Characterisation of Signal Amplitude-Frequency for Indoor Power Line Communication Channel in the 1 — 30 MHz Broadband Frequencies

Original Scientific Paper

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Abstract *– The transmission of data signals over power lines is a very promising technique for delivering indoor broadband communication services. However, since power grids were originally designed for high-voltage low-frequency signal transmission, there is a frequency mismatch between the power grid and high-frequency data signals. This mismatch poses a challenge to deploying power lines as a communication channel. Although, studies and researches conducted in several countries have made transmission of data over power lines possible, the behaviour and properties of the power grid cannot be generalised. Hence, the need for in-depth experimental measurement and analysis on the suitability and capability of the Nigerian power grid for data transmission is crucial for proper characterising and modelling of the power line communication (PLC) channel. In this paper, we present experimental measurement results of the effects of frequency variations on the attenuation experienced by broadband high-speed data signals transmitted over the Nigerian indoor power line network.*

Keywords *– amplitude, attenuation, broadband frequency, channel, indoor PLC, signal*

1. INTRODUCTION

The ubiquitous nature of the power grid has attracted huge interest into its deployment as an alternative and efficient technique for delivering high-speed data signals to end-users around the world [1]. With the ever-increasing global demand of high-speed multimedia data services, the successful deployment of power lines as a communication channel is imperative [2], [3]. This will undoubtedly complement existing technologies currently deployed in many countries of the world. Although, power lines have been used for transmitting communication signals for several decades, its use has only been limited to transmission of low-rate control and monitoring signals by power supply companies. In recent times, power line communication (PLC) technology has also been deployed in smart grid and for automatic meter reading technology [4], [5].

However, the power line network poses a harsh and unconducive environment as channel medium for the transmission of high-speed data signals due to the frequency and voltage mismatch between the two [6]. As a result, data signals undergo mild to severe attenuation as they transverse the power line channel from one point (node) to another. This attenuation is undesired in any communication system, and serves as the basis for power line communication (PLC) channel measurement, characterisation and modelling [6], [7].

Asides frequency and voltage mismatch, certain properties of the power line network contribute to signal attenuation on the power line communication (PLC) channel. Multipath propagation, noise, topology as well as node (load or no load) terminations play a major role in determining the extent of signal attenuation, and by extension, the efficacy of PLC channels for data transmission and delivery [7], [8].

While PLC channels have been characterized in varying capacities in different countries around the world, the characteristics and model(s) obtained in one country cannot be generalised for others [5], [9]. Furthermore, most of the existing literature on power line channel modelling focus on the deterministic approach, where the power line is analysed as a transmission line.

Some research works have been presented in literature on in-home PLC. In [10], characterisation of some urban and sub-urban in-home PLC channels in the 2 – 30 MHz frequency band in terms of the average channel gain (ACG) and the root mean squared delay-spread (RMS-DS) in United State of America was presented. While in [9] and [11], the results for the evaluation of in-home PLC channels – where the average channel gain (ACG), coherence bandwidth (CB) and the root mean squared delay-spread (RMS-DS) were used to evaluate the channel for France were presented. The results of the channel attenuation and noise for frequencies up to 30 MHz in Spain were presented in [12] and [10] where the ACG, RMS-DS and CB were presented. Also, analysis of the ACG, RMS-DS and CB for the upper frequency edge of 300 MHz was carried out in Spain in [11]. In [12] and [13], extensive measurement campaign and numerical analysis of the ACG, RMS-DS and CB parameters for the Brazilian in-home power line channel were presented. In this research work, the results of preliminary measurements on the Nigerian indoor PLC channel are presented. This is to provide a reference for subsequent characterization and modelling of indoor broadband PLC systems in Nigeria.

The remainder of this paper is organized as follows: Section II discusses the Nigerian indoor power line communication channel while section III describes the equipment set up for the experiment and measurement procedures. The results obtained from the experiment are analysed and discussed in section IV; and finally, conclusions are presented in section V.

1.1 Comparative Analysis of General Wired, Wireless and Power Line Communication Systems

Power line communication (PLC) is a form of wire communication, except that the wire medium used are not typical ones like Ethernet data cables or telephone coaxial cables. Rather, existing electric power cables are utilised for transmission of information signals [14], [15]. In the Nigerian scenario, wireless communication has been extensively deployed by mobile telecommunication service vendor that have a very high presence in both urban and rural communities. Internet access is pretty much available as long as subscribers can afford internet subscription. On the other hand, communication over cables have not really been successful, as it is obtainable in developed countries [16]. This is largely due to unavailability of cable infrastructures that ought to have been put in place. Private establishments like institutions of learning, large corporations and few individuals appear to be the only group that can afford the high cost, and other modalities, required for setting up and maintaining these systems. As a result, hitherto, internet user traffic are tilted towards wireless technologies than the wired counterpart.

The potential benefits of deploying PLC systems in Nigeria include cost effectiveness i.e. the use of existing power cables; ease of network setup; huge bandwidth available at the frequency of operation; low latency and high reliability [15], [16]. All these contribute to making PLC technology an excellent candidate for meeting future broadband internet access demands in Nigeria [17].

