

Audio amplifier powered over Ethernet

A study of using IEEE 802.3at Power over Ethernet as a power source for a class-D audio amplifier.

Master of Science Thesis in Integrated Electronic System Design

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Cover: Photo of the PoE-amplifier prototype created in this project

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Abstract

Today, a professional amplifier may be supplied with its input as well as control and monitoring via Ethernet. By Power over Ethernet (PoE) it is now possible to provide its power as well. It means that an amplifier can be fully operating with a single cable. Power over Ethernet is standardized by IEEE and it allows 25-34 W to be distributed over a twisted-pair Ethernet cable.

As a proof of concept, a PoE amplifier is created and evaluated. The performance of the amplifier is analyzed to determine if PoE is suited for powering amplifiers. The amplifier is measured both when it is powered over Ethernet and when it is powered with a regular power supply unit. The result is compared to determine what impact PoE has on the output audio quality.

The PoE amplifier is able to deliver 25 W of continuous output power and it can deliver up to 81.8 W when playing a “music like” signal with good audio quality. For lower level output there is no impact in the audio quality on the PoE amplifier but for higher output power the amplifier loses some of its linearity.

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Abbreviations

AES	Audio Engineering Society.
AES3	AES standard for serial transmission format for two-channel linearly represented digital audio.
BPM	Beats per minuets
dBFS	Decibel full scale, referenced to the maximum of the signal
dBu	Decibel unit for voltage referenced to approximately 0.775 V
DSP	Digital signal processor
DUT	Device under test
EMI	Electromagnetic interference
FET	Field-effect transistor
FPGA	Field Programmable Gate Array.
IEEE	Institute of Electrical and Electronics Engineers.
PCM	Pulse-code modulation
PD	Powered Device
PoE	Power over Ethernet.
PSE	Power Sourcing Equipment
PSU	Power Supply Unit
PTZ	Pan, tilt and zoom. Type of camera.
PWM	Pulse-width modulation
RMS	Root mean square
THD	Total harmonic distortion
THD+N	Total harmonic distortion plus noise
TP	Twisted-pair
UPS	Uninterruptible power supply

1. Introduction

1.1 Background

There are three essential elements in an amplifier. First, the amplifier must have a power source that is capable of driving the amplifier to the desired output power. Even if an amplifier can have varying power sources like batteries for a handheld device or be powered by the generator in the car, almost all amplifiers for professional use are powered from the mains power grid.

Secondly, to have any output from the amplifier there must be an input signal. There are a large variety of audio signal formats and the pro audio market has not settled on a single standard. The most commonly used formats in pro audio are balanced analog signal and AES/EBU which is a digital format. Recently, audio over Ethernet has started to evolve and also here there are a large variety of solutions [1]. IEEE has a task group that is developing a standard that is commonly called Audio Video Bridging which would allow low latency audio and video to be transmitted over Ethernet [2].

The third essential element of an amplifier is the ability to control the amplifier. The most basic control of an amplifier is to adjust the gain but some amplifiers also have the ability to, for example, equalize and add delay to the signal and to set limiters on the output. Most amplifiers have a physical control interface at the unit but some also have the ability to be remotely controlled by, for example, a computer or control panel, and this communication is often based on Ethernet.

When both the audio signal and the control interface are evolving towards Ethernet based solutions it would also be of interest to have a power source that is based on Ethernet. Unifying parts of the amplifier into one standardized and well known technology can bring simplicity to the user. Having power, control, and audio signal all transmitted over Ethernet, would give an amplifier that only needs one single cord to operate.

1.1.1 Power over Ethernet

Power over Ethernet (PoE) is a technology to provide power over a standard Ethernet cable. The idea of PoE is to be able to power

network devices on the same network that the device uses for communication. PoE has been included in the IEEE 802.3 Ethernet standard since 2003 [3]. The last update of the standard makes sure that 25.5 W can be provided on an Ethernet network [4].

1.2 Purpose

An audio amplifier that is powered over Ethernet and that has both control and audio over the network has the advantage of only requiring a single cord to operate. This is especially interesting for amplifiers suited for installation, because the need of new wiring is minimized. Furthermore, by being compliant with the IEEE standards, it will be simple to connect an amplifier to an existing network or to build a network of “off-the-shelf” products.

For this type of amplifier, it is important to limit the physical size of the product to make it easier to fit the amplifier in an installation. It is also important to have high efficiency since the power that can be distributed over Ethernet is limited. A class D amplifier has both the benefit of reduced size and weight and has a high efficiency compared to other common types of amplifiers [5].

Within this thesis the concept of an amplifier that is powered over Ethernet is proven. It is done by constructing a prototype of a PoE amplifier. The focus is on the PoE part of the amplifier. The main challenge is to design a power supply unit (PSU) that fulfills the IEEE 802.3at standard without exceeding the power limit of 25.5 W [4] and that at the same time can drive the amplifier with a peak output power of 100+ W with good sound quality.

Furthermore, the applications of a PoE-amplifier are investigated. It is compared to the system installation solutions of today and new applications that fit PoE-amplifiers well are presented.

1.3 Approach

A prototype is constructed to prove the concept of a PoE-amplifier. The prototype had the requirements to use technology that could be used in a consumer product in the sense of low price, small size and energy efficiency. It also had the requirement to comply to the IEEE standard for PoE which would make it compatible with other PoE equipment.

The prototype is a further development of an existing prototype of a medium power, class-D amplifier. The amplifier has a full-bridge

output stage which basically consists of four transistors packed into a single chip. (See section 3.5 for more details.) The full-bridge is driven with pulse width modulated (PWM) signals which are generated by an FPGA and the input signal to the FPGA comes from an S/PDIF interface.

The prototype is constructed in such a way that the PoE module can easily be bypassed which means that the amplifier can be directly powered by an external power supply. This makes it possible to compare the same amplifier when it is powered over Ethernet and when it is power in a regular way and to determine the impact of PoE on the amplifier.

1.4 Limitation and delimitation

Even if the biggest advantage of a PoE-amplifier is to be able to operate with a single cable, this thesis will not go into details about audio over Ethernet or monitoring/control over Ethernet. Nor will the constructed prototype support audio or monitor/control over Ethernet.

Unlike a final product, the entire prototype is not powered over Ethernet. The FPGA and its peripheral circuitry are powered by a five volt power supply. But the output stage of the amplifier is powered over Ethernet so the power for the output signal comes from PoE.

When the usage of the PoE amplifier is discussed it is only done in the scope of professional usage and not for consumer usage. The focus is on the installation application.

2. Theory

2.1 Power over Ethernet

The PoE standard specifies how power can be provided on an Ethernet network without interfering with the data communication in a safe way.

It also specifies a protocol to detect devices that requests power and a method to dynamically negotiate the power needs. This implies that devices which are not compatible with PoE are not fed with power that can damage the device. Therefore, non-PoE devices and PoE devices can coexist in the same network without disturbing each other. If a powered Ethernet cable is disconnected the power is immediately cut and it makes the system safe and prevents electrical shocks [4].

The early IEEE 802.3af standard can guarantee that 12.95 W reach the unit that requested power [3]. The new IEEE 802.3at standard, which was published in September 2009, extends the allowed power to 25.5 W in the receiving end [4]. The extra power makes it possible not only to power small cameras, IP-telephones and wireless access points but also to power more power consuming products like pan-tilt-zoom cameras, displays, small computers and to be used in emergency power grids.

The following sections (2.1.1 to 2.1.5) are all referred to IEEE standard 802.3at [4] unless otherwise stated. Some parts have references to specific sections in the IEEE standard 802.3at and they are written within parentheses.

2.1.1 Power sourcing equipment

The unit that is supplying power to an Ethernet cable is called power sourcing equipment (PSE) and the unit that is receiving power is called powered device (PD). In a twisted-pair (TP) cable used for Ethernet, there are four wire pairs and two or four pairs are used for the data link layer depending on the Ethernet implementation that is used. The PSE may provide power on two of the four wire pairs. In a standard Ethernet TP cable, the power must be provided over either pair 1/2 and 3/6 or over pair 4/5 and 7/8 but it is up to the PSE to decide which pairs to use.

The PSE does not affect the data link since the data is transmitted by differential mode within the pairs and the PSE provides power in common mode to one pair and thereby creating a potential difference between the pairs.

The main functions of the PSE, as described in the IEEE 802.3at standard, are as follows:

- To search the link section for a PD
- To supply power to the detected PD through the link section
- To monitor the power on the link section
- To remove power when no longer requested or required, returning to the searching state

The PSE can be placed in two different locations relative to the cable. It can be merged together with the unit that is using the data link layer and then it is called an Endpoint PSE. This can for instance be a switch or a hub. The PSE can also be placed in between the units using the data link layer and inject power to the cable without dealing with the data and then it is called an Midspan PSE.

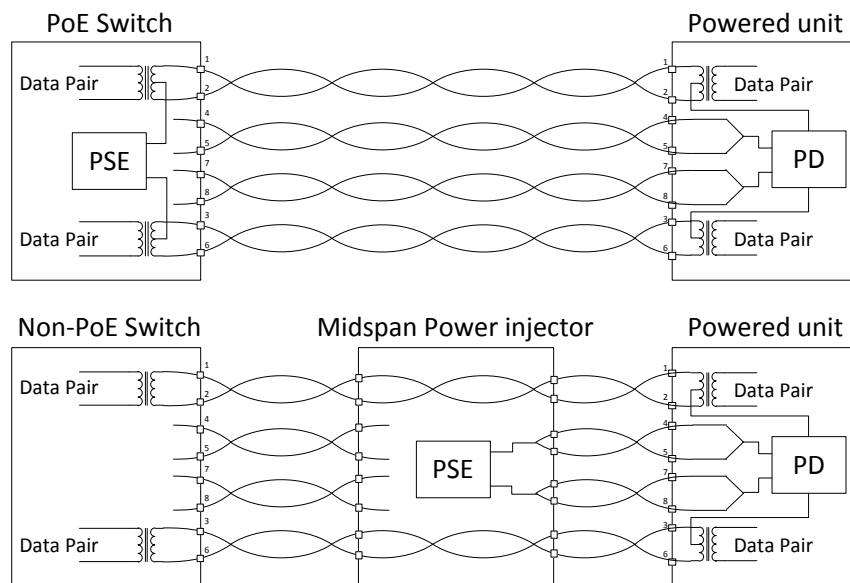


Figure 2.1 Schematic view of endpoint PSE and midspan PSE.

2.1.2 Powered Device

A PD must be able to identify itself as a PD to receive power from the PSE. It must also be able to negotiate its power need with the PSE.

