1. IEEE 802.3 PoE Technology Overview

The **802.3af** specification was originally conceived to create an environment whereby **Powered Devices** (**PD**'s) from numerous different manufacturers could be interconnected to **Power Sourcing** (inter-networking) **Equipment** (**PSE**) including switches, routers, and hubs produced by many different networking equipment manufacturers. Such devices included IP telephones, wireless access points, and digital security cameras that could operate with 13 watts or less power. The interoperability created by 802.3af led to lower cost and higher proliferation among both the sourcing equipment and the networked PD's. PD's no longer required DC power supplies and could be installed in a variety of locations without the need for running an electrical service.

The basic features of IEEE 802.3af (802.3 clause 33, 2004) PoE were:

- 48V DC Supply to PD's
- Guaranteed 13 Watts of Power Consumption per network connection (PD and cabling)
- Power Sourcing from both "End-Point" switches/routers as well as "Mid-Span" power "adder" devices.
- Safety "interlocks" to prevent powering when no PD's are connected and to assure prompt power removal when PD's are disconnected as well as to limit DC current flow at all voltage levels.
- Physical layer mechanism for PSE's to characterize power demands of individual PD's and thus manage power delivered per port.

1.1. IEEE 802.3at Enhancements

The **802.3at** specification (ratified in 2009, 802.3 clause 33) both replaced and expanded upon 802.3af in several key areas:

- Enabled higher power **Type-2** PD's such as wireless access points, panning security cameras, video phones, and audio appliances requiring continuous power to 25.5 watts at distances up to 100M from the PSE. **Type-2** PSE's furnish at least 30.0 Watts at the PSE output.
- Provided full backward compatibility and interoperability to existing **Type-1** 802.3af compliant PSE's and PD's.
- Enabled all PSE's, including midspan injectors, and all PD's to support 1000BaseT data links.
- Minimized cost increases for PSE ports and PD equipment so that services requiring more than 13 watts were economically viable.
- Improved potential power management granularity through a datalink protocol (LLDP) allowing Type-2 PSE's to more effectively distribute a shared DC power supply.
- Resolved well known issues of specification clarity inherent in the 802.3af specification.

802.3at defined all PSE's as either **Type-1** or **Type-2**. Any PSE developed strictly to the original IEEE 802.3af specification was a **Type-1** PSE. PSE's that deliver at least 30 Watts per port must be **Type-2** PSE's. Many of the 802.3at specifications were divided according to Type-1 versus Type-2 PSE's. However, 802.3at allowed Type-1 PSE's to evolve in ways that gained many of the IEEE 802.3at feature enhancements described above even if they continue to limit minimum output power to the 15.4 watt range.

1.2. IEEE 802.3bt Enhancements

The **802.3bt** specification (ratified in 2018 as 802.3 clause 145) is a new and separate specification from IEEE 802.3at.

IEEE 802.3at (and 802.3af before it), restricted the delivery of PoE power to just two of the four wire pairs found in a Category 5 or 6 LAN cable. However, prior to the release of the 802.3at standard, cabling standards bodies (EIA/TIA, ISO) had determined that Cat 5 and 6 LAN cable could safely support up to 600mA of continuous current flow on the unused wire pairs (or pairsets) in a LAN cable meaning that if all four wire pairs were used for power delivery, PD's could safely draw up to 51 watts instead of 25.5 watts.

Why did 802.3at not take advantage of this option? Going back to 802.3af, PD's were required to operate from a two wire pair power source in order to accommodate older wiring systems that only provided two wire pairs for data. Further, those PD's had to be designed to accept the power on the 10/100Base-T data pairs (**pairset A**) or the 10/100Base-T spare pairs (**pairset B**), and to accept the power in either polarity so that crossover patch cabling or system wiring did not disturb the delivery of PoE power. To retain backward compatibility, 802.3at retained the same requirement at the PD interface. PD's therefore implemented full-wave bridging circuits to accept power from either pairset A or pairset B in either positive or negative polarity.

This typical design of a PD created significant complications if power were to suddenly appear on all four wire pairs, that is both **pairset A** and **pairset B**. Fundamentally, there was no way to assure that the DC current would ever split evenly between the two pairsets as there was nothing in the PoE system that would regulate that behavior. For this reason, 4-pair powering was abandoned during the development of the 802.3at standard.

Besides the delivery of more power, a second key advantage of 4-pair PoE is the reduced power lost in cabling. Using four wire pairs rather than two wire pairs reduces total end-to-end electrical resistance by a factor of two meaning the I^2R loss is also reduced by at least a factor of two. So if 13W or 25.5W PD's could operate from 4-pair power, total system power consumption is reduced.

IEEE 802.3bt tackled the whole issue of 4-Pair powering through a combination of new requirements for 802.3bt compliant PSE's, 802.3bt PD's that draw more than 25.5 watts, and LAN cabling systems. 802.3bt allowed for twice as much power delivery as was available under 802.3at given no impact to installed cabling plants. PSE's and PD's that support up to 51 watts at the PD are referred to as **Type-3** devices.

Further, 802.3bt enabled even higher power services whereby PD's could receive up to 71.3 watts from PSE's that furnish 90 watts on their outputs. PSE's that support 90W and PD's that draw more than 51W are referred to as **Type-4** devices. Implementation of PoE systems using Type-4 equipment requires certain constraints that must be applied to cabling plants. These constraints involve the type of LAN cable used (e.g. electrical insulation properties) and limitations on the way cables are bundled when running through ceilings and walls. In North America, installations of Type-4 systems may require compliance to new electrical codes (NEC) and associated inspections.

The key features of the 802.3bt specification are:

- 4-Pair Powering up to 71.3W at the PD and 90W at the PSE. (Actually, the standard allows for systems where PD's could, under controlled circumstances, draw up to 90W).
- Full backward compatibility with 802.3at, and therefore, with 802.3af equipment, both PSE's and PD's.
- Full range of PD classifications including 3.8W (class 1), 6.5W (class 2), 13W (class 3), 25.5W (class 4), 40W (class 5), 51W (class 6), 62W (class 7) and 71.3W (class 8).
- Full range of PSE powering capability including 2-Pair powering from 4W up to 30W and 4-Pair powering from 4W up to 90W.
- Extensions to the PoE datalink (LLDP) protocol to enable more refined power management by system PSE's.
- Implementation of a very low power "sleep mode" where PD's can remain powered while drawing negligible power from a PSE. This is a key feature to LED lighting systems that operate from PoE power.
- An alternative "dual signature" PD front-end architecture where in essence, a PD can be operated as two PD's, one powered by each pairset.
- An alternative PD power classification scheme, "autoclass", that also allows very refined power management by a system PSE without relying on datalink protocols. This also is a feature aimed at LED lighting systems.
- Support of 2.5GBase-T, 5GBase-T, and 10GBase-T data links carrying PoE power.

