



Subjective Quality Evaluation of Speech Signals Transmitted via BPL-PLC Wired System

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Abstract

The broadband over power line – power line communication (BPL-PLC) cable is resistant to electricity stoppage and partial damage of phase conductors. It maintains continuity of transmission in case of an emergency. These features make it an ideal solution for delivering data, e.g. in an underground mine environment, especially clear and easily understandable voice messages. This paper describes a subjective quality evaluation of such a system. The solution was designed and tested in real-time operating conditions. It consists of a one-way transmission system, dedicated to delivering speech signals and voice commands. The study involved signal samples in three languages: English, German, and Polish, processed at different bitrates: 8, 16, and 24 kbps. Obtained results confirmed the usefulness of BPL-PLC technology for speech transmission purposes. Even in a narrowband scenario, with bitrates smaller than 1 Mbps, it proved to be a potentially life-saving communication system. Results of this study may aid researchers and parties from the mining and oil industry, as well as professionals involved in rescue operations.

Index Terms: coding, communication applications, compression, signal processing, speech processing, quality of service

1. Introduction

Effective use of power line communication (PLC) technology, in existing common power network infrastructure of both low and high voltage, encouraged designers and users to verify its performance, also under onerous and dangerous environmental conditions. Reliable on-line data transmission is particularly important, wherever hazards for health and/or life appear. This is mainly the case in all mines, especially underground ones. Considering the fact that power cable lines are the most resistant to mechanical damage, during any crumps, after bursts and/or mine goafs, authors decided to take advantage of it.

An attempt therefore was made, both theoretically and practically, under real operating conditions of a selected copper ore underground mine. Particular attention was focused on

simultaneous use of broadband over power line (BPL) technology, as a wire medium for voice communication in medium voltage (6 kV) cable lines. For this purpose, a specially developed system, composed of a digital transmitter and receiver, was used. Of course, PLC communication should not deteriorate the transmission of electricity in the power network under any circumstances. On the other hand, deformations of current and voltage waveforms in the cable line (due to non-linear loads of the mine) should not degrade the efficiency of PLC data transmission, including voice communication as well.

Accepting this challenge required to carry out a number of laboratory tests, but most of all field tests under real working conditions [1]. It should be emphasized that from a technical point of view, meeting restrictive mine requirements, this project was not easy. The effectiveness of unidirectional voice transmission has been evaluated for two selected modes working in the 2-7.5 MHz range, labeled as MODE 1 (3-7.5 MHz) and MODE 11 (2-7 MHz). The purpose of the study was to demonstrate the usefulness of BPL-PLC technology also for reliable voice communication.

2. BPL-PLC Wired Transmission System

Although BPL-PLC technology (compared to other wire-based, e.g. fiber optic) is relatively cheap and easy to apply in power networks, its transmission quality, to be honest, is not the best. Its biggest deficiency is the sensitivity to electromagnetic interference, both conductive and inductive [2]. However, in low-voltage power networks, large disturbances in PLC transmission (narrowband frequency range 3-148 kHz) are also present, due to the so-called impedance shunting effect caused by low-power non-linear electric receivers (e.g. hair dryers, etc.) [3].

In medium voltage applications interference, caused by non-linear loads, are usually not harmful. Of course, they may increase under emergency situations (earth fault, phase break, etc.). However, the effective operation of BPL-PLC (wideband frequency range) requires appropriate matching of the transmission channel parameters (cable characteristic impedance, attenuation, frequency mode, etc.).

Furthermore, it is also necessary to use the appropriate type of coupling (inductive or capacitive) of modems with the utilized cable [4]. It should be noted that in mine shafts, only inductive couplers can be installed. However, it can be disadvantageous, when increasing the range of BPL-PLC transmission [5, 6, 7]. The frequency bands allocated to PLC networks are shown in Fig. 1.

