ethernet alliance

Power over Ethernet - Cable Losses

Lennart Yseboodt, Philips Lighting
Chad Jones, Cisco
David Tremblay, HPE

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1. Introduction

Power over Ethernet is a popular technology to supply low voltage DC power to devices, such as a WiFi access points, security cameras, or LED lighting. Power over Ethernet is standardized by the IEEE 802.3 Working Group [1], in Clause 33 of IEEE Std 802.3-2015 [2]. The main benefit of PoE is that the data cable is also used to provide power to the device, thereby taking away the need to provide a mains outlet. This saves substantially on installation costs. This standard describes the transfer of power using 2 pairs out of the 4 available pairs in a network cable and allows up to 25.5 W to be delivered to a load.

A new version of the specification is currently being developed by the IEEE P802.3bt Task Force [3] in Clause 145, with an expected release date early 2018. This new version will define operation over all 4 pairs of the network cable. By using all of the available copper, power is delivered with lower losses, and a larger amount of power can be delivered.

The need for this white paper arises out of a lack of available information about cable losses in Power over Ethernet systems. Often quoted cable power loss numbers from the standard give the impression that cable losses are very high. In this white paper we'll look at the existing standard, and the draft standard in development to explore what is really going on.

The conductors in network cable are much thinner than those in well known appliance cords or AC mains cable. Figure 1 shows the cross section of a common 2.5 mm^2 AC mains cable, next to 23 AWG CAT6 cable at the same scale. Obviously the amount of copper in the network cable is much less than the AC mains cable. Therefore it is undeniable that losses will be high. Gut feeling strongly pushes us toward this erroneous conclusion. This perception is further strengthened by the total physical size of the cable. Mains cable requires much thicker isolation than network cable, further contributing to the impression that network cables are very inefficient at transferring power.

Figure 1: Cross section of 2.5 mm^2 solid copper mains wire, next to solid copper 23 AWG CAT6 cable at the same scale.

Network wire gauge

How much copper is there really in network cables ? And how much of it conducts electricity?

In the AC mains cable leftmost in Figure 1, the brown and blue jacketed conductors supply power. The green/yellow conductor is the earth conductor. It does not carry current in normal operation, 66% of the copper is used for power transfer.

The network cable on the right has eight individual conductors. Each two conductors are twisted and form a twisted pair. The current IEEE Std 802.3-2015 standard allows two pairs to be used to supply power. The new standard will allow all four pairs to be used to supply power. This means that either 50% or 100% of the copper in the network cable is used for power transfer.

Figure 2 compares the cross-sectional area of typical mains wiring and typical network wires at various gauges. To be able to accurately compare the equivalent amount of copper in a network cable, the area of 4 conductors is added up and displayed as if it were a single conductor at the same scale. The individual conductors in a network cable give the impression of a small amount of copper. However, in reality, the 4 conductors of a 24 AWG network cable are equivalent to a 1 mm^2 copper conductor. 22 AWG is equivalent to 1.3 mm^2.

This comparison illustrates that network cables in fact have a significant amount of copper. The amount of copper a cable is relevant because it is related to the resistance of the cable, and hence the power which will be lost in the cable due to Ohm's Law.

