Noise in Broadband Power-Line Communication and Future Bandwidth Growth

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Abstract: *In recent times there have been major advances in smart home technologies with the advent of the Internet-Of-Things (IOT). The demand for more intelligent, smarter and carbon efficient home devices such as light fittings and appliances is on the increase. If these devices are to be connected without extra cabling infrastructure then there is a need for research into more efficient transmission within current Power Line Communication (PLC) media. Currently PLC is limited by usable bandwidth and noise.*

Future network speeds will increase exponentially in the next ten years. If broadband PLC is to keep up with the growing capacity of the external telecommunications network then the local area PLC network must work around the issues of multi-path, carrier interferers and the external emissions of RF interference.

This paper proposes a solution that includes bandwidth growth to meet the current growth-rate forecast of PLC network capacity, and with a novel measurement solution, demonstrates that the average noise floor should be lowered. Lowering the average noise floor has a two-fold benefit of increasing data capacity and also provides a better Quality of Service (QOS). Also examined are the benefits obtained by shielding to reduce spectral masking thereby increasing the Orthogonal Frequency Division Multiplexing (OFDM) carriers that may then become available for increased data-throughput.

Introduction

Applying Nielson's Law reveals that residential internet bandwidth may reach over 5.3 Gb/s within ten years (Nielson, 2013), whereas the current Wireless Local Area Network (WLAN) IEEE 802.11n standard can only reach reliable data rates up to 200Mb/s (Ansah, 2011). This increase in usage assumes an expectation that many more items will be attached to the home broadband routers. It can be seen that vigilance with regard to reliability issues is essential to hold good connectivity and increase capacity as Internet bandwidth and computing capabilities increase further. This can be also seen when applying Moore's law of computing power growth (60 per cent per year increase) (Nielson, 2013).

For smart homes to become widespread ease of installation must be a priority and while multi-gigabit WLAN 802.11ad may become available by that point in time, PLC would be a better option due to the appliance already having a connection to the AC power supply.

As Internet speed grows then the usable bandwidth available in the smart home PLC system must keep pace, and barriers to higher data rates should if possible be removed. The main barriers to more efficient transmissions are electromagnetic emissions, both internal and external.

In respect to networking speed, for maximum efficiency the internal network should match as closely as possible the external supply network to take advantage of the higher data rate of that network.

This study also proposes the need to treat the power line more as a Local Area Network (LAN) than the noisy supply line that is the current position. As internet is mostly distributed via the telephone network (using line codes, higher order modulation and error correction) the power line must be seen and treated as a purpose made communication network using similar techniques. This must also include harmonising the signal to noise ratio across the entire network.

Literature Review

To take advantage of efficient coding techniques there should be as little interference as possible on the line. Currently most attention to PLC has involved coding techniques to mitigate against the interference. This study intends to remove the need for mitigation of noise by looking more closely at the physical layer freeing up extra usable bandwidth.

WLAN has become the de-facto standard for broadband connections in most households because of its reduced cost and easy installation. This increased usage is congesting the airwaves in only a few channels resulting in co-channel and adjacent channel interference (Cisco, 2007) (Ruslan and Tat-Chee, 2009). When channel settings are not changed, especially in densely populated locations such as blocks of flats, there is a reduction in maximum achievable data rates caused by shared channel capacity.

The major problems for broad deployment of wireless LAN networks for real-time applications include limited Quality of Service (QOS) support and electromagnetic interference (Gagro, 2009).

The rationale for this research is that for a truly smart home all lights, appliances and power sockets should have total connectivity within a fast data network. As these are usually connected to the mains power supply system it makes sense to use PLC rather than other network technologies.

