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Heating Effects for Remote Power Delivery over Bundled Cables

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Introduction

There is a lot of interest in the industry about the power handling capability of different cables to power up devices that can consume up to 60 Watts or more of power. Some applications, for example HDBASET are looking at the capability of delivering up to 100 Watts of power for audio/video devices such as HDTV monitors. When I see these high power values, my first concern is the heating effect resulting from the current that is flowing in the cables to power up these devices.

The official position in the industry is the IEEE 802.3at Power over Ethernet Standard that specifies a Power handling capability for Type 2 operation of 25.5 Watts over 2 pairs of Category 5e cabling and potentially up to 60 Watts when powering over 4 pairs using Category 6 and Category 6A cables. TIA has also published a Telecommunications Systems Bulletin (TSB-184) that supplements the information contained in the IEEE 802.3at Standard regarding cable bundling, temperature rise and current capacity.

The Power Sourcing Equipment needs to comply with Safety Extra Low Voltage (SELV) limited power source requirements, which limit the maximum voltage to 60 volts for safety. The maximum current per pair that is specified in the IEEE 802.3at PoE Standard is 600 mA. Using these values, the maximum power delivery is between 50 and 60 Watts when all 4 pairs are energized. What happens when we try to deliver higher power levels to the remote device? The source current will need to increase, which will generate more heat due to resistive heating of the conductors. The heating effect is proportional to the square of the current flowing in the conductors. For example, a 50% increase in the source current results in a 125% increase in the heat generated within the cable. Obviously, there is a concern about overheating the cables.

How much power can be delivered from the Power Sourcing Equipment (PSE) to the Powered Device (PD) without overheating the cables?

In order to answer this question we performed a controlled experiment to evaluate the heat generated in a cable bundle when delivering DC power to the powered device. The general test setup is shown in Figure 1 below. The same test setup was used for testing different cable types, including Category 5e, Category 6 and Category 6A.

Additional detail on the cable spooling configuration is shown in Figure 2.

The cutaway view of the spool shows a compact arrangement of surrounding cables (side-by-side) and (top-to-bottom) that are touching each other. The portion of the cable that is positioned in the center of the spool (shown in yellow) is surrounded by four layers above and four layers below as well as four cables on either side. This spooling simulates a tight bundled configuration of 81 cables (9x9). However, as far as the heating effect is concerned, this configuration is actually worse than an 81 cable bundle suspended in the air. This is because the total surface area exposed to ambient air temperature for a spool is less than the surface area when the cables are suspended in air. The plastic flanges of the spool also act as an insulating barrier. Our results show that the simulated 81 cable configuration on a spool is equivalent to the results expected for a 100 cable bundle suspended in air.

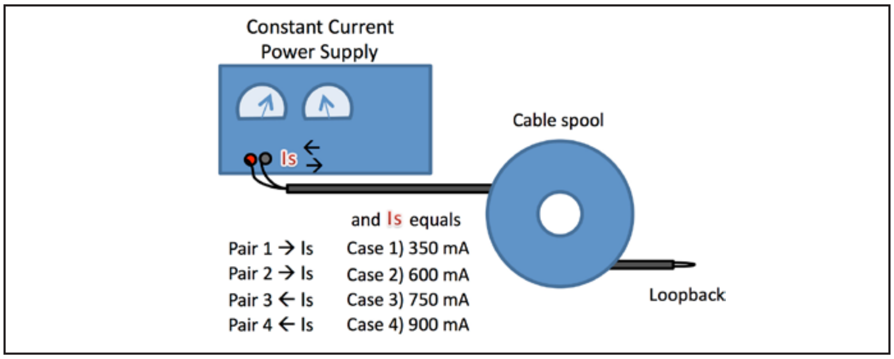


Figure 1 – General test setup for PoE heating experiment with all 4 pairs energized

The controlled experiment was performed by energizing 2 pairs as well as 4 pairs with different levels of applied current as shown in Figure 1.