Since it is the PSE that decides which pairs in a TP-cable that should be powered, the PD must be able to receive power in both alternatives. The TP-cable can also be crossed over and therefore the power must be full wave rectified at the PD to ensure the polarity.

2.1.3 Identifying Powered Devices

The PSE must identify the device on the network as a PD before a power connection can be established. The PSE is searching for PDs by probing for a signature resistor of 25 kΩ at the powered wire pair. The PSE shall make at least two measurements at different voltages in the range of 2.8 V to 10.0 V. The effective resistance calculated by equation (2.1) must be in the range of 19.0 kΩ to 26.5 kΩ. (IEEE 802.3at-2009, 33.2.5)

$$R = \frac{V_2 - V_1}{I_2 - I_1} \quad (2.1)$$

Where V_1 and V_2 are the probing voltages for the first and second measurement and where I_1 and I_2 are the measured current. R is the effective resistance.

2.1.4 Classification of Powered Devices

The PD must be classified in order to determine the power requirements of the PD. This is done so that a PSE, with many PoE ports but a limited total available power, can know how much each PD is requesting and deny further PDs when the limit of the total power is reached.

There are four fixed power classes the PD can request. Table 1 shows the classes and the maximum power at the PSE and the guaranteed power at the PD.

Class	Maximum power at PSE	Power at PD	Nominal Signature load current
0	15.4 W	12.95 W	< 4.00 mA
1	4.00 W	3.84 W	10.5 mA
2	7.00 W	6.49 W	18.5 mA
3	15.4 W	12.95 W	28.0 mA
4	30.0 W*	25.5 W*	38.0 mA

* Only used in IEEE 802.3at, otherwise equal to class 0.

Table 1: Power classes in 802.3af and 802.3at

The method for communicating the classification from the PD to the PSE is used in the older IEEE 802.3af standard and it is called 1-event classification. This method got extended in IEEE 802.3at into the 2-event classification. It is backwards compatible so that PD and PSE from both standards can be mixed.

In both 1-event and 2-event, the PSE is probing for the classification by applying a voltage in the range of 14.5 V to 20.5 V and the PD signals the desired power classification by drawing a specific load current. The load currents can be found in Table 1. The PD knows if it is probed for identification (see 2.1.3) or if it is probed for classification since the probing is done in different voltage ranges.

What distinguishes 2-event from 1-event classification is that in the 2-event classification, the PSE is probing two times with a mark voltage in between. If the PD responds correctly to the mark state and the second probing, the PSE knows that the PD is supporting the newer 802.3at standard. And the other way around, if a PD sees a 2-event probing, it knows that the PSE is of standard 802.3at. In the mark state the PSE is applying a voltage in the range of 7.0 V to 10.0 V and the PD should response by drawing a load current between 0.25 mA and 4.00 mA.

The 802.3at standard also introduces another method for classification. It uses the data layer and sends a data packet with the requested power. This gives the possibility to specify a much more specific desired power in steps of 0.1 W. It also gives the PSE and PD the ability to dynamically negotiate the power needs and exchange other information like: power priority, if the PD has an auxiliary power supply or if the PSE is running on backup power.

2.1.5 802.3at specifications

The following specifications are only a part of the specifications in the IEEE 802.3at. These specifications are the most essential or important for this project.

The power that can be distributed over Ethernet is limited by an maximal current which depends on the classification. The highest classification has a current limitation of 600 mA. This value has been specified with respect to the capacity of a CAT5 cable and

that it should withstand the heat generated due to losses in the cable (IEEE 802.3at-2009, 33.1.4). The PSE may cut the power if the PD draws more current than it has been classified for but the PD is also allowed to exceed the classified power for a short time. This peak power is about 11% over the classified power and it can be drawn for 50 ms. This can be repeated with a duty cycle of 5% (IEEE 802.3at-2009, 33.3.7.4).

The output voltage from the PSE ($V_{\text{Port_PSE}}$) can be in the range of 50 V to 57 V. The input voltage at the PD ($V_{\text{Port_PD}}$) is allowed to drop down to 42.5 V due to losses in cables. The PSE may turn off the power if $V_{\text{Port_PSE}}$ drops below 50 V. The PD may turn off if $V_{\text{Port_PD}}$ is below 42.5 V and must turn off if $V_{\text{Port_PD}}$ gets below 30 V. (IEEE 802.3at-2009, 33.2.7, 33.3.7)

The result is that an 802.3at PSE must have a minimum power output of 30 W (50 V * 600 mA) but the maximum power can be up to 34.2 W (57 V * 600 mA) and that the PD are guaranteed an input power of 25.5 W (42.5 V * 600 mA) but the power can be as high as 34.2 W under ideal circumstances.

During power up state, the inrush current should be limited to 450 mA by the PSE (IEEE 802.3at-2009, 33.2.7.5). When the PD has reached the power on state, it must keep the power consumption low for another 80 ms to allow the PSE to switch from power up to power on state. (IEEE 802.3at-2009, 33.3.7.3)

2.2 Audio Measurements

2.2.1 dBu

dBu is a voltage-based decibel unit referred to 0.7746 V and it is a unit commonly used in professional audio and broadcast industry. The reference is derived from the fact that with this voltage 1 mW is dissipated when the load is 600 Ω [6]. This is remains from old technology when it was important to have matching output impedance with the input impedance of the next device and 600 Ω was the standard.

2.2.2 dBFS

dBFS stands for decibel full scale and it is commonly used for amplitude level in digital systems. 0 dBFS is the highest possible

value in a given digital representation. Therefore, all dBFS measurements must be zero or below.

2.2.3 Power

The output power of an amplifier is the power that drives the speakers and it can be measured by looking at the output root mean square (RMS) voltage over a known load. Specifying the output power of an amplifier can be done in many ways and there is no perfect way to do it. The problem is that the output power of an amplifier that is designed for audio should be specified by a signal similar to audio. But since audio can be anything from one single tone to speech and music there is no such signal. Also, to be able to compare different amplifiers with each other there must be a simple way to recreate the signal. The output power of the amplifier in this project is shown in two ways.

Continuous power is measured with an input signal that is a 1 kHz sine wave signal at a level such that the amplifier is not clipping and has a low harmonic distortion. The load is purely resistive and it has an impedance of 8 Ω . The measurement is done over several minutes. This measurement does not represent audio very well but it gives an indication of what the amplifier is capable of and it is very easy to compare with tests of other amplifiers.

“12 dB burst” is a signal that has an energy content which is similar to music. The input signal is a 1 kHz sine wave with a part with high amplitude and a part with low amplitude. The high part last for 25 ms and it is followed by the low part for 375 ms that together gives a crest factor (peak-to-average ratio) of 12 dB.

$$C = \frac{|x|_{peak}}{x_{rms}} \quad (2.2)$$

To get a crest factor of 12 dB with the given times for the high and low parts above, the low part must have an amplitude that is 25.8% or of the amplitude of the high part

The signal is repeated for a long time. The signal can be seen as music with a bass beat at 150 BPM. The 25 ms peak has the same energy content as one period of a 40 Hz sine wave.

It is possible to drive a signal that has a higher output power than the maximum continuous power if the amplifier has a capacitor

bank that stores energy. In the beginning of the peak when the capacitor bank is fully charged the output might be as high as expected but if the output from the bank is higher than the input the stored energy will decrease and the output peak will lose amplitude. One may say that the signal decays and it can be represented by the factor of the damping from the beginning to the end of the peak.

The output power is measured for the RMS voltage of the peak when the amplifier is loaded with 8Ω purely resistive load. Also the harmonic distortion and the decay are observed during the measurement.

2.2.4 Total Harmonic Distortion

Total harmonic distortion (THD) is a measurement of the harmonic tones that appears at integer multiples of the frequency of the fundamental tone. This is an unwanted disturbance added by the amplifier and it is desirable to keep it as low as possible. The THD is defined as the RMS voltage of all overtones, divided by the fundamental tone as in equation (2.3) [7].

$$THD = \frac{V_2^2 + V_3^2 + \dots + V_\infty^2}{V_1^2} \quad (2.3)$$

2.2.5 Total Harmonic Distortion plus Noise

It is hard to measure each individual harmonic in a signal and distinguish the harmonics from other noise. Therefore another way of measuring the distortion is more commonly used. Instead of trying to distinguish each harmonic from the noise, both the harmonics and the noise are compared with the fundamental signal and this is called Total Harmonic Distortion plus Noise (THD+N). THD+N is measured by applying a fundamental signal to the amplifier and then applying a notch filter on the output that removes the fundamental signal. The outputs with and without the fundamental signal is compared to get the THD+N ratio [7].

2.3 Class-D

A class D amplifier is also called a switching amplifier. The name comes from the fact the output stage is not operating in linear mode but instead is using switches to turn the power to the load fully on or off at a high rate.

There are several steps of signal processing in a class D amplifier. The input audio signal is encoded into a stream of pulses where the width of the pulse is representing the signal's amplitude. This is called pulse width modulation (PWM) and it is described in section 2.3.2. The PWM signals are driving the output stage and the output signal is low-passed filtered to recreate the desired signal.

2.3.1 Output stage

The load of a class-D amplifier is alternately connected to each supply rail in the output stage. In a basic output stage the switching is done by two power FETs connected between the positive and negative supply rail and the load is connected in between the FETs in a so called half-bridge configuration as seen in Figure 2.2. Half-bridge configuration requires a ground point right between the rails where the load is tied. Either the high side FET or the low side FET are turned on at any given time, driving the current through the load in opposing directions. The FETs are switching at ultrasonic frequency and the average on/off ratio gives the output voltage to the load. A typically used switching frequency is between 50 kHz to 1 MHz. [5]

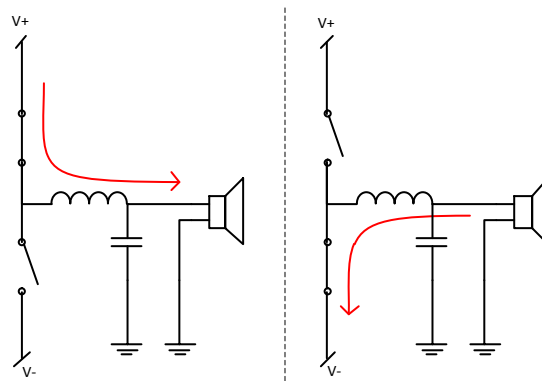


Figure 2.2 Half-bridge configuration.

