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Research Paper

Quality Evaluation of Speech Transmission via Two-way BPL-PLC Voice Communication System in an Underground Mine

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In order to design a stable and reliable voice communication system, it is essential to know how many resources are necessary for conveying quality content. These parameters may include objective quality of service (QoS) metrics, such as: available bandwidth, bit error rate (BER), delay, latency as well as subjective quality of experience (QoE) related to user expectations. QoE is expressed as clarity of speech and the ability to interpret voice commands with adequate mean opinion score (MOS) grades. This paper describes a quality evaluation study of a two-way speech transmission system via bandwidth over power line – power line communication (BPL-PLC) technology in an operating underground mine. We investigate how different features of the available wired medium can affect end-user quality. The results of the described study include: two types of coupling (capacitive and inductive), two transmission modes (mode 1 and 11), and four language sets of speech samples (American English, British English, German, and Polish) encoded at three different bit rates (8, 16, and 24 kbps). Our findings can aid both researchers working on low-bit rate coding and compression, signal processing and speech perception, as well as professionals active in the mining and oil industry.

Keywords: coding; communication applications; compression; signal processing; speech processing; quality of service.

1. Introduction

The applicability of electric power networks for efficient data transmission has gained interest from both designers and users. This applies especially to all kinds of local area networks (LANs) employed in general plant communication systems. However, it should be emphasized that power line communication (PLC) technology does not provide such high-quality services as traditional wired and wireless transmission, including copper and optic fibers, or ZigBee. Nevertheless, in many applications, PLC technology is quite sufficient. Evidence of this fact may be found in the increasing development of the so-called smart grids and industrial automation (Morello *et al.*, 2017; Ding *et al.*, 2021; Hao, Zhang, 2021).

One has to know that the main drawback of PLC transmission is its sensitivity to both conducted and induced electromagnetic interference (EMI) (Bernacki *et al.*, 2019). This problem is of great importance, particularly in low-voltage networks. In this case, a bridging of the transmitted signals can occur due to impedances close in frequency to the range and values of PLC signals of randomly connected electrical receivers (Held, 2016).

The main advantage of this technology is its ability of utilizing existing power grids, both low and high voltage. This approach does not incur additional investment costs or operator fees. Authors who are experienced with the challenges of creating secure and reliable communication systems, including mine operation, have identified the positive effects of using bandwidth over power line – power line communication (BPL-PLC) technology for data transmission. However, this requires a careful selection of many technical factors, including: signal frequency, type of coupling, and matching the characteristic impedance of the transmission medium (usually medium voltage cables).

The use of high frequency, in the range from 2 to 32 MHz, offers the opportunity to increase the speed of information transfer up to about 200 Mbps. This bit rate is about 1000 times faster compared to narrowband transmission (Debita *et al.*, 2019). Satisfactory field test results, under real-time mine operational conditions, encouraged the authors to utilize the BPL-PLC technology in middle voltage cable lines for voice transmission purposes.

It should be emphasized that safe working conditions, present in the mining and oil industry, particularly in underground environments, require an appropriate and reliable communication system. Such an exemplary environment is shown in Fig. 1.

Fig. 1. Exemplary underground mine environment.

Therefore, various wired and wireless loudspeaker and emergency communication systems are widely used. For example, a plant-wide telephone system can be connected to a radio communication system using the so-called radiating cable (Miśkiewicz, Wojaczek, 2016). The voice over Internet protocol (VoIP) telephony, which is becoming increasingly popular in mines, uses packet commutation network just like PLC.

The packet header contains data for both source and destination addresses. Thus, voice packets, in a digital form, are sent to the target device without using telephone exchanges with a switching field. It is obvious that the mine's technical environment significantly affects the efficiency of data transmission. Damage to pavements during mine failures usually results in interruptions of any wired system and significant degradation of wireless communication (Miśkiewicz, Wojaczek, 2010).

In medium-voltage BPL-PLC technology, the transmission medium is the armored power cable itself. This theoretically makes it the most resistant to mechanical damage, ensuring continuity of transmission through both phase conductors as well as shields and armor. Therefore, in the case of pavement backfilling, BPL-PLC transmission, with battery powered modems, can serve as a last resort, significantly improving rescue operations. Considering the above, the authors conducted a series of simulations and field-test experiments. The obtained results enabled for both objective and subjective evaluation of a custom-build two-way voice transmission system via medium-voltage cable lines using BPL-PLC technology.

