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Indika U. Perera, Dinusha R. Thotagamuwa, Jean Paul Freyssinier, Nadarajah Narendran, "Characterization of a Power-over-Ethernet (PoE)-based LED lighting system," Proc. SPIE 10940, Light-Emitting Devices, Materials, and Applications, 109401K (2 April 2019); doi: 10.1117/12.2510019

SPIE.

Event: SPIE OPTO, 2019, San Francisco, California, United States

Characterization of a Power-over-Ethernet (PoE)-based LED lighting system

Indika U. Perera, Dinusha R. Thotagamuwa, Jean Paul Freyssinier, and Nadarajah Narendran*
Lighting Research Center, Rensselaer Polytechnic Institute, 21 Union St., Troy, NY 12180 USA

ABSTRACT

LED lighting systems using Power-over-Ethernet (PoE) technology have been introduced to the lighting market in recent years as a network-connected lighting solution. PoE technology can provide low-voltage direct current (dc) power and control information to LED lighting over a standard Ethernet cable. One of the commonly claimed benefits of the PoE-based lighting system is higher system efficiency compared to traditional line voltage alternating current (ac) systems. This is due to the fact that in the case of PoE systems, the ac-dc power conversion losses are minimized because the ac-dc power conversion takes place at the PoE switch rather than at all the LED drivers within the lighting fixtures. However, it is well known that power losses can occur as a result of increased voltage drop along the low-voltage cables. The objective of this study was to characterize a PoE lighting system and identify the power losses at the different parts of the system. Based on the findings, we developed a methodology for characterizing the electrical efficiency of a PoE-based LED lighting system and then used this methodology to characterize commercially available PoE-based LED lighting systems and compare their performance. The electrical efficiency characterization included both the system as a whole and each individual component in the systems, such as the power sourcing equipment, powered device, Ethernet cables, and LED driver. The study results also investigated the discrepancy between the measured and reported energy use of the system components.

Keywords: PoE, switch, Ethernet, connected, networked, controls, lighting, IoT

1. INTRODUCTION

Power-over-Ethernet (PoE) technology is an alternative to the traditional alternating current (ac) electrical power distribution infrastructure in a building, which supplies low-voltage direct current (dc) power in addition to communication using a standard Ethernet cable. Over the past few decades, the maximum power delivered to compatible devices designed to be operated on PoE has increased. The Institute of Electrical and Electronics Engineers (IEEE) 802.3af standard in 2003 specified 15.4 W of minimum power per Ethernet port, which increased to 100 W in the 2018 draft version of the 802.3bt standard. This increase in the available power from a compatible PoE source enabled telephones, security cameras, and networking devices to be powered, but lighting remained an elusive application due to the power requirements of traditional lighting technologies until the recent prominence of light-emitting diode (LED) technology. In recent years, LED technology-based lighting products not only penetrated nearly 30% of all outdoor and over 12% of all indoor lighting applications, they also drastically decreased the electrical power demand.[1]

As an example, based on a report from the United States Department of Energy CALiPER program, all LED luminaire median efficacy values increased from 49 lumens per Watt (lm/W) in 2010 to 105 lm/W in 2019.[2] Assuming a 5,000 lumen luminaire light output, the estimated input power demand for such a luminaire would decrease from 102 W in 2010 to 48 W in 2019. This decrease in required power due to the increase of luminous efficacy of LED lighting technology provided an avenue for PoE technology to power lighting systems to be used as an alternative to traditional ac powered lighting systems.

PoE lighting systems could also have higher system efficiencies over ac powered lighting systems, similar to reported literature on dc powered lighting systems.[3][4] Some literature has looked into experimentally determining the actual efficiencies of some components, such as cable losses, of PoE-based LED lighting systems.[5],[6] Petroski investigated the Ethernet connector in PoE applications using mechanical and thermal modeling.[7] He concluded dc voltage transmission was feasible with dc power up to 90 W, but beyond 90 W of power would result in damage to the Ethernet connectors due to excessive heating caused by high operating temperatures. Petroski also stated that long Ethernet cables bundled together would result in heating of cables, prompting safety concerns and unsatisfactory performance.

**Email:* narenn2@rpi.edu; Web: http://www.lrc.rpi.edu/programs/solidstate/*

Light-Emitting Devices, Materials, and Applications, edited by Jong Kyu Kim,
Michael R. Krames, Martin Strassburg, Proc. of SPIE Vol. 10940, 109401K
© 2019 SPIE · CCC code: 0277-786X/19/$18 · doi: 10.1117/12.2510019

Although these studies investigated and quantified Ethernet cable and connector losses, system and component level electrical performance reported in the literature is limited.

Therefore, the objectives of this study were: (1) to develop a methodology to characterize electrical performance of PoE lighting systems; (2) to use this methodology to characterize the system and component performance of three PoE lighting systems; and (3) to compare a PoE LED lighting system to a traditional ac powered LED lighting system. To the best of our knowledge, at the time of the study in December 2016 we were not aware of available literature specifying a standardized method for testing PoE-based lighting systems.

2. BACKGROUND

The main components of a PoE-based LED lighting system include the PoE switch, the Ethernet cable(s), the powered device(s) (PD), and the lighting fixture. These main components are illustrated in Figure 1. These Power Sourcing Equipment (PSE) devices could be of either endspan or midspan configuration. The midspan PSE is used to inject dc power on to 4-paired wires of the Ethernet cable that is already used to transfer data via an Ethernet data switch. Both data and dc power are delivered to PDs via Ethernet cables through the midspan PSE. The endspan PSE device is a hardware equivalent of both the data switch and the PoE midspan device in comparison to having the said two separate hardware devices, as indicated by the purple discontinuous line in Figure 1. The PSE and PD in the PoE system is equivalent to the traditional ac-dc driver in a traditional lighting system.