The load can also be tied between two half-bridges in an H-bridge configuration, seen in Figure 2.3. The half-bridges are operating in opposite phase and it gives twice the voltage swing across the load. [5]

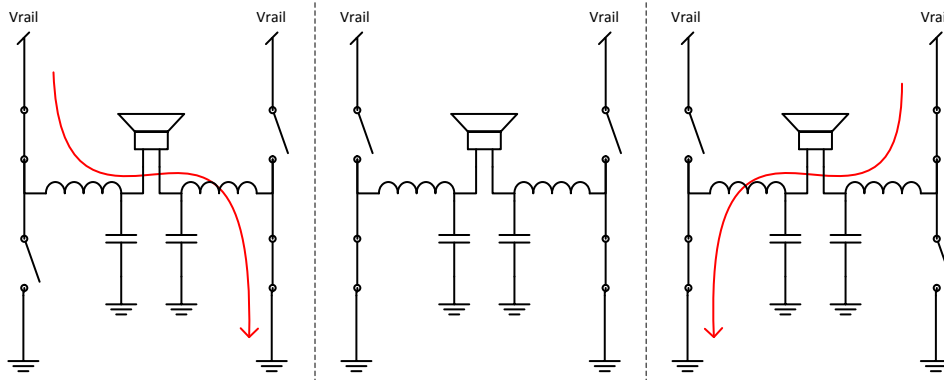


Figure 2.3 H-bridge configuration.

2.3.2 Modulation

The input signal must be modulated into a stream of pulses and it can be done in many ways. The most commonly used modulation in a class D amplifier is **pulse width modulation** (PWM). The width of the pulse corresponds to the amplitude of the audio signal. The pulses have a much higher frequency (typically 50 kHz to 1 MHz) than the audio signal and they are outside the hearable range for a human.

Conceptually, the PWM signal is generated by comparing the audio signal to a ramp or triangular waveform running at a carrier frequency higher than audio range. As seen in Figure 2.4, if the input signal is higher than the triangular waveform, the PWM signal is high and if the input signal is lower than the triangle waveform, the PWM signal is low.

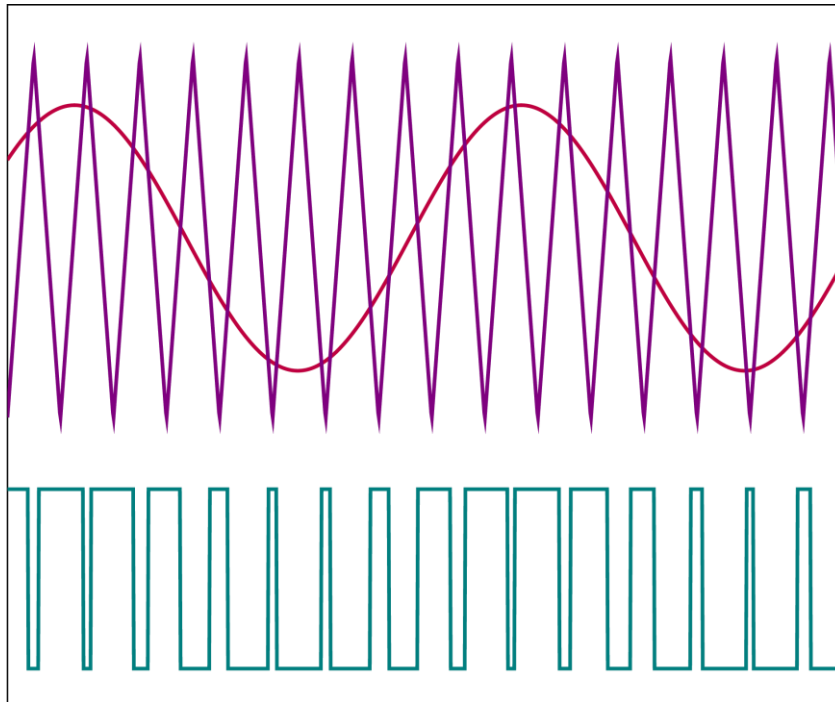


Figure 2.4 PWM representation of the signal generated with a triangle wave.

A large positive input signal corresponds to a duty cycle of near 100% and a large negative input corresponds to near 0%. For a silent audio signal, when the signal is 0, the duty cycle will be 50%. In other words, the output will be switching in full speed even when the desired output signal is 0. An amplifier with PWM has a high electromagnetic interference (EMI) at the carrier frequency. [5] [8]

There is a variant of PWM called three-level or three-state PWM. The output stage must be an H-bridge to use three-level PWM. The three states are one positive state when one half-bridge is driving the current in positive direction through the load and one negative state when the other half-bridge is driving the current in the negative direction. In the third neutral state both half-bridges are grounded and no current is drawn from the rail. Three-level PWM have a little higher efficiency since no power is drawn in the neutral state and since the switch losses are less because it is only one transistor switching at any given time. It has also a little less EMI. [8]

3. System design and Implementation

To prove the concept of an amplifier that is powered over Ethernet a prototype of a PoE amplifier is developed. The amplifier that is designed within this project is a further development of an existing prototype for a class D amplifier. This prototype was developed by the company TC Electronics in Denmark as an investigation of a FPGA based class D amplifier.

The earlier prototype consists of an output stage board with a single-chip full bridge which is mounted on an evaluation board for a Virtex 4 FPGA from Xilinx. It is the FPGA that controls the full bridge and it is done with the help of an IP block that converts the incoming audio signal to a PWM signal. The evaluation board and the IP block are reused in the development of the new amplifier and the output stage board is redesigned to have a full bridge with higher voltage rating and whereby make it possible to be powered over Ethernet.

The main blocks, beside the full-bridge on the new board created in this project, are a PD interface that establishes the powered connection to the PSE, a “power good” switch that keeps the amplifier turned off until the powered connection is established, a current limiter that ensures that the maximum allowed current is not exceeded and a capacitor bank that stores energy which makes it possible to have a much higher burst output power than the maximum input power. Figure 3.1 shows a block diagram of the amplifier and its most significant parts.

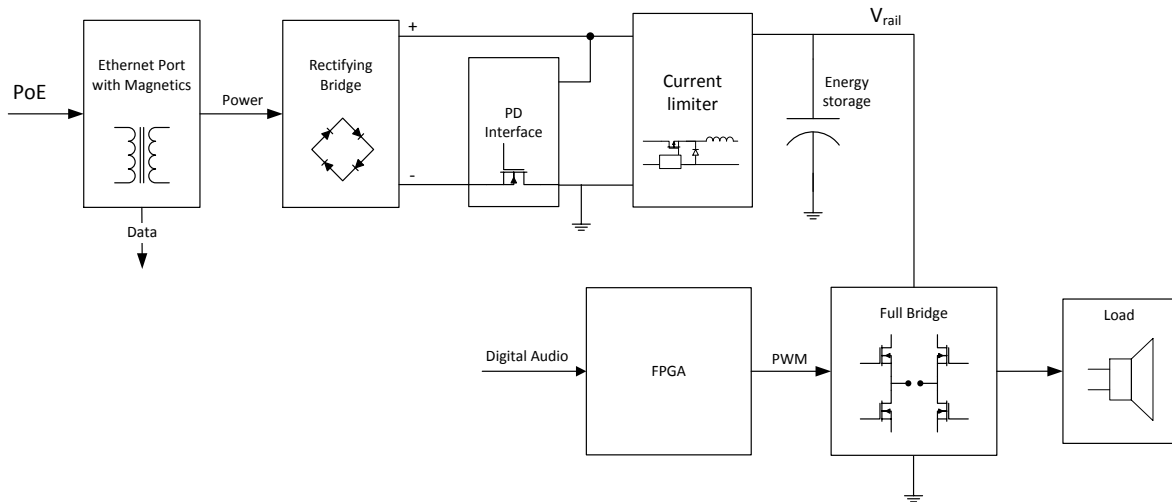


Figure 3.1 Block diagram over the PoE amplifier.

3.1 Powered Device Interface

To use PoE a PD interface is implemented. The purpose of the PD interface is to establish a connection to a PSE that can power the amplifier. The PD interface is built around a single chip device from Linear Technology called LTC4265 [9]. The device is a PD interface controller that meets the requirements of the IEEE802.3at standard. It takes care of the identification of the PD and it responds to the classification request from the PSE.

When power is provided at the Ethernet port, the LTC4265 has a smooth power-up transition that limits inrush current and a “power good”-signal is raised when the power is valid and the PD has entered the power on state. [9]

Beside the interface controller, the PD interface has a connector for a twisted-pair cable. The connector has isolation transformers with center taps for separating the DC power from the differential data link communication.

The PD interface also has two rectifying diode bridges to ensure the polarity even when a crossed over cable is used.

Figure 3.2 shows a simplified schematic of the PD interface used in this project.

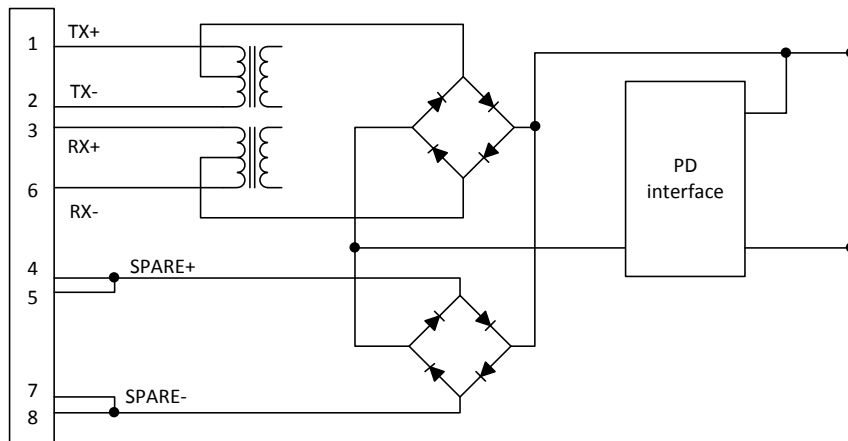


Figure 3.2 A simplified schematic of the PD-interface

3.2 Power good switch

The load of the PD is not allowed to draw any power before the PD interface is in the power on state because it would interfere with the identification and classification of the PD. Therefore the rest of the amplifier is disconnected from the PD interface before it signals that power is good. The connection of the amplifier is delayed so that the current limit is not exceeded before the PSE has had time to change state according to the specifications described in 2.1.5.

The switch that connects the PD interface to the amplifier is made by a transistor that disables the current limiter and the signal is delayed by a RC circuit.