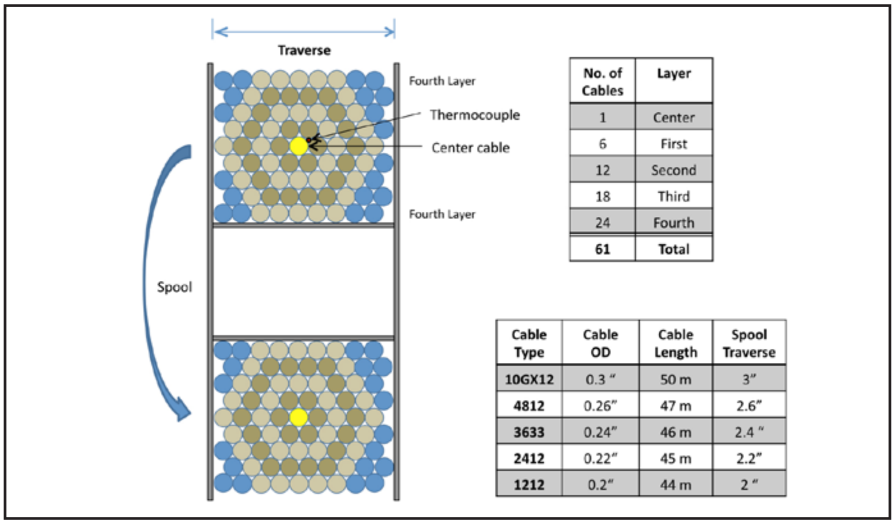
Resistive Heating and Remote Power Delivery

For the system shown in Figure 2, heat is generated within the cable bundle due to the current flowing in the conductors of the pairs that are energized. The amount of resistive heating that is generated is proportional to the (I^2R) losses of the conductors that are carrying the current.

If the resistance of each conductor is R, the resistance of a pair (two conductors in parallel) is R/2. Since the current travels along one pair and returns along another pair, the loop resistance when powering over two pairs is (R/2 + R/2) = R, which is the same as the resistance of a single conductor. The IEEE 802.3at Powering over Ethernet (PoE) Standard assumes that the maximum DC pair loop resistance of a 100 meter channel (R_{Chan}) is 12.5 Ohms for Category 5e and higher Category cabling. This takes into account temperature variations and resistance of connections.

The top left and the top right quadrant of Table 1 identifies the variables and the associated values specified in the IEEE 802.3at Standard for remote power delivery corresponding to Type 1 and Type 2 operation over 2 pairs. The nominal highest DC current per pair (I_{Cable}) for Type 2 operation is 600 mA. Type 2 operation provides the capability to deliver between 25 to 30 Watts at the Powered Device (PD) when powering over two pairs. The power delivery over 4 pairs is effectively doubled, i.e., between 50 to 60 Watts.

The bottom left and the bottom right quadrant of Table 1 shows the power delivery capability for a source current (I_{Cable}) 25% and 50% higher than Type 2 operation and keeping the same R_{Chan} value of 12.5 Ohms. For I_{Cable} of 750 mA the power delivery capability is between 30 Watts to 36 Watts over 2 pairs and between 60 to 72 Watts over 4 pairs. For I_{Cable} of 900 mA the power delivery capability is in the range of 35 Watts to 41 Watts over 2 pairs and between 70 to 82 Watts over 4 pairs.