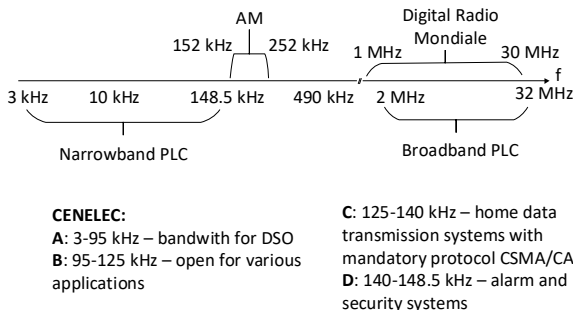


Figure 1: Frequency bands allocated to PLC networks [7].

The main advantage of the BPL (2-32 MHz) technology is the additional possibility of implementing voice communication, which is of great importance in case of any mine rescue operation. The cable can work as a transmission medium, even when being partly (mechanically) damaged. The signals are then conducted through the phase shields and cable armor. In such cases, the modems must be battery-powered. It should be noted that the BPL-PLC technology can be also useful for voice communication in urban agglomerations, where power cables are laid underground in tunnels. This enables to set a secure voice transmission, both peer-to-peer and/or master-slave, in case of a power stoppage (e.g. blackout).

3. Speech Processing and Coding

In order to provide clear and understandable voice information in the BPL-PLC wired system, one needs to know how many bits are sufficient to convey quality content. When it comes to voice transmission systems, the key issue is to provide high-quality audio services over varying bandwidth conditions and heterogeneous networks. In this case packets may be lost or delayed, which is not acceptable for real-time applications. This may cause degradation in quality, observed as either network Quality of Service (QoS) or perceived user Quality of Experience (QoE) [8].

The use of network communication imposes serious restrictions, including bandwidth limitations, associated with available bitrates. In the last two decades, many research efforts have been devoted to the problem of audio compression. Particularly, two different compression categories, namely high performance and low bitrate audio coding [9]. The first one is aimed to achieve the audio quality as high as possible at a certain bitrate. On the other hand, lossless compression always ensures the highest possible quality, in which the objective redundancy in the multimedia content is the only source of compression.

Of course, each coding algorithm has a limit for lowest acceptable bitrate. Nevertheless, this limit may be sometimes hard to determine [10]. In most cases, the higher the bitrate,

the higher the quality. However, this increase in quality does not resemble a linear scale. In every coding algorithm there is always a break point, when further increase in bitrate does not imply further raise in perceived quality [11]. This breakpoint is highly dependable on the type of transmitted content, as well as type of medium. In our case, we investigate different couplings (inductive and capacitive), transmission modes (MODE 1 and MODE 11), and speech samples (English, German, and Polish).

4. Related Work

In a recent study [12], researchers investigated the audio quality of speech and music signals, including mono and stereo, using the Perceptual Evaluation of Audio Quality (PEAQ) algorithm. In this case, audio samples were processed using 2 codecs at different bitrates, from 24 to 320 kbps. Their analysis showed a break point for each codec, where objective scores did not raise significantly with increasing bitrate.

In [13] authors investigated the impact of different audio codecs, including Ogg Vorbis. The bitrate ranged from 24 to 320 kbps, depending on the particular codec. Studies involved both subjective and objective metrics, including Perceptual Evaluation of Audio Quality (PEAQ) and Perceptual Objective Listening Quality Assessment (POLQA) algorithms. The study provides a good introduction to currently utilized commercial services, including pros and cons of different coding algorithms.

After a careful examination, authors did not encounter other scientific publications regarding the utilization of BPL-PLC technology for transmitting additional data services, e.g. audio or audio-video signals, particularly for communication purposes. That is why this investigation was carried out.

5. About the Study

The main aim of the study was to determine the feasibility of utilizing a given BPL-PLC line for voice communication services. In this scenario, the wired medium was located in an underground mine environment, operating in real-time conditions. In this case, we have selected a 3-phase cable, about 300 m long, located in the mine shaft headroom. This cable was a part of the tested medium voltage radial network of 6 kV, its total length was equal to approx. 1300 m. This study is a direct continuation of previous work described in [14, 15].

5.1. Environment and test conditions

In order to simulate an emergency situation, the tested cable, shown in Fig. 2, was disconnected from the power supply and shorted as well as earthed at both ends. A specially developed digital transmitter and receiver were connected respectively to BPL-PLC modems.