802.3bt opened the doors to many future applications of Power-over-Ethernet, most notably lighting systems, large panel displays, wireless microcells, higher power wireless LAN access points and controllers, and IOT components.

1.3. The Power Connection

Balanced wire pairs in LAN cables carry high speed differential electrical signals used by 10/100/1000/MG-Base-T communications links. From their inception, Ethernet interfaces have been designed to work over distances of up to 100 meters.

In order to assure electrical isolation between equipment and also from electrical disturbances appearing on long cabling runs, Ethernet ports include isolation transformers on each wire pair. This enables the insertion of DC voltage and current in common mode to each wire pair meaning that both conductors of the wire pair experience the exact same DC voltage and share 50% of the DC current. Insertion of voltages and extraction of currents is performed using the primary coil center taps of the Ethernet transformers. So long as the center taps are truly "centered", the addition of the DC power has no impact to the integrity of the high speed LAN signaling.

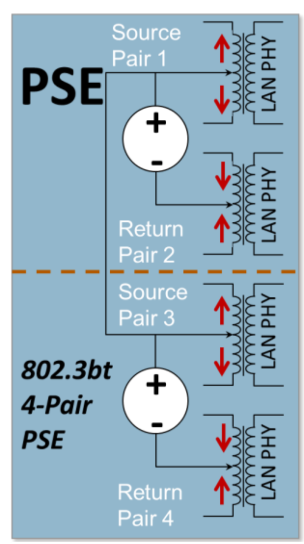

Figure 2.1 PSE Connection

Figure 2.1 depicts a typical PSE interface. A 2-Pair (e.g. 802.3at) PSE would be

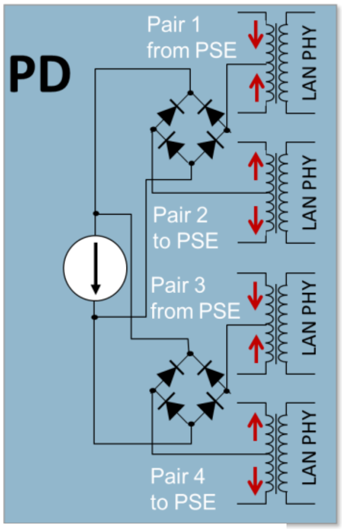

Figure 2.2 PD Connection

represented by the top half of this figure. A 4-Pair PSE would encompass the entire figure. The diagram includes two voltage sources in the 4-Pair PSE because typically, 4-Pair PSE's can independently connect each voltage source to each pairset and also, typically, the "switched" side of the voltage source is the negative, or low side.

Unlike PSE's, PD's are always "4-Pair" devices because going back to the 802.3af specification, PD's needed to receive power on either pairset in either polarity. **Figure 2.2** demonstrates a typical PD physical interface (PI) whereby all four wire pairs are combined through full wave diode bridges to serve the PD power load. In 802.3bt terms, this PI represents a **single signature** PD because the bridge outputs are combined and do not serve separate, independent loads. 802.3bt also describes **dual signature** PD's where the diode bridges are not combined but rather are wired to separate, independent loads much as if the PD was really two PD's, one connected to each pairset. Dual signature PD's are generally not common.

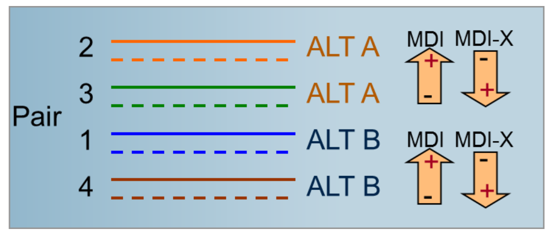

Figure 2.3 PSE Pairsets

1.4. Pairset Terminology & Polarity

A pairset consists of one wire pair that sources current from the PSE to the PD and one wire pair that returns current from a PD to the PSE. On the PSE side of the link, pairsets are referred to as Alternative A (**Alt-A**) and Alternative B (**Alt-B**). A 2-Pair 802.3at or 802.3bt PSE will source power on just one pairset, Alt-A or Alt-B. A 4-Pair 802.3bt PSE will source power on both pairsets Alt-A and Alt-B.

The **Alt-A** pairset refers to the same two wire pairs used to transmit data in 10/100Base-T links. The **Alt-B** pairset refers to the wire pairs not used in 10/100Base-T links. 2-Pair PSE's compliant to 802.3at and 802.3bt may source power on either pairset. In terms of TIA-568 wire pairs, Alt-A consists of wire pairs 2 (orange) and 3 (green) while Alt-B consists of wire pairs 1 (blue) and 4 (brown).

On the PD side of the link, pairsets are referred to as **Mode A** and **Mode B**. These are each identical to Alt-A and Alt-B on the PSE side of the link.

Each pairset provides voltage and current to the PD in either a positive polarity or a negative polarity, thus necessitating the full wave bridges in the PD PI (*see **Figure 2.2***). The Alt-A pairset is said to be in an **MDI** polarity when the positive voltage is on wire pair 2 and the negative voltage is on wire pair 3 (*see **Figure 2.3***). Conversely, Alt-A is in an **MDI-X** polarity when the positive voltage is on pair 3 and the negative voltage is on pair 2. The same applies for the Alt-B pairset where **MDI** means positive voltage on pair 1 and negative voltage on pair 2 while **MDI-X** means positive voltage on pair 4 and negative voltage on pair 1.

In practice, many 2-Pair PSE's are configured to **Alt-A**, **MDI-X** and many 4-Pair PSE's are configured to **Alt-A, MDI-X** combined with **Alt-B**, **MDI**.

802.3bt requires **Type-4** PSE's to be configured as Alt-A, MDI-X and Alt-B, MDI. Older 802.3af mid-span PSE's were required to power on **Alt-B** with **MDI** only, however, that restriction was lifted under the 802.3at standard when midspan PSE's needed to support 1000Base-T (4-pair LAN) connections.;

1.5. Basic PoE Processes

PoE power is entirely managed by PSE's. PSE's are responsible for:

- Discriminating Powered Devices from other devices that might be damaged if PoE voltages were applied
- Assessing the basic power requirements of a newly connected PD
- Supporting surge (or inrush) power required to start up a PD
- Conducting PoE link-layer (LLDP) mutual discovery and power negotiation
- Supporting spurious peak power demands from a PD
- Reacting to PD's that are drawing more power than they should

- Supporting surge power demands from a PD when PSE power sources are replaced by back-up power sources
- Supporting unbalanced load currents between pairsets when powering 4-pair to single signature PD's
- Limiting maximum possible current in the event of short circuit in order to protect the PSE power supply and to limit cable heating or sparking
- Reacting to PD's that have been disconnected by removing power before another device can be plugged into the PSE port.