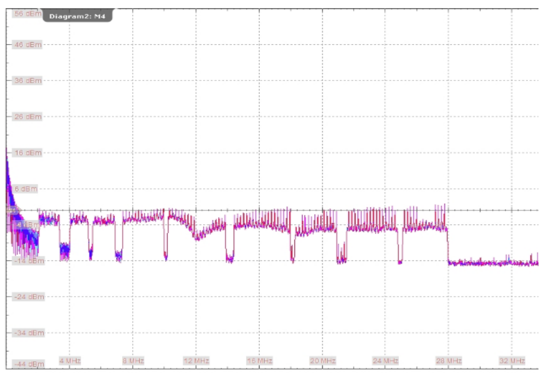

Figure 1 Measured OFDM Spectrum

By increasing the current bandwidth that is shown in figure1, capacity is increased, however the bandwidth should also be kept to a minimal level to avoid unnecessary interference. This paper will ascertain the minimum level needed to meet future expectations of capacity demand. It has been shown during previous research how an increase in data rate may be accomplished by different methods:

- Higher modulating techniques such as 4096-QAM (12 bits/symbol) OFDM (HomePlug, 2013),(ITU, 2012).
- Noise avoidance techniques such as MIMO (ITU, 2012), (HomePlug, 2005) and (Itagi, 2011).
- More condensed line codes such as 8b9b line codes (Itagi, 2011).
- MAC protocols such as IEEE1901 to avoid collision (Mudriievskyi, 2013)
- Error detection codes such as BCH (Itagi, 2011), FEC (ITU, 2012)or GAC (Andreadou, 2008).

Whilst these techniques may increase efficiency, more bandwidth is needed for a greater payload and further increases in data throughput.

The research previously stated suggests that the best solution to an improved data rate throughput is dependent upon improving the transmission medium itself.

To increase the data rate of PLC, one or more of these components should be advanced further, either by upgrading present methods or by implementing alternative methods such as upgrading the electrical infrastructure of the building and removing obstacles to more efficient communication such as noise and spectral masks. The power line should be treated both as a purpose-made data communication network, whilst still providing AC power capability.

Problem Statements

AC inherent noise

The most important concern with PLC efficiency is noise in both the supply and the system itself. Lin (2013) states that synchronous impulsive noise and periodic impulsive noise restrict communication performance in OFDM power line communication systems. The noise has been described as Middleton's A-class noise and appears due to the poor design of the electrical network causing multipath and impedance mismatches.

Hirata et al. (2005) attempted to use choke coil-filters to remove both common mode and differential disturbances, even though the experiment was on Japanese two cables live and earth only system. Inherent ac power noise may be removed with conditioned power, and impedance mismatches could be removed by modifying each electrical outlet with impedance matching stubs.

RF interference

The Canadian Communications Research Centre (Gagnon, 2009) assessed electromagnetic noise radiation at three and ten metres including bandwidths between 0 and 108MHz. Significant emissions were measured at up to 30 MHz and little was found thereafter because older PLC systems only utilise a bandwidth of up to around 30MHz. The newer standards are moving towards higher bandwidths of up to 83MHz (Achaichia, 2013). These emissions interfere with various radio bandwidths.

RF shielding

The need for frequency blocking spectral masks on newer systems could be removed by effective shielding of cables; employing similar shielding techniques to the proposed category 8 Ethernet standards on the power line itself and would likely be very beneficial. Without the need for blocking spectral masks the carriers available may greatly increase due to bandwidth becoming available.

Possible security concerns exist due to techniques such as 'Phreaking' where electromagnetic emissions are detected and the signal is re-combined so the non-intrusive (passive) hacker can see the same as the user sees (Van Eck, 1985).This issue would also be removed if current emissions were minimised.

Coupled with suitable line and error coding methods, these changes could provide for power line communication at much higher data rates than are currently possible. This could then be the basis for future research.