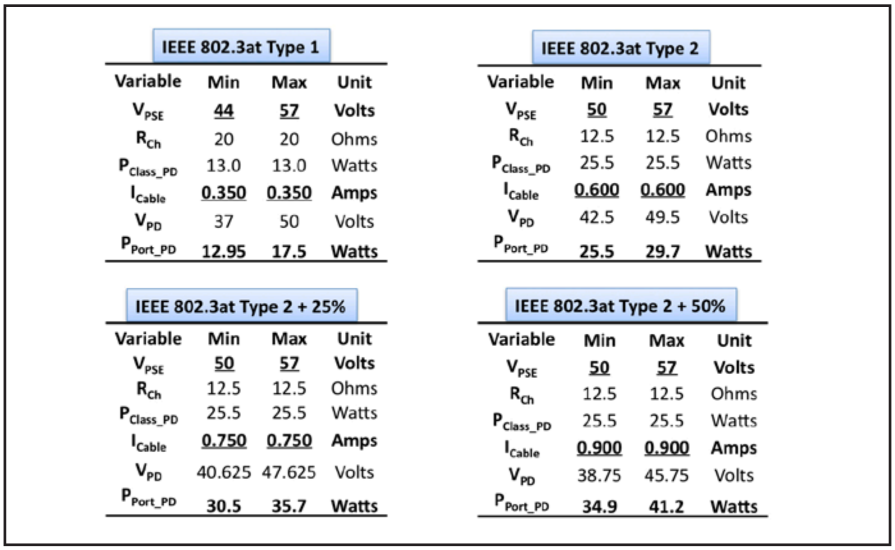


No. of Cables	Layer
1	Center
6	First
12	Second
18	Third
24	Fourth
61	**Total**

Cable Type	Cable OD	Cable Length	Spool Traverse
10GX12	0.3 "	50 m	3"
4812	0.26"	47 m	2.6"
3633	0.24"	46 m	2.4 "
2412	0.22"	45 m	2.2"
1212	0.2"	44 m	2 "

Figure 2 –Cable spooling configuration simulates a tight bundle of 61 cables

Note: The cables highlighted in light and dark gray correspond to a "60 around 1" cable bundle, i.e., with four layers of cable surrounding the center cable. The additional cables in the outer layers (shown in blue colour) generate more heat than a 61 cable bundle suspended in air. Also, the side and bottom flanges of the spool reduce the heat dissipation of the cable bundle to ambient air due to convective cooling.



IEEE 802.3at Type 1

Variable	Min	Max	Unit
V_{PSE}	44	57	Volts
R_{Ch}	20	20	Ohms
P_{Class_PD}	13.0	13.0	Watts
I_{Cable}	0.350	0.350	Amps
V_{PD}	37	50	Volts
P_{Port_PD}	12.95	17.5	Watts

IEEE 802.3at Type 2

Variable	Min	Max	Unit
V_{PSE}	50	57	Volts
R_{Ch}	12.5	12.5	Ohms
P_{Class_PD}	25.5	25.5	Watts
I_{Cable}	0.600	0.600	Amps
V_{PD}	42.5	49.5	Volts
P_{Port_PD}	25.5	29.7	Watts

IEEE 802.3at Type 2 + 25%

Variable	Min	Max	Unit
V_{PSE}	50	57	Volts
R_{Ch}	12.5	12.5	Ohms
P_{Class_PD}	25.5	25.5	Watts
I_{Cable}	0.750	0.750	Amps
V_{PD}	40.625	47.625	Volts
P_{Port_PD}	30.5	35.7	Watts

IEEE 802.3at Type 2 + 50%

Variable	Min	Max	Unit
V_{PSE}	50	57	Volts
R_{Ch}	12.5	12.5	Ohms
P_{Class_PD}	25.5	25.5	Watts
I_{Cable}	0.900	0.900	Amps
V_{PD}	38.75	45.75	Volts
P_{Port_PD}	34.9	41.2	Watts

Table 1 – Power delivered over 2-pairs for a source current of 350 mA, 600 mA, 750 mA and 900 mA

Note: Table 1 assumes a worst case resistance R_{Chan} of 12.5 Ohms. For Category 6/6A cabling, R_{Chan} is typically much lower e.g. 10 Ohms. Lowering R_{Chan} from 12.5 Ohms to 10 Ohms would reduce the heat generated within the cable bundle and increase the power delivered to the PD by about 5% for the same source voltage (V_{PSE}) and the same source current (I_{Cable})

Thermal Time constant

Figure 3 illustrates the heat transfer mechanism for a system comprised of a Power Source, a Powered Device and a Cable that carries current from the Power Source to the Powered Device. Heat is generated within the cable bundle due to resistive heating of the conductors that are carrying the current and is dissipated to the environment through convective cooling.

