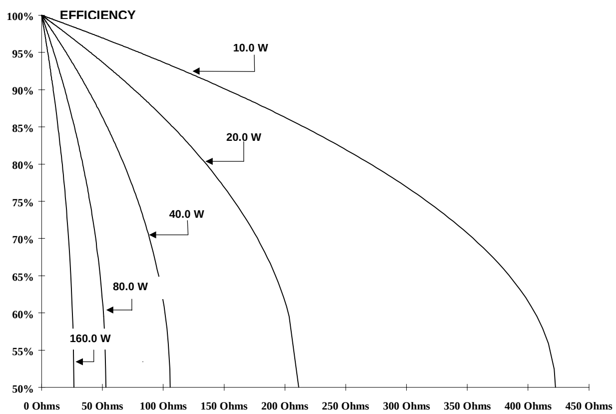

Figure 3. Transmission efficiency for different ONU loads. Powers listed in legend are the ONU power P_{ONU}

Figure 3 can be used to calculate the efficiency of loops using a specific wire gage and length, along with ONU power. As an example, with a ONU load P_{ONU} of 40W, and a 1.33-km (4,360 foot) loop length, using 22 A.W.G. twisted pair with a loop resistance of 112.9Ω per kilometer (34.4Ω per 1,000 feet) at 90°F, or total resistance of 150Ω, the transmission efficiency from Fig. 3 is slightly greater than 75 percent, and from Fig. 4, the power dissipated in transmission is slightly greater than 30 percent of the ONU power P_{ONU}. As more twisted pairs are used for transmitting the power from the power node to the ONU, the resistance of the parallel combination is used in Figs. 3 - 5. For example, use of two 22 A.W.G. pairs over the same 1.33-km loop create a resistance of 56.45Ω, and from Fig. 4 transmission losses which are 10 percent of the ONU power.

An assessment of costs associated with the power transmission losses is based on energy costs. Figure 4 illustrates the ratio between the power delivered to the ONU, which is the power that presumable generates revenue, and the power consumed in transmission losses.

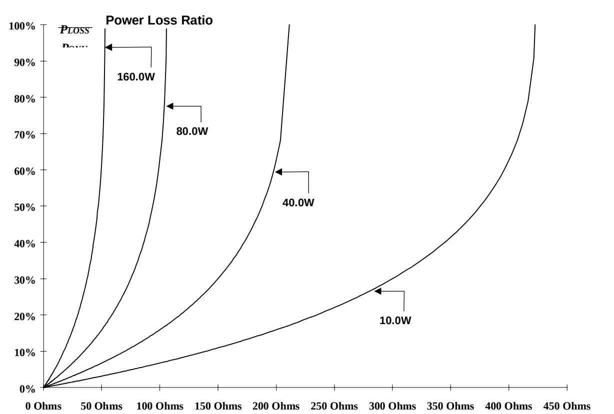

Figure 4. Fraction of ONU power dissipated as transmission losses. Data generated from Fig. 3, with $\frac{P_{LOSS}}{P_{ONU}} = \frac{1}{\eta} - 1$.

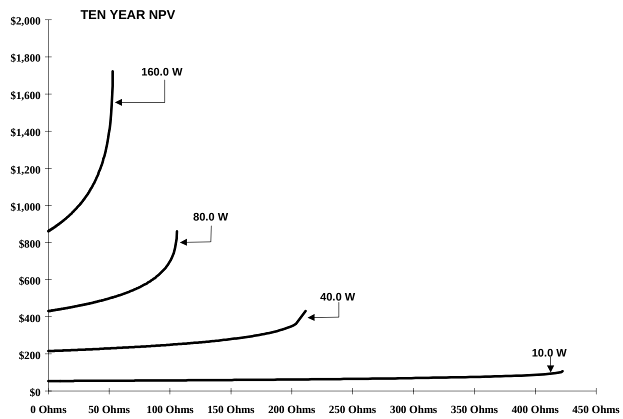

Figure 5. Transmission losses calculated as a net present value costs for a ten-year period. A annual 10 percent cost of money is assumed along with a $0.1/kW-Hr energy cost.