1.2 Modulation Techniques for Power Line Communication Systems

For power line communication systems, digital modulation techniques, including frequency-shift keying (FSK), Phase-shift keying (PSK), and quadrature-amplitude modulation (QAM) have been deployed as modulation scheme for PLC systems [18]. However, due to the multipath characteristics of power line communication systems, a more suitable modulation technique is the orthogonal frequency-division multiplexing (OFDM) [19], [20].

Although, the separate subcarriers in OFDM overlap, they are orthogonal to one another; the orthogonality implies that the peak of one subcarrier occurs when the others are at zero. Intersymbol interference (ISI) is mitigated in OFDM by inserting a cyclic prefix (CP) (or guard interval) [21], [22]. The insertion of CP also permits proper demodulation of the symbol streams without spectrum overlap [22]. Asides mitigation of ISI in OFDM, the technique is very reliable in multipath propagation environments like the PLC network [23], [24]. It offers very high resistance to fading and can accommodate delay spread induced by multipath propagation [19], [25].

1.3 Potential Applications of Power Line Communication in Nigeria

The huge population of Nigeria, coupled with the continuous increase in the demand for internet and multimedia services hawe necessitated the need for complementary technologies and services that will ensure perennial internet access [16]. In about 20 years of mobile communication systems' existence in Nigeria, the number of active mobile internet subscribers has risen from just about a million to over 50 million. Presently, Nigeria ranks highest in Africa in internet accessibility, and among the top 20 in the world [16], [17]. Even with the deployment of fourth generation (4G) mobile networks, the existing networks are insufficient to meet prevailing demand. It is envisaged that in the next few years, demand for broadband internet services may exceed network providers' capacity.

Power line communication (PLC) system offers an alternative technology for providing reliable broadband internet access to Nigerian residential homes, offices and industrial environment. Although, only about 40 per cent of Nigerians have access to power - which are largely in urban areas and cities, government are putting infrastructures in place to make sure that at least 80% of its population have access to electricity within the next few years [16]. Asides electric power challenges, telephones and data cable connections are severely limited, even in urban regions and cities. When these power infrastructures are in place, PLC deployment will ensure that people in remote rural areas and urban centres will have access to power. However, even with access to power, broadband internet access in rural and remote areas are rare or non-existent, in most cases [16], [17]. Thus, as long as there is connection to the electric power grid, PLC systems can be deployed to provide reliable and affordable internet access over the power line [26]. In light of this, characterisation and modelling of the Nigerian PLC channel is important in preparation for the depolyment of in-home PLC in Nigeria.

2. OVERVIEW OF THE NIGERIAN POWER LINE NETWORK

The availability and reach of electric power cables make it an alternative medium for transmission of data signals [27]. Since the power line infrastructures (power grid) are already in existence in virtually all countries of the world, the deployment cost for PLC systems is reduced drastically when compared to other communication technologies [27], [28]. While PLC channels display strong resilience against natural hazards, power lines are still capable of transmitting low-voltage communication signals even with the occurrence of faults that may render them incapable of transmitting high-voltage electric power signals [29]. However, PLC channels exhibit certain propagation characteristics that affect signal-carrying capability [29], [30]. These characteristics in relation to the Nigerian indoor power line networks are discussed in this section.

The Nigerian low-voltage indoor power line network has a last-mile alternating current (AC) voltage of 240 V, 60 Hz (one-phase) and 415 V, 60 Hz (three-phase). This experiment was restricted to single-phase measurements only. As shown in Fig. 1, indoor power line networks usually terminate in socket outlets that are connected to derivation boxes (DBs) in either bus or star topology [31]. All DBs in a building are then connected to a service panel that feeds energy from the service provider into the building. Joints in the power cables and connection boxes, as well as series connection of cables with different characteristic impedances result in reflections (or echoes) on the PLC channel [31], [32]. Also, socket outlets are terminated in load (appliance) impedances of varying values or are open-circuited. Load impedances on the channel affects the performance by altering the channel frequency response and input impedance, and also contribute to the level of background noise [31], [33].

Thus, due of the contributions of connected impedances to background noise, additive white Gaussian noise (AWGN) is not sufficient in modelling PLC noise [31], [34]. Multipath propagation due to reflections on the power line, varying load impedance terminations and peculiar noise behaviour of the PLC channel all contribute to the attenuation of signals as they transverse the power line channel [29], [35], [36].

The experiment and measurements in subsequent sections show the variations in the level of attenuation experienced by signals in the indoor broadband frequencies of 1 – 30 MHz on a PLC channel.

3. EXPERIMENTAL METHOD AND MEASUREMENT PROCEDURES

The equipment set up for the measurement is shown in Fig. 2 and Fig. 3. The experiment was carried out in two different laboratory rooms in the Electrical/Electronic and Computer Engineering Department, College of Engineering of Afe Babalola University, Ado Ekiti, Nigeria.