3.3 Current limiter

The power that can be distributed over Ethernet is limited to a maximum current of 600 mA as described in 2.1.5. A current limiter is implemented to make sure that the current never exceeds this limitation. The limiter is a current-mode-controlled buck converter. The switch in the buck is controlled so that it is closed and lets current flow through as long as the current is lower than the reference. If the current exceeds the reference, the switch is opened, preventing more current to be drawn from the Ethernet port. Figure 3.3 shows a simplified schematic of the current limiter.

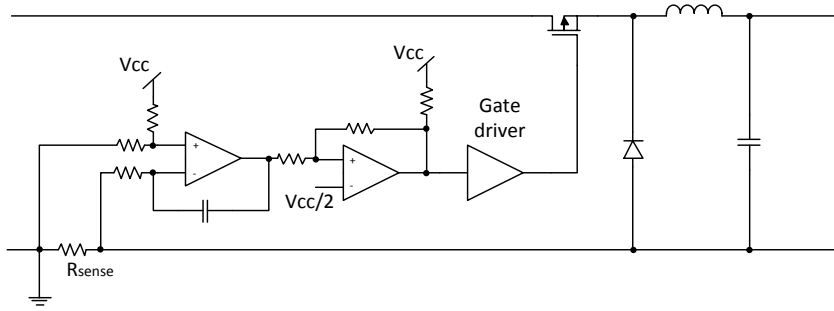


Figure 3.3 Simplified schematic of the switched current limiter.

The current is sensed by an operational amplifier that measures the voltage drop over a small resistance (R_{sense}). The operational amplifier has an integrating factor to set a maximum switching frequency of the system. The time constant is $15 \mu\text{s}$ as found in equation (3.1)

$$\tau = RC = 10k\Omega * 1500pF = 15\mu\text{s} \quad (3.1)$$

The following comparator has a hysteresis to prevent it from fluctuating when both inputs are equal.

This circuit will have problems limiting the output current during power-up because the supply voltage to the operational amplifier and comparator will not be operational. Therefore, a linear current limiter is implemented in series with the switched limiter. The linear limiter has a little higher reference current than the switched limiter. The purpose of this is that the linear limiter should limit the current during power up and then the switched limiter should take over.

3.4 Capacitor bank

Energy is stored in capacitor banks to be able to momentarily have a higher output power than the supplied input. The capacitor is connected between the voltage rail and ground. When there is no output it will be fully loaded. If more current than the current limiter allows is requested the capacitor bank will start to discharge and the voltage of the supply rail will start to drop. In this prototype, it leads to a drop in output voltage since output voltage is directly dependent on the rail voltage.

The capacitor bank must be large enough to ensure that the output signal is not lowered too much during burst outputs and at the

same time, it can't be so large that it is not fully recharged between two burst outputs.

The PoE amplifier is designed to handle burst outputs as described in section 2.2.3. The capacitor bank was chosen to be 9600 μF and it was found using the following approximation:

An acceptable voltage drop would be 6 volt. If the rail voltage is 50 V then the max peak output voltage would be 25 V. If the load is 8 Ω then the maximum output current can be 2.2 A found in (3.2).

$$I_{rms} = \frac{25 V}{\sqrt{2} \cdot 8 \Omega} = 2.2 A \quad (3.2)$$

And

$$\begin{cases} Q = i \cdot t \\ Q = v \cdot C \end{cases} \quad (3.3)$$

$$\Rightarrow C = \frac{i \cdot t}{\Delta v} = \frac{2.2 A \cdot 25 ms}{6} = 9100 \mu F$$

9600 μF was chosen instead of 9100 μF since it was easier to find that component value.

3.5 Output stage

The output stage is a full-bridge configuration with dual power FETs at each node. The full-bridge is integrated in a single chip called STA516b manufactured by STMicroelectronics [10]. The chip has four power half-bridges which can be configured to either drive four channels in half-bridge mode or two channels in full-bridge mode. It can also be configured to combine the two full-bridge channels into one channel with dual half-bridges on each side of the load which means that twice the current can pass through the nodes.

STA516b has an input to each of the four half-bridges. This gives a high degree of freedom for the designer to control the output stage but in the same time, special care must be taken not to drive the output stage into a bad state that can permanently damage the circuit. The output stage can be driven by both regular PWM signals and tree-level PWM.

STA516b has protections for under-voltage, thermal and over-current. The protection shuts down the circuit and puts the outputs in high impedance mode if a fault occurs. [10]

In this amplifier the STA516b output stage is configured to run as one channel with dual half-bridges on each side of the load. It is driven from the FPGA with either a regular PWM signal or a three-level signal that can be selected by a switch but for all results in this report a three-level signal is used.

3.6 Powering the system

The connection from the output of the current limiter to the capacitor bank is made so that it can easily be opened and thereby separating the PD and current limiter on one side and the capacitor bank and whole output stage on the other. This makes it possible to choose if the amplifier should be powered over Ethernet or if an external power supply should be connected directly to the capacitor bank and the output stage.

In a final product the whole system would be powered over Ethernet but in this prototype some parts are powered from another source than PoE. The whole evaluation board containing the FPGA and its surrounding components is powered by a separate 5 V PSU. See section 4.1.

3.7 Evaluation board

The evaluation board consists of a Virtex 4 FPGA from Xilinx and a flash memory to configure the FPGA on power up.

The board also contains:

- Power supply unit
- Sample rate converter
- 196MHz clock generator
- AES receiver
- RS-232 interface
- #40 Pin Head

Inputs and outputs:

- RCA for S/PDIF input
- 2 x TOSLINK for optical tx / rx
- BNC for world clock generation

- #100 pin connector for mounting an extension board, in this case, an output stage board.

User interface:

- 20 x double colored LEDs
- 16 x DIP switches
- 2 x adjustment knobs

3.8 IP block for converting audio signal to PWM signals

The input to the IP block is an audio signal that is pulse-code modulated (PCM) which complies with the AES3 standard. The PCM signal is processed by the FPGA to generate PWM signals to drive a full- or half-bridge. The block is designed for two channels of audio. Figure 3.4 shows a diagram of the internal processing blocks in the FPGA.

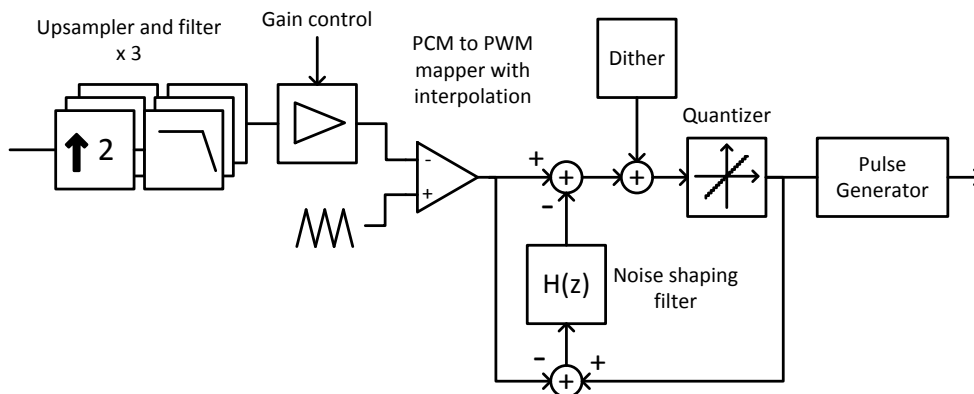


Figure 3.4 Block diagram over the processing blocks in the FPGA.

First, the signal is up-sampled to the desired carrier frequency of the PWM signal. The up-sampling is done in three steps where each step doubles the sampling frequency. Each step has an anti-aliasing filter and the filters are of half-band type which is a symmetric filter with zero on half of the coefficients. It gives an easy implementation with low computation requirements. An input signal with a sampling rate of 48 kHz that is up-sampled 8 times will give a carrier frequency of 384 kHz.

Next, there is a gain block that operates directly on each PCM sample, followed by the PCM to PWM mapper. The PCM samples are matched against a saw tooth curve. To lower the harmonic distortion, quadratic interpolation is used. The resolution of the

PWM signal is limited by the clock speed of the system. This system has a 9 bits resolution for the PWM signal which requires a system clock of 196.608 Mhz ($384 \text{ kHz} * 2^9$).

The quantization of the signal to 9 bits resolution introduces quantization noise. With the help of a 5th order noise shaping filter the quantization noise is pushed outside of the hearable range for a human. Dithering is used to get rid of the cyclic and repeating noise from quantization with otherwise appears as unpleasant distortion. Dithering means that a random noise is added to the quantization noise with basically distributes the noise more evenly.

Finally, there is a pulse generator block that has the ability to both output a standard binary PWM signal and three-level PWM signal to the output stage.

4. Test setup and test method

To measure and compare the amplifier when it is powered over Ethernet to when it is powered with an external power supply a set of equipment is used. This section will describe the equipment and the setup used. Figure 4.1 shows a block diagram of the test setup.

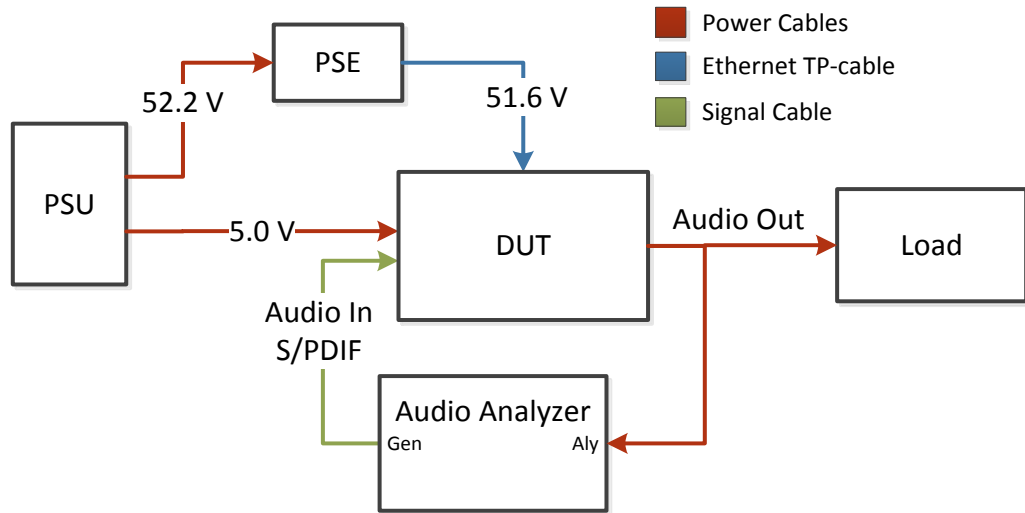


Figure 4.1 Block diagram over the test setup.