The best quality of BPL-PLC transmission was obtained within the frequency range of 2-7.5 MHz. That is why we have selected two different transmission modes, namely MODE 1 (3-7.5 MHz) and MODE 11 (2-7 MHz). However, it should be emphasized that the BPL-PLC transmission is asymmetrical, showing different values of both capacity (bitrate) and signal-to-noise ratio (SNR), as well as channel frequency response (CFR) factors, for different transmission directions (either from point A to B, or vice versa). In this case, the measured capacity from point B to A, related with the transmission of speech signal samples, was equal to approx. 27 Mbps.



Figure 2: Tested wired medium in an underground mine shaft.

5.2. Signal samples

The tested speech samples were sourced from ITU-T P.501 [16]. In this recommendation, available signal samples consist of two sentences spoken by two female and two male individuals, in different languages. Due to the international character of the oil and mining industry, we have selected samples from 4 sets, namely: American English (AE), British English (EN), German (GE), and Polish (PL).

The original signal samples were available in the WAV 16-bit PCM format, with sampling frequency set to 32 kHz. Next, each sample was coded using the Ogg Vorbis format. The degraded signal samples were processed and then transmitted through the wired medium at 3 bitrates: 8, 16, and 24 kbps, whereas the sampling frequency was changed to 44.1 kHz. All transmitted signal samples were recorded at the end for further processing and evaluation purposes, namely a subjective quality assessment study. Previous studies, including

preliminary ones, shown that further raising the bitrate did not relate with higher grades. That is why the threshold of 24 kbps was considered as a breakpoint for this codec. Additional information on signal processing, especially low bitrate audio coding, may be found in [17, 18, 19, 20].

5.3. Listeners and listening equipment

When it comes to the background of tested individuals, namely a group of 16 people aged between 25-35 years old, it is worth mentioning that for each one Polish was the mother tongue, whereas both English and German were the second language of choice (advanced language skills without a significant difference). Of course none of them had hearing disorders.

The subjective assessment was carried out using Beyerdynamic Custom One headphones in a 5-step Mean Opinion Score (MOS) Absolute Category Rating (ACR) scale, with no reference, ranging from 1 (bad quality) to 5 (excellent quality). Each individual evaluated the quality individually, one by one, according to [21]. The speech samples were presented in a randomized way, separated by a 1 s interval. Of course listeners were not informed about the bitrate of the current sample, labeled as either female or male lector. Furthermore, every person took a training phase before starting the essential test, in order to acquaint with the aim of the study and become familiar with the listening equipment.

Moreover, during the training phase, participants pointed out that sentences spoken by a male lector seemed more appealing. In our case, due to the profile of the mining industry, this feedback becomes an important factor.

6. Results

In this test, the goal was to investigate how does a BPL-PLC cable operate, when it comes to providing voice services. How does the type of coupling, transmission mode, as well as varying bandwidth conditions, affect the perceived speech quality.

The results of the subjective quality evaluation, including both types of coupling (inductive and capacitive) as well as transmission modes (MODE 1 within 3-7.5 MHz and MODE 11 within 2-7 MHz) of the cable network, are shown in Figs. 3-10. Grades for inductive coupling are shown in Figs. 3-6, whereas those for capacitive coupling in Figs. 7-10.

Obtained data were processed using the Analysis of Variance (ANOVA) statistical method. The confidence intervals were set to 95% ($\alpha = 0.05$). The dispersion was less than 10%. Additional information on improving the quality of acoustic signals in the presence of noise, interference, etc., are available in [22, 23, 24].

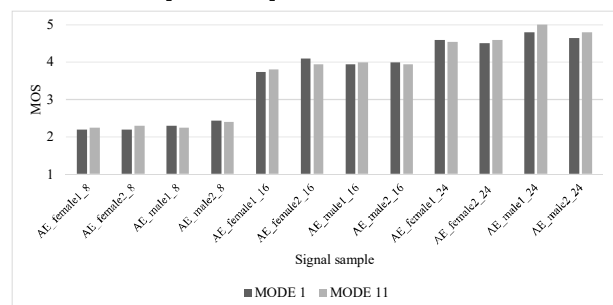


Figure 3: Inductive coupling – speech signals in American English.

