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APPLIED RESEARCH

Stochastic Power Supply Technologies for Energy-Efficient, Networked, and Sound-Reinforcement Systems

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ABSTRACT The migration of professional audio systems towards Ethernet-based networking allows optimisation software to maximise key performance indicators (KPIs) such as the power required for particular applications. In this study, we focus on minimising peak power requirements by the use of supercapacitors (SCs) for demand smoothing with Class D audio amplification of at least 600 W root mean square (rms) output. Depending on the content, a 600 W maximum r.m.s output music programme is shown to draw just 60 W (10% of peak rms) on average. Our studies used music programme statistical analysis and probability theory, which enabled the minimum value of SC for a predetermined voltage drop to be found exactly and hence minimise costs/size requirements. The use of energy storage in audio (and other contexts) is not new of course, but we believe the probabilistic calculation and use of unprecedented SC reservoir capacitance values is original. This power averaging technique then allows Power-over-Ethernet (PoE) to be used, particularly the IEEE802.3 bt type 4 variant and AES67 Ethernet over powerline. As commercial PoE systems are now available for this standard, we have constructed a complete 600 W r.m.s class D sound system which has type 4 PoE as its sole power input. Again, PoE sound systems are not new but the extension to very high powers has not been reported to the best of our knowledge. In the powerline context, we describe a first-of-its-kind, outdoor venue, 5000 W peak rms, Class D audio system with > 1 km of standard 5 A mains cable, AES67 audio transport over powerline and lithium-ion energy storage at the amplifier location. An added benefit is that solar assistance can be used.

INDEX TERMS Supercapacitor, power-over-Ethernet, audio-over-Ethernet, powerline communication, energy-efficient, stochastic, audio systems.

I. INTRODUCTION

The implementation of AES67 Ethernet-based audio network systems has transformed professional digital audio in contrast to the traditional analogue methods, with Class D amplifiers in common usage [1]. These techniques set an interoperability standard for the audio networks and link previously incompatible networked audio solutions together, allowing low latency and reliability for switched Ethernet networks, and higher bit rates [2].

The transition to Ethernet-based audio networks, which transmit power, control, and audio signals through standard Category 5 (CAT5) or Category 6 (CAT6) twisted-pair cables, has been discussed in [3], [4], [5], and [6] for its ability to streamline system applications. In audio and broadcast engineering, Audio over Ethernet (AoE) technology utilises Ethernet networks to deliver real-time digital audio. Unlike traditional systems that use specialised low-voltage wiring for audio signals [7], AoE employs standard network cabling

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like CAT5 or CAT6. This paradigm shift simplifies the infrastructure, facilitating easier management and integration with existing networks.

AoE is designed to handle high-fidelity, low-latency audio, which is crucial for professional audio applications that demand precise and clear sound reproduction. This technology is particularly useful in large-scale audio setups, such as those needed for sound reinforcement in large venues like sports stadiums, airports, and concert halls. By using a network-based approach, AoE ensures that audio signals are transmitted reliably across the network without the need for dedicated, specialised wiring systems [8].

While AoE shares some similarities with other network-based audio technologies like Voice over IP (VoIP) [9], [10], [11] and Audio over IP (AoIP) [12], [13], [14], it is specifically tailored to meet the rigorous demands of professional audio. VoIP and AoIP are more general technologies that handle a variety of audio and voice applications over networks, but AoE is focused on delivering high-quality audio with minimal delay [15]

The AES67 standard for AoE was recently featured in an extended experiment involving high-power audio-over-powerline systems, demonstrating its capability in long-range applications. This experiment is discussed in the later section of this work. In contrast, an earlier example, known as the supercapacitor (SC) system, only transmitted digitized audio over CAT5 cables with power insertion. This older system did not have the same level of fidelity or range as the newer AoE technologies including highlighting the advancements in audio transmission that AoE offers [16].

Additionally, Power-over-Ethernet (PoE) technology, which enables the transmission of both electrical power and data signals over the same Ethernet cables, has become increasingly prevalent in professional digital audio systems. This advancement allows for a more streamlined setup by reducing the need for separate power supplies and simplifying cable management, ultimately contributing to a more efficient and integrated audio infrastructure [17], [18], [19], [20].

In our proposed and demonstrated methods, we first present a very high-power (600 W), SC enhanced, Class-D amplifier-based system which uses the latest PoE techniques. A much lower power (50 W) approach has been demonstrated in [21] but, as a case in point, we use probabilistic evaluation of SC value (reflecting the stochastic nature of audio programme demand) for reliable playback of different music genres. In short, by using unprecedented levels of energy storage in SCs, peaks of the audio power demand are very effectively averaged such that only the average power is needed. With the accepted power$_{in}$ = power$_{out}$ operation of nearly 100% efficient class D amplifiers, this average can be as little as 10% of peak rms.