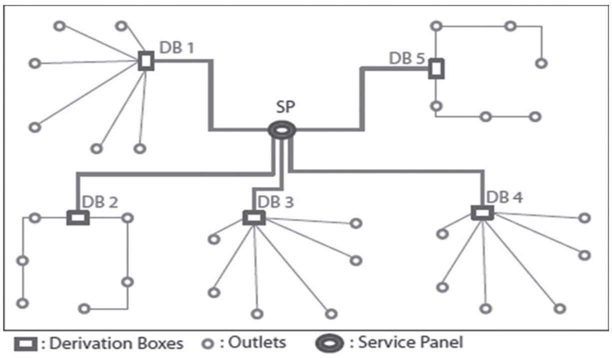


Fig. 1. Indoor power line distribution [19]

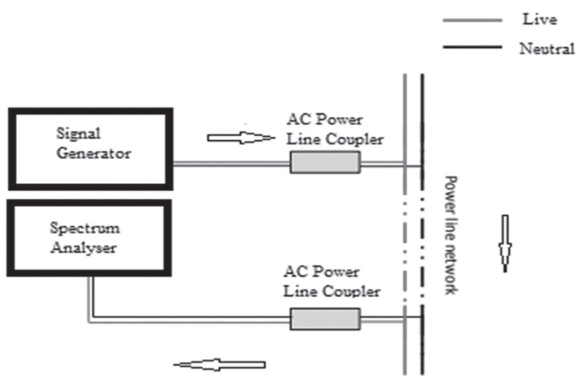


Fig. 2. Block representation of the PLC channel measurement setup

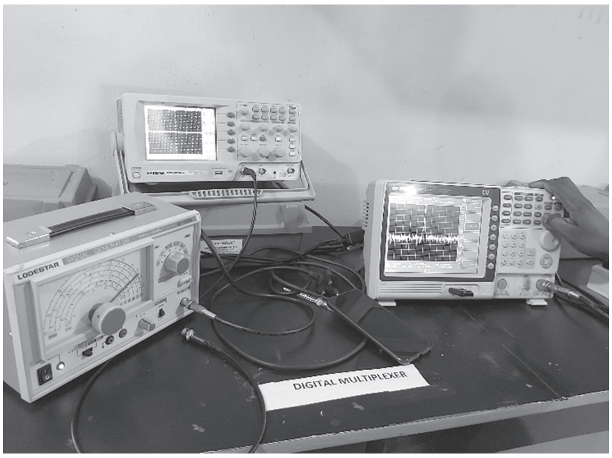


Fig. 3. Pictorial diagram of the PLC channel measurement setup

As shown, the set up consists of a function generator, a spectrum analyser, a pair of AC power line couplers and an indoor AC power line that links two socket outlets. Low pass filter AC coupling circuits were used to connect both the function generator and spectrum analyser to the power line. Asides isolating the measuring equipment from the mains high-voltage power network, these couplers also function to protects the measuring equipment from the 60 Hz AC frequency, and provide points of entry and exit for the low-voltage high-frequency signals respectively, into and from the power network.

The experiment was conducted over a fixed PLC channel cable length of about 5 m between two indoor socket outlets. The spectrum analyser measured and displayed the attenuation (in decibels) experienced by signals traversing the power line at particular frequencies. The waveforms were then saved as trace files on the spectrum analyser; and were processed and analysed using MATLAB and Excel software.

Three loads connected for this experiment include: a 20 W energy-saving bulb (a capacitive load); an 8 W mobile phone charger and a 65 W laptop charger (inductive loads). Signals at specific frequencies were injected in steps from the narrowband range of about 1.5 MHz up to the broadband range of 30 MHz into the system – under both no-load and load conditions. Also, the attenuation-frequency waveform for each level of signal frequency was obtained. The bandwidth and sweep for each level of injected signal were 3 MHz and 0.24 seconds respectively, with the frequency of interest at the centre. The injected signals were increased in steps of 5 MHz up to 30 MHz.

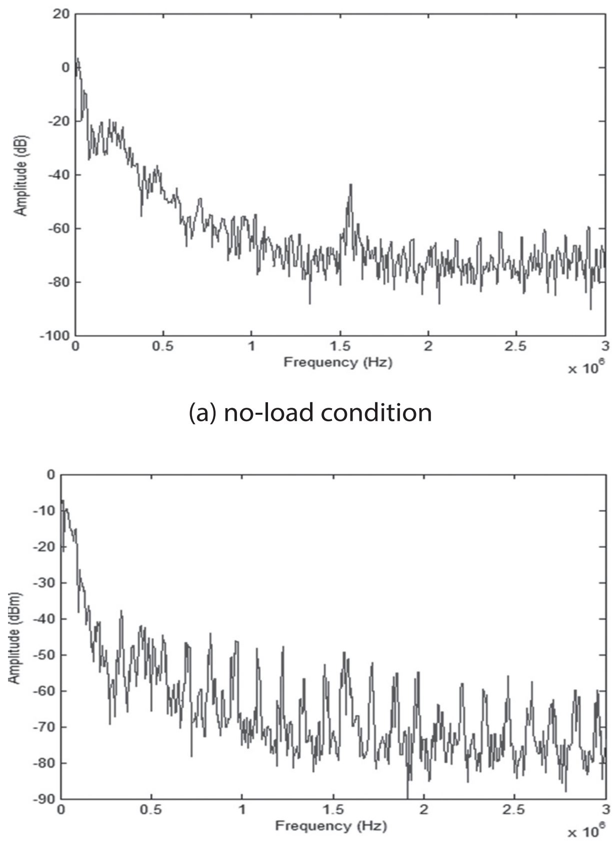
4. RESULTS AND DISCUSSION

In this section, the data and waveforms obtained from the broadband frequency measurement up to 30 MHz are presented, and their variations with the corresponding signal power are discussed. Also, the results of the statistical computation of the average channel attenuation are presented, and comparison with results available from existing literature are made.