4.1 Power supply unit

A laboratory power supply is used to power the device under test (DUT). The PSU used is called HM7042-5 produced by Hameg. The PSU has three separate adjustable outputs. Two outputs which can deliver up to 30 V at 2 A and one that can deliver up to 5.5 V at 5 A.

According to the specification of PoE as described in section 2.1.5 the output voltage from the PSE is 50 to 57 V and to get that level from the PSU the two “30 V” outputs are connected in series which give a maximum of 60 V. Throughout all tests and measurements in this thesis the output level from the PSU is adjusted so that the rail voltage (V_{rail} in Figure 3.1 Block diagram over the PoE amplifier. Figure 3.1) is 50.0 V. It means that when the amplifier is powered over Ethernet the output voltage from the PSU is 52.2 V which gives 51.6 V at the input of the PD interface. When the amplifier is powered directly from the PSU without PoE, the output from the PSU is 50.1 V.

The third output of the PSU is used to power the evaluation board with the FPGA and its surrounding components. It is adjusted to output 5.0 V.

4.2 Power sourcing equipment

The PSE used in the test setup is an evaluation board of the component Si3461 which is a single-port 802.3at PoE PSE Interface manufactured by Silicon Labs [11].

The evaluation board (Si3461-EVB) has connectors for easy connection to the PSU and it can be configured to run both as a midspan and endspan PSE (see section 2.1.1). It is configured as an endpoint in this project since there is no need of data transfer over Ethernet.

4.3 Audio analyzer

An audio analyzer is used to both generate the test stimulus in the form of audio signals and to analyze the performance of the amplifier by sampling the output.

The output from the audio analyzer is in S/PDIF format and it can be controlled with very high accuracy both for magnitude and frequency and the output from the amplifier can be analyzed by an analog analyzer with high precision. When the generator and analyzer are acting together the audio analyzer is capable of measuring linearity, measuring output power, do a spectrum analysis and measure THD+N among other things. The audio analyzer also has scripting abilities that makes it possible to make advanced tests as measuring the burst output power.

The audio analyzer used is produced by Audio Precision and it's called 2722.

4.4 Load

Instead of a real speaker for loading the system, a dummy load is used. The dummy load is basically a huge amount of effect resistors connected in a grid which makes a load that can sink over 1000 W. The dummy load is purely resistive and the resistance can be selected by a switch to be 2 Ω , 4 Ω , 8 Ω or 16 Ω . For all tests in this thesis the load is 8 Ω if otherwise not stated.

4.5 Test settings

The basic setup for all tests is that the input to the amplifier is from the digital signal generator of the audio analyzer. The output of the amplifier is connected to the dummy load of 8 Ω and the analog analyzer is connected in parallel measuring the voltage over the load.

4.5.1 Linearity and continuous power

The input level is swept from -50 dBFS to 0 dBFS with a step size of 0.5 dB which gives 101 measurement points. The whole sweep takes about 4 seconds. The output voltage is measured and with the given load the analyzer is able to calculate the output power.

4.5.2 Spectrum analysis

The output the signal is analyzed with fast Fourier transform (FFT) to find the frequency spectrum. The output is sampled at 48 kHz and the length of the FFT is 4096 samples. It gives 2048 bins and the distance between two bins is 23.44 Hz given by (4.1).

$$\frac{48 \text{ kHz}}{2048} \approx 23.44 \text{ Hz} \quad (4.1)$$

The spectrum of the output is measured at -40, -20, -10 and 0 dBFS.

4.5.3 THD+N

To find the THD+N the measured output signal is passed through a notch filter that rejects the fundamental component. The notch filter center frequency is automatically following the strongest component in the signal. THD+N is the ratio between the sum of the distortion products and the noise amplitude relative the unfiltered signal.

The THD+N is measured in relation to input amplitude of the fundamental signal and in relation to the input signal frequency. For THD+N in relation to amplitude, the input frequency is fixed at 1 kHz sine wave and the amplitude is swept from 0 dBFS down to -50 dBFS with a step size of 1 dB. For THD+N in relation to frequency the input level is -15 dBFS and the input frequency is swept from 20 kHz down to 20 Hz at a total number of 120 points.

4.5.4 Burst power

A custom made script is used to measure the burst power. The input signal is the “12 dB-burst” signal described in section 2.2.3. The signal has a short high part and a longer lower part where the amplifier can recover. The script starts with measuring the gain of the amplifier. It is done at a low signal level and it is used to calculate the expected power from the amplifier. Next, the script will increase the input level in steps. For each step it isolates the high part and measures the voltage and calculates the power with help of the known load. Both the average power of the peak and the power of the first part of the peak are found.

The script can be run in a mode where a maximum allowed drop from the early power to the average power is specified and the script will find the input level with that drop by a successive approximation method.

The script also finds the high part of the signal which can be used to show how the signal is losing strength throughout the peak.

5. Results

5.1 Audio measurements

5.1.1 Linearity

The linearity of the output power is measured by applying a continuous 1 kHz sine wave at a varying amplitude and measure the output RMS voltage when the amplifier is driving an $8\ \Omega$ resistive load. The rail voltage is 50 V. The result is shown in Figure 5.1. The x-axis is the input signal in dBFS and y-axis is the output voltage in dBu.

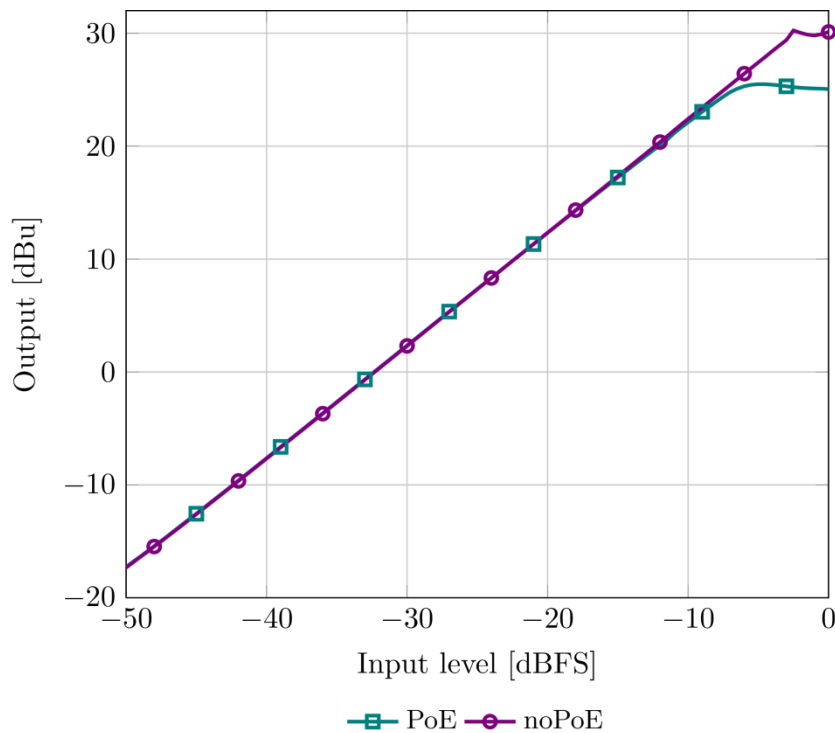


Figure 5.1 Linearity.

The teal colored curve shows the linearity for the PoE amplifier and the violet colored curve shows the linearity for the amplifier powered by an external power supply.

5.1.2 Continuous Power

Continuous output power is measured with the same setup as for linearity measuring. On the x-axis is the input level as dBFS and on the Y-axis is the output power in W. The output power is found by measuring the output voltage and taking it in relation to the known and fixed $8\ \Omega$ resistive load.

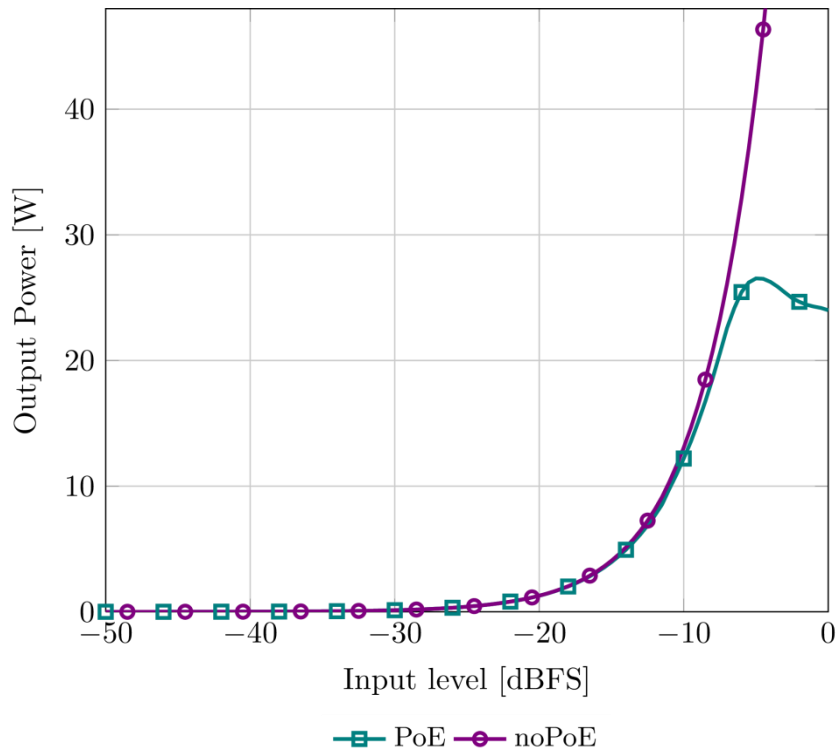


Figure 5.2 Continuous output power.

The teal colored curve shows the continuous output power for the PoE amplifier and the violet colored curve shows the output power for the amplifier with an external power supply.

5.1.3 Burst Power

The output power when playing a more music-like (see section 2.2.3) signal is shown in Figure 5.3. The signal is a “12 dB burst” described in section 2.2.3. The teal and violet colored solid curve shows the average output power during the high peak and the dashed curves shows the power of the first sinusoid period in each peak. The blue colored solid curve shows the expected output power. It is based on measured gain of the amplifier at a low input, and then calculated as if it was perfectly linear.