The data in Fig. 4 may be rearranged to provide the power losses in transmission, and these power losses can be assigned a cost, based on the cost of electricity, assumed at $0.1/kW-Hr. These costs of these transmission losses can be assessed on an annual basis and the ten-year cost or ownership derived using as a net present value, as seen in Fig. 5.

3.2 Approximations

Throughout the planning of the power node deployment, transmission losses for different deployment architectures must be compared with a relatively straightforward technique. From a review of Figs. 3 – 5, it is apparent that as the distance between the ONU and power node increases, losses increase approximately as the square of the distance. A review of (4) shows that the voltage is not directly related to the square of the distance, but for planning purposes, assuming the transmission losses are proportional to the square of the distance will allow some simplifying assumptions to be made. Figure 6 illustrates this square-low approximation for the 10-W case. A least squares fit to this loss data, using a square-law loss

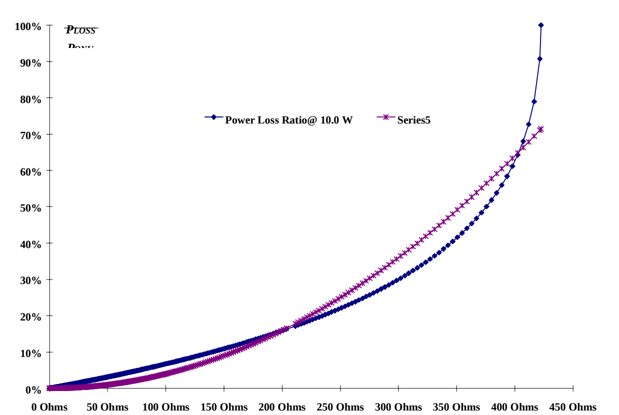

Figure 6. Square law approximation of transmission losses with distance between ONU and power node.

assumption, produces the lighter line in Fig. 6. The equation of this approximation in Fig. 6 is

$$\frac{P_{LOSS}}{P_{ONU}} = 4 \times 10^{-6} R^2 \tag{6}$$

Given the approximation of (6), the total transmission losses in a deployment of ONUs powered by a power node can be approximated by *summing of the square of each individual ONU to power node distance*.

Consider the evaluation of three ONUs arranged in a equilateral triangle, each ONU separated by a distance x. If a power node is collocated with one of the ONUs, power is transmitted to the other two ONUs, each with an ONU-to-power node distance of x. Transmission losses associated with each of these ONUs are proportional to x^2, with total transmission losses of $2x^2$ for this deployment Compare these losses to a deployment architecture with the power node at the center of the equilateral triangle. The power node must transmit power to three ONUs, each at a ONU-to-power node distance $x/\sqrt{3}$. Losses associated with each transmission are this proportional to $x^2/3$. Thus, the total losses in this deployment are proportional to x^2.

A comparison of the transmission losses shows the total transmission losses with the power node located at one of the ONUs are proportional to $2x^2$, while losses with a power node located at the center of three ONUs, produces transmission losses proportional to x^2. Thus a power node located at one of the ONUs produces transmission losses which are twice as large when the power node is located at the geographic center of the three ONUs. Designers now would understand the compromise between the costs and difficulties of acquiring an additional right of way for the power node along with the need to route the copper twisted pairs carrying the power from the power node to the ONUs along routings which differ from the RT-ONU fiber routings. Transmission losses can be compared with the losses when the power node is collocated at one of the ONUs, which also allows sharing of the ONU easement.

The root mean squared distance L_{RMS} is used as the name for the distance quantity which can be used to compute to approximate the total transmission losses for a deployment of ONUs around a power node. The root mean squared distance L_{RMS} is calculated by summing the squares of the ONU-power node distance for each power node and averaging over the number of power nodes, then taking the square root. Transmission losses are approximated from L_{RMS} by squaring L_{RMS} and multiplying by the number of ONUs. Consider the two example given earlier in this section. First, with the power node collocated at one of three ONUs, and at a distance x from the two remote ONUs

$$L_{RMS} = \sqrt{\frac{1}{3}\left\{x^2 + x^2\right\}} = \frac{\sqrt{2}}{\sqrt{3}}x \tag{7}$$

Thus, from (7), the total transmission losses for the three ONUs are proportional to $3L_{RMS}^2$ or $3\left\{\frac{\sqrt{2}}{\sqrt{3}}x\right\}^2 = 2x^2$.