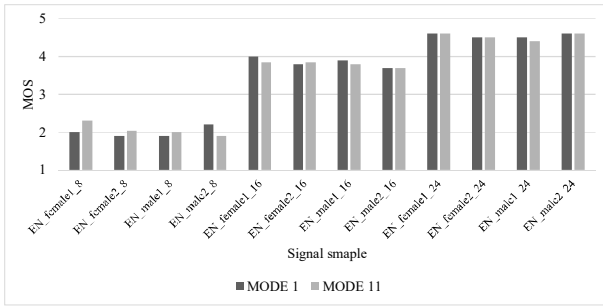


Figure 4: Inductive coupling – speech signals in British English.

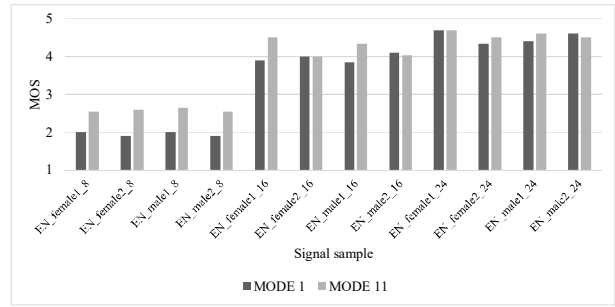


Figure 8: Capacitive coupling – speech signals in British English.

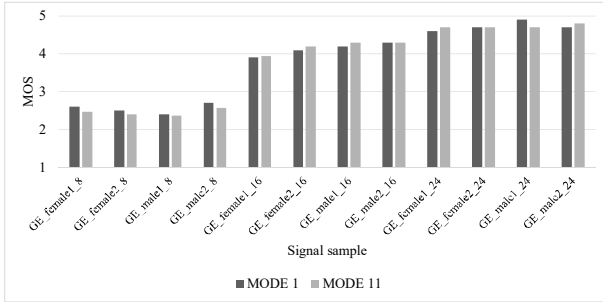


Figure 5: Inductive coupling – speech signals in German.

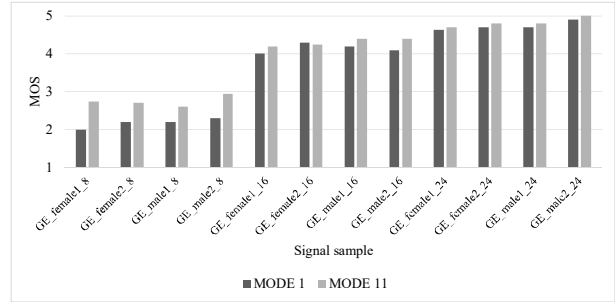


Figure 9: Capacitive coupling – speech signals in German.

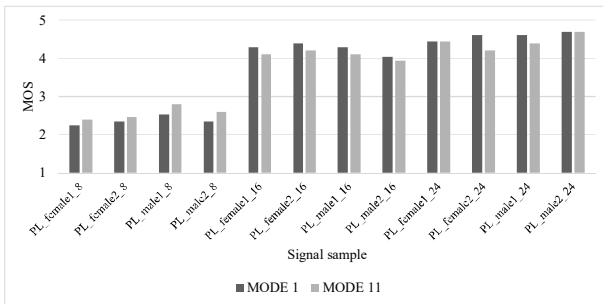


Figure 6: Inductive coupling – speech signals in Polish.

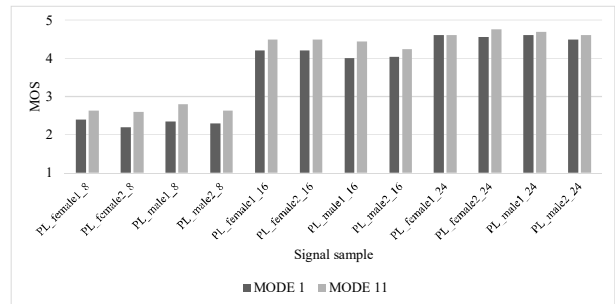


Figure 10: Capacitive coupling – speech signals in Polish.