4.1 Received Signal Amplitude versus frequency for No-load and Load Conditions

Fig 4 shows the Amplitude-Frequency waveform at frequency up to 1.5 MHz. It can be observed that at the lower frequencies up to 1.5 MHz, the amplitude of the received signal dropped steadily to very low values of -42 dBm and -52dBm for both no-load and load conditions respectively. This implies that the severity of the attenuating effects of the PLC channel on transmitted signal at frequencies within this range rapidly increased. From 500 Hz, the signal amplitude declined in a fairly stable manner until 1.5 MHz, when the amplitude improved to about -39 dB and -46 dBm for no-load and load conditions respectively.

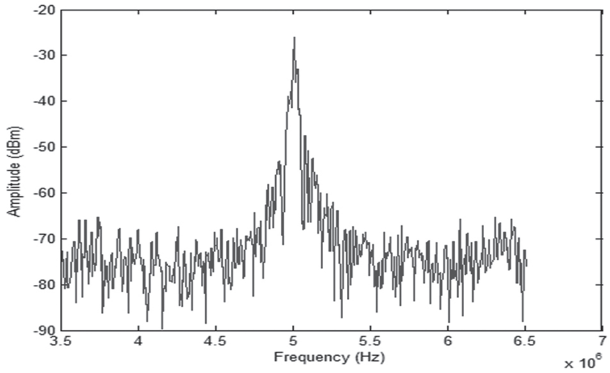
The Amplitude-Frequency waveform at 5 MHz is shown in Fig. 5. It can be observed that at 5 MHz, the amplitude of the received signal improved further to about -24 dB for no-load and -25 dBm for load conditions. This implies a much less attenuation experienced by the signal at 5 MHz. Also, the attenuation values for both conditions are almost equal at this frequency i.e. the PLC channel effects on the transmitted signal was load-independent.