The structure of this paper is as follows. Section II describes the theoretical analysis requirements and circuit modelling. The circuit design with some numerical results for the new approach together with performance analysis are presented in section III. In section IV, we simulate and validate our results in a proof of concept embodiment with actual music programme. In section V, we describe a new AES67 over powerline approach with localized energy storage in a 5 kW peak rms power application. Finally, concluding remarks relating to opportunities for the new stochastic techniques are offered in section VI.

II. THEORETICAL ANALYSIS AND MODELLING

We now present a heuristic mathematical analysis to estimate the average power demand. To inform our analysis, some examples of various audio programme probability density functions (PDFs) were found in [22]. We selected a generic Laplacian probability density function (PDF) expressed in terms of normalised audio power P_{norm}. This chosen PDF is structured to model the distribution of power across audio signals and it is characterised by a Laplacian distribution, which is often utilised in signal processing due to its ability to capture sudden changes or spikes in the signal. Furthermore, using the guidance of [22], we determined that a Laplacian PDF normalised to unity over a power range of 0 to 1 (1 = maximum rms power) was appropriate.

The expression for the power PDF $P(P_{norm})$ is defined as follows:

$$P(P_{norm}) = b\exp^{(-a\ P_{norm})} \tag{1}$$

where $P_{norm} = \dfrac{P}{P_{max}}$. As $P_{norm} \leq 1$ because $P_{norm} > 1$ is impossible, we obtain b from

$$b = \int_0^1 \exp^{(-a\ P_{norm})}\,\delta P_{norm}. \tag{2}$$

Such that $b = \dfrac{\exp(a) - 1}{a\exp(a)}$ and a is a scaling constant. Equation (1) is therefore normalised to:

$$P(P_{norm}) = \frac{a\exp(a)}{\exp(a) - 1}\exp(-a\ P_{norm}). \tag{3}$$

As described in [22], the empirical evidence obtained from sampling a wide variety of music genres suggested that $a = 10$. This has the convenience of setting $\dfrac{a\exp(a)}{\exp(a) - 1}$ above to closely approximate 10 (9.999546 to be exact) with $P(1) = 4.54 \times 10^{-5}$.

Equation (3) therefore becomes:

$$P(P_{norm}) = 10\exp(-10\ P_{norm}). \tag{4}$$

We can determine $< P_{norm} >$ (preserving physicality by noting that $P_{norm} \leq 1$) from:

$$< P_{norm} >= 10\int_0^1 P_{norm}\exp(-10\ P_{norm})\delta P_{norm}. \tag{5}$$

Or,

$$< P_{norm} >= 0.1 \tag{6}$$

where the approximation $\dfrac{\exp(10) - 11}{10\exp(10)} \approx 0.1$ is included. So the average power to sustain, for example, a 600 W peak rms audio signal is just 60 W. This important conclusion forms the basis for this work. The variance of P_{norm} about $< P_{norm} >$ or $< (P_{norm} - < P_{norm} >)^2 >$ is given by:

$$< (P_{norm} - < P_{norm} >)^2 >= 10 \int_0^1 (P_{norm} - < P_{norm} >)^2 \times \exp(-10\, P_{norm}) \delta P_{norm} = 0.01 \tag{7}$$

(where the approximation $\dfrac{\exp(10) - 101}{100 \exp(10)} \approx 0.01\ (0.009954)$ is used). This shows the audio proramme standard deviation is ± 0.1 about the mean or ± 60 W for 600 W peak rms audio signal and indcates that capacitive energy storage can be used. As the amplifer power requirement fluctuates above and below the mean, stored energy depletion will be balanced by a constant current charge. The precise capacitance value will be determined through simulation with an actual audio programme.

III. POWER-OVER-ETHERNET SIMULATION

Given the extensive variety of possible speaker motor and cabinet combinations, an equivalent circuit, as illustrated in Figure 1, can be simplified to a series-connected resistor and inductor. This simplification has led us to examine the Class D loudspeaker drive scenario more closely.