As shown, the lowest bitrate equal to 8 kbps proved to be insufficient when it comes to delivering clear and understandable voice messages. The medium bitrate of 16 kbps was ranked evidently better. Nevertheless, not all samples were perceived as of high quality. In case of the highest bitrate of 24 kbps, all voice messages, whether spoken by a male or female lector, were clear and easily understandable.

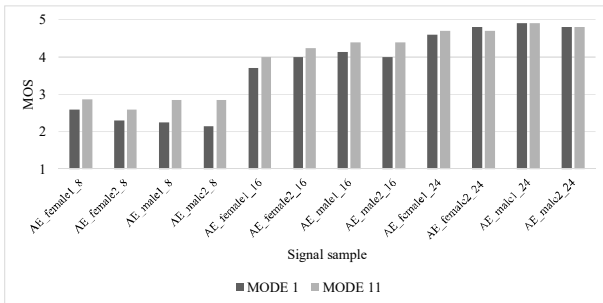


Figure 7: Capacitive coupling – speech signals in American English.

7. Conclusions

As shown, the BPL-PLC wired medium, thanks to its high resistance to mechanical damage and other physical properties, can provide a reliable voice transmission system. This technology, even in a narrowband scenario (bitrates of less than 1 Mbps), e.g. caused by bandwidth limitations, severe damage, etc., ensures a stable and reliable connection. Whenever an emergency situation occurs, voice commands, i.e. from a supervisor or paramedic, can help provide instructions and ease during any rescue operation.

Furthermore, according to obtained results, sentences spoken by a male lector were ranked most often higher. Moreover, transmission MODE 11 proved to be superior compared to MODE 1, resulting in higher MOS scores. This becomes an important feedback, as similar results were formulated regardless of the type of coupling. Outcomes of carried out work may be of aid for parties related with the mining and oil industry, as well as researchers and professionals active in the aforementioned and related fields of study.