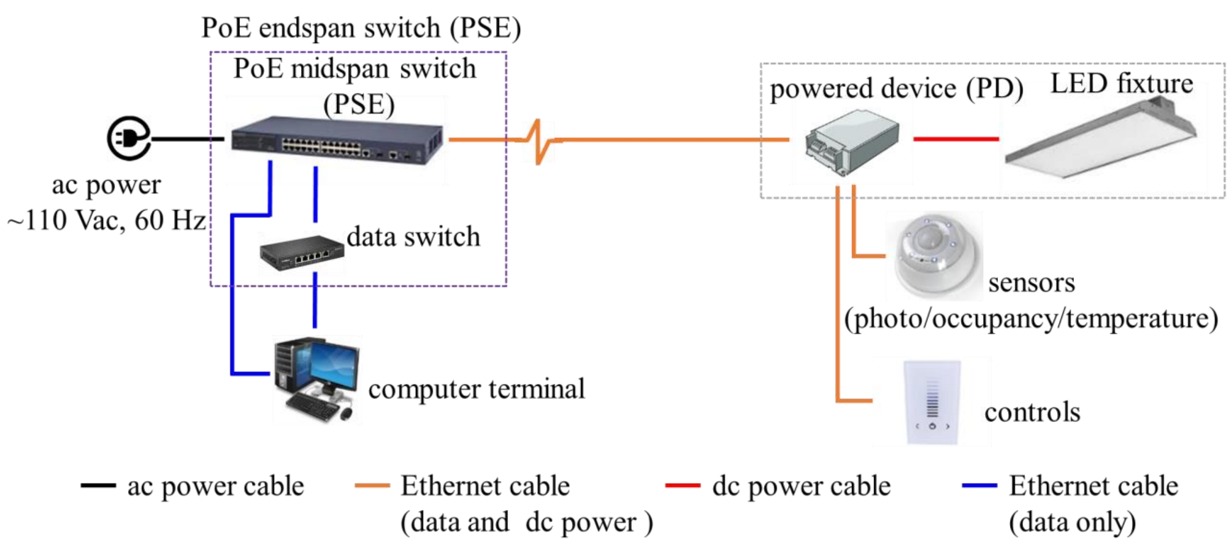

Figure 1. Schematic diagram of a PoE-based LED lighting system

In most cases, the PoE switch is housed in a central location. The PDs are proximal to the LED lighting fixtures or even integrated with the lighting fixture similar to the LED driver being mounted or positioned on the LED fixture in a traditional ac lighting system (the components in the localized area are indicated by the gray discontinuous outline). The Ethernet cable(s) connect the PSE to the PD. Although multiple PDs can be connected to the same PSE port via daisy-chaining PDs or intermediary PDs (not shown in Figure 1), in a typical PoE lighting system each PD is connected to a single port of the PSE. The ability of a PSE port to be daisy-chained to multiple PDs depends on the power available at the PSE output port. The LED fixture is wired with regular electrical hook-up cables or Ethernet cables from the PD. Similarly, the sensors and controls can be connected to the PD (as shown in Figure 1) or the PSE with either regular electrical hook-up cables or Ethernet cables (not indicated in Figure 1).

3. METHODOLOGY

Three PSE devices, a single-port PoE injector, an 8-port midspan PoE switch, and a 12-port midspan PoE switch, were selected for this laboratory study. Each channel of these PSEs was connected to a single type of PD for powering an LED fixture. Table 1 shows the main characteristics of the PSE devices used in the study.

Table 1. Characteristics of the PoE switches (PSEs) used

		Single port injector	8-port switch	12-port switch
Type		Midspan	Midspan	Midspan
# Port(s)		1	8	12
Total max. output power [W]		60	240	864
Max. output power per port [W]		60 over 4-pairs	32 over 2-pairs	72 over 4-pairs
Output voltage per port [V]		55 Vdc	54 to 57 Vdc	50 to 57 Vdc
Output current per port [mA]		1350	10 to 555	~1400
Pin-out configuration	Data Pairs	1/2 (-) and 3/6 (+)	1/2 (-) and 3/6 (+)	1/2 (-) and 3/6 (+)
	Spare Pairs	7/8 (-) and 4/5 (+)	7/8 (-) and 4/5 (+)	7/8 (-) and 4/5 (+)
	Power Pairs	1/2, 3/6, 4/5, and 7/8	1/2 and 3/6	1/2, 3/6, 4/5, and 7/8
Compatible connector(s)		Shielded RJ-45, EIA 568A and 568B	RJ-45, EIA 568A and 568B	Shielded RJ-45, EIA 568A and 568B

The main power input and output characteristics of the PD used in this study are listed below in Table 2.

Table 2. PD input and output characteristics

PD feature	Value
Class type	2
Input power	60 W
Input voltage	57 Vdc
Output voltage	24-48 Vdc
Max. current output	1.4 A

To investigate the effects of Ethernet cable length and category type, three lengths of Ethernet cables and three different category types of Ethernet cables were used for the study. Table 3 lists the Ethernet cable variants used.

Table 3. Ethernet cable characteristics used

Category type	Cable gauge (AWG)	Solid/Stranded	Length of cable ± 0.01 m [m]
Cat 5E	24	Stranded	25.08
			49.96
			99.92
Cat 6	24	Stranded	24.97
			49.91
			100.07
Cat 6A	23	Solid	24.94
			50.06
			100.04

Figure 2 illustrates the measurement setup used for the electrical characterization of the PoE-based LED lighting system. The electrical power input to the system was measured using power analyzers. The power analyzers had a power measurement accuracy of 0.1%. All dc voltages were measured using a 6½ digit digital multimeter (DMM). The power analyzer and DMM measurements were recorded using a data acquisition (DAQ) system and computer via a National Instruments LabVIEW software interface.