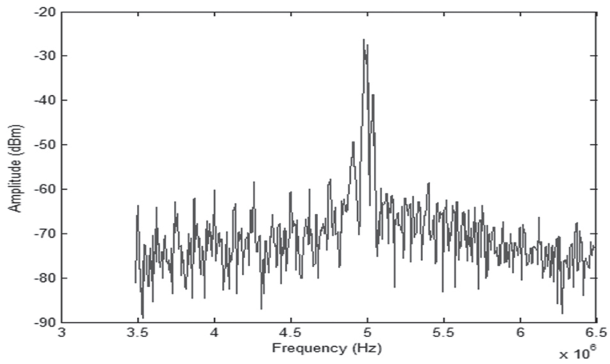
(a) no-load condition

(b) load condition

Fig. 4. Amplitude-frequency waveform at 1.5 MHz

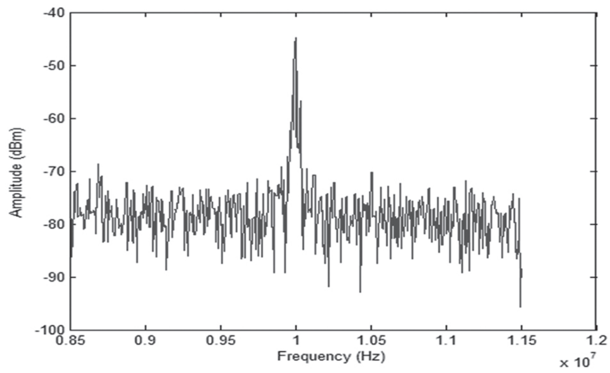


(a) no-load condition

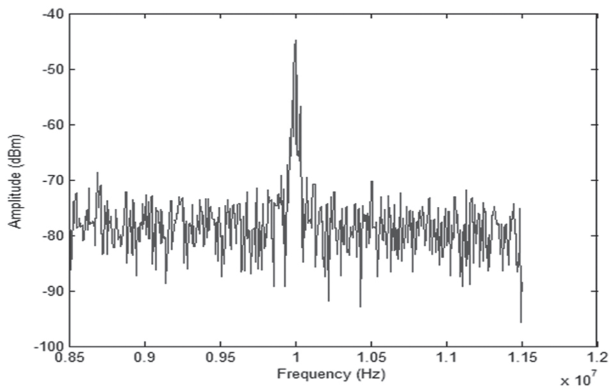


(b) load condition

Fig. 5. Amplitude-frequency waveform at 5 MHz

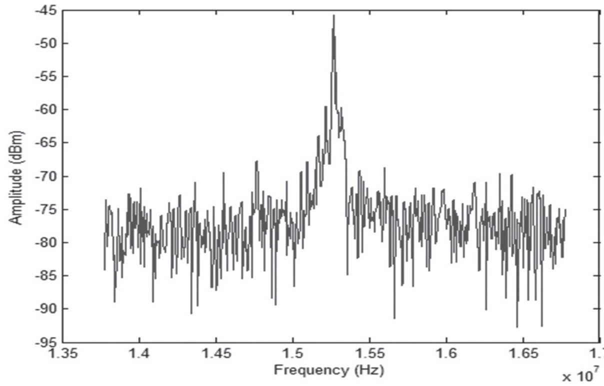


(a) no-load condition

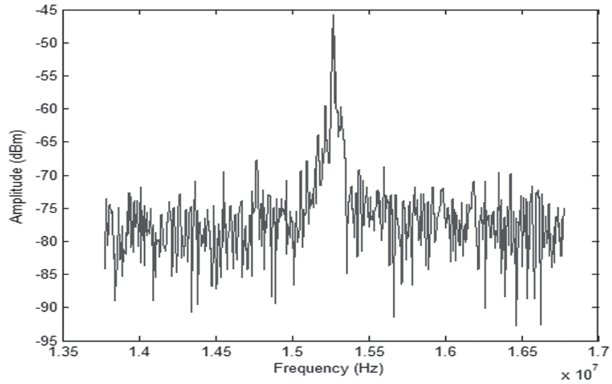


(b) load condition

Fig. 6. Amplitude-frequency waveform at 10 **MHz**



(a) no-load condition



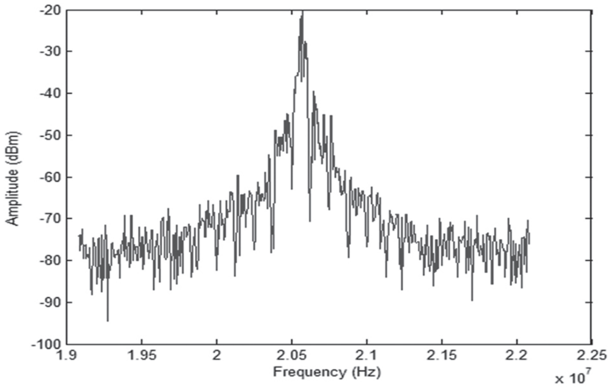
(b) load condition

Fig. 7. Amplitude-frequency waveform at 15 MHz

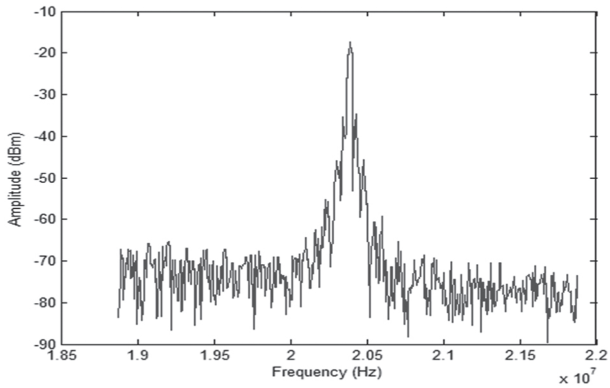
Fig. 6 shows the waveform at 10 MHz, where it can be observed that the received signal amplitude further dropped to -43 dBm and -42 dBm for no-load and load conditions respectively, as can be observed from Fig. 6. The received signal amplitude for both load conditions are approximately the same i.e. the load conditions had negligible effects on the PLC channel attenuation at this frequency as well.

Similar to the results obtained for 5 MHz and 10 MHz transmitted signal, the attenuation experienced by the signal over the PLC channel at 15 MHz was observed to be quite comparable for the no-load and load conditions, as shown in Fig. 7, i.e. -46 dBm for the former and -43 dBm for the latter. Furthermore, it can be observed that the signal attenuation increased steadily for signals at 5 MHz through 10 MHz to 15 MHz for both load conditions.

At 20 MHz signal frequency, the attenuation experienced by the signal traversing the PLC channel did not deviate significantly from each other. However, at this frequency, the signal amplitude greatly improved to -18 dBm and -20 dBm for no-load and load conditions respectively, as seen in Fig. 8. This indicates that the PLC channel had the least attenuating effect so far on the transmitted signal, as the signal amplitudes were highest for all signal frequencies up to 20 MHz.