For **convective cooling or warming**, the equation for the difference between the temperature of the system that is generating heat and its surroundings as a function of time $\Delta T(t)$ is given by:

$$\Delta T(t) = \Delta T_f \, (1 - e^{-t/\tau}) \qquad (1)$$

where $\Delta T(t) = T(t) - Ta$ is the temperature rise at time t, Ta is the constant ambient temperature and ΔT_f is the final temperature difference when the system reaches equilibriuym, $T = T_f$. In words, the temperature rises at an exponentially slow rate until equilibrium is reached, which is determined by the thermal time constant.

$$\tau = \frac{\rho c_p V}{h A_s} \qquad (2)$$

where ρ = density, c_p = specific heat and V is the body volume, h is the heat transfer coefficient, and A_s is the surface area. The time constant says that larger masses and larger heat capacities lead to slower changes in temperature, while larger surface areas and better heat transfer lead to faster temperature changes.

Source:
http://en.wikipedia.org/wiki/Time_constant

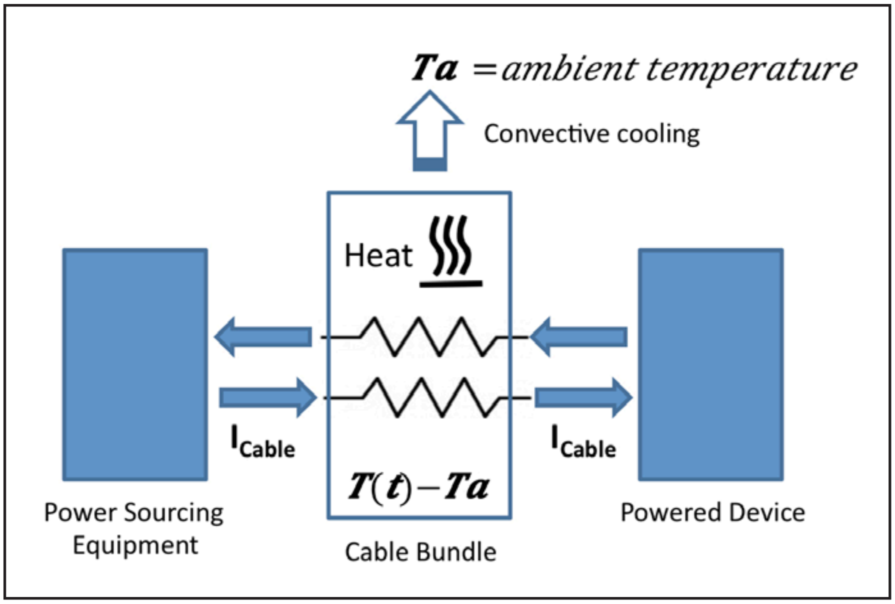


Figure 3 – Temperature rise within a cable bundle due to resistive heating

The effect of "temperature rise" on transmission performance

For copper cabling, the parameter that is most affected by temperature is the Insertion Loss (IL). The TIA 568 C.2 Standard specifies Insertion Loss at a temperature of 20 °C. For every 10 °C increase in temperature, the Insertion Loss of the cable can increase by up to 4% for temperatures up to 40 °C and up to 6% for temperatures between 40 °C and 60 °C. Therefore, in order to meet a full-100 meter channel distance without "length de-rating" at higher temperatures requires more IL margin. Generally speaking, Category 6 and Category 6A cables are manufactured with larger 23 AWG and provide more IL margin for applications such as Gigabit Ethernet. Because of the heating effect of Power over Ethernet over bundled cables, it makes sense to install higher performance Category cabling to provide additional IL margin. Table 3 shows the IL margin for Category 5e, Category 6 and Category 6A channels for the Gigabit Ethernet (1000BASE-T) application. Category 6 channels provide an IL margin of 11%, which can offset the increase in Insertion Loss due to a temperature rise of 25 °C.