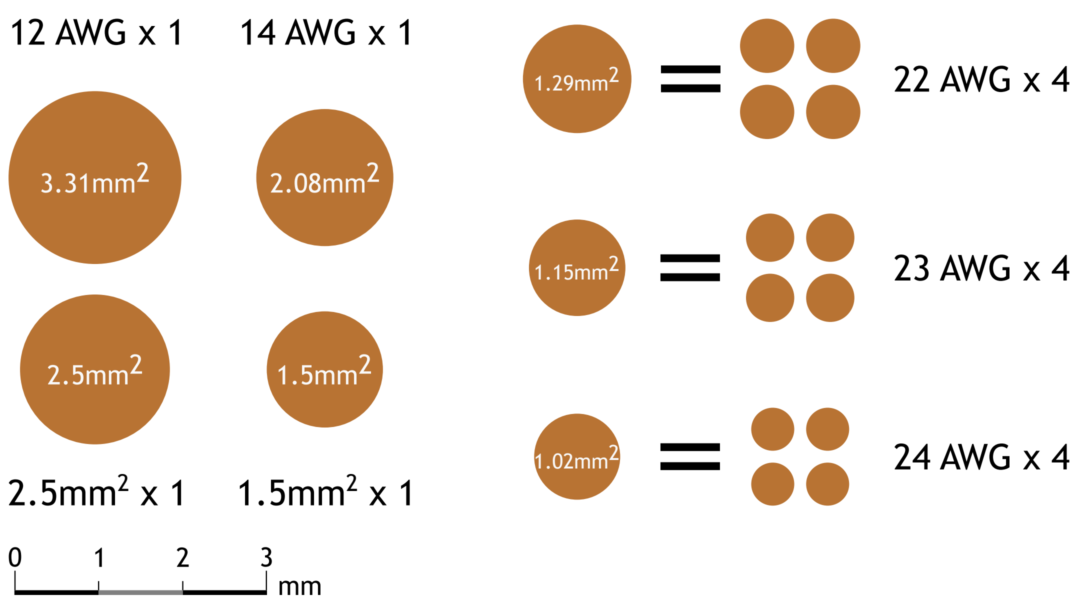

Figure 2: The amount of current carrying copper in AC mains cable compared to multi-conductor network cabling (same scale).

Definition of cable loss

A clear definition of cable loss is needed. In this paper we will refer to "relative cable loss". Relative cable loss is defined as the amount of power dissipated in the cable, divided by the amount of power provided at the source side of the cable. In Power over Ethernet terminology the sourcing device is called the PSE (Power Sourcing Equipment), while the consuming side is called the PD (Powered Device).

$$\text{relative cable loss} = \frac{\text{power dissipated in cable}}{\text{power provided by PSE}} \cdot 100\% \qquad (1)$$

This definition of relative cable loss is used throughout this document.

2. Theoretical losses

An interoperability standard describes the limits under which a system remains operational. Those limits are determined by a number of essential parameters. Concerning power loss in the cable, the parameters from the IEEE P802.3bt standard listed in Table 1 are relevant and used in this paper.

Table 1: IEEE P802.3bt parameters that influence cable loss

V_{PSE}	The output voltage at the PSE, which is in the range of $V_{Port\_PSE\text{-}2P}$
$V_{Port\_PSE\text{-}2P}$	The allowed output voltage range at the output of the PSE
I_{Cable}	The highest nominal DC current through a twisted pair
R_{Chan}	The actual channel resistance which is in the range of R_{Ch} when operating in 2-pair mode, or in the range of $R_{Ch}/2$ when operating in 4-pair mode
R_{Ch}	The maximum channel resistance, specified for two pairs in series.
P_{Class}	The power sourced by the PSE
P_{Class_PD}	The power consumed by the PD

In a worst-case operating condition, the PSE voltage (V_{PSE}) will be the minimum allowed, the channel resistance will be the highest that is supported (R_{Ch}), and the power consumed will be the highest that is allowed for a given PD Class (P_{Class_PD}) . This particular combination result in a current of I_{Cable} flowing through the channel. The power dissipated in the cable is then:

$$P_{Cable} = I_{Cable}^2 \cdot R_{Ch} \qquad (2)$$

Alternatively, given V_{PSE}, P_{Class_PD}, and R_{Chan}, the power dissipated in the cable can be calculated as follows:

$$P_{Cable} = \left(\frac{V_{PSE} - \sqrt{V_{PSE}^2 - 4 \cdot R_{Chan} \cdot P_{Class\_PD}}}{2 \cdot R_{Chan}} \right)^2 \cdot R_{Chan} \quad (3)$$

The worst-case parameters depend on the amount of power that is provided by the PSE. The PSE's power allocation happens during classification, when the PSE allocates a certain power Class to the PD. IEEE P802.3bt supports nine Classes, numbered 0 through 8. Each corresponds to a certain PSE power level and a PD power level. An overview, as well as the calculation of the maximum P_{Cable}, is shown in Table 2 and Equation 3. The last column in Table 2 shows that the maximum relative cable loss can be quite high.

For example, the worst-case parameters would lead you to believe that operating at Class 6, the PSE can deliver 60 W, of which 51 W is delivered to the PD, and 9 W is dissipated in the cable. 15% of the sourced power is dissipated in the cable! When operating at Class 8 power levels, up to 20.8% of the power can be lost in the cable. The legacy 802.3af standard may support very high cable power losses as well, due to it allowing operation over CAT3 cable, which can have to 20 Ω of loop resistance. A Class 3 system can have up to 15.9% power lost in the cable.

These theoretical losses are precisely that: theoretical. It would take three parameters to be precisely at their worst case value, in order to actually have the losses as listed in Table 2. Moreover, the loss equations 2 and 3, that determine the power dissipated in the cable are non-linear. Changing any of the basic parameters causes a quadratic decline in cable losses. Actual losses are discussed in Section 3.