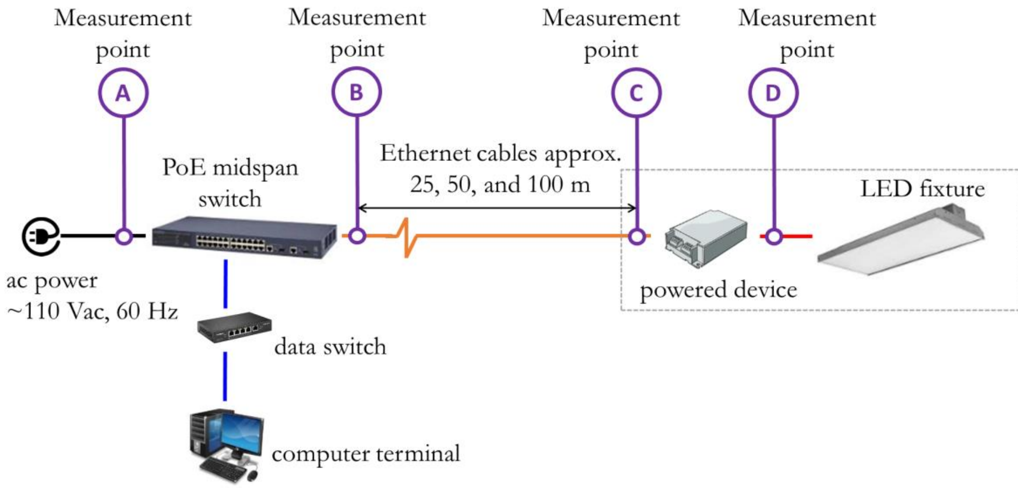

Figure 2. PoE-based LED lighting system electrical efficiency measurement setup

All dc current measurements were evaluated using the voltage across the shunt resistors of 0.001Ω. Commercial 32W 2×2 LED fixtures were used as the lighting load for the traditional ac lighting system and the PoE lighting systems. This 2×2 LED fixture was selected based on the PoE enabled system integrated by the LED fixture manufacturer's recommendations.

To compare the electrical performance of PoE LED lighting systems, a traditional ac-dc LED lighting system with hook-up cables of 12-AWG (American wire gauge) wire was also used in the evaluation, keeping the same LED lighting load. Figure 3 illustrates the measurement setup used for characterizing the traditional ac-dc LED lighting system. A 700 mA constant current dimmable driver controlled the drive current to the LED fixture. Similar to the Ethernet cable analysis conducted for the PoE-based lighting system, the 12-AWG hook-up cables used between the ac power outlet to the constant current LED driver were investigated for cable length effects on electrical performance of the lighting system. Electrical hook-up cable lengths of 25.07, 50.09, 100.04 m were used. The measured cable length tolerances were to the nearest ±0.01 m. The LED ac-dc driver was selected based on LED fixture manufacturer recommendations.

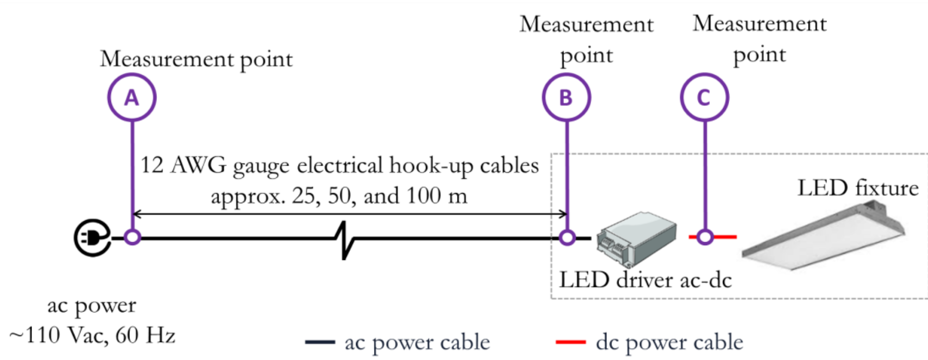

Figure 3. Traditional ac-dc LED lighting system electrical efficiency measurement setup

The measurement methodology is composed of a number of steps (listed below) for evaluating electrical power and efficiency of a general PoE-based LED lighting system.

Step 1: Identification of the PoE system components

The PoE switch (PSE) and PD component type and class have to be correctly identified from name plates, user manuals, and customer support available from the component manufacturers. This enables the interface circuitry used for the evaluation stage to be designed and constructed to be capable of measuring electrical current, voltage potential, and electrical power. Special attention has to be given to the type of Ethernet cable (e.g., Cat5e, Cat6, Cat 6a, etc. and the wire gauge) used in the system.

For PSE and PD type and class classifications and information, please refer to the relevant PoE standards from IEEE standards.

Table 4 lists the minimum wire gauge requirements for Ethernet cables. “AWG” denotes the American Wire Gauge provided in ASTM standard B 258 to denote wire diameter of round, solid, nonferrous, electrically conducting wire.

Table 4. Minimum wire gauge requirements[8]

Maximum total rated DC power of PD (P_{PD})	Minimum wire gauage of cable
$P_{PD} \leq 25.5$ W	24 AWG
25.5 W < $P_{PD} \leq 55$ W	24 AWG
55 W < $P_{PD} \leq 71$ W	23 AWG

Step 2: Component input-output electrical measurement

The electrical measurement points have to be identified, which enables both input and output electrical parameters of each individual system component in the PoE lighting system to be evaluated. As an example, the ac input to the PSE and the dc output from the PSE have to be measured to evaluate the PSE electrical efficiency.

Step 3: Determine test conditions

The system level testing of the PoE lighting systems was conducted with Ethernet cables with lengths <1 m. The system level testing of the single port injector PoE system was conducted by varying the lighting load of the single port. In the PSEs with multiple ports, the lighting load on a chosen single port (e.g., port #1) was varied from 0% to 100% while all other remaining ports (e.g., port #2 through n, in an n-port PSE) were loaded to a number of varying loading conditions from 0% to 100%.

Step 4. Measuring electrical parameters in the ac input

The electrical hook-up cables that supply the ac power to the PoE lighting system are used by tapping into the electrical cables with electrical connections to connect the power meter to measure the ac input parameters. The measured parameters include but are not limited to ac root mean square (rms) voltage, ac rms current, ac average power, power factor, total harmonic distortion, etc. Care must be taken to minimize the electrical impedance of the introduced connections, lead wires, and power meters. As an example, the lead wires need to be at least 18 AWG (single core or multi-stranded copper with insulation) twisted wire and no longer than 10 feet in total length.

Step 5: Measuring electrical parameters in the dc output

As a minimum measurement requirement, both dc voltage and dc current have to be measured. The measurement of dc voltage from any component should be conducted in parallel with the measurement of dc voltage with the probing points close to the physical system component of interest along the electrical hook-up or Ethernet cables. A series connection method is recommended for dc current with shunt resistors which contribute ≤0.001Ω in the measurement path. For these measurements, appropriate digital multimeters with at least 10 GΩ of input impedance should be used to reduce the impact on measured dc voltages.