Insertion Loss for 100m channel at 20°C		
	Maximum IL @ 100 MHz (dB)	IL Margin (%)
1000BASE-T	24	
Category 5e	24	0.0%
Category 6	21.3	11.3%
Category 6A	20.9	12.9%

Table 2 — Insertion Loss margin for 1000BASE-T application

Test Results

The following cable types were tested using the test setup shown in Figure 1 and the cable spooling configuration shown in Figure 2

Cable Code	Category	Maximum Conductor DC Resistance @ 20C	Description
10GX12	6A	7.4 Ohms/100m	23 AWG solid copper, 4 pairs, H-Spline, CMR
4812	6	6.6 Ohms/100m	23 AWG solid copper, 4 pairs, X-Spline, CMR
3633	6	7.7 Ohms/100m	23 AWG solid copper, 4 bonded prs, X-Spline, CMP
2413	6	8.2 Ohms/100m	23 AWG solid copper, 4 pairs, tape separator, CMP
1212	5e	8.9 Ohms/100m	24 AWG solid copper, 4 pairs, CMR

Table 3 – Cable Codes, Category, DC Resistance & Description of Cables Tested

The heating experiment was performed using a source current (I_{Cable}) of 350 mA, 600 mA, 750 mA and 900 mA for all the cable types listed in Table 3. The temperature in the center of the cable bundle (shown in yellow in Figure 2) and the ambient temperature of the room were measured using thermocouples. The temperature rise as a function of time for each cable type with all four pairs energized is plotted in Figure 4, 5, 6, and 7 respectively. The temperature rise curves are determined from equation (1) by adjusting the thermal time constant to provide the best fit to the measured data. For all the cable types it takes between 4 to 6 hours ($t \geq 4\frac{1}{2}$ thermal time constants) to reach an equilibrium temperature.

Figure 4, 5, 6 and 7 shows the temperature rise as a function of time for different cable bundles with all 4 pairs energized. The temperature rise increases asymptotically until an equilibrium temperature is reached at the center of the cable bundle. For some of the cable bundles, we also looked at the temperature rise with only 2 pairs energized. Table 4 (on the next page) shows the temperature rise at equilibrium in the center of a cable bundle with 2 pairs energized compared to 4 pairs energized.

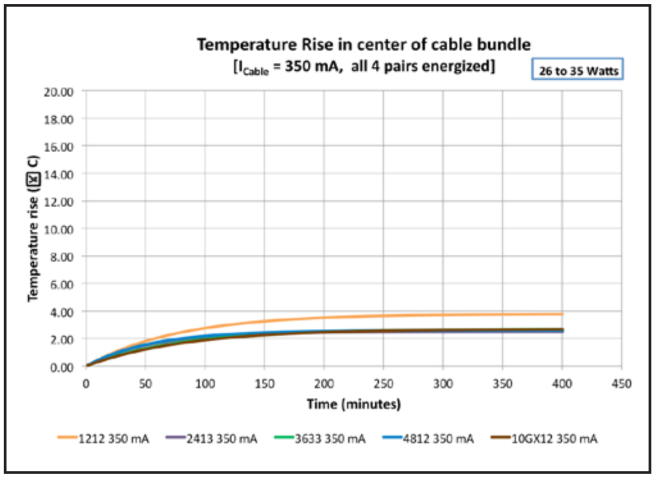


Figure 4 – Temperature rise in center of bundle for I_{Cable} = 350 mA, all 4 pairs energized

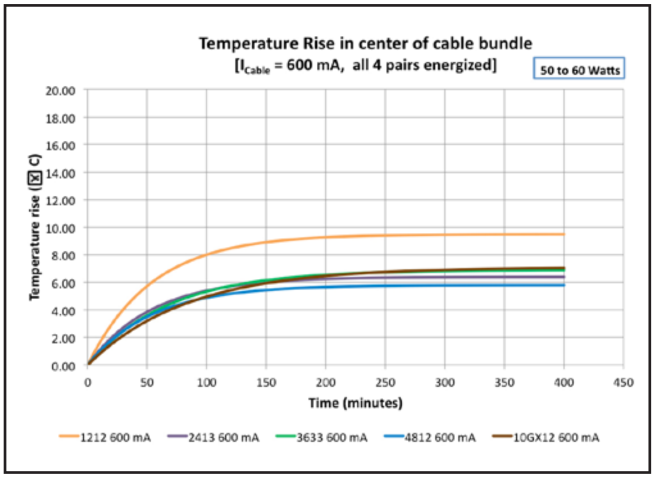


Figure 5 – Temperature rise in center of bundle for I_{Cable} = 600 mA, all 4 pairs energized