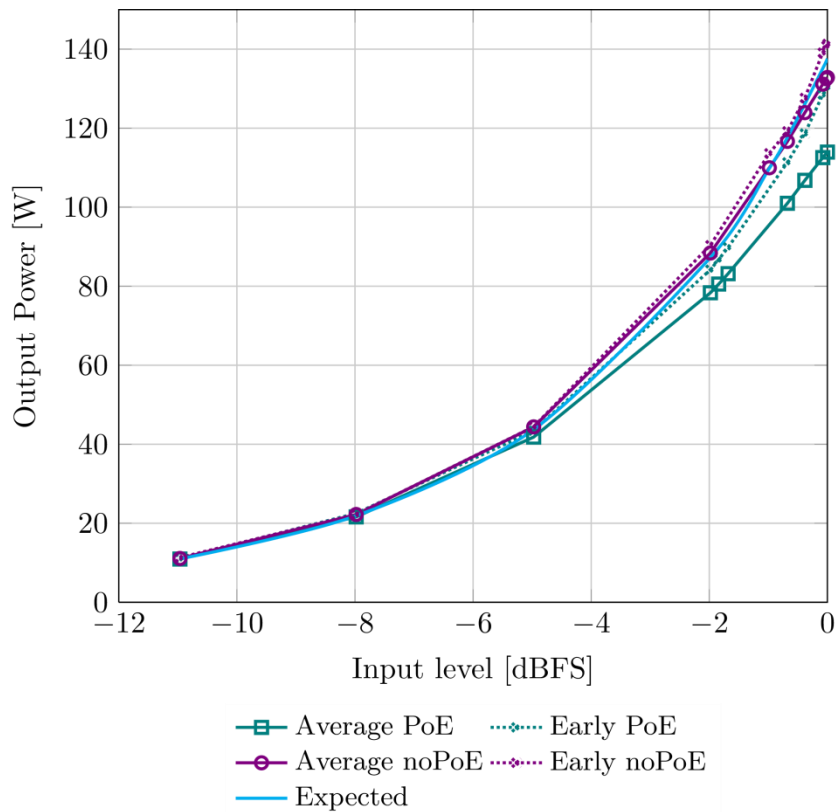


Figure 5.3 Burst power.

When playing a peak that has higher output than the maximum continuous power the output will decay as the rail voltage drops. As seen in Figure 5.3 the output power of the early part of the peak is much higher than the average. Figure 5.4 and Figure 5.5 shows how the peak loses strength when the stored energy decreases in the capacitor bank. The x-axis is time and the y-axis is output voltage.

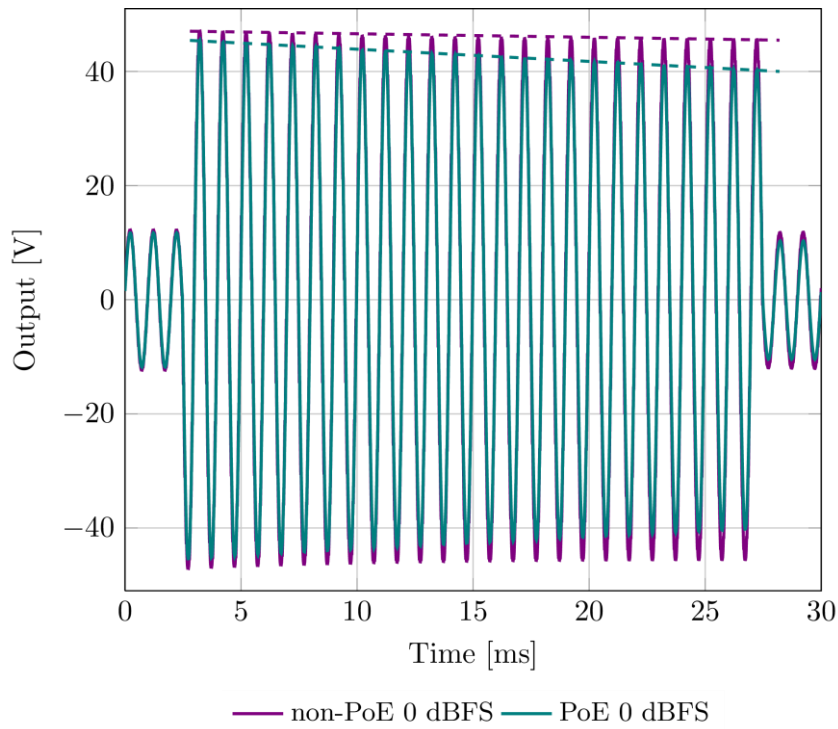


Figure 5.4 Output during one burst. Input 0 dBFS.

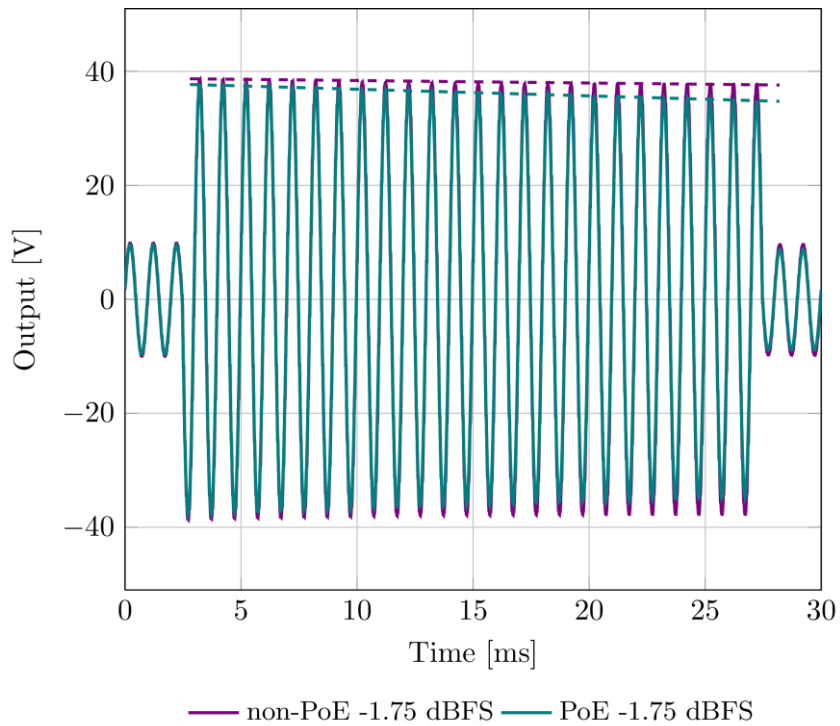


Figure 5.5 Output during one burst. Input -1.75 dBFS.

The graphs show an output peak for both the PoE amplifier and the amplifier powered with an external power supply. In Figure 5.4 full input signal level is used and in Figure 5.5 the input is -1.75 dBFS which is the level where the output has dropped 0.5 dB from the expected as discussed in section 6.1.

5.1.4 Noise floor and THD+N

Figure 5.6 and Figure 5.7 shows a spectrum analysis of the output from the amplifier when powered by both power methods. The input signal is a 1 kHz sinusoid wave and the spectra are shown for -40, -20, -10 and 0 dBFS input level. The magnitude of the output in the spectra is in dBu.

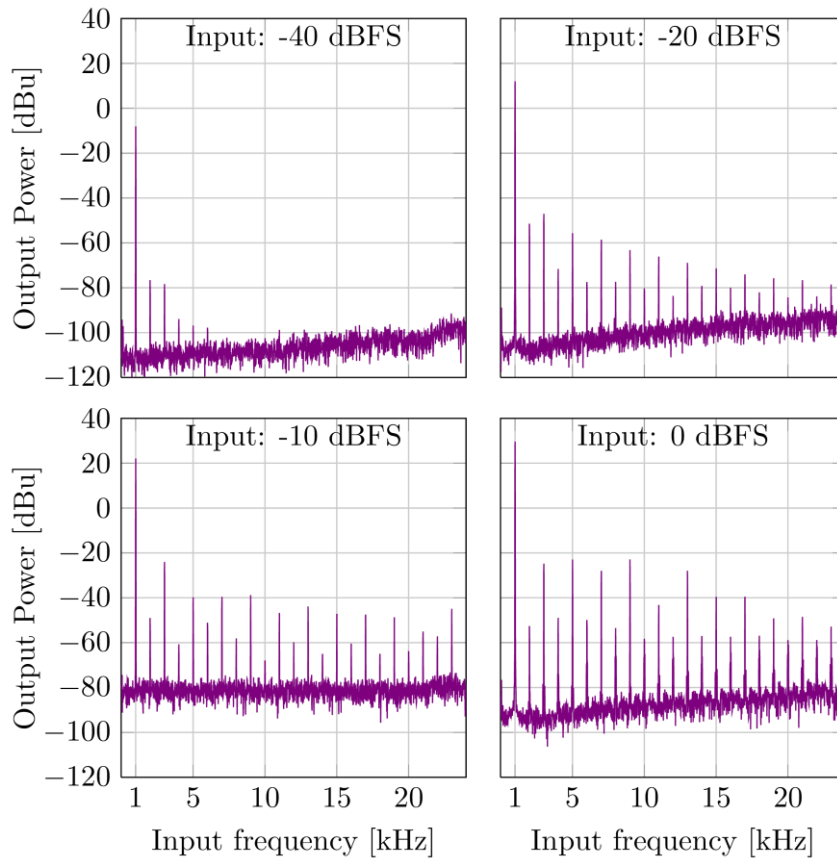


Figure 5.6 Spectrum analysis for the non-PoE amplifier.

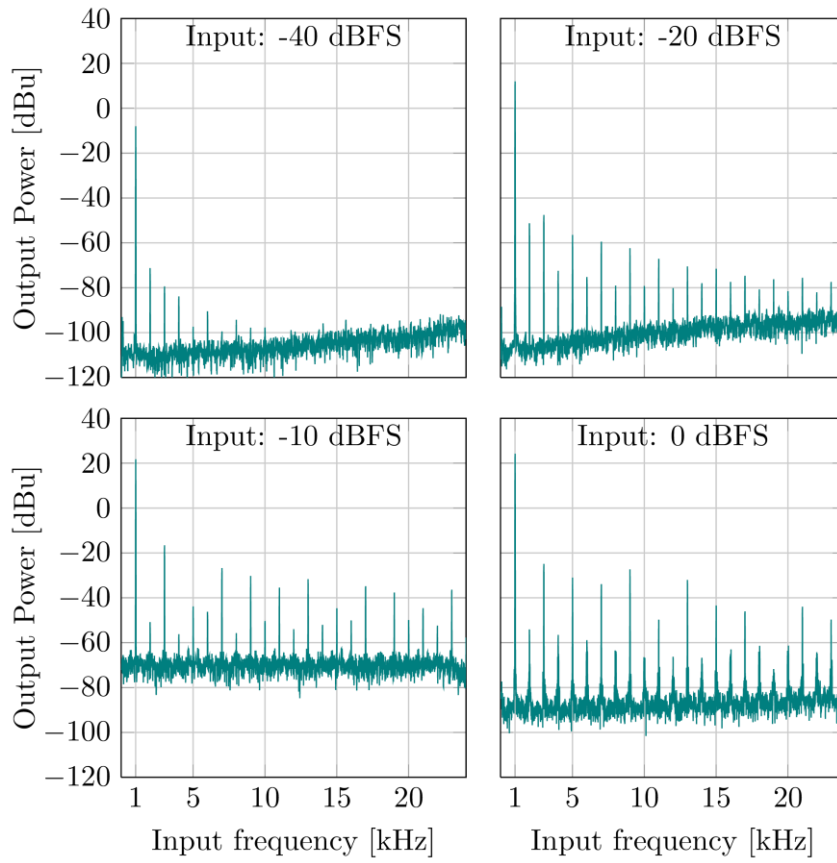


Figure 5.7 Spectrum analysis for the PoE amplifier.