Solution

At present, to reach speeds of over 5 Gb/s on mains ring power supplies, the increase in bandwidth would be almost 2 GHz, which is excessive and would generate significant RF interferers. The increase in speed is more achievable by increasing the SNR and then raising the bandwidth to at least 416.67 MHz (with zero noise), taking into account the SNR ratio of a purpose made communication system such as the telephone system, which is around 30dB. The minimum bandwidth would need to be raised to 501 MHz

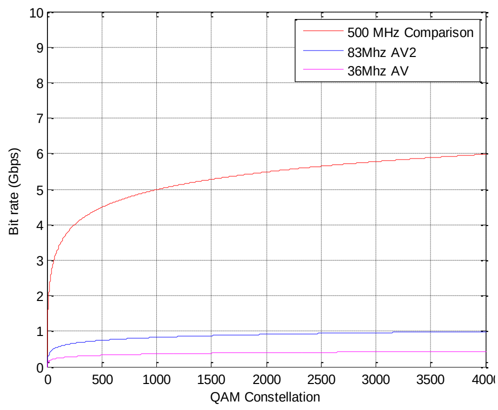

Figure 2 QAM multi-level signalling

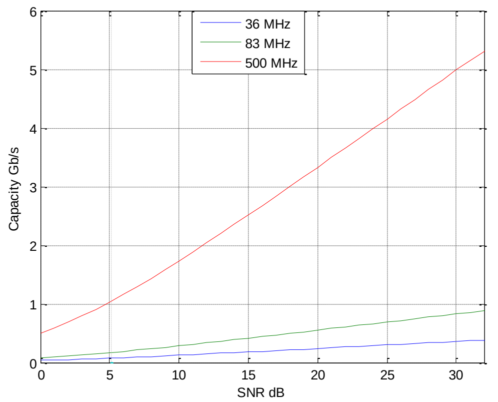

Figure 3 Noise to capacity

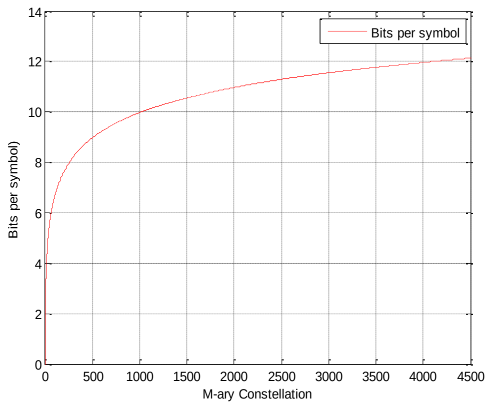

Figure 4 Bits per symbol at 4096 QAM

This figure could be achieved with a suitable band stop filter on each power supply socket, removing both interferers by dropping the average noise floor and providing impedance matching to remove multipath. This is an area for future research.

Testing

To achieve an accurate result it was necessary to find the current SNR. For this test the PLC adapters used were AV standard 200Mb/s and 500Mb/s models as well as a 1000Mb/s MIMO AV2 standard model.

The testing bench was setup in multiple configurations. Peer-to-peer gigabit maximum throughput test software was used to generate and ensure constant maximum traffic measuring the maximum bit rate possible. The monitoring instrument used was the Rhode and Schwarz RTO1004 oscilloscope. This was set to average1000 samples, enveloped and persistence mode FFT spectrum analysis.

The spectrum of the OFDM signal was measured over 0 to 40 MHz with a bandwidth resolution view of 20 KHz to achieve the clearest views of the signal. A wideband antenna was used to measure RF emissions between 0-30MHz from a distance of 1 metre

An average was taken over the captured OFDM spectrum, which ran from approximately 2 to 28 MHz in each test configuration.

The test setup was based on the current UK mains ring configuration. This was supplied with both regular ‘dirty’ mains 230V 50Hz electricity, and ‘clean’ 230V 50Hz electricity filtered through a UPS. The 3 different PLC adapters were tested this way with measurements taken via the plug socket as well as antenna measurements from a distance of 1 metre.

The tests that followed were configured in ‘t’ junction and line type ‘_’ (single-cable) configurations, which approximate closely to bus and star configurations in a regular Ethernet network.