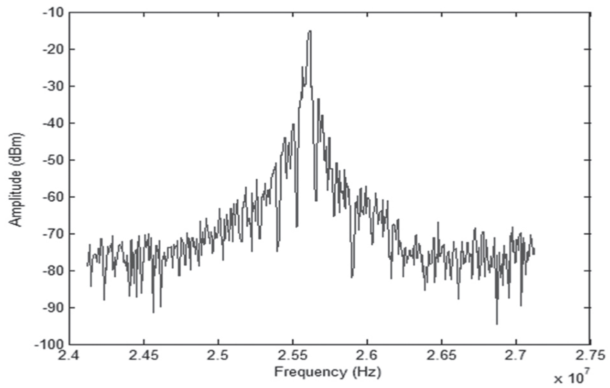


(a) no-load condition

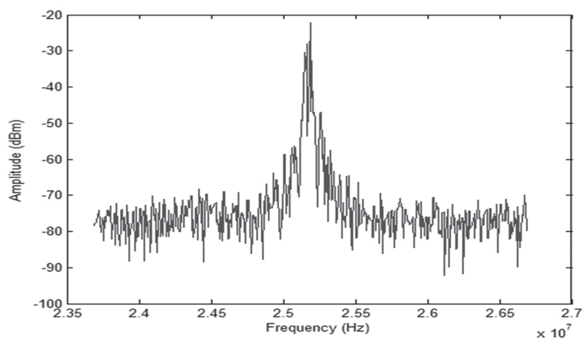


(b) load condition

Fig. 8. Amplitude-frequency waveform at 20 MHz

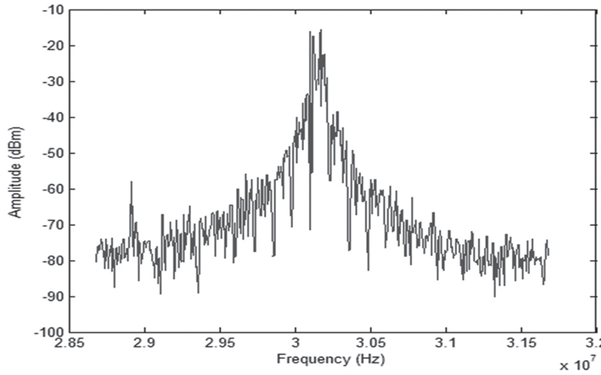


(a) no-load condition

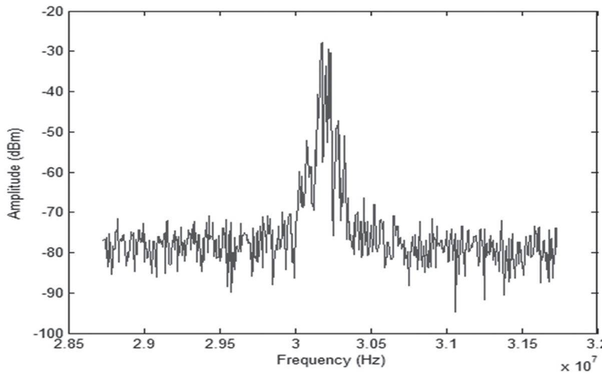


(b) load condition

Fig. 9. Amplitude-frequency waveform at 25 MHz



(a) no-load condition



(b) load condition

Fig. 10. Amplitude-frequency waveform at 30 MHz

As can be observed from Fig. 9, at 25 MHz, the amplitude of the received signal for the PLC channel on load was much higher than without load. With amplitude of -14 dBm on no-load and -22 dBm on load, the load conditions on the PLC channel had a huge attenuating impact on the signals traversing the channel at this frequency.

Lastly, at 30 MHz signal frequency, Fig.10 shows that the disparity in the amplitude of the received signal has further widened from -16 dBm for the no-load PLC channel condition to -28 dBm for the loaded condition. This means that the load on the PLC channel induced greater attenuation for signals at 30 MHz frequency than at all previous sampled frequencies.

4.2 Variations in the received signal power with frequency for no-load and load conditions

Table 1 shows the variations in the received signal power with frequency for the no-load and on-load PLC channel. From the table, for both load and no-load conditions, it can be observed that the received signal power is very low from narrowband range up to about 5 MHz signal frequency i.e. the point the signal power started increasing. The implication is that the channel attenuation is more profound at this low frequency range. But, at 10 MHz and 15 MHz signal frequencies, the signal attenuation became high again, resulting in low signal power within this range.

This conforms to the communication theory that signal attenuation increases with frequency in a non-ideal conductor. Finally, from 20 MHz up to 30 MHz frequencies, the received signal power improved significantly for both no-load and load conditions.

Table 1 Variations in the received signal power with frequency for PLC channel on no-load and load conditions

Frequency (MHz)	Signal power (mW) (no-load)	Signal power (mW) (load)
0.5	0.00006	0.00001
1.5	0.00013	0.00003
5	0.00398	0.00316
10	0.00005	0.00006
15	0.00003	0.00005
20	0.01585	0.01000
25	0.03981	0.00631
30	0.02519	0.00159

4.3 Statistical measurement of the average attenuation on the PLC channel

The average channel attenuation (ACA) is a well-established parameter used in characterizing indoor PLC channels. The average channel attenuation is the negative of the average channel gain (ACG), and is expressed mathematically as [37]:

$$ACA = -ACG = -10log_{10}\left(\frac{1}{N}\sum_{K=0}^{N-1}|H[k]|^2\right) \quad (1)$$

Where N is the number of subcarriers and $H[k]$ is the kth coefficient of the discrete Fourier transform of the linear time-invariant PLC channel impulse response.

For our PLC channel setup, using Eq. (1), the ACA was determined by considering channel frequency response (CFR) estimates over 1 – 30 MHz frequency range. Several CFR estimates were taken over varying length of a.c. socket outlet pairs in the laboratory rooms, each with its own range of connected equipent and appliances. The overall values for the maximum, minimum and mean of the average channel attenuation (ACA) in dB are presented, as shown in Table 2.

The table also compares the ACA values with those that exist in literature from other countries [13], [37].