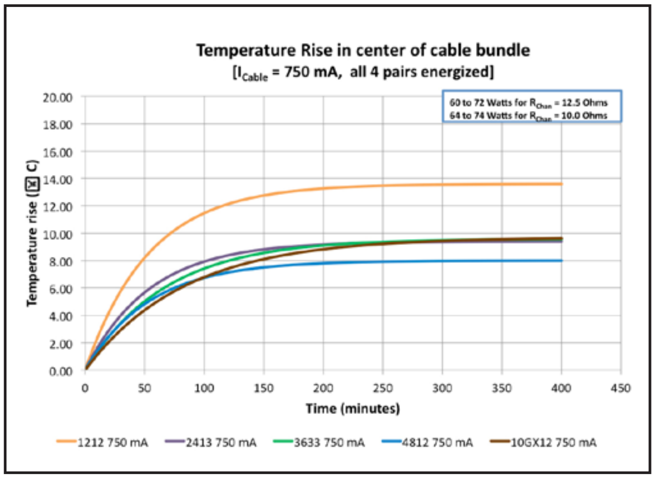


Figure 6 – Temperature rise in center of bundle for I_{Cable} = 750 mA, all 4 pairs energized

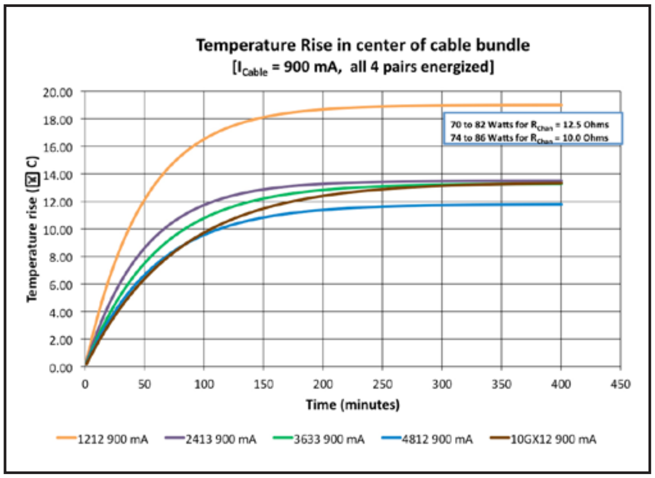


Figure 7 – Temperature rise in center of bundle for I_{Cable} = 900 mA, all 4 pairs energized

I_{Cable}	No. of Pairs Energized	Temperature Rise (°C)	
		10GX12 3633	12 12
350 mA	2 pairs	1.8	1.9
	4 pairs	2.7	3.8
600 mA	2 pairs	3	4.4
	4 pairs	7	9.5
750 mA	2 pairs	5.8	7.6
	4 pairs	9.6	13.6
900 mA	2 pairs	7.7	10.4
	4 pairs	13.3	19

Table 4 – Temperature rise at equilibrium when powering over 2 pairs vs. 4 pairs

Discussion

It is observed that the Category 5e Cable (1212) with 24 AWG conductors exhibits a higher temperature rise at equilibrium than Category 6 and Category 6A cables. For Type 2 operation with a source current of 600 mA and all 4 pairs energized (see Figure 5), the temperature rise at equilibrium approaches 10 degrees Celsius for the Category 5e (1212) cable bundle. The corresponding temperature rise for the Category 6 and Category 6A cables, when tested under the same conditions, is 7 degrees Celsius for 2413, 3633 and 10GX12 cable bundles and 6 degrees Celsius for the 4812 cable bundle. The reason for the lower temperature rise with 4812 cable is that it is a low loss cable design with a larger conductor diameter (at the high end of 23 AWG tolerance range). This is evident when comparing the DC conductor resistance values in Table 3.