The following sections will address these PoE behaviors with associated responsibilities of the PSE and the PD.

1.6. PD Detection Processes: Discriminating PD's from non PD's

A PoE enabled PSE port provides a low power signaling mechanism that constantly monitors for an 802.3 Powered Device (PD) to appear at the end of the LAN cable. If a non-powered network device is connected, the PSE port can function just as would a non-PoE port and link to the networked device. However, if an 802.3 PD is connected, the PSE port will quickly recognize this and begin the process of powering up the PD.

The primary means of detection is a measurement of PD PI electrical resistance performed by the PSE port. 802.3at and 802.3bt specify that compliant PDs will present a load resistance between 23.7KΩ and 26.3KΩ that when measured at the PSE is between 19 KΩ and 26.5 KΩ given an input voltage under 10 VDC. They further specify that the method of resistance measurement shall allow for an unknown voltage drop up to 2.8 volts associated with one or more diode junctions in series with this load resistance. This implies that "AC" resistance must be determined from a [ΔV / ΔI] measurement performed at 2 (or more) voltage levels and that the minimum detection voltage must be at least 2.8 VDC.

Some of the relevant specifications affecting the detection process are:

Characteristic	Minimum	Maximum	Units
Unterminated (Open Circuit) Detection Voltage		30	VDC
Terminated Detection Voltages given Valid Signatures	2.8	10	VDC
Detection Current Limit (compliance)		5	mA
[ΔV / ΔI] Voltage Step	1	7.2	VDC
Maximum Acceptable Load Resistance	26.5	33	KΩ
Minimum Acceptable Load Resistance	15	19	KΩ
Maximum Acceptable Load Capacitance	0.15	10	μF
Slew Rate of Voltage Step		0.1	V / μsec
Detection Duration		500	mSec
Detection Backoff (following unsuccessful detection) (does not apply to End-Span PSE's)	2		Sec

It should be noted that despite the various requirements described for PD Detection signaling in the 802.3 specification, there is considerable room for design variation and that in practice, detection pulses and detection measurement schemes do vary significantly across PSE interface technologies. The 802.3 PoE standards do *not* prohibit the use of complementary schemes that might improve detection accuracy and speed while also reducing risk of possible damage to non-PoE capable end station equipment.

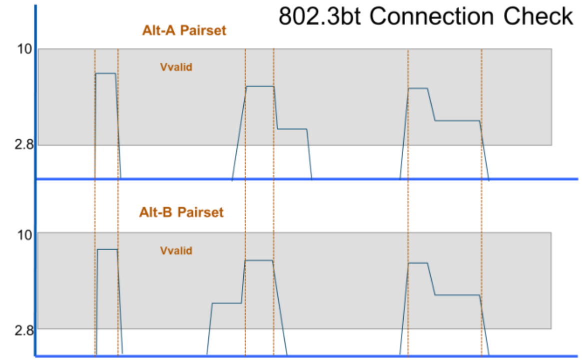

Figure 2.5 802.3bt Connection Check

Figure 2.4 demonstrates some of the range of signaling characteristics that might be observed from 802.3at and 802.3bt PSE's. In truth, the range of options including number of detection current-voltage steps, use of voltage versus current sourcing, and use of low voltage pre-detection scheme is really unlimited with the one exception that detection must complete in 500msec and that a subsequent decision to apply power must be completed in 400msec or less.

The 802.3bt standard adds a separate phase of PD qualification and characterization referred to a **connection check**. The sole function of this PSE "measurement" is to allow a 4-Pair PSE to determine if the PD is a **single signature** or a **dual signature** PD, or neither. 4-Pair PSE's manage single signature PD's differently from dual signature PD's so this is an essential part of the detection process. In developing the 802.3bt standard, participants deliberately decided to only put a vague description to the connection check process stating that it must function in the same voltage range as PD detection and that, like PD detection, it must be completed within 400 msec of a decision to apply power. This essentially allows vendors of integrated PSE controllers to do their own thing regarding connection check.

Figure 2.5 depicts the basic concept of 802.3bt PD connection check where during the process, signaling is applied simultaneously to both pairsets and some form of measurement is done to determine if the presence of a single signature PD is causing an interference of some sort between the respective pairset signals.

As an example, if both pairsets inject an equal current source to a single signature PD, the voltage appearing will be a function of the combined currents and the ~25KΩ PD detection resistance. Conversely, if this same source is applied to a dual signature PD, the voltage appearing on each pairset will be approximately half because each current source experiences its own ~25KΩ load. This is the basic concept of connection check.

1.7. PD Classification – 802.3at

802.3at specification allows for PD's to communicate their power demands to a PSE port via a **classification** process. From the perspective of a PSE port, PD's can be classified as follows:

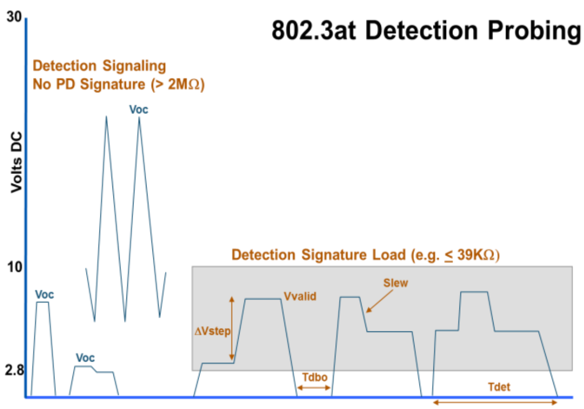

Figure 2.4 802.3 PoE Detection

PSE Type	Classification	Guaranteed Power at PSE Output	Minimum Power at PSE Output	Units
Type-1	Class 0	15.4	~ 0.5	Watts
	Class 1	4.0	~ 0.5	
	Class 2	7.0	~ 4.0	
	Class 3	15.4	~ 7.0	
Type-2	Class 4	30.0	~ 15.4	

A **Type-1** PSE has the option not to classify the PD in which case the PD must be assumed to require **Class 0** power.

Classification is performed by applying a voltage in the band from 15.5V to 20.5V and measuring the fixed DC current load presented by the PD. The magnitude of measured current is then translated into a classification as follows:

Minimum Current	Maximum Current	Units	Classification	PD Type
0	5	mA	Class 0	Type-1
8	13	mA	Class 1	Type-1
16	21	mA	Class 2	Type-1
25	31	mA	Class 3	Type-1
35	45	mA	Class 4	Type-2

The PSE is free to make decisions regarding current measurements that fall between the above bands. Classification must be completed in 75 mSec, so typically classification involves a short duration pulse with amplitude between 15.5 and 20.5 Volts. A "single-event" class pulse (*see **Figure 2.6***) may return to zero or may hold its value (or anything in between) following completion of classification.