2. Related work

Počta and Beerends (2015) investigated a set of audio codecs, including Ogg Vorbis, with bit rates ranging from 24 to 320 kbps. Their tests included subjective and objective metrics, with perceptual evaluation of audio quality (PEAQ) and perceptual objective listening quality assessment (POLQA) methods. Their paper is a valuable source of information concerning various commercial services available in terrestrial and online networks. Since modern-day users prefer mobile devices, particularly when consuming content via online streaming services (Falkowski-Gilski, 2020), with Spotify using the Ogg Vorbis format, Počta and Beerends' research becomes a major feedback for our upcoming studies.

Another study (Fuchs *et al.*, 2019) focused on improving the quality of speech coders by expanding the frequency range (from narrowband to wideband). The authors evaluated their model using both subjective and objective methods, on a set of signal samples including male and female speakers in three languages: French, German, and English. The speech samples were processed at 24 kbps, with sampling frequency set at 32 kHz. The subjective study, in a 100-step multiple stimuli with hidden reference and anchor (MUSHRA) scale, involved a group of 10 listeners. Whereas, the objective part was carried out utilizing the POLQA metric.

The topic of speech recognition, including end-to-end automatic solutions, as well as numerous simultaneous speakers, is discussed in (Meng *et al.*, 2019; Dubey *et al.*, 2019; Delcroix *et al.*, 2019). Whereas, more information on annotating speech data, including massive big data sets, may be found in (Fallgren *et al.*, 2019; Kostek, 2019). Matters related to audio signal processing, including low bit rate and perceptual coding, is available in (Helmrich *et al.*, 2014).

Similar solutions, together with noise classification and mapping applications (Kotus *et al.*, 2012; Szczodrak *et al.*, 2014; Marciniuk, Kostek, 2015), may be of great importance and aid for any voice communication system, particularly in the mining and oil industry.

It is evident that the topic of digital signal coding and compression, quality evaluation including both QoS and QoE aspects, as well as the design and maintenance of stable and reliable multimedia content distribution and communication services, continue to be extensively discussed topic (Gibson *et al.*, 1998; Möller, Raake, 2014; Hossfeld *et al.*, 2014; Boz *et al.*, 2019; Falkowski-Gilski, Uhl, 2020).

3. Tested BPL-PLC system

In order to conduct research on the effectiveness of voice transmission via a BPL-PLC system, the authors selected a segment of a medium-voltage 6 kV cable line, about 300 m long, located in a tunnel in one of the operating mines in Southern Poland. The entire transmission channel was composed of a radial line (over 2 km long), connecting the switchgear at the top of the shaft with the switchgear at the bottom of the shaft.

Thanks to accessible busbars in the switchgears, it was possible to examine both inductive and capacitive coupling of modems with the cable. The digital transmitter and receiver, designed and developed by the authors, were first simulated in the Matlab-Octave environment. The block diagram of the evaluated system is shown in Fig. 2.

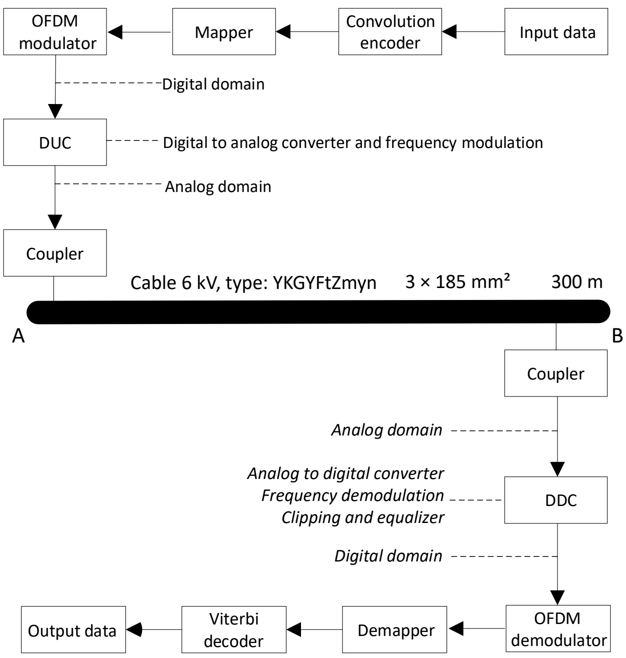

Fig. 2. Block diagram of the tested PLC-BPL speech communication system.

Next, the possibilities and limitations associated with the tested wired medium were examined in an objective QoS and subjective QoE studies.

4. QoS evaluation

According to the 3rd Generation Partnership Project (2011), digital communication services can be divided into two groups, namely: guaranteed bit rate (GBR) and non-guaranteed bit rate (Non-GBR), each with different QoS class identifier (QCI) requirements. Table 1 describes the main communication services with their requirements, including delay and error rate.