Firstly, the class D amplifier can be viewed as an impedance converter. For a bipolar power supply with a modular rail voltage V, the output voltage V_o is $V(2D - 1)$ where D is the duty cycle and D ranges from 0 to 1. When $D = 1/2$ $V_o = 0$, $D = 1$ gives $V_o = +V$ and $D = 0$ gives $V_o = -V$. The little used impedance transformer model is $Z_{in} = Z_{load} \times 1/(2D - 1)^2$. When $D = 1/2$, Z_{in} is a maximum (infinite in theory). When $D = 0$ or 1, $Z_{in} = Z_{load}$, so the amplifier impedance ranges over a very wide range with dynamic programme with a minimum of Z_{load}.

Secondly, the impedance of a loudspeaker is complex due to the inductive, resistive and capacitive components. It is purely resistive only at the main bass resonance, at higher frequencies in a multi-component system, and at DC as in Figure 1, [23]. An important characteristic of Class D amplifiers is that they only draw real power, while the imaginary component is recirculated in the output stage. Therefore, we propose that the loudspeaker's DC resistance serves as the worst-case scenario for Z_{load}. This is why we have chosen a resistor-only model as depicted in Figure 2.

The SC energy storage and discharge model shown in Figure 2 embodies a crucial aspect of the system's functionality. Even in these early stages of development, it was necessary to incorporate an element of practicality to ensure the simulation reflects real-world conditions accurately, thereby avoiding unrealistic scenarios.

For the model, we assumed a supercapacitor (SC) energy storage capacity of 29.4 farads, with a full-charge voltage of 50 volts. This choice was determined based on product availability, specifically utilising 17 supercapacitors with a capacitance of 500 farads each, connected in series to achieve the required voltage level.

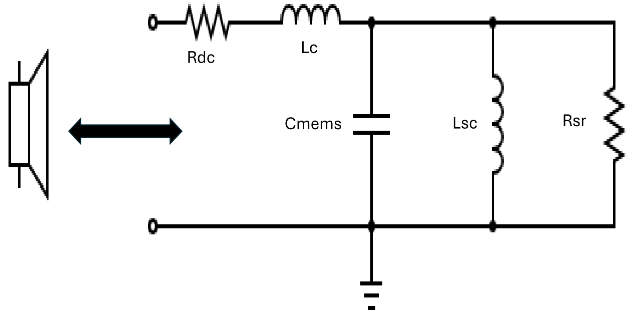


FIGURE 1. A loudspeaker schematic which represents a step towards the more complete model.

A 600 W peak root mean square (rms) supply was considered, with a voltage of 50 volts and utilising a Class D amplifier (Texas Instruments TAS5630) [24]. Assuming 100% efficiency, this setup corresponds to an equivalent resistive load of 4.17 Ω. The time constant, calculated as the product of the equivalent resistance and the capacitance (4.17 Ω × 29.4 farads), yields a hold-up time of approximately 122.6 seconds for the supercapacitor at a 600 watt rms output.

Utilising (6) mentioned earlier, the indicated charging current is estimated at 1.2 amperes at 50 volts, resulting in a power of 60 watts (calculated as 600 W divided by 10). These calculations provide essential insights into the charging dynamics and energy storage capabilities of the supercapacitor system under consideration.

For the PoE system, the booting time from a total discharge is calculated as 29.4 farads × 50 volts = 1.2 ampere × booting time, resulting in ≈ 20 minutes for the batteries. These would normally be kept charged by the solar or PoE input power, which matches the average demand. In the unlikely event of low battery voltage, with a 30 Ah battery and a 20 A solar charge, it would take 1.5 hours to charge. Again, this is an unlikely scenario and just a part of the installation time.

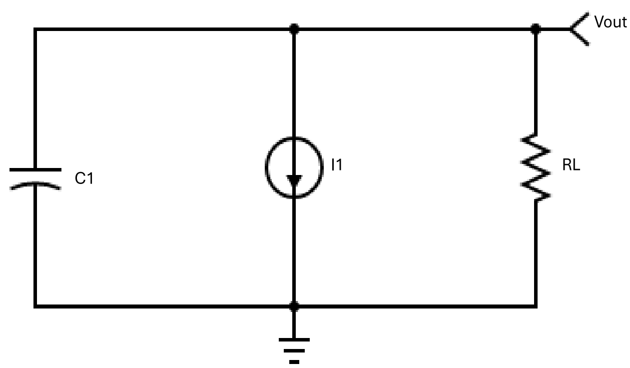


FIGURE 2. Load charge/discharge schematic.