The 802.3at specification requires that all compliant PSE's perform classification and it adds an expanded classification measurement option that allows PSE's to "signal" their 82.3at Type-2 power capability to a powered device while reading the power demand of the powered device. The "2-event" classification (*see **Figure 2.6***) involves 2 successive classification current measurements separated by a "mark" region. The 802.3at Type-2 PD must be capable of discharging the class voltage in order to "see" this mark region and thereby detect the presence of an 802.3at capable PSE. The 2-event classification cannot ever drop below 2.8V, or the PD will reset and forget that the PSE is Type-2 power capable.

Type-2 PSE's may use either single-event or 2-event PD classification. Those that use single event method are required to us MAC layer LLDP protocol to negotiate power with a Type-2 PD following initial PD power-up. See Section 1.10 below for more information concerning LLDP PD power classification.

1.8. PD Classification – 802.3bt

The 802.3bt specification significantly extended the model of 2-Event classification so that PSE's and PD's could signal new classification bands that relate to power levels above Type-2 (Class 4). As with 802.3at, classification is a process that follows PD detection and precedes PSE powering of the PD.

802.3bt introduced nine new PD classifications, four that pertain to single signature PD's and five that pertain to dual signature PD's. 802.3bt also retained 803.2at PD classifications 1-4. As with 2-Event classification in 802.3bt, the count of classification pulses represents the method by which a PSE authorizes power levels to a PD.

The following table describes the 13 possible PD classifications described in the 802.3bt specification.

PD Signature Type	Classification	PSE Output Power*	PD Input Power	Units
Single	Class 1	4.0	3.94	Watts Total on 2-Pairs or 4-Pairs
	Class 2	7.0	6.5	
	Class 3	15.4	13.0	
	Class 4	30.0	25.5	
	Class 5	45.0	40.0	Watts Total on

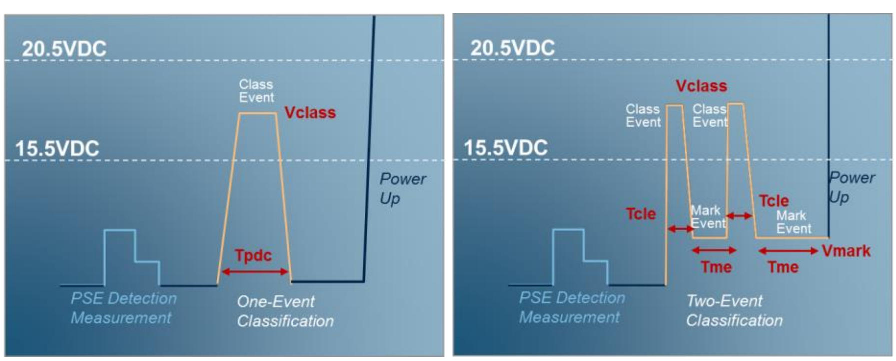

Figure 2.6 PD Classification under the **802.3at** Specification

	Class 6	60.0	51.0	4-Pairs
	Class 7	75.0	62.0	
	Class 8	90.0	71.3	
Dual	Class 1 (D)	4.0	3.94	Watts per Pairset
	Class 2 (D)	7.0	6.5	
	Class 3 (D)	15.4	13.0	
	Class 4 (D)	30.0	25.5	
	Class 5 (D)	45.0	35.6	

Unlike 802.3at, 802.3bt requires that classification currents drawn by the newer classes of PD's change after the first two events are completed. The change in class current then encodes information regarding the power the PD demands. This difference enables 802.3bt PSE's to differentiate between 802.3at PD's where the classification signature never changes after the second class event and 802.3bt PD's where that signature always changes. Figure 2.7 diagrams the relationship between PSE voltage and PD current draw during a 4-Event classification sequence.

***** PSE output power is actually dependent on PSE output voltage. Higher voltage PSE's can deliver the same power to the PD with PSE output power less than shown in the table. Table values are based on PSE's with minimum output voltage.
As with PD detection, a single signature PD can be probed on either the Alt-A or Alt-B pairset and will produce the same classification signature. A dual signature PD must be probed on both pairsets, Alt-A and Alt-B, independently and may possibly produce different signatures on each pairset.

As stated above, the classification current sequence across three to five classification events, or pulses, encodes the power demand of the single signature PD and also the power demand of a single pairset of a dual signature PD. Conversely, the count of classification events, or pulses, from the PSE encodes the power grant, that is authorized power level to the 802.3bt PD. While much more complex than the 802.3at classification scheme, the 802.3bt classification scheme was designed to be fully backward compatible with 802.3at PSE's and PD's.

The following table describes 802.3bt classification signatures. Note that 802.3at **Class 0** is not included in 802.3bt, however a Class 0 PD will typically be managed as if it was a Class 3 PD drawing up to 13 watts maximum.

PD Class	Events 1 & 2	Events 3-5	Power Request at the PD	Units
Class 1	10.5 mA	10.5 mA	3.84	Watts Total on 2-Pairs or 4-Pairs
Class 2	18.5 mA	18.5 mA	6.5	
Class 3	28.0 mA	28.0 mA	13.0	
Class 4	40.0 mA	40.0 mA	25.5	