8. References

- [1] D. Pyda, M. Habrych, K. Rutecki, and B. Miedzinski, "Analysis of Narrow Band PLC Technology Performance in Low-Voltage Network," *Elektronika ir Elektrotechnika*, vol. 20, no. 5, pp. 61–64, 2014.
- [2] P. Mlynek, J. Misurec, and M. Koutny, "Modeling and Evaluation of Power Line for Smart Grid Communication," *Przeglad Elektrotechniczny*, vol. 87, no. 8, pp. 228–232, 2011.
- [3] H. Meng, S. Chen, Y. L. Guan, C. L. Law, P. L. So, E. Gunawan, and T. T. Lie, "Modeling of Transfer Characteristics for the Broadband Power Line Communication Channel," *IEEE Transactions on Power Delivery*, vol. 19, no. 3, pp. 1057–1064, 2004.
- [4] L. Lampe, A. M. Tonell, and T. G. Swart, *Power Line Communications: Principles, Standards and Applications from Multimedia to Smart Grid*, Chichester: John Wiley & Sons, 2016.
- [5] X. Carcell, *Power Line Communications in Practice*, London: Artec House, 2006.
- [6] M. Habrych and M. Wasowski, "Analysis of the Transmission Capacity of Various PLC Systems Working in the Same Network," *Przeglad Elektrotechniczny*, vol. 94, no. 11, pp. 130–134, 2018.
- [7] CENELEC EN 50065-1, *Signalling on Low-Voltage Electrical Installations in the Frequency Range 3 kHz to 148.5 kHz – Part 1: General Requirements, Frequency Bands and Electromagnetic Disturbances*, 2011.
- [8] P. Gilski and J. Stefanski, "Subjective and Objective Comparative Study of DAB+ Broadcast System," *Archives of Acoustics*, vol. 42, no. 1, pp. 3–11, 2017.
- [9] M. Yang, "Low Bit Rate Speech Coding," *IEEE Potentials*, vol. 23, no. 4, pp. 32–36, 2004.
- [10] S. Brachmanski, "Quality Evaluation of Speech AAC and HE-AAC Coding," in *Joint Conference – Acoustics 2018, September 11-14, Ustka, Poland, Proceedings*, 2018, pp. 1–6.
- [11] P. Falkowski-Gilski, "Transmitting Alarm Information in DAB+ Broadcasting System," in *SPA 2018 – Signal Processing: Algorithms, Architectures, Arrangements, and Applications, September 19-21, Poznan, Poland, Proceedings*, 2018, pp. 217–222.
- [12] K. Ulovec and M. Smutny, "Perceived Audio Quality Analysis in Digital Audio Broadcasting plus System Based on PEAQ," *Radioengineering*, vol. 27, no. 1, pp. 342–352, 2018.
- [13] P. Pošta and J. G. Beerends, "Subjective and Objective Assessment of Perceived Audio Quality of Current Digital Audio Broadcasting Systems and Web-Casting Applications," *IEEE Transactions on Broadcasting*, vol. 61, no. 3, pp. 407–415, 2015.
- [14] G. Debita, M. Habrych, A. Tomczyk, B. Miedzinski, and J. Wandzio, "Implementing BPL Transmission in MV Cable Network Effectively," *Elektronika ir Elektrotechnika*, vol. 25, no. 1, pp. 59–65, 2019.
- [15] G. Debita, P. Falkowski-Gilski, M. Habrych, B. Miedzinski, J. Wandzio, and P. Jedlikowski, "Quality Evaluation of Voice Transmission Using BPL Communication System in MV Mine Cable Network," *Elektronika ir Elektrotechnika*, vol. 25, no. 5, pp. 43–46, 2019.
- [16] ITU-T P.501, *Test Signals for Telecommunication Systems*, 2017.
- [17] T. Li, S. Rahardja, and S. N. Koh, "Fixed Quality Layered Audio Based on Scalable Lossless Coding," *IEEE Transactions on Multimedia*, vol. 11, no. 3, pp. 422–432, 2009.
- [18] A. Griffin, T. Hirvonen, C. Tzagkarakis, A. Mouchtaris, and P. Tsakalides, "Single-Channel and Multi-Channel Sinusoidal Audio Coding Using Compressed Sensing," *IEEE Transactions on Audio, Speech, and Language Processing*, vol. 19, no. 5, pp. 1382–1395, 2011.
- [19] C. R. Helmrich, G. Markovic, and B. Edler, "Improved Low-Delay MDCT-Based Coding of Both Stationary and Transient Audio Signals," in *ICASSP 2014 – IEEE International Conference on Acoustic, Speech and Signal Processing, May 4-9, Florence, Italy, Proceedings*, 2014, pp. 6954–6958.
- [20] J. Lin, W. Min, Y. Shengyu, G. Ying, and X. Mangan, "Adaptive Bandwidth Extension of Low Bitrate Compressed Audio Based on Spectral Correlation," in *ICICTA 2015 – International Conference on Intelligent Computation Technology and Automation, June 14-15, Nanchang, China, Proceedings*, 2015, pp. 113–117.
- [21] ITU-R BS.1284, *General Methods for the Subjective Assessment of Sound Quality*, 2003.
- [22] J. Kotus, M. Szczodrak, A. Czyzewski, and B. Kostek, "Distributed System for Noise Threat Evaluation Based on Psychoacoustic Measurements," *Metrology and Measurement Systems*, vol. 19, no. 2, pp. 219–230, 2012.
- [23] K. Marciniuk, M. Szczodrak, and B. Kostek, "Performance of Noise Map Service Working in Cloud Computing Environment," *Archives of Acoustics*, vol. 41, no. 2, pp. 297–302, 2016.
- [24] B. Kostek and K. Kakol, "Improving the Quality of Speech in the Conditions of Noise and Interference," *Journal of the Acoustical Society of America*, vol. 144, no. 3, pp. 1905–1905, 2018.