The circuit dynamics shown in Figure 2 can be modelled as:

$$I_{in} R_{load} \left(1 - \exp - \left(\frac{t}{R_{load}\, c_1}\right)\right) \approx I_{in} \frac{\delta t}{c_1} \text{ for } \delta V \text{ increase} \tag{8}$$

and

$$(I_{in} - I_{load})\,\frac{\delta t}{c_1} \text{ for } \delta V \text{ decrease.} \tag{9}$$

Finally, we obtain the instantaneous time variation for $V_{out}(t)$ for time-varying $I_{load}(t)$ over a programme run-time T_{final} as:

$$V_{out}(T_{final}) = V_{out}(0) + \frac{1}{c}\int_0^{T_{final}} (I_{in} - I_{load}(t))\delta t. \tag{10}$$

where $(I_{in} - I_{load}(t))$ is bipolar and the expectation is that $V_{out}(T_{final}) = V_{out}(0)$. Equation (10) can be converted to a discrete time summation as:

$$V_{out}(N.\Delta t) = V_{out}(0) + \frac{1}{c}\sum_{n=0}^{N}(I_{in} - I_{load}(n.\Delta t)) \tag{11}$$

and

$$N.\Delta t = T_{final} \tag{12}$$

The analysis of various audio genres was conducted using MATLAB version 9.12 R2022a on a 64-bit machine. The initial focus of this analysis was to validate the experimental setup, as depicted in Figure 2, with the aim of determining the exact supercapacitor requirements for the entire system. By utilising MATLAB's powerful computational capabilities, we were able to rigorously evaluate and assess the performance of the experimental setup and refine our understanding of the system's requirements. This validation process was crucial for ensuring the accuracy and reliability of our subsequent experiments and findings.

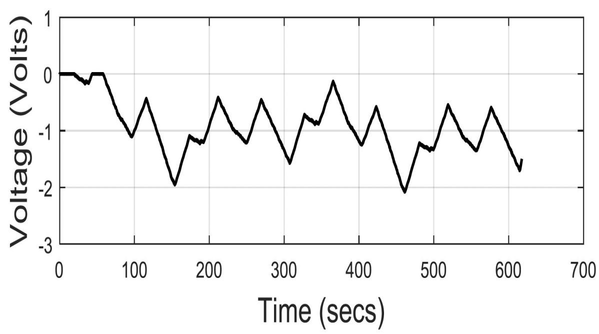
Figure 2 served as a top level schematic representation, guiding our efforts in configuring and optimising the system components. Through systematic analysis and experimentation, we identified the precise specifications of the supercapacitor needed to support the desired functionality and performance of the entire audio system. This rigorous validation approach laid the foundation for our subsequent investigations and enabled us to make informed decisions regarding the design and implementation of the audio system.

The brief description provided in Algorithm 1 offers only a subset of the input parameters, emphasising those most pertinent to the current task. These parameters play a crucial role in determining how the output voltage changes over time. Furthermore, the algorithm highlights the fundamental procedures necessary for conducting the simulation within the framework of Power over Ethernet (PoE) configuration, as illustrated in Figure 5. This approach ensures a thorough method for modelling and analysing the system's behaviour under consideration. By covering these critical elements, Algorithm 1 acts as a practical guide for implementing simulations designed to explore the dynamics and performance of PoE systems.

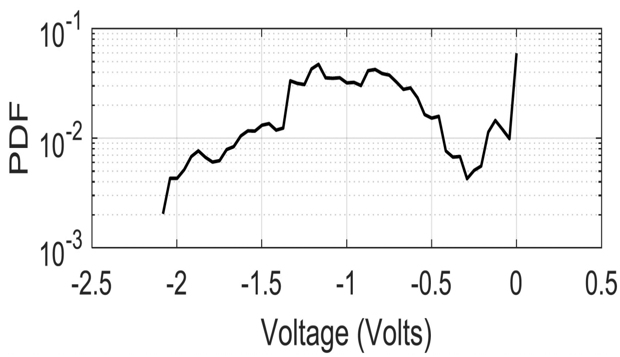
Inspection of Figure 3 (a,b) reveals an intriguing "buoyancy (used metaphorically here to describe the tendency of the SC voltage to stabilise at a certain level akin to an object floating on water)" phenomenon in which the voltage across the supercapacitor (SC) appears to have settled around a mean value of 49 volts.