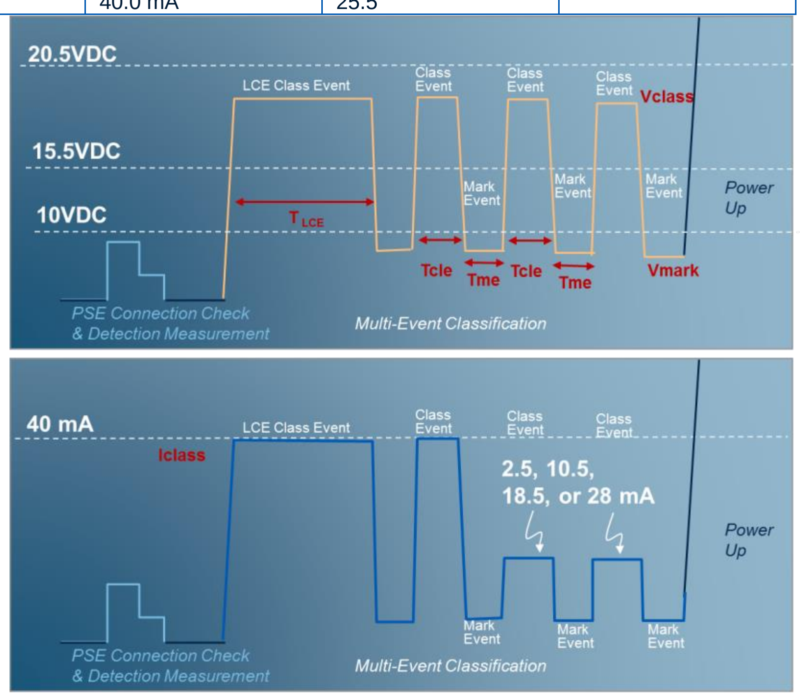

Figure 2.7 PD Classification under the 802.3bt Specification

Class 5	40.0 mA	2.5 mA	40.0	Watts Total on 4-Pairs
Class 6	40.0 mA	10.5 mA	51.0	
Class 7	40.0 mA	18.5 mA	62.0	
Class 8	40.0 mA	28.0 mA	71.3	
Class 1 (Dual)	10.5 mA	2.5 mA	3.94	Watts per Pairset
Class 2 (Dual)	18.5 mA	2.5 mA	6.5	
Class 3 (Dual)	28.0 mA	2.5 mA	13.0	
Class 4 (Dual)	40.0 mA	2.5 mA	25.5	
Class 5 (Dual)	40.0 mA	28.0 mA	35.6	

The following table describes PSE power authorizations, also referred to as "assigned class" in the standard.

PD Signature Type	Total Events (= Class Pulses before power-up)	PD Class	Authorized Power Draw at the PD	Units	Assigned Class
Single	1	Class 1	3.84	Watts Total	Class 1
		Class 2	6.5		Class 2
		Class 3-8	13.0		Class 3
	2	All Classes	25.5		Class 4
	3	All Classes	25.5		
	4	Class 5	40.0		Class 5
		Class 6	51.0		Class 6
	5	Class 7	62.0		Class 7
		Class 8	71.3		Class 8
Dual	1	Class 1 (Dual)	3.84	Watts per Pairset	Class 1 (Dual)
		Class 2 (Dual)	6.5		Class 2 (Dual)
		Class 3-5 (Dual)	13.0		Class 3 (Dual)
	2	All Classes	25.5		Class 4 (Dual)
	3	All Classes	25.5		
	4	Class 5 (Dual)	35.6		Class 5 (Dual)

As with the 802.3at specification, classification probing is done with class pulses providing between 15.5V and 20.5V at the PSE output and between 14.5V and 20.5V at the PD input (*see **Figure 2.7***). Multiple event classification requires that each class pulse, or class event, be separated by mark regions where the PSE voltage drops to between 7V and 10V for a period of at least 6 msec. The mark voltage provides a "battery" voltage enabling the PD to count and store the number of classification events so the PD is aware of the power authorization, or **assigned class**, prior to power-up.

Another unique feature of 802.3bt is that the first class event must be between 88msec and 105msec duration (*see **Figure 2.7***). This is considerably longer than 802.3at class pulses and much longer than class pulses following the first event. This elongated (**LCE**) class pulse signals to an 802.3bt PD that the PSE is 802.3bt compliant and operates according to 802.3bt PSE rules and requirements. An 802.3at PSE would never exceed 72 msec during a class event. Finally, one other feature of 802.3bt classification is referred to as **Autoclass**. Autoclass allows a PD to demonstrate to a PSE, soon after the application of operating voltage, the maximum level of power draw that PD will ever produce. A PSE that supports the optional autoclass feature can then measure that power level and use it in the management of total power budgets across multiple PSE ports. This is especially useful because the measured power draw takes into account the power loss in the cabling between the PSE and the PD.

An 802.3bt single signature PD communicates that it will support an autoclass power measurement by altering the current in the first (elongated) class event after 88msec to a value in the range 1 to 4 mA (e.g. 2.5mA). The PSE that supports autoclass will implement an LCE (first event) class pulse that exceeds 88msec so that it can capture the load current change from 40mA to ~2.5mA. The PD that supports autoclass will always draw maximum power in a time interval between 1.5 seconds and 3.3 seconds following the application of operating voltage.

In practice, autoclass is limited in application because many PD's will not have the ability to provide a maximum load condition in this time interval (1.35 to 3.65 seconds) following power-up. Many PD's are early in their boot process during this time interval. One important target application for autoclass would be LED lighting systems.

1.9. Power-Up

Following detection and classification, the PSE will apply power (voltage and current) to the PD. The DC voltage while powered at the output of a PSE port is defined for each PSE type as follows.

PSE Type	Minimum Output Voltage	Maximum Output Voltage
1	44 VDC	57 VDC
2 or 3	50 VDC	
4	52 VDC	

Figure 2.8 depicts the typical sequence of events after a PD connects to a PSE. This diagram pertains to a single pairset, Alt-A or Alt-B, but similar action could occur on both pairsets of a 4-pair PSE.

On the PSE side, there are three timing criteria of interest. The first parameter, **Tpon**, measures time from end of detection until power-up is completed. This includes classification time and must be under 400 mSec. **Tpon** exists to minimize the chance that a PSE powers a non-PD in the event a valid PD is briefly connected, then quickly replaced by the non-PD.

The power-on rise time is required to be longer than 15 μsec. This limitation minimizes possible RF emissions when PSE ports activate power to PD's.

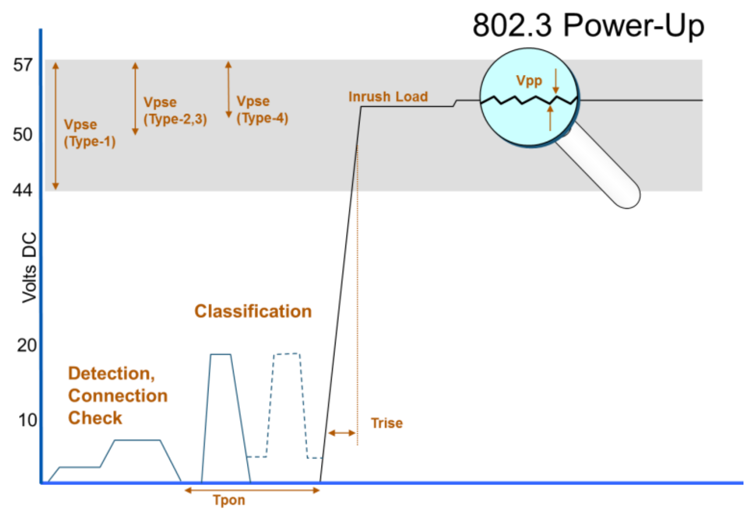

Figure 2.8 802.3 Power-Up

Once the PD is powered, it will typically draw an initial inrush (or charging) current (*see **Figure 2.9***). The PSE is designed to expect this sudden load and to tolerate it for a period of time referred to as **Tinrush**. During this period and depending upon the PSE type, the PSE may restrict current output on a pairset to a band between 200mA and 450mA. Given a 4-pair power-up, this amounts to between 400mA and 900mA total current, again depending up on the PSE type. Given a two pair power-up, the band will be 400mA to 450mA.