Figure 5.8 shows the harmonic distortion and the noise vs. input levels. The input signal is a 1 kHz sine wave with an input level which is swept from -50 dBFS to 0 dBFS. The input level is on the x-axis and the THD+N is on the y-axis in percentage.

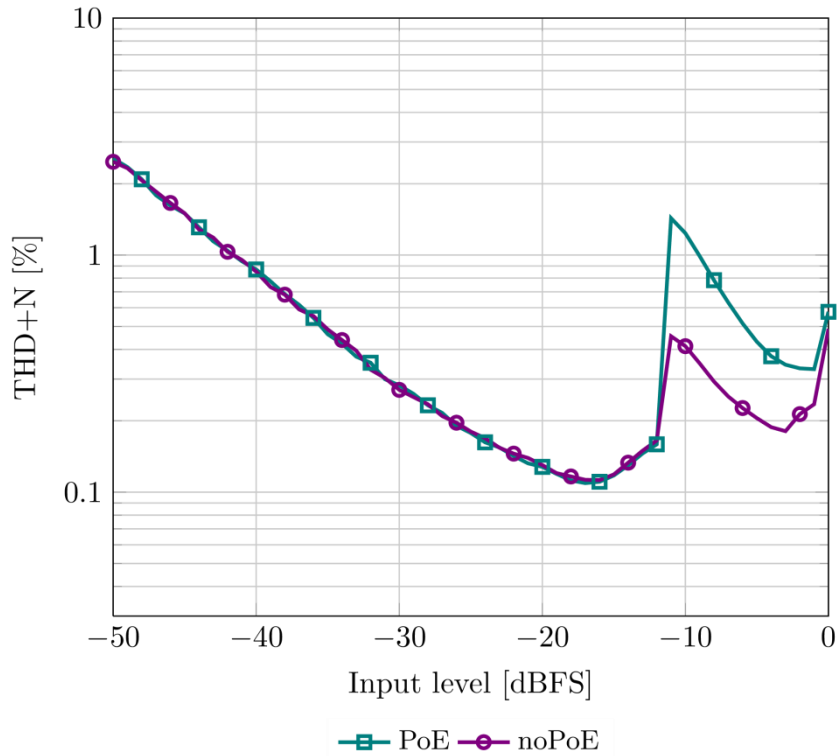


Figure 5.8 THD+N vs Input level, Input freq. 1 kHz.

The teal colored curve shows the THD+N for the PoE amplifier and the violet colored curve shows the THD+N for the amplifier powered with an external power supply.

Figure 5.9 shows the harmonic distortion and the noise vs. frequency. In this graph the input level is fixed and the frequency is swept from 20 Hz to 20 kHz. The input level is -15 dBFS which is a level below the carrier signal artifact discussed in section 6.1. Input frequency is on the x-axis and THD+N is on the y-axis in percentage.

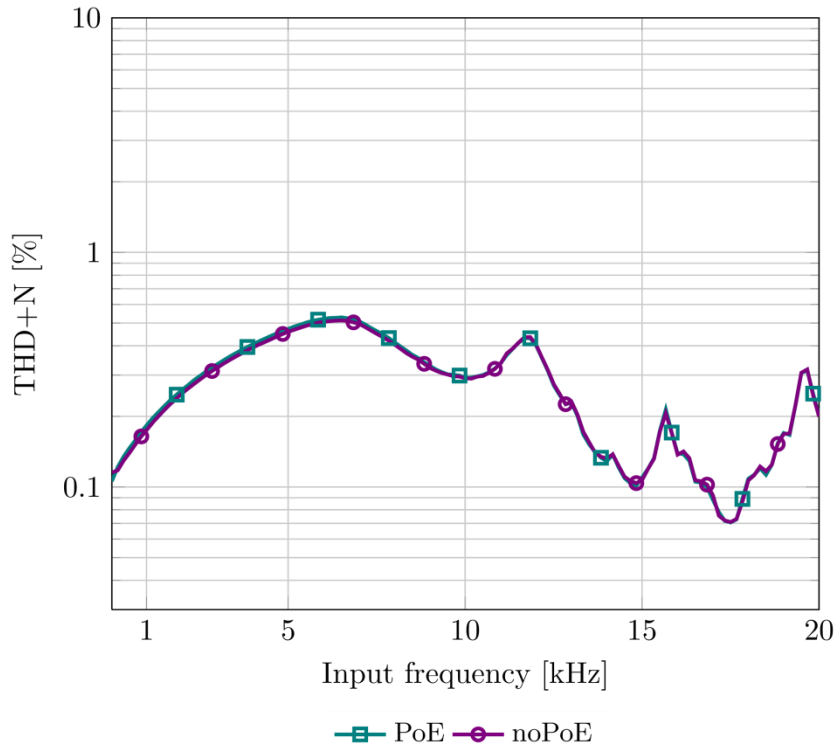


Figure 5.9 THD+N vs Input frequency, input level -15dBFS.

The teal colored curve shows the THD+N for the PoE amplifier and the violet colored curve shows the THD+N for the amplifier powered by an external power supply.

6. Discussion

6.1 Discussion of results

With the setup used during the tests the maximum output power is 26.5 W for a continuous signal with 8 Ω load. The input power to the PD is then 30.9 W. That gives an efficiency of 85.7%.

The results of the linearity measurements show that the amplifier has good linearity both when it is powered over Ethernet and when it is powered by an external power supply.

As seen in Figure 5.1, the non-PoE amplifier has good output power linearity for the whole input range up to around -3 dBFS or an output of 30 dBu. Above -3 dBFS the output is limited by the external power supply that is used to power the amplifier. In other words, it is not the output stage that limits the output power and it is believed to have a linear output power above -3 dBFS if the power supply unit would allow it.

The PoE-amplifier has decent output linearity up to an input of -7 dBFS or an output of 25 dBu which is the point where the power limit of PoE is reached. But if one looks closely in Figure 5.1, the curve starts to lean away from the ideal curve at an input of -16 dBFS. This is because at this point the output is 16 dBu which is driving a load of 8 Ω and it gives an output current just above 600 mA.

$$I = \frac{0.775 * 10^{16dBu/20}}{8 \Omega} = 0.611 A \quad (6.1)$$

It means that the current limit of the PoE has been reached and that the current limiter has started to operate.

Continuous Power

As Figure 5.2 shows the PoE amplifier is able to deliver up to 26.5 W into a load of 8 Ω . At an input of -7 dBFS, which was the maximum input for good linearity, the continuous output power is 22.6W.

As soon as the input level is higher than -16 dBFS and the current limiter has started to operate the output is relying on the stored energy in the capacitor bank. When the average output current is

higher than the input current of 600 mA the average voltage will drop in the capacitor bank. And since the output is directly related to the rail voltage, the output will be affected and that is why the output power is lower for the PoE amplifier than the non-PoE amplifier and why the linearity is compromised for higher levels.

Burst Power

In the more music-like situation when playing a “12 dB burst” signal the PoE amplifier is able to deliver an average of 114 W for the 25 ms long burst as shown in Figure 5.3. But at this level the amplitude is dropping quite a lot. At the beginning of the burst the output power is 131 W but the amplitude is lowered by 11.5% until the end of the burst as shown in Figure 5.4.

If the amplifier is powered with an external power supply it is able to deliver an average burst of 133 W (early: 141 W) and during the burst the amplitude is just dropping 3.2%

The output from the PoE amplifier is 0.67 dB lower than the output of the non-PoE amplifier given by (6.2) and it is 0.82 dB lower than the expected output given by (6.3). The expected output is 138 W.

$$10 \log \frac{P_1}{P_0} = 10 \log \frac{113.95}{132.83} = -0.67 \text{ dB} \quad (6.2)$$

$$10 \log \frac{P_1}{P_0} = 10 \log \frac{113.95}{137.71} = -0.82 \text{ dB} \quad (6.3)$$

A more acceptable limitation to the output would be a loss of 0.5 dB from the expected value. At an input of -1.75 dBFS the output of the PoE amplifier is 81.8 W and it is 0.5 dB below the expected value.

$$10 \log \frac{P_1}{P_0} = 10 \log \frac{81.81}{91.85} = -0.50 \text{ dB} \quad (6.4)$$

At this level the amplitude is losing 7.5% throughout the burst as shown in Figure 5.5.

What can also be noticed is that the first periods of the low part after the peak also suffer from the depletion of the energy storage since the output voltage is directly related to the rail voltage. This happens even if it has a lower output power than the input power

from PoE and it will be lower than expected until energy storage is recovered.

THD+N

For lower signals the THD+N is the same for both the PoE and the non-PoE amplifier as shown in Figure 5.8. The THD+N gets lower and lower for higher input as expected since the desired signal gets stronger compared to the noise floor. The THD+N starts to rise for a signal higher than -17 dBFS and at -11 dBFS, the THD+N level suddenly jumps quite dramatically.

If observing the output signal with an oscilloscope and zooming in to time scale 5 $\mu\text{s}/\text{div}$, it is possible to see the traces of the carrier signal for the PWM that is overlaying the signal. These traces have a very low level and are outside the hearable range. But at an output of 8.5 V (input of -11dBFS) there is suddenly a hiccup in the overlaid trace signal and this artifact is causing the raised THD+N level. The largest impact from the artifact is when the output is around 8.5 V because at that time the artifact is on top of the sine wave. Stronger signals are just passing the troubling level more quickly.