Algorithm 1 Audio Output Voltage Analysis

procedure Outputs(*voltage*)
 C_T Initialization
 $[y, fs] \leftarrow$ Read audio files
 Filtering unwanted values from audio data $y(:,:)$
 $t \leftarrow 0 : dt : (len(y(:,1)) * dt) - dt$
 $WattsOut \leftarrow 600 * y$ Amplication of audio signal
 $dt \leftarrow \frac{i}{fs}$ Evaluate audio sample period at interval
 $CurrentOut \leftarrow (WattsOut)./50$ Current outputs
 $AverageCurrent = \sum(CurrentOut)/50$
 for $x = 2 : len(CurrentOut)$ **do**
  $\Delta(x) = AverageCurrent - CurrentOut(x)$
  if $(\Gamma(x-1) > 0) \wedge (\Delta(x) > 0)$ **then**
   $\Delta(x) = 0$
  end if
  $\Gamma(x) = \Gamma(x-1) + \Delta(x)$
 end for
 $VoltageOutputs = (\Gamma * dt)./C_T$
end procedure



(a) Supercapacitor (SC) voltage derivation



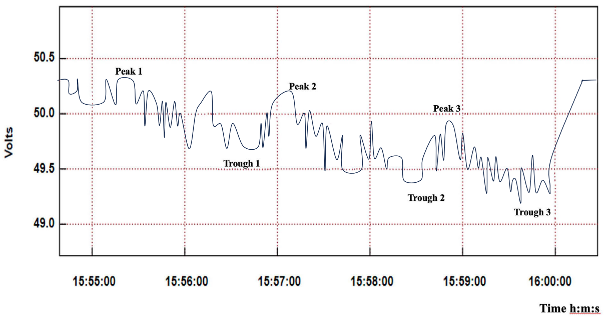
(b) Resulting Probability Density Function (PDF)

FIGURE 3. (a) Supercapacitor (SC) voltage derivation and (b) Resulting PDF.

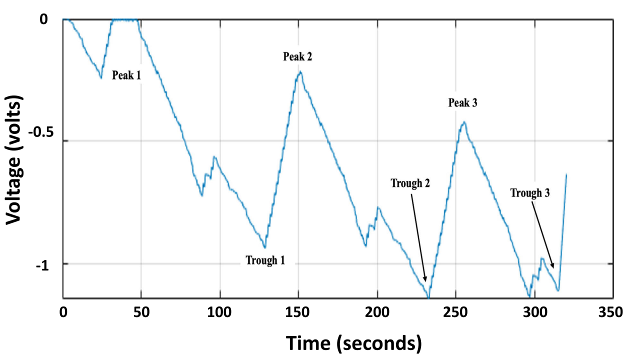
This observation is accompanied by a relatively narrow variation of approximately $\approx \pm 1$ V around this mean level. Despite potential fluctuations in the system, the voltage seems to exhibit a consistent behaviour, suggesting a robust equilibrium state around the mean value of 49 volts.

This phenomenon provides valuable insights into the behaviour of the SC system, indicating its ability to maintain a stable voltage level within a relatively tight range despite external influences or variations in operating conditions. Understanding and characterising such effects are essential for optimising the performance and reliability of the system in practical applications.

Figure 4 describes the results obtained from measured and simulated data for a specific programme, "heavy rock," illustrating good agreement between the two. It concludes that having sufficient energy storage in supercapacitors (SC) reduces the power feed requirement to just 10% of the peak root mean square (rms) signal. Furthermore, it suggests that an energy storage capacity of approximately 62 joules per watt (62 seconds of power hold-up for a 4% SC voltage variation) is adequate for general music programme material. We note, in passing that the RC time constant of 125 seconds as shown in Figure 2 corresponds to an exponential discharge to the e^{-1} level. This implies a typical capacitance value of around 50 farads per kilowatts (in this instance, 30 farads for a 600-watt system). The analysis target was 96 kHz sampled 24-bit audio; a data stream rate of 2.3 Mbit/s mono or 4.6 Mbit/s stereo.



(a) Measured $V_{out}(t)$



(b) Simulated $V_{out}(t)$

FIGURE 4. Presents (a) the measured and (b) simulated.

Additionally, a total of 32 music genres were downloaded, with each file having a run-time of up to 10 minutes and sizes reaching up to 345 MB. This accumulated to an overall total of 11 GB. The selection of 32 genres were chosen to ensure a strong central tendency in the data. Although more examples could have been included, the file sizes would have become unmanageable. The complete dataset was converted into the signal power envelope, and a PDF was extracted using standard mathematical tools described in [25].

For higher power applications, lithium-ion batteries are recommended as a cost-effective energy storage solution with ample capacity. For instance, a 5-kilowatt peak rms installation, which is further discussed in Section V, would necessitate an average power of 500 watts and storage of 31 kilojoules. An off-the-shelf 20 ampere-hour, 72-volt lithium-ion battery provides approximately 5 megajoules of energy storage, demonstrating its suitability for such requirements.