Further tests were run by shielding the mains cables with half inch earthed mild steel tubing and measurements taken from the shielding skin in addition to the socket and antenna measurements. The maximum speed achievable was about 200Mb/s on the 1000Mb/s MIMO AV2 adapter. To gain maximum data rates the SNR must then reach 30 dB and the full AV2 standard spectrum must also be used, not the 28MHz currently recorded in the measurements.

Simulation Results

To find the minimum bandwidth for the proposed 5Gb/s signal to propagate the minimum Nyquist frequency had to be found normally. This is half the speed of the bit-rate as seen in equation (1). However as PLC uses multi-level signalling the multi-level Nyquist equation (2) was used as shown in figure 2;

$$\boldsymbol{Fb = 2B} \tag{1}$$

$$\boldsymbol{Fb = B * Log2(M)} \tag{2}$$

Where;

- ***Fb = bitrate (b/s)***
- ***B = Nyquist bandwidth (Hz), and***
- ***M = number of discrete voltage levels***

As up to 4096 discrete level QAM is currently being deployed on the Home plug AV2 standard, the upper amount of discrete signals in use is known. Placing the bandwidths of the older and newer PLC standards into equation (2) gives maximum bit rates possible as shown in figure 3.

It can be seen that even the newer AV2 standard only just reaches 1Gb/s capability, however if the bandwidth is raised to 500 MHz it is easily possible to achieve over 5Gb/s using even less complex QAM. To find the bits per symbol achieved using 4096 QAM equation (3) (Hartley, 1928) was used;

$$\boldsymbol{N = Log2(M)} \qquad \textbf{(3)}$$

Where;

- ***N = bits per symbol, and***
- ***M = number of discrete levels***

The figures obtained were plotted in figure 4 and using the previous results with equation (4) the absolute minimum usable bandwidth to gain 5 Gb/s was calculated.

$$\boldsymbol{B = \frac{\mathbf{Fb}}{\mathbf{N}}} \qquad \textbf{(4)}$$

= 416.67MHz with zero noise.

$$\boldsymbol{C = B * Log2(1 + \frac{\mathbf{S}}{\mathbf{N}})} \qquad \textbf{(5)}$$

Where;

- ***S/N = signal to noise ratio (dB)***

Using the above equation for the Shannon limit for information capacity (5) (Shannon, 1984) the bitrate versus signal to noise ratio could be found. As can be seen in figure4, to gain 5 Gb/s at current average noise levels over 2GHz bandwidth would be needed whilst only 501MHz is needed if the line is cleaned to current average telephone line noise levels.

Table 1 Channel capacity

SNR	5.141dB	SNR	30dB
Bandwidth (MHz)	Capacity (Gb/s)	Bandwidth (MHz)	Capacity (Gb/s)
36.00	0.08	36.00	0.36
83.00	0.17	83.00	0.83
500.00	1.05	500.00	4.98
1930.00	4.04	1930.00	19.24

Baud is the encoded rate of change divided by bits;

$$\boldsymbol{Baud = (\frac{\mathbf{Fb}}{\mathbf{N}})} \qquad \textbf{(6)}$$

This makes the Baud the same as the bandwidth.

Bandwidth efficiency ($B\eta$) is shown as;

$$\boldsymbol{B\eta = (\frac{\textbf{Transmission rate}(\frac{\mathbf{b}}{\mathbf{s}})}{\textbf{Min Bandwidth (Hz)}})} \qquad \textbf{(7)}$$

$$\boldsymbol{B\eta = \left(\frac{5000000000}{416700000}\right) = 11.99(\frac{\frac{b}{s}}{Hz})} \qquad \textbf{(8)}$$

If the 30dB figure of 501 MHz is plugged into equation (8) then an efficiency of 10 bit/s/Hz for 5 Gb /s is seen as shown in table 1.