Also, it is interesting to observe what happens to the temperature rise when delivering higher power levels than specified for IEEE 802.3at Type 2 operation. For a source current of 750 mA and all 4 pairs energized (see Figure 6), the temperature rise at equilibrium approaches 14 degrees Celsius for a Category 5e (1212) cable bundle. For the same source current, the temperature rise is ≤ 10 degrees Celsius for 2413, 3633 and 10GX12 cable bundles and ≤ 8 degrees Celsius for the 4812 cable bundle. This means that Category 6 /6A cables (2413, 3633 & 10GX12) are capable of delivering up to 25% more power that Category 5e cables while remaining within the maximum temperature rise of 10 degrees Celsius that is specified in the IEEE 802.3at Standard. The results also show that 4812 cables are capable of delivering up to 35% more power that Category 5e cables while remaining within the specified constraints on the maximum temperature rise of 10 degrees Celsius.

What is the temperature rise for different size cable bundles?

Table A.3 in TIA TSB-184 "Guidelines for Supporting Power Delivery over Balanced Twisted-Pair Cabling" provides an example, based on empirical data, of the temperature rise for different size cable bundles when applying a current of 720mA per pair with all 4 pairs energized. I have taken this example and applied the same relationship to the temperature rise data that we measured at 750 mA for different cable types. The results are shown in Figure 8. We measured a temperature rise of 13.6 °C for a bundle size equivalent to one hundred 1212 (Category 5e) cables. If the cable bundle size is reduced to 70 cables, the temperature rise is limited to 10 °C. For fifty cables, the temperature rise is limited to about 7 °C or roughly half the temperature rise that was measured for a bundle size of 100 cables.

This argument can work both ways. If we have a cable tray that is filled with cables and all the cables are delivering maximum power with all pairs energized, the temperature rise can be significantly higher. For the conditions shown in Figure 8, the temperature rise can be as high as 20 °C for a projected bundle size of 150 (Category 5e) cables. Fortunately, not all cables are carrying maximum power and not all cable pairs are energized at the same time. Therefore, for any installation with remote powering requirements, it is important to consider the number of powered devices, the maximum and average power delivered to each device, the density and bundling configuration of cables and the power handling capability of the installed cables.

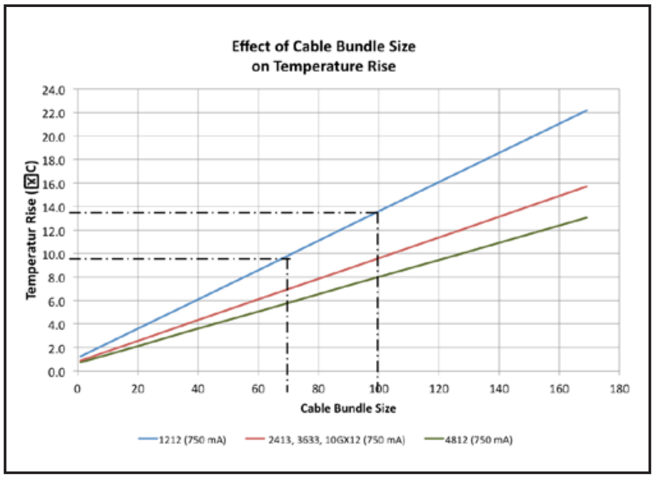


Figure 8 – Temperature Rise vs. Cable Bundle Size for ICable = 750 mA, all 4 pairs energized

Conclusions

How much power can be delivered to a powered device through the telecommunications cable? This is a question that is often asked and the answer is not black and white. It depends on the cable type and the cable configuration. This paper provides some insight to answer this question. The main variable is the temperature rise in a bundle of cables. The maximum temperature rise that is specified in the IEEE 802.3 at Standard for DTE Power is 10 degrees Celsius when powering the device using all four pairs. Based on this constraint, the results of the heating study indicate that, the maximum power delivery is 50 to 60 Watts over Category 5e cables (Belden 1200 series) and potentially up to 74 Watts over Category 6/6A cables (Belden 2400, 3600 and 10GX series) and up to 80 Watts for Belden 4800 series cables.

One of the results of the heating study is a controlled test methodology that can be easily implemented to evaluate power handling capability of specific cable designs. Another result is the validation of a model for the thermal time constant that provides a good fit with the measured temperature rise data.