The PD is obligated to assure that it can complete its surge load in 50msec or less given the lowest allowed current limiting (e.g. 400mA) by the PSE. Further, the PD is obligated to operate at a power level less than 13W, or more specifically a Type-1 peak power level less than 14.4W for a period of 30msec following the completion of inrush, in other words, for a period of 80msec following power-up (*see **Figure 2.9***).

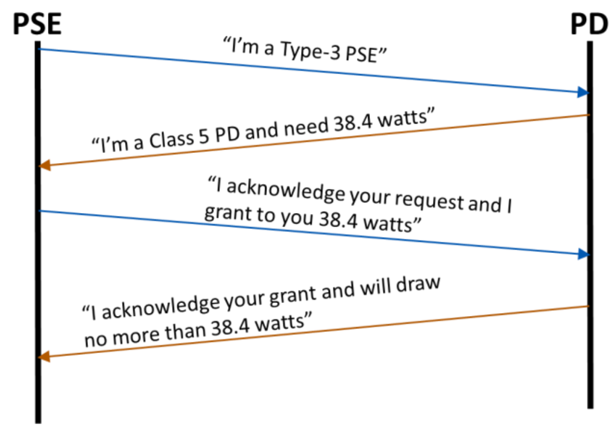

Figure 2.10 PoE LLDP Dialog/Negotiation

PD's may be implemented with their own internal current limiting such that charging periods are extended without overdrawing current from the PSE. PD's with large surge demands and/or delayed surge loads will reduce risk of PSE inrush shutdown by internally limiting current draw during startup.

While the PSE is furnishing operating power to the PD, 802.3 specifications include restrictions on the amount of AC ripple and noise that appears on the DC supply voltage. In a 2-pair (e.g. 802.3at) powering context, this would be AC peak-peak voltage across a pairset (Alt-A or Alt-B) and in a 4-pair powering scenario, would be the AC peak-peak voltage appearing across both pairsets. The AC peak-peak voltage is split into frequency bands with lower limits for higher frequency bands up to 1MHz. Restricting peak-peak DC voltage reduces the possibility that common mode AC ripple and noise could be converted into differential noise that might interfere with LAN signaling. It is worth noting that as a practical matter, PSE's have output capacitance on the order of 0.1μF to 0.5μF and PD's have input capacitance on the order of 5μF or higher while powered. These levels of capacitance will typically limit the AC peak-peak noise that can develop across the pairsets.

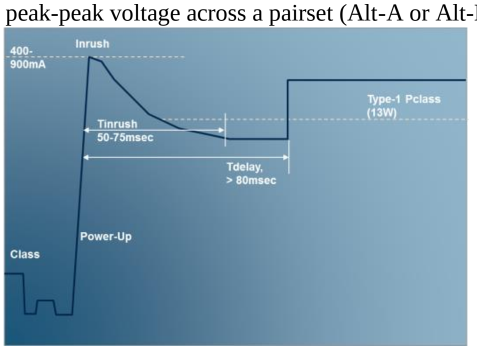

Figure 2.9 PD Inrush and Power Delay

1.10. PoE LLDP Dialog / Power

Negotiation

After a PSE powers up a PD, it may utilize a link layer discovery protocol (LLDP) to better understand the PD's power needs. LLDP protocols only exist between two physical link partners and are not visible anywhere else on a network.

All PSE's are allowed but not required to deploy PoE LLDP. All Type-2, Type-3, and Type-4 PD's are required by 802.3at and 802.3bt to support PoE LLDP protocols.

LLDP is particularly useful to large system PSE's with 24 or more ports where power allocations to each PD are more challenging. Under PoE LLDP, a PD communicates its maximum power demand with a granularity of 0.1 watt. This in turn enables the PSE to allocate power more precisely across many PSE ports. In sections 1.7 and 1.8 above, it was seen that physical layer classification typically provides granularity of about 15 watts.

While there are many details to the PoE LLDP protocol, **Figure 2.10** shows in simple form what the essence of such dialog accomplishes. While historically LLDP protocols are stateless an generally used so that link partners just advertise information about themselves, the PoE rendition of LLDP is a more stateful, handshaking dialog.

As a practical matter, since the advent of 802.3at and Type-2 PD's, a large segment of the industry has avoided implementing LLDP support in PD's as a cost saving strategy, thus causing considerable interop problems. Many PD manufacturers offer low cost Type-2 midspan PoE injectors to help customers overcome the non-compliance of their PD's. While time will tell, the same issues may persist as 802.3bt PD's deploy into the world.

1.11. PSE Load Regulation and Overload Management

While the PSE is furnishing power to the PD, the PSE is responsible for regulating total power delivered to the PD. On the PSE side, there are three essential parameters governing the ongoing power the PSE is obligated to provide to a PD.

1. **Pclass**: The steady-state continuous or average power required by the PD translated to the PSE interface
2. **Ppeak**: The sporadic and transient (< 50msec) peak power required by a PD also translated to the PSE interface
3. **Ilim_min**: The maximum current a PSE should tolerate over a short transient (< 10msec) interval

As most PD's are constant power loads, the power output at the PSE must account both for the PD power load and the power that will be lost in LAN cabling. The power lost in LAN cabling is a function of the distance between PSE and PD, the resistivity characteristic of the LAN conductors, and the DC current flowing to satisfy the power demand of the PD. The DC current required is a function of the PSE output voltage – higher voltage means less required current. As an example, a Class 4 PD requiring the maximum allowed 25.5 watts and connected across 100meters of Cat5e cabling to a PSE will require the PSE to furnish 30 watts IF the PSE output voltage is the minimum of 50 VDC for a Type-2 PSE. In this case, there will be 600mA of DC current in the wires. If the Type-2 PSE implemented a 56 VDC output, then the PSE would need to support just 28.8 watts at its output and the current flowing in the wires would be 514mA.

The following table provides requirements for Pclass, Ppeak, and Ilim_min output requirements at the PSE assuming the PSE is operating at its minimum allowable (Vpse) output voltage.