Physical test results

Figure 5 1000trcu spectrum plot

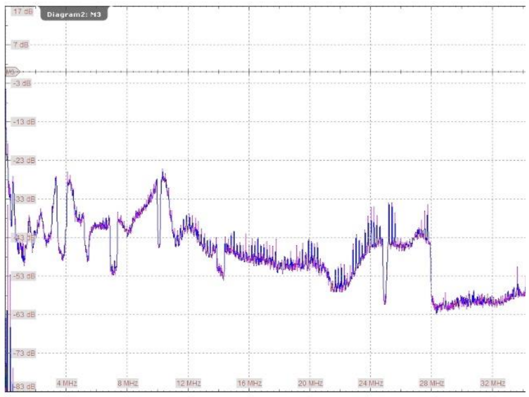

Figure 6 1000trcs spectrum plot

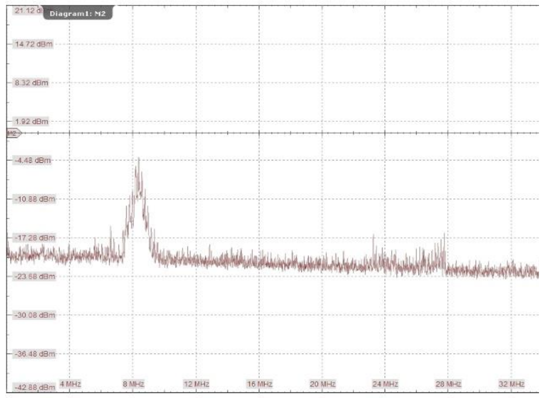

Figure 8 500oscs spectrum plot

Table 2 Configuration descriptors

Speed	**Description**	**Config**	**Description**
200	200 Mb/s	_	Single length cable
500	500 Mb/s	t	Multiple single metrics
1000	1000 Mb/s	O	UK mains ring
Device tested	**Description**	**Noise**	**Description**
p	Plug	c	Clean filtered UPS
r	Radio antenna	d	Normal UK mains supply
s	Shielding		
Shield	**Description**		
s	shielded		
u	unshielded		

For the physical testing multiple configurations were used and these are described in table 2.

*Note that the 200 and 500 Mb/s devices only have a 100Mb/s Fast Ethernet port, and that the1000Mb/s device has 2x2 MIMO that delivers approximately 1.8 times the theoretical capacity in EU mains power supplies

Antenna Measurements

The antenna spectrum results were again measured over an average of 1000 samples. As expected the OFDM spectrum can be clearly seen in the antenna measurements in table 3 due to electromagnetic RF emissions. As seen in figures 5 and 6 while the power level and definition of the signal is significantly lower than the direct plug measurements, the signal to noise ratio is much higher.

When comparing the shielded and unshielded versions the power level seems to be slightly higher in the shielded version, and when comparing this to the direct shield measurement in figure 7, the shielding appears to act as a power amplifier.