Figure 4 illustrates a schematic diagram of the electrical measurement points and the terminal blocks needed to access the Ethernet twisted pairs at either end of the Ethernet cable.

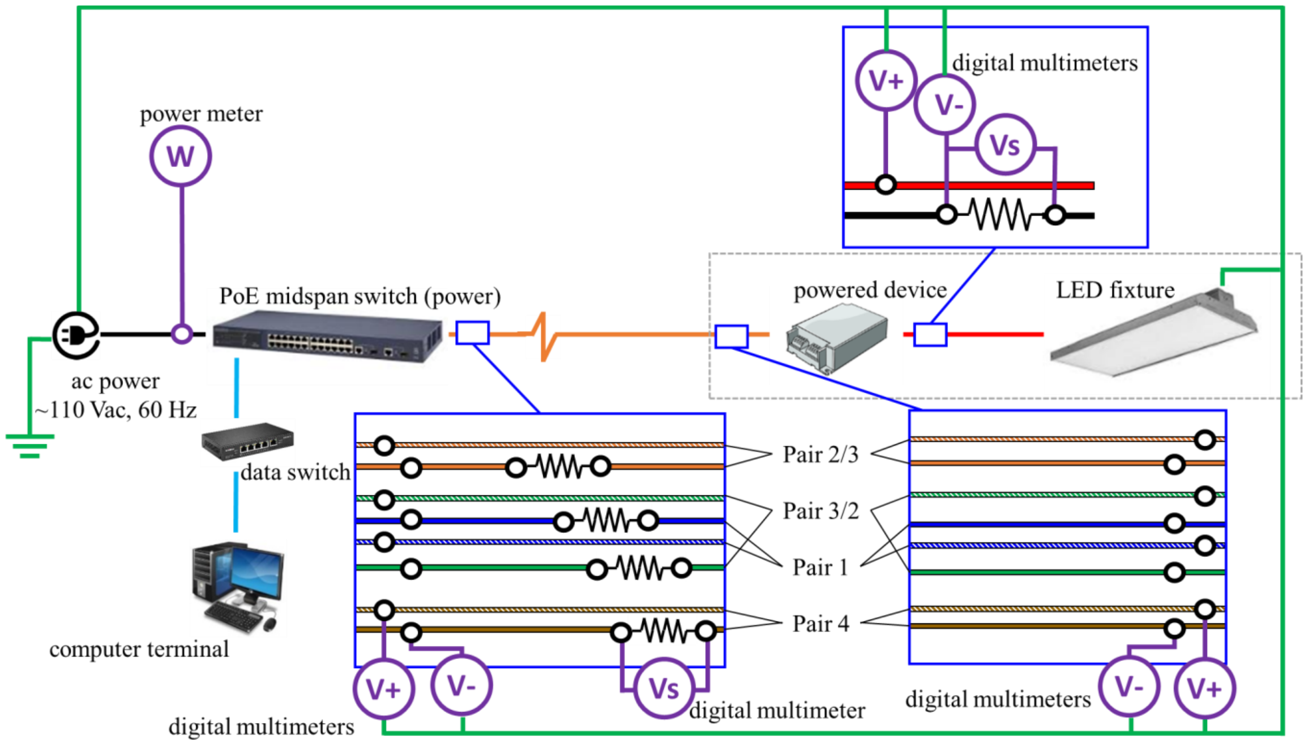

Figure 4. Schematic diagram of the proposed PoE measurement setup

Step 6: Measuring electrical parameters in the Ethernet cables

The type of PoE system must be identified correctly at this step in order to determine if the electrical power is supplied over 2- or 4-pairs of the wire in the Ethernet cable. The potential difference across each of the four-pairs of wire in the Ethernet cable is measured at the terminal blocks (illustrated in Figure 4). The dc current in each of the four-pairs of the Ethernet cable is measured using shunt resistors which contribute a potential increase less than ≤0.001 V dc in the path.

Step 7: Steady-state measurement and calculation of measured electrical parameters

The electrical power losses are either measured or calculated from the dc voltage and current measurements at steady-state operation. The PoE system is assumed to have steady-state operation after the input dc power variation to the LED lighting fixture is less than 2% for three measurements taken within 20 minutes of continuous operation. As an example, most conditions tested with the PoE lighting systems reached steady-state within this 20-minute window.

4. RESULTS

The results section of this study is manly focused on the electrical input power, output power, and the subsequent power loss and efficiency at both the system level and component level.

The results from the traditional ac LED lighting system with 12-AWG hook-up cables are shown in Figure 5. The system input and output electrical power were not observed to be affected by the length of the 12-AWG hook-up cables since the 25 m, 50 m, and 100 m cable lengths had similar power and efficiency characteristics at different lighting load conditions (only 25 m and 100 m cable results are illustrated in Figure 5). This was expected based on National Electrical Code NEC 210-19(a) FPN No. 4, which requires the voltage drop for ac branch circuits for lighting to be <3%, which would amount to <3% power loss. The ac lighting system consumed 2.4 W at 0% lighting load (standby power) while the power loss increased to 4.4 W at 76% loading (estimated to be 6.0 W at 100% loading). Based on the measured input and output power characteristics, a maximum efficiency of ~85% was estimated at 100% lighting load. The results indicated that the power loss in the traditional ac lighting system is mainly due to the LED driver ac-dc conversion inefficiencies. The LED driver efficiency increases with an increase in lighting load since the standby power at 0% lighting load was similar in magnitude to the ac-dc conversion losses at 100% lighting load.