Table 1. Main communication services with their QoS requirements.

QCI	Type	Delay [ms]	Error rate	Service
1	GBR	100	10^{-2}	Conversational voice (real-time)
2		150	10^{-3}	Conversational video (live streaming)
3		50	10^{-3}	Online gaming (real-time)
4		300	10^{-6}	Non-conversational voice (buffered streaming)
5	Non-GBR	100	10^{-6}	IMS signaling
6		300	10^{-6}	Video (buffered streaming), TCP-based (e-mail, chat)
7		100	10^{-3}	Voice, video (live streaming), Interactive gaming
8–9		300	10^{-6}	Video (buffered streaming), TCP-based (e-mail, chat)

As shown, the GBR variant is linked with QCI from 1–4, whereas Non-GBR is related with QCI from 5–9. Our study focuses on voice (speech) communication. In the GBR variant, such services require delays ranging from approximately 100 ms (conversational voice) to 300 ms (non-conversational voice). For the Non-GBR variant, the required delay should be smaller than 100 ms. Regarding error rate, it should oscillate around 10^{-2} or 10^{-3} up to 10^{-6}. The results of our analysis, considering the tested wired medium, are shown in Fig. 3.

When examining obtained results for both transmission modes (mode 1: 3–7.5 MHz and mode 11: 2–7 MHz), IC refers to inductive coupling, whereas CC represents capacitive coupling. It was found that the error rate ranges from 10^{-2} to 10^{-3}, which is adequate for voice communication services. The results for jitter (time delay between packets) at various data packet sizes, during a 10 min interval, along with available

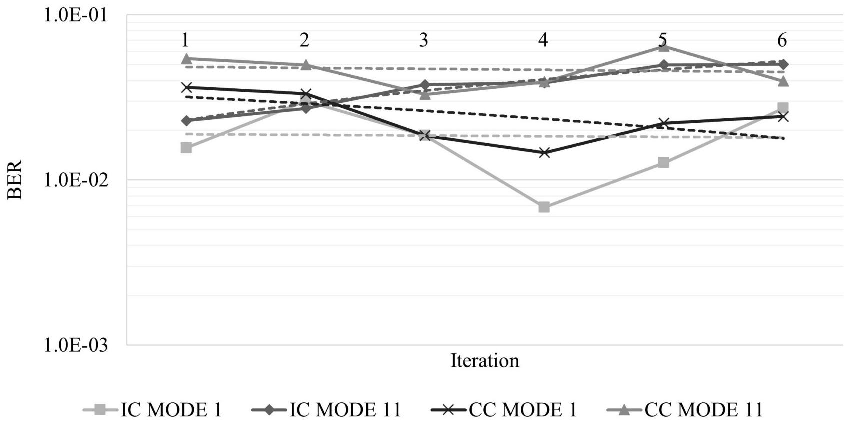

Fig. 3. Simulated BER for inductive coupling (IC) and capacitive coupling (CC) in both transmission modes (1 and 11).

bandwidth and as well as the number of retransmitted packets, are described in Table 2.

Table 2. Simulation results for both inductive and capacitive coupling.

Data packet size [B]	Jitter [ms]	Bandwidth [Mbps]	No. of retransmitted packets
187	0.011	9.85	585
375	0.085	14.8	545
750	0.367	18.0	787
1500	0.857	18.9	1696

As observed, the jitter is very low, and less than 1 ms, regardless of the size of the utilized data packet, which proves it suitable for speech communication services. When it comes to available bandwidth, the range of approximately 10–19 Mbps is more than sufficient for implementing a simultaneous two-way voice transmission system. However, the number of retransmitted packets tends to increase with the larger data packet sizes. Based on obtained results and aiming for the best balance between factors such as size of a data packet, jitter, bandwidth and the number of retransmitted packets, the subjective QoE evaluation part, considering a fully-deployed custom-build system, was carried out for a data packet size of 375 B.

5. QoE evaluation

In order to evaluate QoE requirements for the designed solution, we transmitted a set of speech signal samples. These samples were sourced from ITU-T P.501 (International Telecommunication Union [ITU], 2017) and included sentences spoken by two female and two male individuals, in different languages. Bearing in mind the international profile of the oil and mining industry, four language sets were selected, namely: English in both American (AE) and British (EN) dialects, as well as German (GE) and Polish (PL).