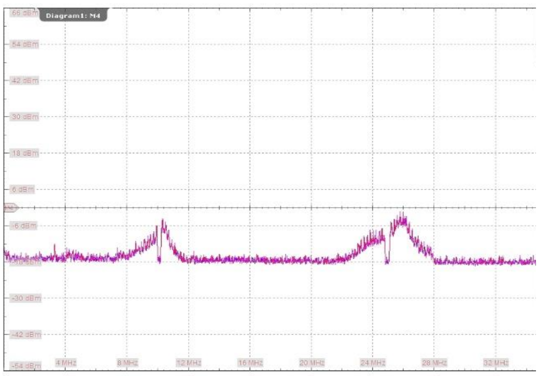

Figure 7 1000tscs spectrum plot

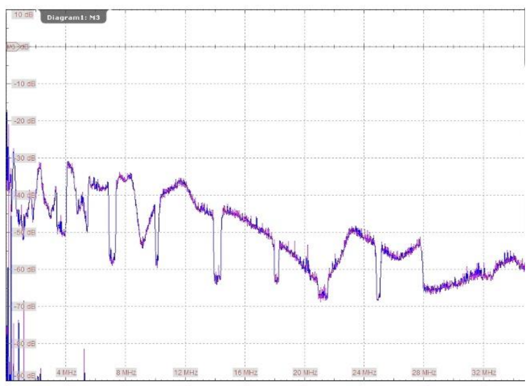

Figure 9 500orcs spectrum plot

Direct socket measurements

The direct plug measurements show a large range in signal to noise ratio, with the best SNR resulting from the 1000Mb/s adapters shown in table 4 as expected.

The difference in quoted speed claims on the adapter packaging and measured speeds was found to be inconsistent and that the 200 and 500 adapters only came with a 100Mb/s fast Ethernet port and so could not reach those speeds even with a perfect network and noise environment.

The most surprising result was the small bandwidth used by every adapter even though their respective standards gave them more usable bandwidth.

The bandwidth in every test came out as only 26MHz over the 2 to 28 MHz range.

Table 3 Antenna Measurements

Conf	Noise dBm	Sig dBm	SNR dB	Conf	Noise dBm	Sig dBm	SNR dB
200_pds	-14.5	-6.3	8.2	500tpds	-13.7	-3.0	10.7
200_pcs	-14.9	-6.4	8.5	200tpdu	-14.5	-3.5	11.0
200opds	-15.0	-6.4	8.6	1000_pcs	-14.1	-2.9	11.2
500tpcs	-13.8	-4.6	9.2	1000tpcu	-13.3	-2.1	11.2
200opdu	-14.9	-5.6	9.2	500opcs	-14.6	-3.3	11.3
200_pdu	-15.2	-5.7	9.5	500_pdu	-14.0	-2.6	11.3
200tpcu	-14.8	-5.3	9.5	500_pcu	-13.9	-2.4	11.5
200tpds	-15.0	-5.2	9.7	1000_pdu	-14.1	-2.3	11.8
500opds	-13.4	-3.6	9.8	1000tpdu	-14.1	-1.8	12.4
200opcs	-14.4	-4.3	10.1	1000tpds	-12.3	0.3	12.5
500tpcu	-14.5	-4.4	10.1	1000opds	-13.9	-0.4	13.6
500_pds	-13.9	-3.7	10.2	200tpcs	-13.2	0.4	13.6
500opdu	-13.5	-3.3	10.2	1000_pds	-13.7	-0.1	13.6
200opcu	-13.8	-3.6	10.2	1000_pcu	-14.2	-0.5	13.7
200_pcu	-14.3	-4.0	10.4	1000opdu	-13.3	1.3	14.6
500_pcs	-14.0	-3.6	10.4	1000opcu	-12.2	2.8	15.0
500tpdu	-14.4	-3.9	10.5	1000opcs	-11.4	4.2	15.6
500opcu	-13.9	-3.2	10.7	1000tpcs	-9.7	10.0	19.6

Table 4 Direct SNR measurements

Conf	SNR dB	Conf	SNR dB	Conf	SNR dB
1000_pcs	25.3	200_pcs	19.6	500_pcu	23.8
1000_pcu	25.3	200_pcu	19.1	500_pds	29.9
1000_pds	25.9	200_pds	26.4	500_pdu	27.8
1000_pdu	26.0	200_pdu	26.7	500opcs	24.6
1000opcs	30.1	200opcs	22.1	500opcu	23.4
1000opcu	28.8	200opcu	28.8	500opds	30.0
1000opds	25.3	200opds	28.9	500opdu	27.5
1000opdu	29.6	200opdu	34.3	500tpcs	21.8
1000tpcs	24.0	200tpcs	31.6	500tpcu	19.5
1000tpcu	23.4	200tpcu	19.8	500tpds	26.5
1000tpds	33.5	200tpds	30.3	500tpdu	24.3
1000tpdu	27.4	500_pcs	22.6		

To check that this was not the result of poor measurements, these results were compared against the maximum throughput bit-rates achieved using Shannon's Information Capacity equation (5) (Shannon,1984).The measurements were found to be correct.