Table 2: Calculated worst-case P_{Cable} for each possible power Class, with each parameter at its worst-case value.

Class	P_{Class} (W)	P_{Class_PD} (W)	V_{PSE} (V)	R_{Chan} (Ω)	I_{Cable} (A)	P_{Cable} (W)	**Loss (%)**
3	15.4	12.95	44	20.00	0.350	2.45	**15.9**
4	30	25.50	50	12.50	0.600	4.50	**15.0**
5	45	39.94	50	6.25	0.900	5.06	**11.3**
6	60	51.00	50	6.25	1.200	9.00	**15.0**
7	75	62.00	52	6.25	1.442	13.00	**17.3**
8	90	71.28	52	6.25	1.731	18.72	**20.8**

3. Actual losses

Actual losses are determined by the amount of current that is flowing through the cable and the effective channel resistance, R_{Chan}. Resistance is determined by the conductor thickness, and the length of the cable. Most PDs are “constant power” devices, means that they will draw a certain amount of power at the PD’s interface. Depending on the input voltage, the PD will draw more or less current to satisfy its power need.

A number of configurations are shown in Figure 3 that show the effect of the combination of PSE voltage, cable length, and cable conductor thickness.

These cases allow a quick comparison of actual losses versus theoretical worst-case losses supported by the standard (the red line). The cases were selected to cover a wide range of practical applications. Refer to [4] for an overview in deployed cable: the average cable length in installations is 40 to 50 meter. CAT6 and CAT6a cable type is picking up rapidly for new installations, these cables typically are constructed with 23 AWG, compared to 24 AWG for CAT5e. Case 4 in Figure 3 is a good candidate for typical performance.

Take the example of a Class 4 PD (25.5W), which may have a loss as high as 15% according to the standard, but in the typical case 4, the loss is below 2%, constituting a 13 percentpoint difference. Class 6 PDs (51W), also may have losses as high as 15%, but case 4 results in losses of only 2.5%.

The red line shows a worst case channel per P802.3bt (R_{Chan} = 20 Ω up until 13 W, after which R_{Chan} = 12.5 Ω) at the lowest PSE voltage of 44 V, 50 V, and 52 V. For a PD power below 25.5 W the PSE is operating in 2-pair mode. Above 25.5 W, the PSE operates in 4-pair, which causes the drop in cable loss at that wattage (R_{Chan} becomes 6.25 Ω). Below 13 W the PSE may have a voltage as low as 44 V, above 13 W the minimum is 50 V. For 51 W and up, the minimum is 52 V.

Case 2: V_{PSE} = 50 V (52 V for $>$51 W), with 100 m of 24 AWG cable in 4-pair mode