PSE Type	Max Class	Voltage	Pclass	Ppeak	Ilim_min
1	1	44 VDC	4.0 watts	5.3 watts	400 mA
	2	44 VDC	7.0 watts	9.2 watts	400 mA
	0, 3	44 VDC	15.4 watts	17.6 watts	400 mA
2	4	50 VDC	30.0 watts	34.1 watts	684 mA
3	5	50 VDC	45.0 watts	47.7 watts	580 mA / pairset
	6	50 VDC	60.0 watts	63.7 watts	720 mA / pairset
	1 Dual Sig.	50 VDC	3.9 watts / pairset	5.1 watts / pairset	400 mA / pairset
	2 Dual Sig.	50 VDC	6.6 watts / pairset	8.5 watts / pairset	400 mA / pairset
	3 Dual Sig.	50 VDC	13.5 watts / pairset	15.0 watts / pairset	400 mA / pairset
	4 Dual Sig.	50 VDC	30.0 watts / pairset	34.1 watts / pairset	684 mA / pairset
4	7	52 VDC	75.0 watts	79.8 watts	850 mA / pairset
	8	52 VDC	90.0 watts	96.3 watts	1005 mA / pairset
	5 Dual Sig.	52 VDC	45.0 watts / pairset	48.1 watts / pairset	990 mA / pairset

On the PD side, there are two essential power load parameters:

1. **Pclass_pd**: The steady-state continuous or average power required by the PD
2. **Ppeak_pd**: The sporadic and transient (< 50msec) peak power required by a PD

These values are:

PD Type	PD Class	Pclass_pd	Ppeak_pd	Minimum Input Voltage
1	1	3.84 watts	5.0 watts	42.8
	2	6.49 watts	8.36 watts	42.0
	0, 3	13.0 watts	14.4 watts	39.9
2	4	25.5 watts	28.3 watts	42.5
3	5	40.0 watts	42.0 watts	44.3
	6	51.0 watts	53.5 watts	42.5
	1 Dual Sig.	3.84 watts / pairset	5.0 watts / pairset	42.8
	2 Dual Sig.	6.49 watts / pairset	8.36 watts / pairset	42.0
	3 Dual Sig.	13.0 watts / pairset	14.4 watts / pairset	39.9
	4 Dual Sig.	25.5 watts / pairset	28.3 watts / pairset	42.5
4	7	62.0 watts	65.1 watts	42.9
	8	71.3 watts	74.9 watts	41.1
	5 Dual Sig.	35.6 watts / pairset	37.4 watts / pairset	41.1

Figure 2.11 describes some of these requirements in a graphical manner that includes time intervals associated with Ppeak and Ilim_min load transients. A PD that exceeds **Pclass_pd** for longer than 50 msec may have power removed by a PSE. A PD that exceeds **Ppeak_pd** for any amount of time may also experience PSE power removal. All of this is very dependent upon PSE configuration and cabling lengths. For example, a Type-2 PSE operating at 50VDC must allow up to 30W power output but may choose to allow 34W power output allowing some headroom for marginal PD's or extra cabling loss.

Finally, the PoE LLDP protocol may be used to refine the value of **Pclass_pd** and **Ppeak_pd**. Once Pclass_pd is "negotiated" to 0.1 watt granularity using LLDP, the PSE is free to police the power draw at the PSE (**Pclass**, **Ppeak**) based on that power negotiation.

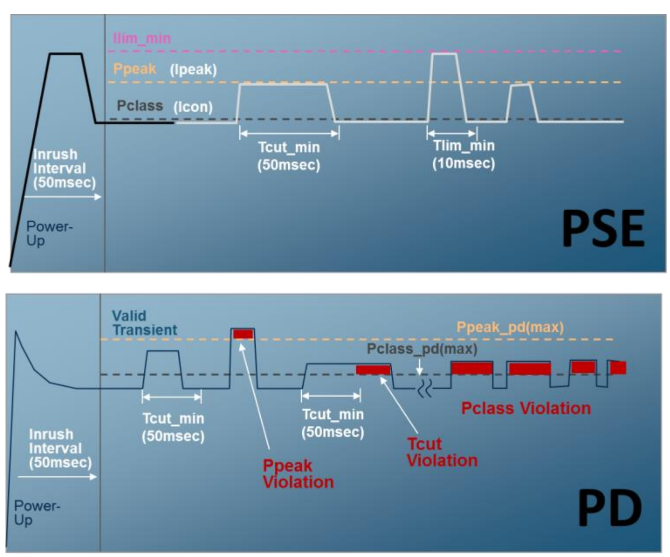

Figure 2.11 Power Regulation and PD Overloads

1.12. Pair to Pair Unbalance with 4-Pair, Single Signature Powering

One of the greatest challenges addressed by the 802.3bt specification was the matter of pair-to-pair current unbalance that will naturally occur when a 4-pair PSE is powering a single signature PD. This is a critical problem because the vast majority of PD's are single signature PD's.

The dilemma of pair-to-pair current unbalance occurs because in prior specifications, there was no explicit regulation of pairset-to-pairset resistances in the output of the PSE port, the LAN cabling, or the PD input. This is complicated by the fact that determinants of pairset-to-pairset DC resistance will involve components such as FET switches in the PSE and PD and diode bridges in the PD. Additionally, EIA/TIA and ISO specifications for LAN cabling systems did not regulate pairset-to-pairset DC resistance.

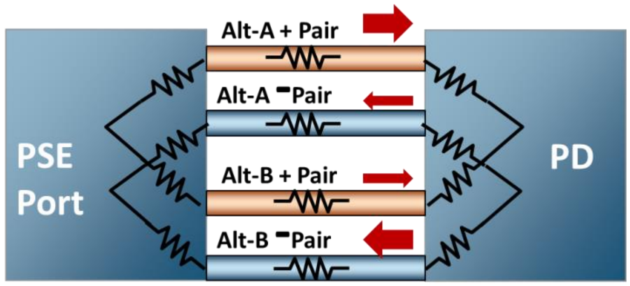

Figure 2.11 Pair-to-Pair Current Unbalance

Figure 2.11 depicts this problem where the current required to power the PD does not split evenly between either the positive or negative rails of the Alt-A and Alt-B pairsets.

Considerable work was done in the 802.3bt standard to model what worst case pair-to-pair unbalances might be present in PSE interfaces, cabling, and PD interfaces. In conjunction with this, the cabling industry published guidelines for pair-to-pair DC resistance unbalance LAN cabling systems. The 802.3bt standard includes some testing procedures to assess that PSE and PD interfaces to not exceed the worst case models used by the specification.

The PSE powering 4-pairs to Class 0 – Class 8 PD's is required to tolerate appreciable levels of current unbalance between the two pairsets.

PD Class	Maximum Pairset Current	% Maximum 4-Pair Current
1	78 mA	100% (= 2-pair powering)
2	132 mA	100% (= 2-pair powering)
3	269 mA	100% (= 2-pair powering)
4	548 mA	100% (= 2-pair powering)
5	560 mA	62.1%
6	692 mA	57.7%
7	794 mA	55.1%
8	948 mA	54.8 %

PSE's must be designed to accept higher pairset current without any notion of which polarities of which pairsets will draw more or less current. Only time will tell if the modeling done within the standard fully accounts for all of the real-world contributions to pair-to-pair current unbalance.