IV. PROOF OF CONCEPT POVER-OVER-EETHERNET SYSTEM

As shown in Figure 5, our proof of concept system is intended to replicate a standard sound-reinforcement application. In the loudspeaker cabinet: 4 × 12 inches, 101 dB SPL, full-range loudspeakers were used with drive provided by a 600 W peak rms class D amplifier (Texas Instruments TPA3255 bridge-mode) with a 50 V power supply applied to 29.4 farad SC combination which consisted of 17 × 500 farads SCs) connected in series. It may be noted, in passing, that no voltage-sharing resistors were required for each 3 V SC. In [26], the difficulties of providing high-power, high-quality audio in music-enabled phones were discussed, including how supercapacitors can address these issues. The paper also compared the audio performance of a standard setup with that of a configuration using a supercapacitor charged to 5 V via a current-limited boost converter. Usually, the power supply for the audio amplifier in a mobile phone is directly linked to the battery voltage, which is similar to our approach in this work.

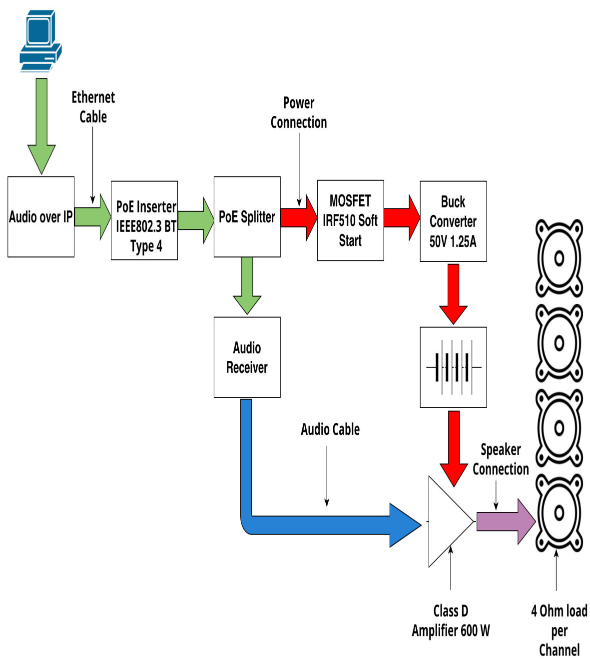


FIGURE 5. Block diagram of the proposed energy-efficient, audio networked, sound-reinforcement system.

The average current for "loud rock music" is 1.2 Amp at 50 VDC exactly as calculated by simulation. This is provided by standard PoE equipment (IEEE802.3 bt class 4)

[22]. The audio conversion is done by AES67 compatible, specially programmed, ADC/DAC boxes which are off-the-shelf [27]. At full volume, the calculated sound pressure level is 27.8 dBW (600 W) +6 dB (4-in-line cabinet) +101 dB (speaker SPL at 1 W, 1 m) ≈ 134.8 dB SPL at 1 metre. This is suitable for medium-level sound reinforcement, with just 60 W power in (1.25 A at 50 VDC). All the parts are commercially available and the design is scalable in power (100 W latest generation PoE [28]) and number of audio channels. Additionally, Figure 5 was deliberately set up to restrict the charging current into the SCs to test the 10% load hypothesis into the 600 W rms, Class D amplifier which we had available, and which was previously unknown (to our knowledge).

V. POWERLINE EXPERIMENTAL SET-UP

In this new scenario, we present a groundbreaking approach where both audio and visual technologies can seamlessly receive power and Ethernet signals through readily-available Powerline modems. Remarkably, this can be achieved using light-duty (5 A) mains cable spanning over a kilometre distance without encountering any issues. A significant advantage of this method is the elimination of the need for long, high-current feeder cables. Instead, the sole requirement is the provision of local energy storage at each audio amplifier, which can conveniently be co-located with the loudspeakers.

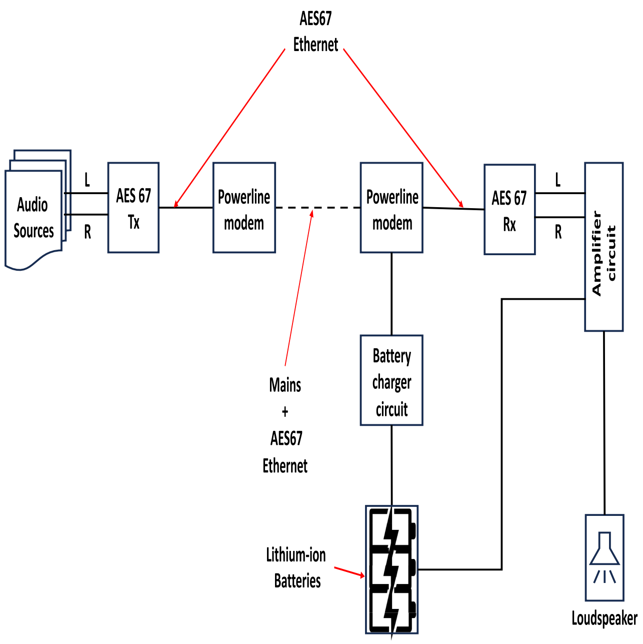


FIGURE 6. A 5-kW AES67-enabled installation with Powerline feed and localized energy storage.