Alternatively, with the power node located equidistant from three ONUs deployed in an equilateral triangle at an ONU-power node distance of $x/\sqrt{3}$

$$L_{RMS} = \sqrt{\frac{1}{3}\left\{\left[\frac{x}{\sqrt{3}}\right]^2 + \left[\frac{x}{\sqrt{3}}\right]^2 + \left[\frac{x}{\sqrt{3}}\right]^2\right\}} = \frac{x}{\sqrt{3}} \tag{8}$$

The total transmission losses with this deployment with three ONUs is $3L_{RMS}^2$ or $3\left\{\frac{x}{\sqrt{3}}\right\}^2 = x^2$.

This approximation of losses with L_{RMS} is used later to approximate the transmission losses for different numbers of ONUs deployed per power node.

3.3 Power Node to ONU Ratio

Here, assumptions are stated which allow the present value cost data to be studied as the number of ONUs per power node is varied. Earlier in this paper, transmission losses and other powering costs have been derived as a function of the loop resistance between ONU and power node. Several rather bold assumptions are made, and these assumptions are not intended to be definitive , but rather to offer a starting point for discussions regarding the cost of different powering architectures.

Assumption 1. The twisted pair(s) running between the ONU and the power node use #22 A.W.G.,and have a round-trip resistance of 34.4Ω per 1,000', which is the resistance of #22 A.W.G. at 90°F.

Assumption 2. Some assumptions regarding the ONU-to-power node spacing are necessary. For lack of any standards, and to allow the analysis to proceed, it is assumed that the ONUs are arranged in ever-widening circles around the power node. The circle closest to the power node is at a radius of 500' from the power node and contains six ONUs. Six is selected since the ONU-ONU distance is thus approximately 500' which is the same as the ONU-power node distance. Located farther away from the power node is another circle of ONUs located at at radius of 1,000 from the power node. To maintain proportions, with the circumference of this second ring equal to twice the circumference of the inner, 500' ring, there are twelve ONUs sited in the 1,000' ring. Finally, at a radius of 1,500' eighteen ONUs are located.

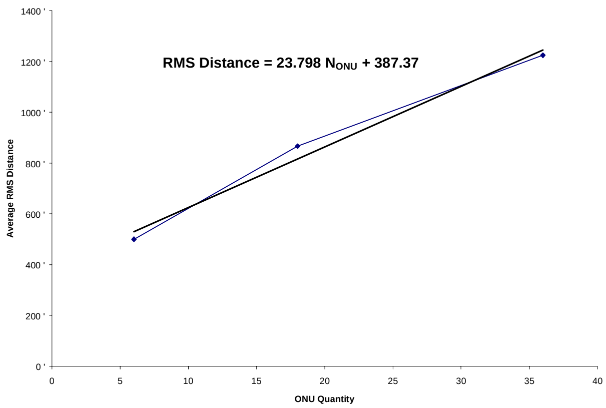

Figure 7. Generated using the assumptions described in Sectoin 3.3, which assume ONU spacings at 500', 1000', and 1,500' radii from a power node. Data plotted here illustrae the mean rms distance between a power node and the ONUs it powers.

For a deployment scenario of six ONUs per power node, the distance between all six ONUs and the power node is 500', and thus the root mean square distance L_{RMS} is also 500'. For deployments of eighteen ONUs, which have six at ONUs located 500' from the power node; and twelve ONUs 1,000' from the same power node, the calculation of the L_{RMS} distance is

$$L_{RMS} = \sqrt{\frac{1}{18}\left\{6[500]^2 + 12[1000]^2\right\}} = 866 \qquad (9)$$

A similar calculation for additional eighteen ONUs at a 1,500' ONU-to-power node distance produces L_{RMS} =1,224'. These root mean square distances are plotted in Fig. 7 along with a straight-line least-mean square fit. Over this range of ONU-to-power node ratios, L_{RMS} can be approximated as

$$L_{RMS} = 23.8 N_{ONU} + 387 \qquad (10)$$

Thus, with (10), the transmission losses can be calculated for any number of ONUs per power node N_{ONU}.