Table 2. Comparison of average channel attenuation (ACA) obtained for the Nigerian 1 – 30 MHz indoor broadband PLC channel with other countries

Statistical Parameters	ACA (dB) Nigeria	ACA (dB) Brazil	ACA (dB) U. S.	ACA (dB) Spain
Maximum	76.86	51.09	68.12	~70
Minimum	16.15	9.18	19.70	~10
Mean	43.5	23.28	48	~30

From table 2, it can be observed that all the three statistical parameters – maximum, minimum and mean values of the ACA for Nigerian PLC channel are higher than what is obtained in Brazil and Spain. However, the maximum ACA value for Nigerian PLC is higher than that of U.S.A. while the mean and minimum vaules are less than the U. S. A. Thus, the Nigerian PLC channel has the highest maximum ACA (dB) value among all four countries considered in the frequency band of interest (i.e. 1 – 30 MHz). Also, the minimum and mean ACA (dB) are higher than that of Spain and Brazil. The high value obtained for maximum ACA may be attributed to the nature and peculiarities of the power grid asides from other 'noisy' equipment that may be connected to the larger power network while measurements were being taken. By extending the measurements campaign further, in order to obtain a wider data set, the ACA values may change. The final values obtained will be very crucial to characterising and modelling the Nigerian PLC channel.

5. CONCLUSIONS

A lot of factors influence the behavior of indoor power line channels. In this work, we have presented the results of experimental measurements on the Nigerian indoor power network, and considered the effects of channel attenuation on signals transmitted across the channel under load and no-load PLC network scenarios. Some conclusions are derived from this work. The narrowband frequencies up to 1 kHz are capable of transmitting high-speed data signals for both conditions of load over the power line channel without significant attenuation. Likewise, higher broadband frequencies from 20 to 30 MHz are shown to offer better immunity to the attenuating effects of the PLC channel on transmitted signals, thereby offering better capacity to transmit information signals. Further measurements at 1 – 30 MHz broadband frequencies with real-time traffic data will allow for characteristics and subsequent modelling of the Nigerian PLC channel for high-speed data transmission.

6. REFERENCES

[1] L. T. Berger, A. Schwager, J. J. Escudero-Garzás, "Power Line Communications for Smart Grid Applications", Journal of Electrical and Computer Engineering, Vol. 2013, 16 pages.

[2] Z. Mingyue, "Measurements and Channel Characteristics of LV Power Line Communications Networks in China", Proceedings of the IEEE International Symposium on Power Line Communications and Its Applications, Orlando, FL, USA, 26-29 March 2006, pp. 212–216.

[3] W. Zhu, X. Zhu, E. Lim, Y. Huang, "State-of-art power line communications channel modelling", Procedia Computer Science, Vol. 17, 2013, pp. 563–570.

[4] S. Guzelgoz, "Characterizing Wireless and Powerline Communication Channels with Applications to Smart Grid Networks", University of South Florida, 2011, Ph.D. Thesis.

[5] A. M. Tonello, "PLC for the Smart Grid : State-of-the-Art and Challenges", Proceedings of the 4th international Conference on Communications, Mobility and Computing, Guilin, China, 21-23 May 2012, pp. 2–5.

[6] M. Mosalaosi, "Power Line Communication (PL)C Channel Measurements and Charaterization", University of Kwazulu-Natal, 2014, M.Sc. Thesis.

[7] F. Zwane, "Power Line Communication Channel Modelling", University of Kwazulu-Natal, 2014, M.Sc. Thesis.

[8] A. M. Tonello, A. Pittolo, M. Girotto, "Power line communications: Understanding the channel for physical layer evolution based on filter bank modulation", IEICE Transactions on Communications, Vol. E97-B, No. 8, 2014, pp. 1494–1503.

[9] A. M. Tonello, S. Member, F. Versolatto, S. Member, A. Pittolo, "In-Home Power Line Communication Channel : Statistical Characterization", IEEE Transactions on Communications, Vol. 62, No. 6, 2014, pp. 2096–2106.

[10] F. J. Canete Corripo, J. A. Cortes, L. Diez, J. T. Entrambasaguas, "A Channel Model Proposal for Indoor Power Line Communications", IEEE Communications Magazine, Vol. 49, No. December, 2011, pp. 166–174.

[11] A. M. Tonello, F. Versolatto, B. Béjar, S. Zazo, "A fitting algorithm for random modeling the PLC channel", IEEE Transactions on Power Delivery, Vol. 27, No.3, 2012, pp. 1477–1484.

[12] T. R. Oliveira, C. B. Zeller, S. L. Netto, M. V. Ribeiro, "Statistical modeling of the average channel gain and delay spread in in-home PLC channels", Proceedings of the IEEE International Symposium on Power Line Communications and Its Applications, Austin, TX, USA, 29 March-1 April 2015, pp. 184–188.

[13] T. Oliveira, A. Picorone, C. Zeller, S. Netto, M. Ribeiro, "Statistical Modeling of Brazilian In-Home PLC Channel Features", Journal of Communication and Information Systems, Vol. 34, No. 1, 2019, pp. 154–168.

[14] S. Shukla, et al, "Comparison of Wireless Network over Wired Network", International Journal of Research Granthaalayah, vol. 5, 2017, pp. 14–20.