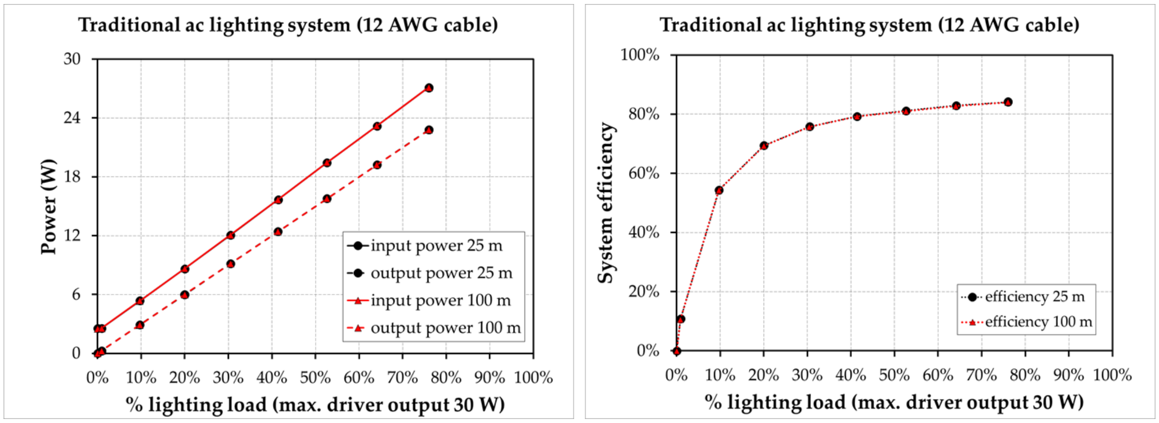

Figure 5. Results for the total system power and efficiency of the traditional ac LED lighting system

The results of the single-port injector PoE lighting system are shown in Figure 6. The system level testing of the PoE lighting systems was conducted with Ethernet cable lengths of <1 m.

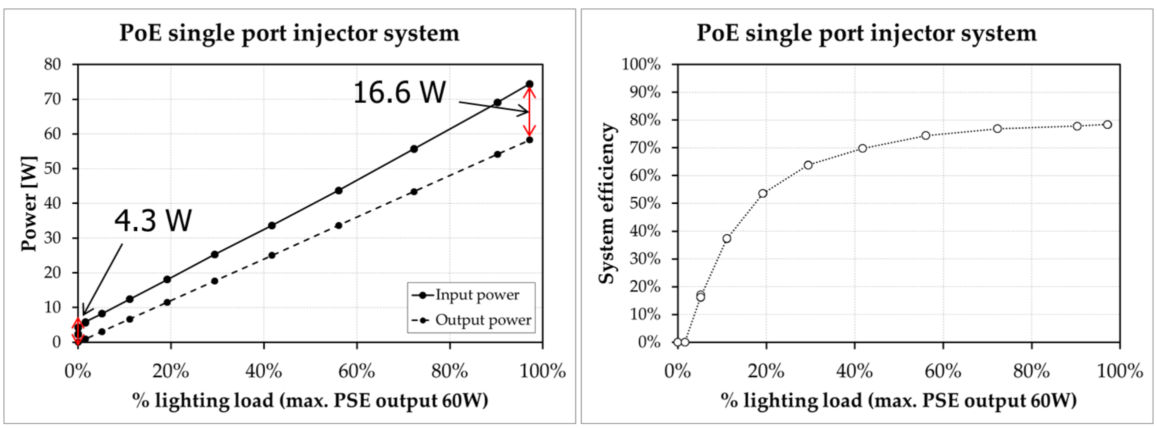

Figure 6. Results for the total system power and efficiency of the PoE single-port injector lighting system

The general trend of the input and output power and system efficiency increase with increase in lighting load was observed, similar to the traditional ac lighting system. The single-port PoE system consumed 4.3 W at 0% lighting load (standby power). The power losses increased to 16.6 W at 97% loading level (estimated to be 16.6 W at 100% lighting load condition). The estimated maximum electrical efficiency was 78% at 100% lighting load.

This same trend of input and output power increase with increase in lighting load and the increase in system efficiency with an increase in lighting load was observed in the multi-port PSEs. As an example, the PoE 12-port lighting system results are illustrated in Figure 7. The results show the power and efficiency were affected when the PSE port #1 lighting load varied from 0 to 100%, with the other remaining PSE ports #2 through 12 having a load increase from 0 to 83% in discrete load conditions. Each port in the PoE 12-port system consumed 5 W at 0% lighting load (standby power). At 83% lighting load, the power loss was 20 W per port. The estimated power loss was 24 W per port at 100% lighting load. The estimated maximum efficiency was 75% at 100% lighting load.

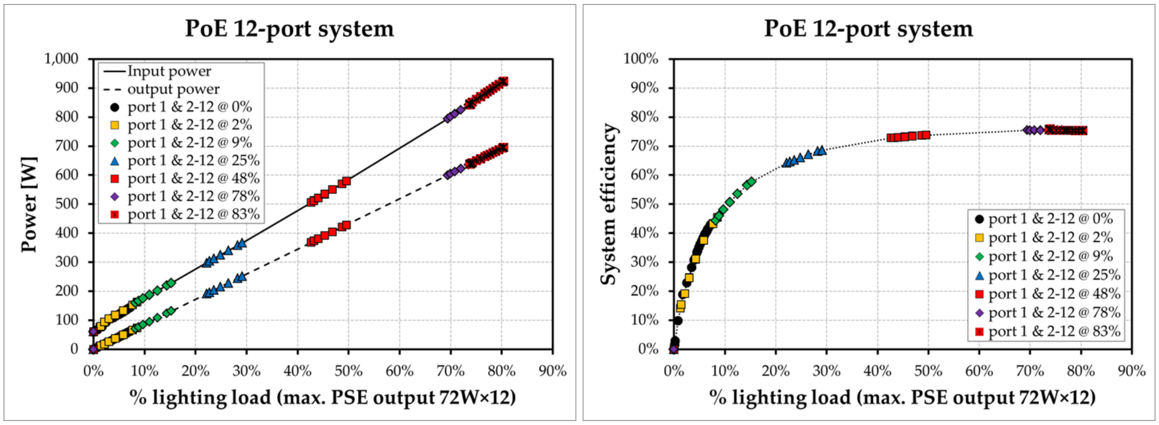

Figure 7. Results for the total system power and efficiency of the PoE 12-port lighting system

The study results showed that at lower PSE lighting load levels, the total system efficiency varied depending on the load distribution among the PSE ports. Figure 8 shows this system efficiency change as lighting load distribution is varied among the PSE ports. Variation in port distribution caused system efficiency variations up to 14% at ~10% lighting load in the 8-port PoE lighting system, amounting to a power loss of ~3.5 W. In the 12-port PoE lighting system, the system efficiency variation is as high as 12% at approximately 5% lighting load of total PSE. The 12% change in the efficiency corresponded to a power loss of 5.2 W. The efficiency variations due to PSE port loading distribution were <5% for total PSE lighting loads >50%.