Case 3: V_{PSE} = 52 V, with 100 m of 23 AWG cable in 4-pair mode

Case 4: V_{PSE} = 55 V, with 50 m of 23 AWG cable in 4-pair mode

Case 5: V_{PSE} = 55 V, with 25 m of 24 AWG cable in 4-pair mode

Case 6: V_{PSE} = 55 V, with 25 m of 22 AWG cable in 4-pair mode

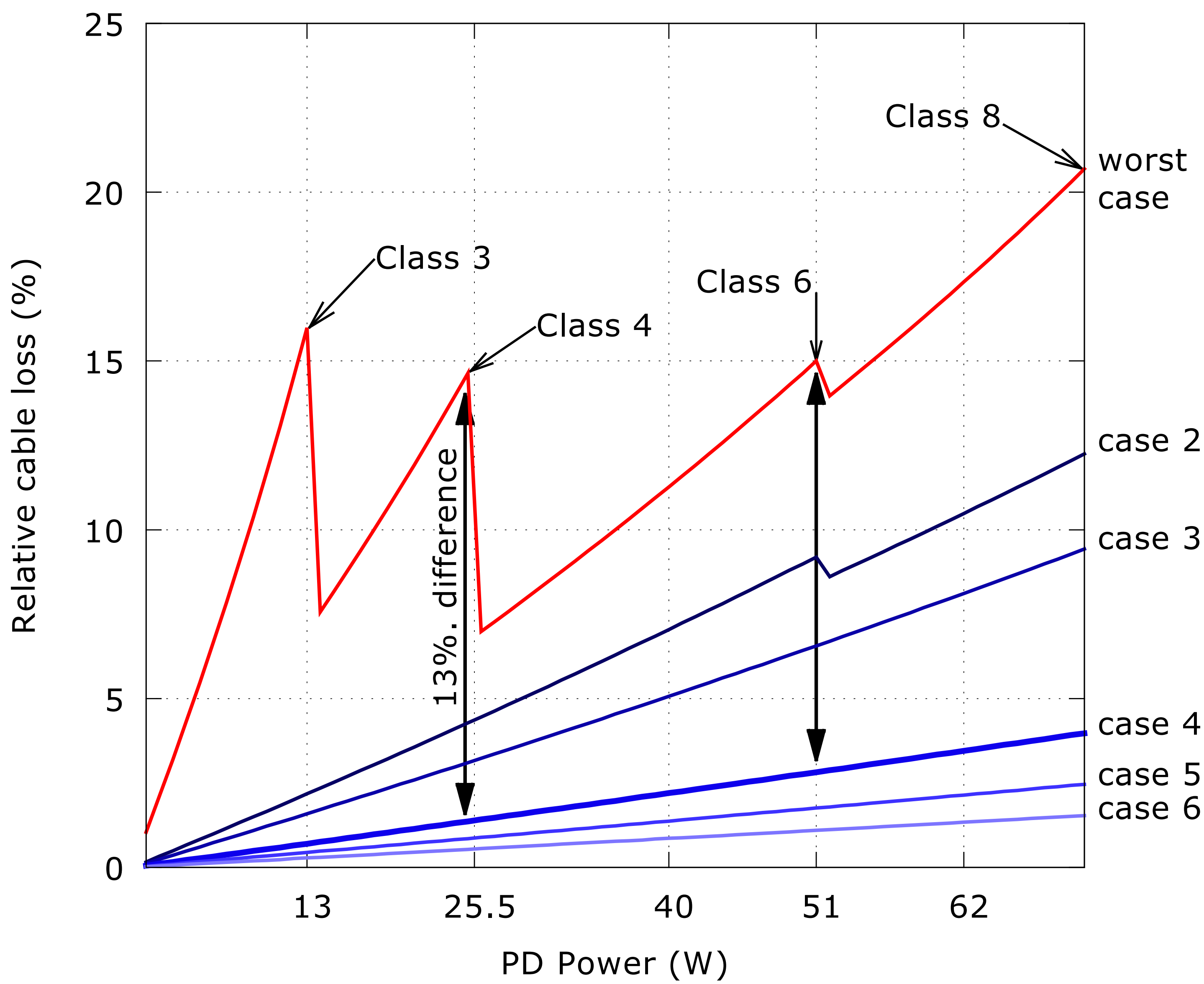

Figure 3: Relative cable losses versus the power consumed in the PD for various scenario's. Actual losses turn out to be far lower than those in a pure worst-case system.

4. Actual system losses

So far we've considered the cable losses for a single PSE and PD. This section will deal with larger installations. A simulation is made of a 2400 square meters (25833 sq. ft.) office building, with PDs distributed throughout. The PDs are PoE LED fixtures, placed in a 1.8 m by 1.8 m grid. The building is schematically shown in Figure 4.

The simulations that are carried out, are aimed to be as realistic as possible. An actual floor plan of the building is used to obtain accurate cable lengths. Also contact resistance from connectors is taken into account, as well as various resistances as encountered in real devices. For the loads, power consumption models based on measurements are used.

Each fixture requires 45 W, and is connected through a 24 AWG network cable. The PSE voltage is 52 V, and power is provided over 4-pair. These conditions are chosen to be typical, even low-end. The simulation calculates each individual fixture (load) and cable independently and then aggregates the results for the entire system.

A floor on this building has 650 fixtures, with a total power demand of nearly 30 kW. Simulation shows the following results:

Average cable length	38.7	m
Longest cable length	71	m
Total cable length	25183	m
Total power sourced by the PSE	29388	W
Total power dissipated in cables & connectors	788	W
Relative cable loss (system)	2.68	%

While cable losses (relative to delivered PSE power) are 2.68%, the longest cable in this system has 9% loss. This demonstrates that there are large differences between the worst-case cable in a system and the actual system performance.