[15] A. O. Ajibade, I. B. Oluwafemi, A. O. Ojo, K. A. Adeniji, "Theoretical Analysis of Transmission Parameters and Interference Issues in Power Line Communication Systems", ABUAD Journal of Engineering Research and Development, Vol. 1, No. 1, 2017, pp. 95–99.

[16] O. J. Femi-Jemilohun, "Broadband Internet Access Services through Power Line Communication to the Rural Dwellers in Nigeria", International Journal of Engineering Research & Tehnology, Vol. 8, No. 4, 2019, pp. 112–115.

[17] L. K. Matthew, F. Olowononi, J. S. Soja, "Power Line Communications: A Platform for Sustainable Development", Proceedings of the 3rd International Conference On African Development Issues, Ota, Nigeria, 9-11 May 2016, pp. 45–61.

[18] A. Recioui, "Application of multiple input multiple output power line communication (MIMO-PLC) to power systems", Acta Physica Polonica A, Vol. 132, No. 3, 2017, pp. 496–499.

[19] W. Zhang, "Design of Power Line Carrier Communication System Based on Orthogonal Frequency Division Multiplexing", Proceedings of the 5th International Conference on Advanced Materials and Computer Science, Qingdao, China, 26-27 March 2016, pp. 784–787.

[20] T. D. Farkas, T. Király, T. Pardy, T. Rang, G. Rang, "Application of power line communication technology in street lighting control", International Journal of Design & Nature and Ecodynamics, Vol. 13, No. 2, 2018, pp. 176–186.

[21] F. Pavliodou, N. Sad, "Power line communications based on OFDM 1", Viatacom Ltd., Vol. 2, No. 1, 2013, pp. 1–4.

[22] E. M. Meza, J. B. Aspiazu, "Design of a Power Line Communications Transceiver Based on OFDM," Procedia Technology, Vol. 17, 2014, pp. 107–113.

[23] N. A. M. Mohammed, "Design of Power Line Communication", University of Khartoum, India, 2017, B.Sc. Thesis.

[24] N. Andreadou, F. N. Pavlidou, "Modeling the noise on the OFDM power-line communications system", IEEE Transactions on Power Delivery, Vol. 25, No. 1, 2010, pp. 150–157.

[25] A. Pandharipande, "Principles of OFDM", IEEE Potentials, Vol. 21, No. 2, 2002, pp. 16–19.

[26] S. Mehfuz, "Performance Analysis and Modeling of Broadband Power line Communications", International Journal of Advanced Research in Electronics and Communication Engineering, Vol. 1, No. 2, 2012, pp. 22–27.

[27] L. T. Berger, A. Schwager, P. Pagani, D. M. Schneider, "MIMO Power Line Communications", IEEE Communications Surveys & Tutorials, Vol. 17, No. 1, 2014, pp. 106–124.

[28] N. Sagar, "Powerline Communications Systems: Overview and Analysis", New Brunswick, New Jersey, 2011, M.Sc. Thesis

[29] N. Weling, N. Nazari, "Statistical evaluation of 55 million PLC channel and topology measurements by more than 75,000 end-users", Proceedings of the IEEE International Symposium on Power Line Communications and Its Applications, Udine, Italy, 3-6 April 2011, pp. 237–242.

[30] M.A. Sonmez, M.Bagriyanik, "Statistical model study for Narrowband Power Line Communication Noises", Proceedings of the 8th International Conference on Electrical and Electronics Engineering, Bursa, Turkey, 28-30 November 2013, pp.539–543.

[31] G. Marrocco, D. Statovci, S. Trautmann, L. A. Gmbh, A. Villach, "A PLC Broadband Channel Simulator for Indoor Communications", Proceedings of the IEEE 17th International Symposium on Power Line Communications and Its Applications, Johannesburg, South Africa, 24-27 March 2013, pp. 321–326.

[32] A. M. Nyete, T. J. O. Afullo, I. E. Davidson, "Power line noise measurements and statistical modelling in the time domain", Proceedings of PIERS, Prague, Czech Republic, July 6-9 2015, pp. 1569–1574.

[33] S. Khan, A. Salami, W. A. Lawal, Z. Alam, S. A. Hameed, M. J. Salami, "Characterization of Indoor Power lines As Data Communication Channels Experimental Details and Results", International Journal of Electronics and Communication Engineering, Vol. 2, No. 10, 2008, pp. 624–629.

[34] P. Mlynek, J. Misurec, M. Koutny, "Noise modeling for power line communication model", Proceedings of the 35th International Conference on Telecommunications and Signal Processing, Prague, Czech Republic, 3-4 July 2012, pp. 282–286.

[35] F. Aalamifar, A. Schlogl, D. Harris, L. Lampe, "Modelling power line communication using network simulator-3", Proceedings of the IEEE Global Communications Conference, Atlanta, GA, USA, 9-13 December 2013, pp. 2969–2974.

[36] P. Mlynek, M. Koutny, J. Misurec, "Multipath channel model of power lines", Elektrorevue, Vol. 1, No. 2, 2010, pp. 48–53.

[37] T. R. Oliveira, A. A. M. Picorone, S. L. Netto, M. V Ribeiro, "Characterization of Brazilian in-home power line channels for data communication", Electric Power Systems Research, Vol. 150, 2017, pp. 188–197.