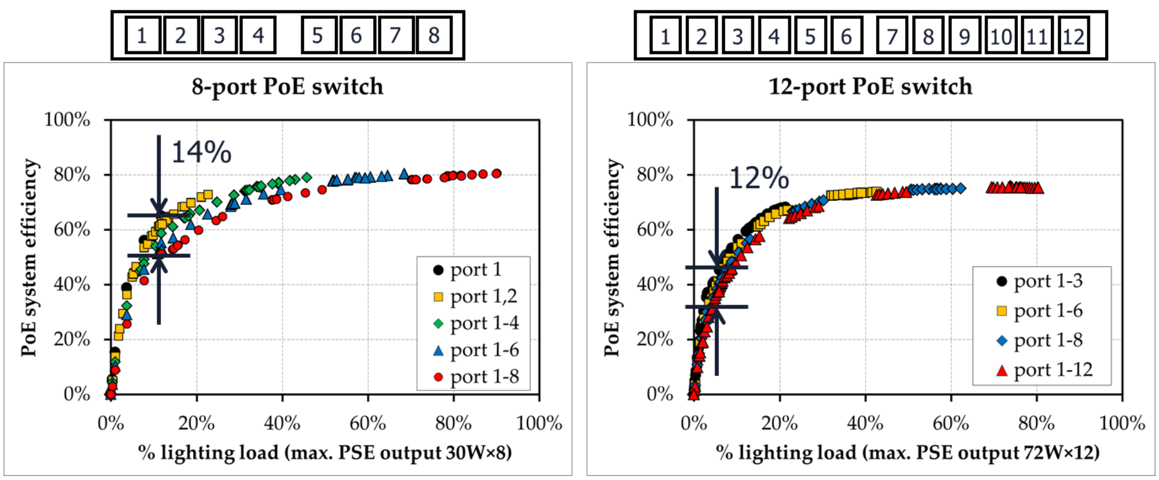

Figure 8. Results for total system efficiency of 8-port and 12-port PoE lighting systems

The results described above illustrate the electrical input, output, and efficiency of the PoE systems. Due to the modularity of the systems where different PSEs can be coupled with PDs using Ethernet cables, individual components such as PSEs, PDs, and Ethernet cable performances are critical. The following section reports these critical component level efficiency results.

Figure 9 shows the PSE component level efficiencies of the three tested PSEs and the system efficiencies. The three PSEs tested showed similar efficiency trends to the PoE system efficiencies. This is mainly due to the system power losses; therefore, efficiencies are dominated by the PSE compared to the Ethernet cable and PD effects. The main contributor to power loss and inefficiencies is the standby power of the PSEs.

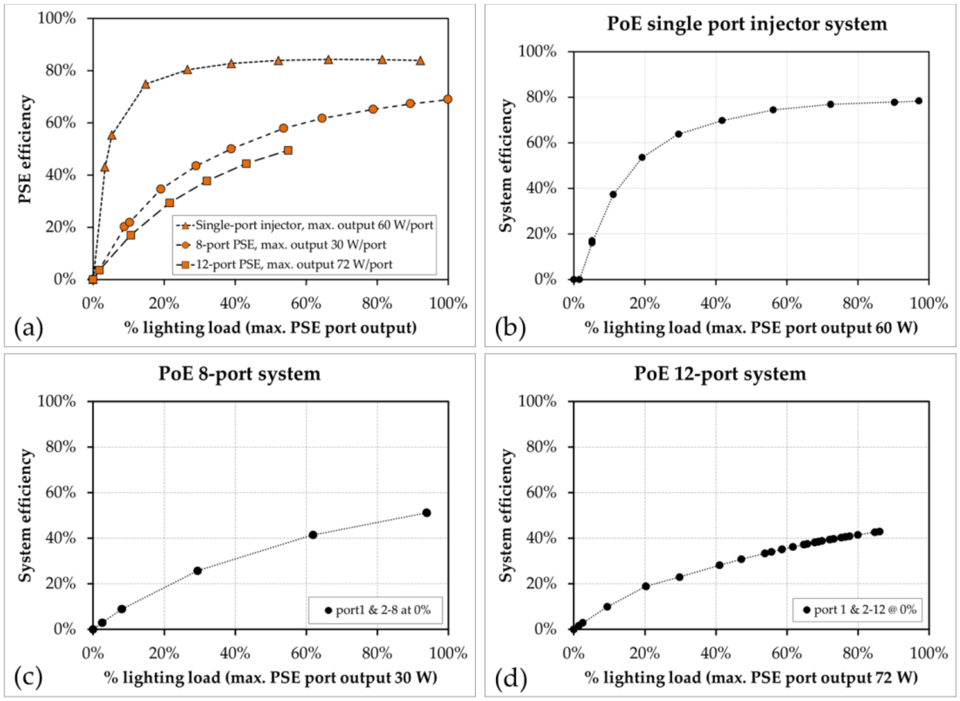

Figure 9. Component level testing results of (a) all three PSEs, (b) single-port injector, (c) 8-port system, and (d) 12-port system

Figure 10 illustrates voltage drop, power loss, and efficiency for Ethernet cable types and Ethernet cable lengths. The Ethernet cable types used in the study included Cat 5e and Cat 6 cables of 24-AWG stranded wire with effective diameter of 0.51 mm, and Cat 6a cable of 23-AWG solid wire with diameter of 0.57 mm.