The calculation of required energy storage for a diverse range of amplifier powers, assuming Class D amplification, can be facilitated using the methodologies outlined in this work. For instance, in our illustrative example of a 5-kW system, a mere 500 W mains power (equivalent to a minimum of 2.2 A) cable is needed, along with 310 kilojoules of energy storage. As previously mentioned, fulfilling this energy storage requirement is effortlessly achieved with the use of lithium-ion (Li-ion) batteries, as depicted in Figure 6. This innovative approach not only streamlines the distribution of power and Ethernet signals but also offers a more efficient and flexible solution compared to traditional setups involving cumbersome feeder cables.

In Figures 7 and 8, we present the results of our proof of experimental study conducted using standard mains wiring cable in conjunction with the PL-1200AV2-PIGGY device. The PL-1200AV2-PIGGY is a standard HomePlug AV2 compliant device specifically engineered for high-speed data transmission over power lines.

Our experimental setup involved utilising the standard mains wiring cable infrastructure commonly found in residential and commercial buildings. This infrastructure serves as the medium for power transmission throughout the building. By integrating the PL-1200AV2-PIGGY device into this existing wiring system, we aimed to assess its effectiveness in facilitating high-speed data communication.

Figure 7 illustrates the performance metrics obtained during our experiments, showcasing the data transfer rates achieved using the PL-1200AV2-PIGGY device over the mains wiring cable. These metrics provide insights into the device's ability to maintain reliable and efficient data transmission within the specified environment.

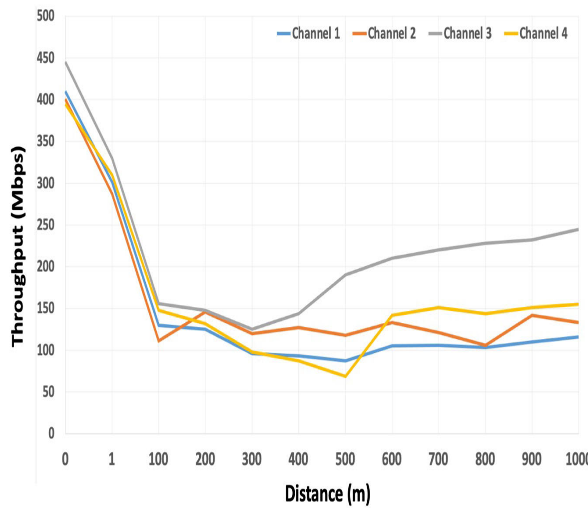


FIGURE 7. Throughput vs distance for a 4-channel Powerline system up to 1 km.

The data was transmitted intact and even exhibited a capacity improvement at longer distances as shown in Figure 7. This phenomenon is attributed to transmission-line-like behaviour and warrants further analysis. In any case, additional distances can be accommodated by incorporating Powerline repeater stages. The aspiration of this study is to facilitate the management of a live concert from the comfort of our homes, promoting a paradigm shift in concert performance with reduced power requirements. This, in turn, could contribute to a carbon-neutral or reduced carbon footprint.

Our experimental results demonstrate the feasibility and efficacy of leveraging standard mains wiring infrastructure for high-speed data transmission purposes, with the PL-1200AV2-PIGGY device serving as a reliable solution for such applications. These findings hold significant implications for enhancing connectivity and networking capabilities within buildings, offering a cost-effective and practical alternative to traditional wired and wireless communication technologies. In summary, the experimental results presented in Figures 7 and 8 validate the viability of utilising the PL-1200AV2-PIGGY device in conjunction with standard mains wiring cable for achieving high-speed data transmission, thereby laying the groundwork for further advancements in powerline communication technologies.