There was little difference between the configurations, but the smoothing of the mains input supply and shielding from external interference made a significant impact over such a small bandwidth usage.

Figure 10 500trcs spectrum plot

Shield skin measurements

Figure 7 shows the shield skin measurements across the second peak in the mains ring circuit, it is significantly degraded and the results can be seen between figures 9 and 10.

In figure 9, the mains ring circuit power is lower however it is more defined than the t type circuit in figure 10.

The plot shows a significant difference between regular mains ring in figure 8 and the other two configurations.

These shielding results suggest a surprising trade-off between signal security and emission power when deciding on shielding. While earthed shielding should in theory degrade RF emissions power, the results suggest that this is only partially happening with the signal detail, and overall power is raised at resonant frequencies.

Bitrate results

The results in table 5 show the results of the throughput testing, and while the 200 and 500 Mb/s adapters have 100Mb/s Fast Ethernet adapters they didn't reach this capacity despite the stated values. The 1000 Mb/s adapters barely reached one fifth of their purported capacity.

Table 5 Bitrate throughput measurements

Conf	O	T	_	Conf	O	T	_
200DU	90.3	89.3	88.6	500CU	94.2	95.3	95.2
200DS	94.2	91.8	77.7	500CS	95	95.2	95.1
200CU	94.7	92.2	92.4	1000DU	192.3	195.6	198.2
200CS	92.3	91.9	93	1000DS	198	197.4	195.4
500DU	94.4	94.4	94	1000CU	197.9	199.4	187.7
500DS	94.2	94.5	94.3	1000CS	198.1	198.1	196.6

The earlier results (figure4) have shown that 1Gb/s could not be achieved over the 26 MHz of bandwidth used.The 1000Mb/s adapter results are broadly comparable with only a few Mb/s between them. These results suggest that while there may be some small bit-rate difference in configurations.

A change from the standard UK mains ring configuration would be unnecessary and too costly to implement in terms of the results from this small network test even with minimal impedance mismatches.

Looking at the AV2 results from the mains ring configuration, it shows that cleanness and shielding do provide an increase in bit-rate from 192.31Mb/s up to 198.13Mb/s. This is a significant increase of 5.82 Mb/s or just over 3%, gain that could equate to approximately 112 Mb/s more data rate over 501MHz of bandwidth.

Conclusions and future work

It has been shown how the information capacity can be grown sufficiently by expanding the bandwidth of the PLC to prepare for the growth in needed capacity envisioned by 2023, including both high internet speeds and smart homes.

The results show how signal to noise ratio affects the PLC as the original Home plug AV standard adapters used were not able to reach their fast Ethernet port speeds and are inefficient. The 1000Mb/s adapters fared badly too and were only able to reach up to a fifth of their capability, due in part to not using enough of the available bandwidth.

The results suggest that to enable a better signal to noise ratio, the AC supply should enter the building supply system clean. This could be done with a simple low pass inductive toroid ring filter to remove the higher frequencies.

Further work should be carried out on the average noise floor, this should be lowered further by using impedance matched band-stop filters on each supply socket removing noise between the 50Hz mains supply and 2MHz start of the PLC signal. The impedance matching would remove multipath interference at localised signal injection/extraction points.

Expanding the available bandwidth by over five times introduces broadcast interference concerns however, while the bandwidth gain could be easily introduced, further work is needed on effective shielding or other noise blocking methods such as spectral power masks, especially with respect to the cost of retrofitting if extra infrastructure is needed to be fitted.

This study was limited in scope by the size of the mains electricity supply model tested. This could be further improved by repeating the tests carried out in this report within a residential setting.

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