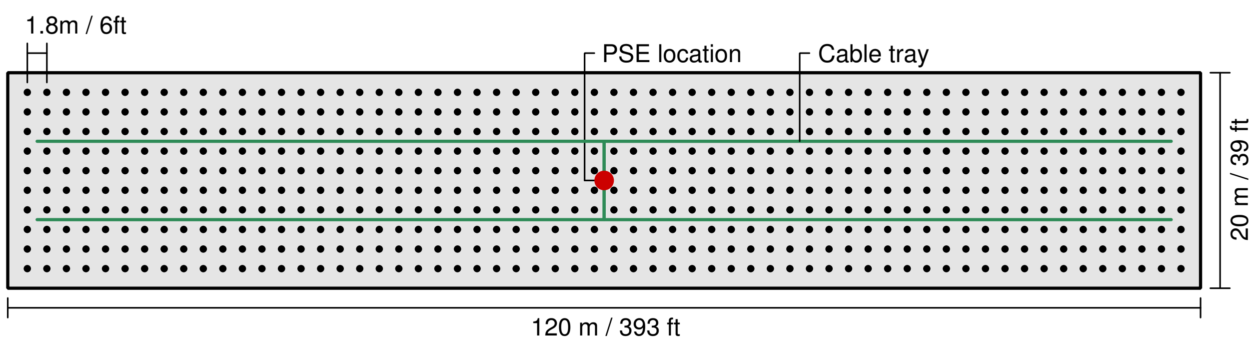

Figure 4: Large building (2400 m^2, 25833 sq. ft.) where one floor is simulated. 650 fixtures with power demand of 45 W are located every 1.8 m. Network cables are routed through cable trays in two corridors in the simulation.

The effect of decreasing the wire gauge on this system is pronounced. The simulation is re-run with 23 AWG and 22 AWG cable:

Cable gauge	Power in cables (W)	Worst cable (%)	**Cable loss (%)**
24 AWG	788	8.99	**2.68**
23 AWG	617	6.99	**2.11**
22 AWG	483	5.44	**1.66**

For installations with high average cable lengths, and make extensive use of PoE, it makes sense to make use of lower gauge cables to reduce losses.

5. Conclusion

This paper covers Power over Ethernet cable power losses. Both the existing IEEE Std 802.3-2015, and the upcoming IEEE P802.3bt standard are covered.

Power over Ethernet is perceived as a system which inevitably comes with high cable losses. This misperception is caused by the assumption that network cables have an insignificant amount of copper and a corresponding high DC resistance, causing high power losses in the cable. This problem is compounded by a common misinterpretation of the corner-case operating points supported by IEEE Std 802.3-2015. While the standard guarantees operation even with high resistance cable, this is assumed to reflect typical performance.

The amount of copper in network cables is actually substantial. When 4-pair Power over Ethernet is applied, all of the copper in the cable is used to deliver power. More important however is that a network cable only carries the current for a single load, due to the star topology of PoE. Power dissipation in the cable is determined by the square of the current, making this the most relevant parameter.

At the interoperability boundary conditions supported by the standard, relative cable losses of 15% seem to be the norm. Operation at 90 W even sees a potential cable loss of 20%. However these numbers are only relevant as the extreme conditions in which interoperability and operation is still guaranteed by the standard. The cable standards on which IEEE Std 802.3-2015 builds, specify a maximum DC resistance of 12.5 Ω loop resistance for any cable type. Actual cable resistance is substantially below this, resulting is much lower actual losses than the worst-case possible.

Actual losses in cables are influenced by: the DC resistance of the cable, the length of the cable, the PSE voltage and the required power of the PD. The majority of PDs draw a constant amount of power. If the PSE voltage is higher, the required current is lower, which in turn affects cable power losses.

The performance of complete PoE systems, which consist of many PSEs and PDs and the cables between them, is determined by the total cable losses. Total cable losses are the sum of the power dissipated in each cable, relative to the total amount of power that is being sourced. In systems where there are many different cable lengths, the performance of the system is much better than the performance of the longest cable in such a system.

In a PoE LED lighting system with short cables, an aggregated cable loss of 0.5% is calculated. A very large scale PoE LED lighting system, with 650 high power PDs connected to a single location, aggregated cable losses of around 2% are calculated, while the worst-case cable in that system has 7% loss.

The conclusion from these calculations is that in Power over Ethernet systems the power losses in network cables are lower than one would expect, and the cable losses in a system are far lower than the losses in the worst cable in said system. The maximum loss numbers allowed by the IEEE Std 802.3-2015 standard do not reflect the actual system performance which is much better.

References

[1] http://www.ieee802.org/3/

[2] https://standards.ieee.org/about/get/802/802.3.html

[3] http://www.ieee802.org/3/bt/

[4] http://www.ieee802.org/3/NGEBASET/public/jan15/jones_ngeabt_04c_0115.pdf