3.4 Transmission Losses: ONUs Per Power Node

The data in Section 3.1 are now recalculated as a function of number of ONUs per power node, using (10). Realize that these characteristics are based on the two assumptions given in Section 3.3. It is expected that deployments may differ greatly from the assumptions given here, but that the techniques developed here can be applied with assumptions more realistic to specific deployments. Figure 8 plots the total power per ONU as the quantity of ONUs per power node varies. As the quantity of ONUs per power node increases, the distance between the ONUs and the power node increases and thus the losses increase. Practically, as the distance becomes too great, the resistance of the twisted pairs carrying power to the ONU restricts the maximum distance. Further ONU-power node distance is possible, but multiple twisted pairs must be devoted to each ONU for power. Figure 8 is entirely based on a single twisted pair for power at each ONU.

The data in Fig. 8 can be recomputed based on a 10-year operating cost, using net present value (NPV). Here, a ten percent cost of money is assumed and a $0.10/kW-Hr is also used. The ten-year NPV for a each ONU is seen in Fig. 9 plotted for different numbers of ONUs served by a single power node. These data will be combined with the NPV data for the status monitoring in Section 6.

4. Redundancy Costs

Cost-effective reliability of the power node is often ensured by using redundant elements in the power-processing path. If a power-processing element should fail, the output is not affected because the redundant unit is present. However, this redundancy has different costs as the size of the power node changes. Also, the cost of a watt varies as the size of the power-processing unit changes. Table 2 contains some examples of rectifier pricing which illustrate the savings which accompany power-processing units of larger size; for larger size rectifiers, the cost per Watt is one half the cost per Watt of

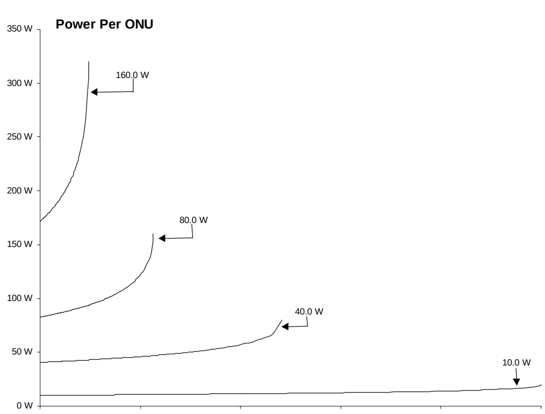

Figure 8. Transmission losses and P_{ONU} plotted as a function of the number of ONUs per power node changes.

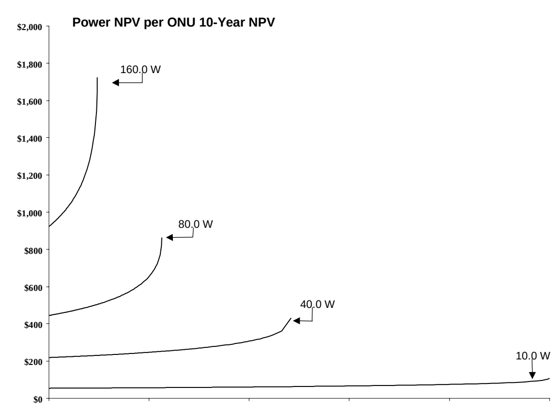

Figure 9. NPV for transmission losses and P_{ONU} from Fig. 7 plotted as a function of the number of ONUs per power node changes.

Size [Watt]	Cost [$/Watt]
150W	$2.07
500W	$1.38
2,500W	$1.23
5,000W	$0.94

Table 2. Price decreases on a dollar per watt basis as the power-processing size becomes larger.

a smaller rectifier.