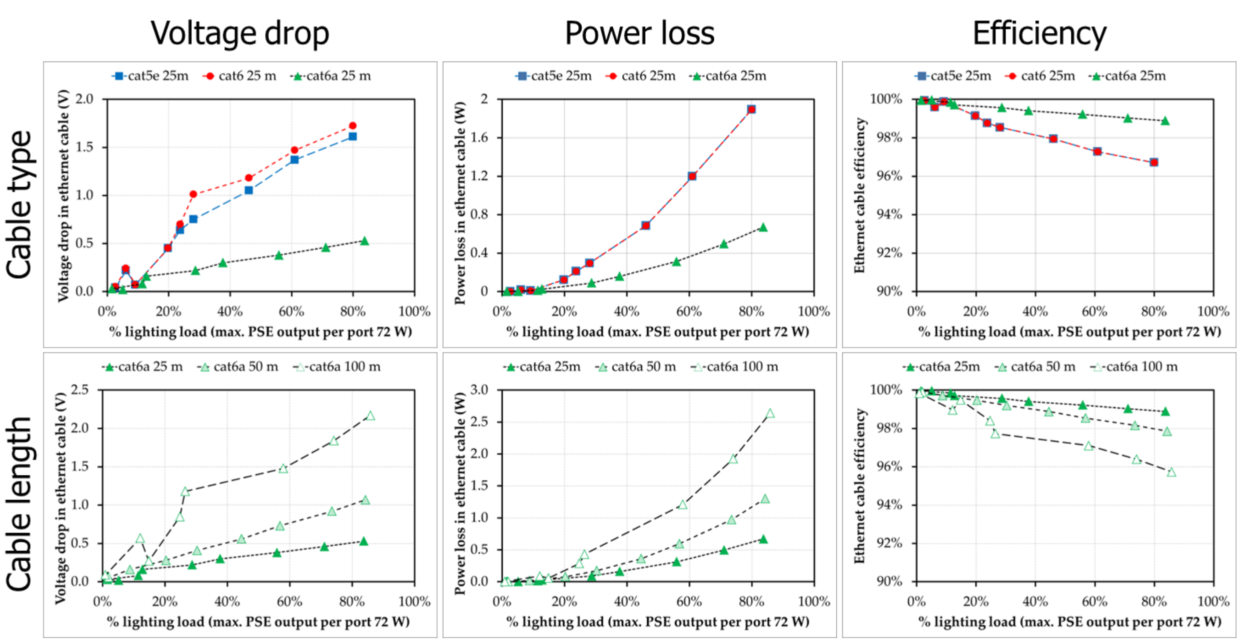

Figure 10. Component level testing results of Ethernet cable lengths and types

The increase in lighting load constitutes an increase in current. This increase in current leads to a linear increase in the voltage drop (i.e., $V_{drop} \propto I$) and a quadratic increase in power loss (i.e., $P_{loss} \propto I^2$), as can be observed in Figure 10. The Cat 5e and Cat 6 Ethernet cables show identical voltage drops and power losses due to the same wire-diameter while the Cat 6a Ethernet cable shows decreased voltage drop and power losses due to the increase in wire-diameter and the solid cable compared to stranded wires of the other Ethernet cables. A similar trend can also be observed for Ethernet cable length. For all Cat 6a cables of 25 m, 50 m, and 100 m lengths, the voltage drop appears to follow a linear $V_{drop} \propto I$ relationship while the power loss appears to follow a quadratic $P_{loss} \propto I^2$ relationship.

Figure 11 shows the PD efficiency as a function of lighting load percentage. The same PD was coupled with the three PSEs. The PD efficiency curves show that the PD electrical power losses and efficiency depend on the PSE and the PSE power configuration where 2- or 4-twisted pairs are used for delivering power to the PD. The standby power of the PD was 2.0 W when interfaced with the single-port injector and the 12-port PSE, which were both delivering power over all 4-twisted pairs, while the standby power increased to 2.7 W when interfaced to the 8-port PSE, which only used 2-twisted pairs for delivering power. The PD reached a dc-dc efficiency of 80% at different loading conditions when interfaced with the three PSEs. As an example, when the PD was interfaced with the 12-port PSE, the PD reached 80% efficiency at 6.5 W lighting load or 9% of maximum power output per port, whereas the lighting load was 15 W to reach 80% efficiency with the single-port injector and 8-port PSEs, equating to 25% and 50% of maximum power output per port, respectively. These results indicate the PD electrical characteristics such as power loss and efficiency at least depend on the loading condition, the PSE, and the PSE power delivery configuration.

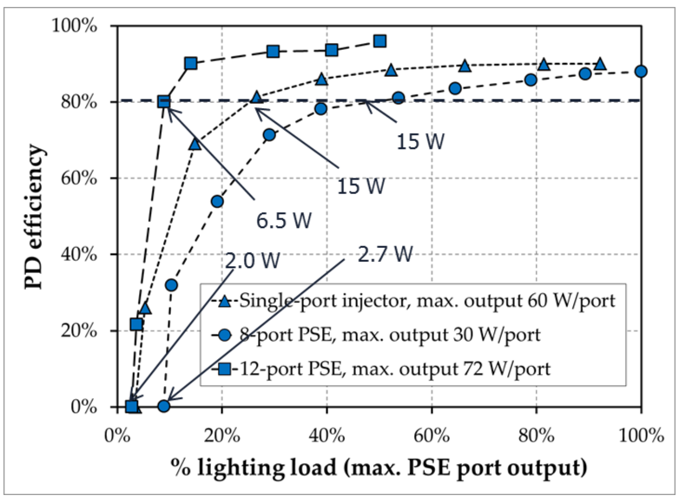

Figure 11. Component level testing results of PDs

5. DISCUSSION

Most available literature on PoE systems focus on the Ethernet cable length effects on power loss and efficiency. Others focus on the efficiency of dc-dc control IC circuitry for PoE applications where they show electrical efficiencies ≥90%.[10],[11] This study investigated the three different PoE system configurations using three commercial PSEs interfaced to a single type of commercial PD using Ethernet cables of different type and different lengths to evaluate the electrical power losses and efficiencies at both the system level and individual component level.

Table 5 shows the summary of the performance comparison of the PoE lighting systems and the traditional ac lighting system. The PoE lighting systems used in the evaluation showed estimated system losses >4% compared to the traditional ac lighting system at 100% lighting load conditions. The PoE system performance is negatively affected by changing the distribution of the channels or dimming light load similar to traditional ac lighting systems. Contrary to the calculated performance of PoE systems reported in literature, this study found that increasing the PoE system lighting load increases the total system efficiency.