The original samples were available in WAV format (16-bit PCM), with a sampling frequency of 32 kHz. Next, each sample was processed using the Ogg Vorbis codec and was then transmitted through the BPL-PLC wired medium at different bit rates: 8, 16, and 24 kbps. A sampling frequency was set to 44.1 kHz. Previous studies (Debita *et al.*, 2020; Falkowski-Gilski *et al.* 2020; Zamłynska *et al.*, 2022) have shown that a bit rate of 24 kbps was sufficient to deliver quality voice commands using this codec.

The transmission system was established in both directions (from point A to B and vice versa) using a set of custom Linux-based modems designed for the purpose of this test. We selected the Ogg Vorbis format (King *et al.*, 2012; Korycki, 2012) in order to have as much control as possible. This format offers full-compatibility with the Linux operating system, which powered both our transmitters and receivers. The transmitted signal samples were recorded at both ends for further processing purposes, namely for a subjective quality evaluation study.

The subjective study was carried out on a group of 16 participants, all of whom were native Polish speakers aged between 25–35 years old. As pointed out in a preliminary questionnaire, each person declared having advanced language skills in both English and German. This involved either possessing an appropriate certificate or being engaged in works with international client-related work. None of the participating individuals had hearing impairments. Each participant assessed the audio quality individually, following the ITU (2003) recommendation in turns (one by one), using Beyerdynamic Custom One headphones. Participants were asked to provide ratings on a 5-step mean opinion score (MOS) scale, with no reference signal available, with options ranging from 1 (poor quality) to 5 (excellent quality). The results of this test, averaged for both directions (from point A to point B and vice versa), including two transmission modes (mode 1 and 11), three bit rates (8, 16, and 24 kbps), as well as two types of coupling (inductive or capacitive), are shown in Figs. 4–9.

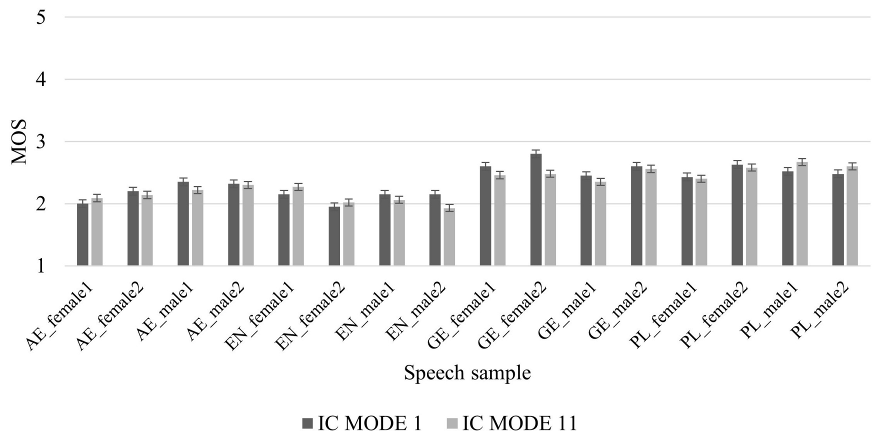

Fig. 4. IC – signal samples processed at 8 kbps.

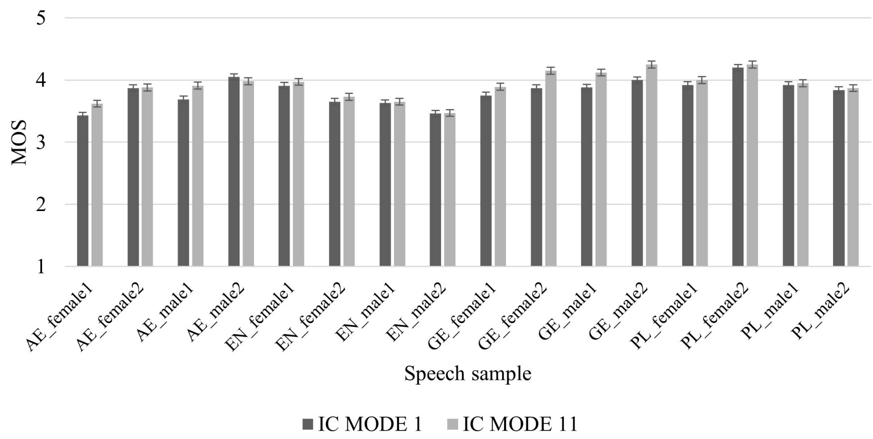

Fig. 5. IC – signal samples processed at 16 kbps.