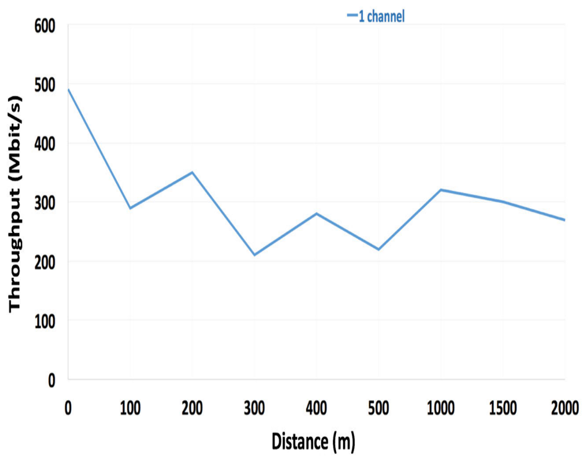


FIGURE 8. Throughput vs distance for a 1-channel Powerline system up to 2 km.

In Table 1, we have listed the optimised parameters with an open-source software known as the Microsoft Network test transmission control protocol (MS NTttcp) [29], thoroughly selected to rigorously stress test the powerline configuration. These parameters were chosen in alignment with previous experiments conducted, ensuring consistency and comparability with prior research efforts [30] and [31]. The numerical results detailed in Table 2 serve as satisfactory evidence supporting the viability and effectiveness of our concept. Through parameter optimisation and rigorous testing, we have validated the robustness and reliability of our approach, thus affirming its potential for practical implementation and real-world applications.

TABLE 1. Microsoft NTttcp software input parameters settings for the poweline configuration shown in Figures 7 and 8.

Transmitting server/switch setting		Receiving server/switch setting	
-l	1048576	-l	1048576
-rb	N/A	-rb	220000
-n	100000	-n	100000
-a	16	-a	16
-w	No value	-w	No value
-v	No value	-v	No value
-fr	No value	-fr	No value

These results were obtained under ideal conditions and would likely degrade with background interference and branching taps. Considering the maximum transmission unit of approximately 1500 bytes used in this experimental setup, the detailed output results presented in Table 2 support our claim of achieving audio transmission over powerline.

TABLE 2. Summary of packet trace numerical results for 1 and 4-channel links of using Microsoft NTttcp benchmark software to validate the powerline configuration presented in Figures 7 and 8.

Tx. outputs		Rx outputs	
Total Bytes (Mega)	12230.10	Total Bytes (Mega)	12211.24
Realtime (s)	254.37	Realtime (s)	254.36
Frame Size (Bytes)	1456.32	Frame Size (Bytes)	1456.32
Total Throughput (Mbit/s)	384.65	Total Throughput (Mbit/s)	376.25
Packet sent (Bytes)	**8397896**	Packet sent (Bytes)	**839725**
Packet received (Bytes)	**839738**	Packet received (Bytes)	**8397884**
Total retransmits	23	Total retransmits	0
Total errors	0	Total errors	0

Once again, the comprehensive output results presented in Table 2, derived from the utilisation of the NTttcp software, distinctly highlight the robustness and reliability inherent in our new approach. One crucial metric for assessing network performance is the retransmission rate, often calculated in terms of segments or bytes. In our study, we have opted to evaluate the byte retransmission rate, a methodology in alignment with previous research such as [32]. Notably, our analysis reveals that the byte retransmission rate remains below 1.0%, underscoring the efficiency and effectiveness of the powerline configuration depicted in Figure 6. This outcome reaffirms the suitability of our proposed approach for the intended application, emphasising its capacity to deliver stable and dependable performance in real-world scenarios. Furthermore, the powerline configuration proves to be a valuable addition to future networks.

VI. CONCLUSION

In this paper, we demonstrated how stochastic techniques can significantly reduce the average power demand for a range of high-power, networked audio systems. Examples are included for both PoE and powerline/AES67 configurations with peak rms powers ranging from 600 W to 5 kW, the latter being up-scalable to 10s - 100s kW. The key premises which underpin the studies are that: Class D amplifiers are used exclusively; localised power storage at least three orders of magnitude greater than that in conventional systems is provided and that the programme material is of a stochastic nature, as generally found in most music genres. Experimental, theoretical and simulation studies showed that a peak-to-average rms power ratio of 10:1 is an adequate descriptor based on a Laplacian probability density function; the actual average rms power demand reducing with volume setting, of course. In terms of power storage, a localised hold-up time of at least 62 secs is required at peak rms power. This is not an onerous stipulation with latest-generation battery technology as shown. It appears, however, that no current high-power systems approach this figure.

In the future, the stochastic techniques described here should allow much greater deployment of sustainable resources in audio networks and systems. For example, a 10 kW peak rms installation should require just 1 kW of continuous input power; a demand which can be met easily by combinations of current solar, wind or hydro technology.

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