Generally, for redundant powering configurations, a good size for the power-processing unit produces a powering system which has two or three parallel units [6], along with an additional redundant unit. Thus, the complete power-processing system contains three or four parallel units. Using smaller powering units, and paralleling produces a more expensive system since the wattage of the individual units is smaller and thus the cost per watt higher as seen in Table 2. If a complete system contains only two power-processing units, a primary unit and a redundant unit, the wattage of the redundant unit must equal the primary unit and a power-processing system with a power rating equal to twice the load power results. Such as system is penalized by cost since the system wattage is twice the load wattage.

Table 3 lists the quantity of and size of the rectifiers necessary to offer redundant power to loads of 100W, 500W, 1,000W, and 2,000W. Clearly, the trend indicated by this Table 3 is that cost per watt decreases as the power node wattage grows larger. Using Table 3, for powers above 500W, the costs, on a dollar per watt cost basis, can be approximated by a linear relationship

$$\frac{Cost[\$]}{Watt} = -0.38P[Watt] + 2.85 \qquad (11)$$

The reduction in powering costs, approximated by (11), are applied to results in the conclusion.

5. Other Costs

Battery plant lifetimes are known to be limited in the

Load Power [Watt]	Rectifiers		Cost [$/Watt]
	Quantity	Size	
150W	2	150W	$6.21
500W	4	150W	$2.48
1,000W	3	500W	$2.07
2,000W	5	500W	$1.72

Table 3. Cost on a dollar per watt basis for rectifier power processing using the costs of Table 2. Rectifier quantities are based on a redundant, N+1, configuration.

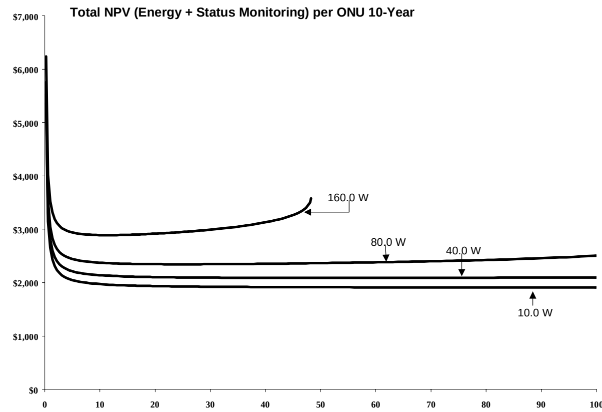

Figure 10. Total NPV per ONU as the number of ONUs per power node varies. Total NPV includes power costs for ONU power, transmission losses, and the NPV of status monitoring.

outside plant. An advantage of a power node, is that the battery plant in the power node is shared among the ONUs powered by the power node, and thus more of an investment can be made to prolong battery life. For example, as seen earlier in Section 2, status monitoring is cost effective when the power node provides power to more than two or three ONUs. Battery life is extended by the status monitoring. Status monitoring can detect a fan failure or other breakdown in an environmental control system which causes an elevated temperature within the battery compartment, before the elevated temperature has an opportunity to shorten the battery life. Since the status monitoring costs, both initial and operating, are proportional to the quantity of power nodes, as more ONUs are powered out of a single power node, the costs are reduced on a per ONU basis.

6. Cost Summation

Combining the cost per ONU which arise from status monitoring of the power node, seen in Fig. 1, along with the cost for the transmission losses in Fig. 9, produces the total cost per ONU to power these ONUs seen in Fig. 10. It is apparent that for smaller ONUs, such as a 40-W ONU, that the minimum cost function contains a broad minimum. Deployments which serve greater numbers of these smaller ONUs from a single power node exhibit cost-effective powering because the transmission losses with the smaller ONUs do not rise greatly as the ONUs are located farther and farther from the power node. A different situation exists with larger ONUs. Transmission losses with larger ONUs rise significantly as these larger ONUs are located farther away from the power node. For this reason, the powering cost profile for larger ONUs increases relatively quickly as the number of ONUs grows. Independent of size, powering each ONU with an independent power source, such that the ONU to power node ratio is one, produces a relatively high powering cost because the status monitoring expenses for placing status monitoring hardware at each and every ONU and for displacing one POTS line at each ONU is expensive.

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