1.13. Power Removal

PSE ports are required to remove DC power very soon after a PD becomes disconnected. This is an essential behavior to protect non-PD devices from damage should they be plugged in immediately after a PD was disconnected from the same PSE port.

Across the 802.3af, 802.3at, and 802.3bt standards, there are two different methods, **DC MPS** and **AC MPS**, by which a PSE detects a disconnected PD. Generally, a PSE deploys one method or the other but not both.

Both methods, described below, require that once a PSE detects the disconnection of a PD, power should be removed within a time band (**Tmpdo**) between 300msec (320msec in 802.3bt) and 400msec (*see **Figure 2.12***). This assures that replacing a PD with a non-PD very quickly would generally be safe.

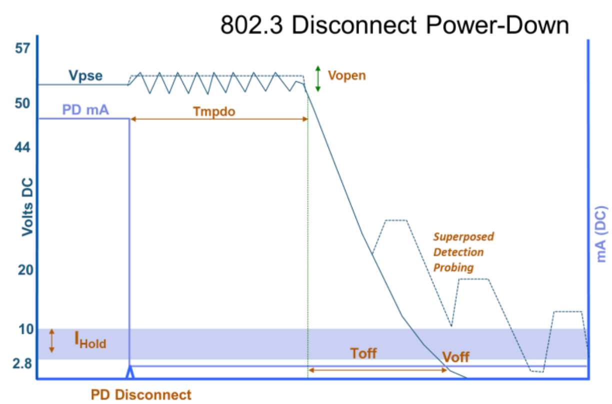

Figure 2.12 802.3 PoE Disconnect Power-Down

Once the PSE removes operating voltage, the PSE is expected to discharge to **Voff**, or 2.8V, in a period of

500msec (**Toff**). Some PSE's may start detection probing as the output voltage discharges resulting in superposed signaling on the discharging output. This could interfere with the **Toff** requirement.

PSE's powering single signature PD's with 4-Pair power have the option to remove power on one pairset immediately at PD disconnect but must keep the other pairset powered over the duration of **Tmdpo** (320 – 400 msec) to be sure the PD disconnect is a real event and not a sudden spurious drop in PD load current.

The **DC MPS** (DC maintain power signature) method for detecting a PD disconnect was allowed in all three specifications (802.3af, 802.3at, and 802.3bt) and relies on a continuous measurement of DC load current to assess PD disconnects. The DC MPS method is the only technique allowed by the more recent **802.3bt** specification. Under this method, a small band of current (**I_{HOLD}**) is defined where a PSE has the option to deem the PD as connected or disconnected. Above this band, the PSE must assume the PD is present. Below this band, the PSE must assume the PD is disconnected. The **I_{HOLD}** current band differs between 802.3at and 802.3bt but has been designed so that 802.3at PD's will interoperate with 802.3bt PSE's and vice versa.

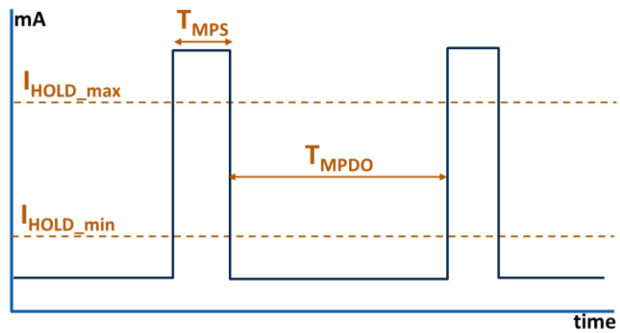

Figure 2.13 DC MPS Minimum Power State

Under 802.3at, the maximum **I_{HOLD}** current was 10mA meaning that a PD needing to stay powered would draw typically 0.5 watts or more continuously. For a PD operating in a "sleeping" state, this was a considerable amount of power and depending on the design of the PD, the quiescent power of 0.5 watt might steal from the power available when the PD was fully operating.

To address this, both 802.3at and 802.3bt allow that the DC MPS signature current, **I_{HOLD}**, need not be present continuously. In Figure 2.13, the PD load current is show to exceed the maximum **I_{HOLD}** level for a period of **T_{MPS}**. Between **T_{MPS}** intervals, the PD load current can drop all the way to 0mA for a maximum period of **T_{MPDO}** (min). This produces a duty cycle of **T_{MPS}** / (**T_{MPS}** + **T_{MPDO}** (min)). A PD meeting or exceeding this duty cycle must be deemed connected by a PSE that uses the DC MPS method.

The following table provides values for **I_{HOLD}**, **T_{MPS}**, and **T_{MPDO}** from 802.3at and 802.3bt.

PSE Type	Powered Pairs	PD Class	I_{HOLD} (Pairset)	I_{HOLD} (4-Pair)	T_{MPS}	T_{MPDO}(min)	T_{MPDO}(max)
1 and 2	2	All	5 to 10 mA	N/A	60 msec	300 msec	400 msec
3	2	1 - 4	4 to 9 mA	N/A	6 msec	320 msec	400 msec
3 and 4	4	1 - 4	2 to 5 mA	4 to 9 mA			
3 and 4	4	5 - 8	2 to 7 mA	4 to 14 mA			
3 and 4	4	1 dual – 5 dual	2 to 7 mA				

From this table, it is evident that any PD connected to an 802.3at PD must draw 10mA with a duty cycle of more than 17% in order to maintain power. However, PD's connected to an 802.3bt (Type-3 or Type-4) PSE can operate at much lower duty cycles on the order of 2.5% and maintain power. This "low power MPS" feature will allow very low power sleep modes in PD's such as lighting systems.

The **AC MPS** method involves the superposition of a low level, relatively low frequency AC resistance probing signal on the DC power rail. The AC MPS probing signal is sourced through high impedance such that when exposed to a nominal load resistance of 25 KΩ, the amplitude of the signal is attenuated to well below 500 mVp-p. Typically it will be far below 200 mVp-p. When the 25 KΩ signature load is removed as a result of PD disconnect, the AC signal amplitude increases and can be detected on the PSE output (*see **Figure 2.12***). **Vopen** specifies maximum allowed AC voltage during this time interval to be 10% of **Vpse.** The PSE must then wait for an interval of at least 300 mSec, but not longer than 400 mSec to remove power.

PD's can present a ~25KΩ or smaller resistive load to assure PSE's using the AC MPS method will keep them powered. This amounts to a continuous power consumption of approximately 0.1 watt. PD's that continuously draw even just two milliamps will also meet this load requirement (50V / .002A = 25KΩ). The key drawback to AC MPS is that it requires additional hardware in the PSE and it may increase power rail ripple by a small amount. AC MPS was not included in the **802.3bt** specification because PSE silicon manufacturers all accepted that DC MPS was a more cost effective solution to PD disconnect detections.