Table 5. Comparison of power losses and efficiency of lighting systems

	Traditional ac lighting system	**Single-port injector PoE lighting system**	**8-port PSE PoE lighting system**	**12-port PSE PoE lighting system**
Standby power loss	2.5 W	4.3 W/port	3.0 W/port	5.0 W/port
Power loss @ 100% lighting load	6.0 W	16.6 W/port	7.2 W/port	23.6 W/port
Maximum system efficiency	85%	78%	81%	75%

Figure 12 shows the aggregated results of all tested Ethernet cable types and lengths tested. All tested Ethernet cable variants had a dc-dc efficiency >95%. ANSI C 137.3-2017 standard recommends the Ethernet cable length of PoE systems to be maintained at no longer than 50 m in order to reduce power losses to <5%.[8] Other literature also recommend that the average length of Ethernet cables should not be exceeded to maintain power losses of <5%.[5], [6], [9] Careful evaluation of the dc-dc cable efficiencies illustrated in Figure 12 shows that as the Ethernet cable length increases the dc-dc cable efficiency decreases, but if the wire diameter is increased, average cable lengths of 100 m can be used for PoE lighting systems since the Cat 6a solid 23-AWG wire had a dc-dc cable efficiency of ~97%. In addition, the cable efficiency also depends on the PSE power configuration such as whether the PSE uses all 4-twisted pairs or only 2-twisted pairs for transmitting power to the PD via the Ethernet cable. As an example, the 25 m Cat 5e Ethernet cable used with the 8-port PSE where only 2-twisted pairs are used for power has the same trend as the 50 m Ethernet cables Cat 5e and Cat 6 used with the 12-port PSE. When 30 W of power is delivered by the 25 m Cat 5e Ethernet cable used with the 8-port PSE, 2-twisted pairs are used where each twisted pair delivers ~15 W of power compared to ~7.5 W in a 4-twisted pair configuration. This increase in power delivered requires an increase in current flow leading to a higher voltage drop and a higher power loss >5%, as the trend of the experiment data suggests.

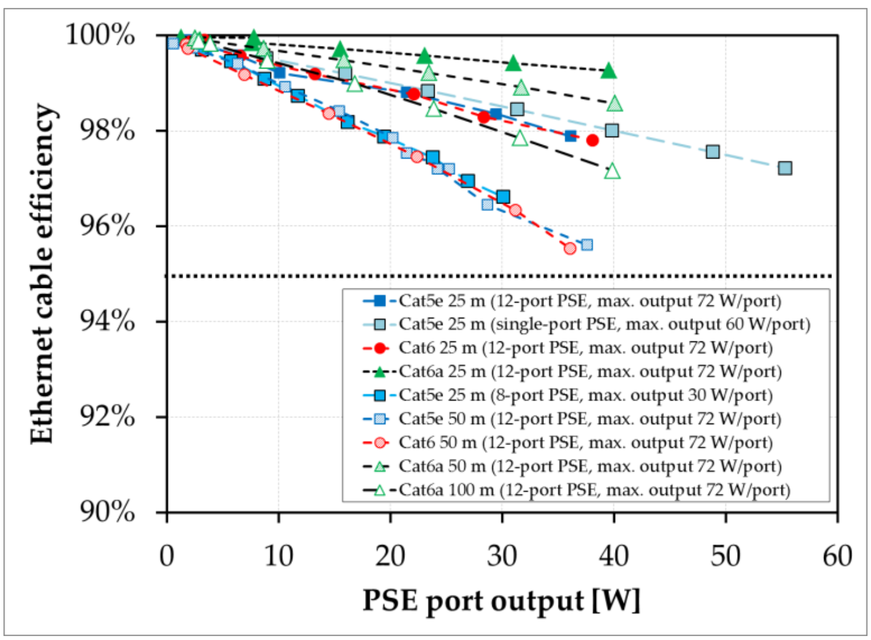

Figure 12. Ethernet cable length effect on dc-dc cable efficiency

These findings of electrical performance and interdependencies of system components require the definitions and photometric testing standards for PoE-based luminaires to be revisited. In addition, these PoE systems might pose reliability-related issues since the PSE is the centralized ac-dc conversion, which could lead to entire system failure. Reliability-related testing also would be more complicated since the PSEs, the Ethernet cables, and PDs all have to be tested with the LED fixture for entire system testing.

Although the PoE lighting systems' electrical efficiency was lower when compared to the traditional ac lighting system tested in this study, the literature claims there are non-energy related benefits such as reduced cost of installation due to the use of the same Ethernet infrastructure for both data and power of compatible devices. This shared infrastructure can provide better control and monitoring, easier integration of sensors and controls, and the ability to expand the lighting system with minimal added cost, increased data security, and less susceptibility to interference from radio frequencies.

6. SUMMARY

The highest system efficiency at 100% lighting loading for a PoE lighting system was estimated at ~81%, compared to 85% for a traditional ac lighting system, when Ethernet cable losses were considered negligible due to tested cable lengths of <1 m. This study also found that contrary to available literature, PoE system performance is negatively affected by a decrease in system efficiency due to decreases in the channel lighting load and decreases in the number of channels that the lighting load is distributed among in a PSE. The PSE ac-dc efficiency was ≤85%, while the Ethernet cable dc-dc efficiency was ≥96% for the tested 23-AWG category cables (Cat 5e and Cat 6a) of ≤50 m length, and PD efficiency was ≤95%. Comparatively, the LED driver ac-dc efficiency was ≤85% and the 12-AWG electrical hook-up cable efficiency was ≥99% for cable lengths ≤100 m. The PoE system standby power was ~5 W per PSE channel of which ~2 W was the standby power consumption of the PD. The traditional ac-dc driver standby power consumption was 2.5 W.

ACKNOWLEDGMENTS

The authors would like to acknowledge the contributions and efforts of Kasey Holland, Martin Overington, and Jennifer Taylor of the Lighting Research Center, and the financial support from the Alliance for Solid-State Illumination Systems and Technologies (ASSIST) and the New York State Energy Research and Development Authority (NYSERDA, Contract #61723) to conduct this study.

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