Not too much effort has been put into explaining exactly what causes these hiccups, it can either be introduced during the generation of the PWM signal or it can be introduced by the output stage. But the phenomena shows up on the amplifier independently of power supply and it can also be seen on the older prototype that was the base for this project. What can be observed is that the PoE amplifier has a harder time dealing with these hiccups.

The spectra for both power supply methods are shown in Figure 5.6 and Figure 5.7 and they are as expected. There are overtones on all fundamental frequencies and even overtones are higher than odd. The highest overtone is about 50 dB lower than the desired signal for both power supply methods and that can be considered acceptable. It can also be noticed that there is a slightly elevation of the noise floor for higher frequencies and where there is quite a dramatic rise of the noise-floor due to the artifact on the carrier that was explained above.

6.2 How to use the amplifier

6.2.1 Installation

Permanently audio installations are done in many different places and for different applications. It can be heavy-duty music installations at stages and nightclubs or turned down background music in stores and restaurants. It can also be for reproducing speech in auditoriums and houses of worship, or announcement systems and paging systems in malls, stations or other venues.

Many installations are in need of distributing the audio over a large area or into remote areas of the venue and therefore are in need of distributed speakers. Distributed speaker systems can be implemented in many ways and PoE amplifiers can be a good solution or a good complement in a distributed speaker system.

Distributed speaker system today

If using a traditional low impedance system one can either use powerful amplifiers that are driving many speakers or one can use several smaller amplifiers, distributed over the venue, which each drives a smaller number of speakers. The problem with driving many speakers from one amplifier is that a complex wiring schema of parallel and serial speakers must be used to match the desired impedance of the amplifier. The wires to the speakers cannot be too long or must be very thick to minimize the losses when driving high currents. The relative sound pressure for each speaker can just be controlled by the placement in the parallel / serial network. [12] [13]

Having many smaller amplifier is more flexible and it can lead to lower power loses but it comes with a high overhead cost because every amplifier needs its own power supply unit. It may also imply that a lot of extra cable installation is needed. In addition to cable for low level signals and speaker cables, the amplifier must have wires for power and maybe wires to be controlled.

A smarter way for a distributed speaker system is to, instead of connecting the speakers in a low impedance system, use a so called 70-volt or 100-volt system. The amplifiers are designed so that the full power output exists at 70 V or 100 V RMS. Each speaker is then connected to the output line with a step-down transformer that lowers the output voltage to a matching level for

that speaker. The amplifier sees a high impedance load and one powerful amplifier can drive many speakers. By having a higher voltage, less current is needed which gives lesser losses. 70-volt system is more common in North America while 100-volt systems are more common in Europe and the rest of the world [13]. From now on will the text only refer to 100-volt system but all statements will also apply to 70-volt system if otherwise not stated.

The speakers in a 100-volt system can draw different amount of power and they can be added and removed without problem as long as the amplifier is strong enough to drive all speakers. The sound pressure of each individual speaker can be controlled by changing the transformer, often done by having many taps on the transformer which gives different number of turns in the windings. But it is hard to control during operation and it has only a low number of fixed levels corresponding to the taps. [12] [13]

Distributed speakers system with PoE

An amplifier that is powered over Ethernet can in many places be an excellent solution for a distributed speaker system. PoE amplifiers can cover a large area like a paging system or a sports arena or it can extend a regular PA system to cover the remote parts.

The benefit of having PoE amplifiers instead of having many small amplifiers is that they only needs one single cable to have audio signal, power and control and every amplifier doesn't need a power supply unit to get power from the 230 V power outlets.

One single cable minimizes the need of new wiring. Using Ethernet has the benefit that no special license is required to be allowed to install new twisted-pair cables as it is if new power cords have to be installed. Today many buildings already have an Ethernet network and since the PoE standard makes sure that non-PoE devices should not be disturbed by PoE devices, the existing network can be extended to carry power, audio signals and control signals to the amplifiers.

Using a well-known standard, as Ethernet is, has the benefit that many people have the understanding of the system and makes it easier for the technician to use off-the-shelf products.

As for the case of 100-volt system, the power in a PoE system is distributed with higher voltage than a traditional system with low impedance speakers directly connected to the amplifier and therefore the losses are less. The sound pressure can be individually set for different parts of the system like the 100-volt system but it doesn't have a limited number of fixed levels and with Ethernet based control, the sound pressure can be set and changed without the need of physically walk up to each speaker. A PoE amplifier also works with all kinds of speakers because it doesn't need a transformer.

A PoE system that uses audio over Ethernet would be more flexible than a 100-volt system in the sense that it would be easy to route different audio channels to different parts of the system and it can instantly be reconfigured while in the 100-volt system, all speakers on the same line must play the same output and has to be manually reconfigured.

It is also more flexible than the 100-volt system when it comes to the planning of an installation. In both systems it is easy to add or remove single speakers gradually. But if the maximum capacity of the amplifier in the 100-volt system is reached, then it must be replaced with a more powerful amplifier, and the other way around, if too much overhead is taken, one might end up with an unnecessary strong amplifier. The same happens if the maximum total power of a PoE switch is reached but it is much easier and cheaper to extend the network with a few extra PoE ports. For example by add single port PoE injector or a low number PoE switch.

A 100-volt system has one benefit when it comes to wiring. All the speakers in a 100-volt system can be decoupled from a long single cable or they can be branched into many cables. But in the PoE system, each amplifier must be connected in a star topology where either the hub is a PSE or each branch has a midspan power injector.

Self-powered module

A PoE amplifier would work well as a self-powered speaker module. In other words, a speaker that has a built in power-amplifier. The small size of the amplifier would make it easy to fit

into a speaker cabinet and a single cable for both power and audio signal would make the speaker very easy and flexible to install since the speaker can be connected anywhere on the network.

6.2.2 Surveillance and emergency system

Today many surveillance system are based on IP and some are making use of Power over Ethernet. PoE is a good way of distributing power to units that are placed in inaccessible places where it can be hard to install many different wires for each unit. PoE also makes it easy to have a centralized backup power. Instead of having a UPS backup for each node in a surveillance system or installing a backup power to the regular AC power grid in the building; an UPS can be installed at the PSE unit in the PoE based surveillance system that can provide backup power for the whole system.

An PoE amplifier would fit nicely in a surveillance system where there is a need to be able to make announcement calls and voice alarms.

EN54-16

EN 54 is a standard of the European Union for fire alarms and fire detection. EN54-16 is a product standard governing "Voice Alarm Control and Indicating Equipment" (VACIE) which requires, among other things, that the fire alarm system has a voice alarm that plays a spoken message in case of fire. The standard also requires that the system itself can detect that the path from the audio source, through the amplifier and to the speaker is intact and that the system has a redundant power supply.

A system that uses self-powered speakers with power over Ethernet modules covers many of the requirements of the EN 54 standard. The system can detect that the audio path is intact by TCP/IP communication from the audio source to the speakers through the Ethernet cable. The self-powered speaker can be powered from the regular AC power grid during normal operation and in case of outage; a centralized UPS can power the speakers through PoE.

6.2.3 Centralized Signal Processing and distributed amplification.

In many audio systems, there is a need for signal processing for every output node. In high-end amplifiers, signal processing is built in which makes it possible to e.g. equalize the audio and compensate for different speakers, add delay and limiters.

Having signal processing in every amplifier in a system is costly and therefore the signal processing is often centralized and processed audio is distributed to the output nodes. A PSE with a DSP matrix that both distributes processed audio and power over Ethernet to many PoE amplifiers would make a cheap, easy configured and easy to install system.

A product like Lab.gruppen's LM26, which is a 2-in / 6-out stand-alone digital audio loudspeaker processor, merged together with a 24-ports Ethernet switch with PoE would make a unit that has inputs for analog audio, AES3 and audio over Ethernet and could send out six different channels of audio to 24 self-powered PoE speakers.

With TCP/IP communication between the PoE amplifier and the central unit it would become easy to configure when the amplifier can identify itself and for example, pre-defined settings can be loaded in the DSP depending on what Speaker/amplifier that got connected.

6.3 Future work

The prototype turned out to work pretty well but there are of course some improvements that can be done.

6.3.1 Feedback loop

This prototype amplifier has no feedback loop. By having a feedback loop the linearity of the amplifier would increase and it would mean that the output power would be closer to the expected output. During a high output signal when the output power starts to lose its strength due to limited input power, the feedback loop would increase the gain and the output power would hold its strength. This requires headroom between the maximum allowed input signal to the real maximum of the amplifier.

The output power losses comes from the act that the capacitor bank is losing energy and a feedback loop that increases the gain

when the stored energy decreases would mean that the energy decreases even faster. The gain compensation can only be effective as long as the rail voltage over the capacity bank is higher than the desired output level. An estimate of the burst output power with a feedback loop is over 100 W.

One way to close the feedback loop would be for the amplifier to measure the rail voltage and from that, calculate the gain compensation it has to add. This is easily done since the output voltage of a class D amplifier is directly dependent of the rail voltage.

$$V_{out} \sim V_{rail} * [Duty\ cycle] \quad (6.5)$$

6.3.2 More power than 25.5 W

The 802.3at standard allows the PSE to provide about 30 W over two of four pairs in a twisted-pair cable and it gives 25.5 W at the PD as mentioned in section 2.1.5. But the standard also allows the PSE to utilize the other two pairs in the cable to provide an additional 30 W to another PD interface and there is no limitation how many PD interfaces that can be placed in one unit [4].

In other word, one unit can have two PD interfaces that are connected to two wire pairs each in in the same cable giving that twice the power can be distributed to the unit over a single TP-cable. The guaranteed power at the PD is 51 W and it can be as high as 68.4 W.

7. Conclusion

The prototype that is constructed to prove the concept of an amplifier that is powered over Ethernet was found to work relatively well. The result shows that PoE has no impact on the performance or the sound quality for low power levels when the amplifier is compared to an amplifier with an external power supply.

The PoE amplifier did meet the proposed goal of 100+ W but not without losing linearity and having an output that is losing strength over time throughout a peak. A more reasonable maximum output power level is found to be 81.8 W which is the level there the signal only loses 0.5 dB during a peak. With a feedback loop it would probably be possible to get more than 100 W as output.

A PoE amplifier would be a good solution for a distributed speaker system. It is not possible to say which of a 100 volt system or a PoE system that is the best in every situation. It is something that must be considered case by case. But when it comes to extending an installation with a small number of speakers or when there is a need of having different audio channels on each speaker a PoE system would be perfect.

I think that an amplifier that is powered over Ethernet would be a great product for the professional audio business. The best section of application would be as a PoE self-powered speaker. This, since speakers often are placed where the ability to run many wires is limited.

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