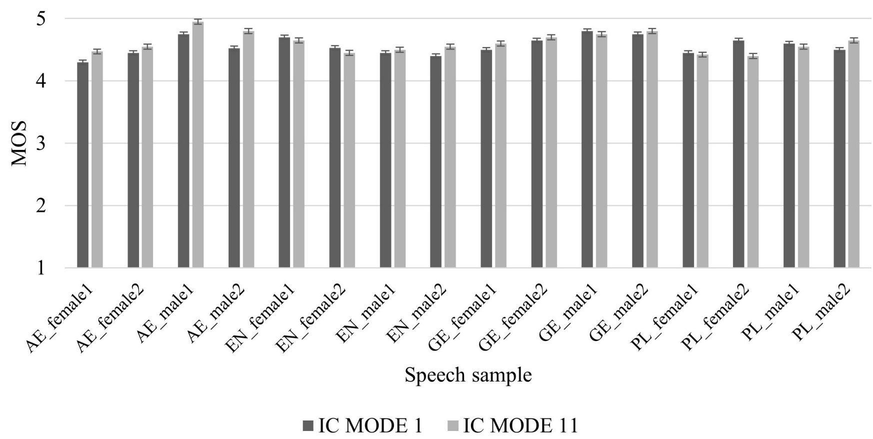

Fig. 6. IC – signal samples processed at 24 kbps.

All the obtained results were processed using the analysis of variance (ANOVA) statistical method, with confidence intervals set at 95% ($\alpha = 0.05$). The dispersion was less than 10%. Results related with inductive coupling (IC) are shown in Figs. 4–6, while those for capacitive coupling (CC) are presented in Figs. 7–9.

A single session took approximately 25 minutes, with a short break in the middle of the study. Before starting the main test, each person underwent a training phase to adjust the volume and become familiar with the listening equipment. Further information on loudness and related topics may be found in (Kostek *et al.*, 2016; Maijala *et al.*, 2018; Une, Miyazaki, 2020).

The obtained results have shown whether theoretical objective simulations, as well as field-test measurements, can be used to adequately predict and evaluate the subjective quality of this speech communication system during both the design and maintenance phases.

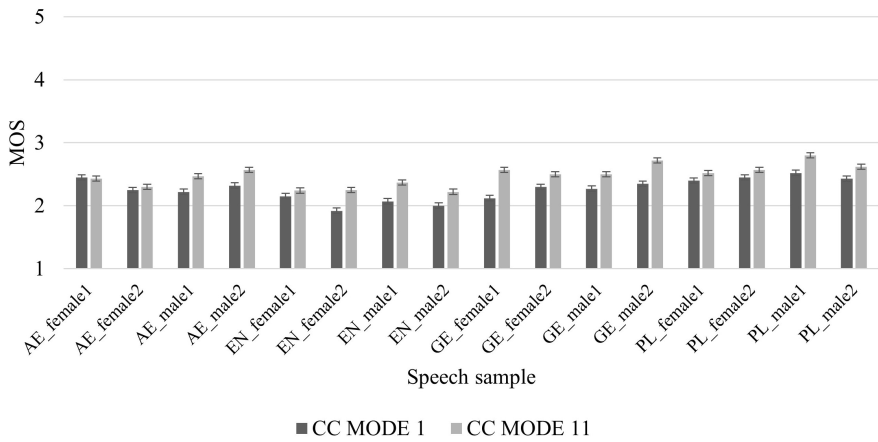

Fig. 7. CC – signal samples processed at 8 kbps.

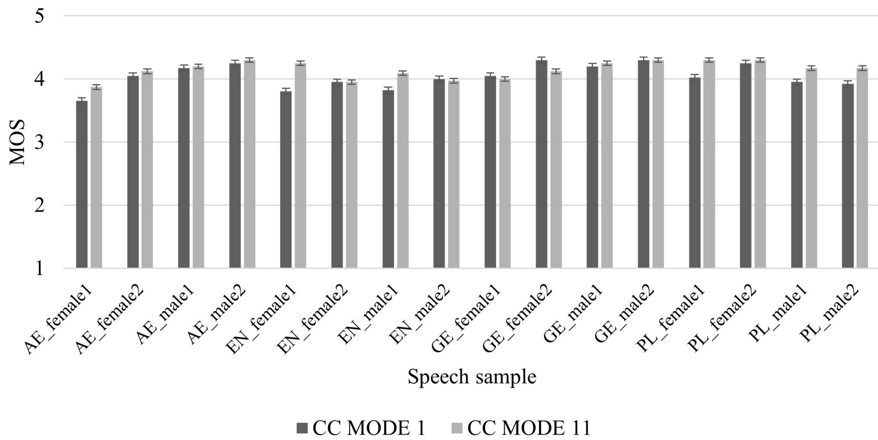

Fig. 8. CC – signal samples processed at 16 kbps.

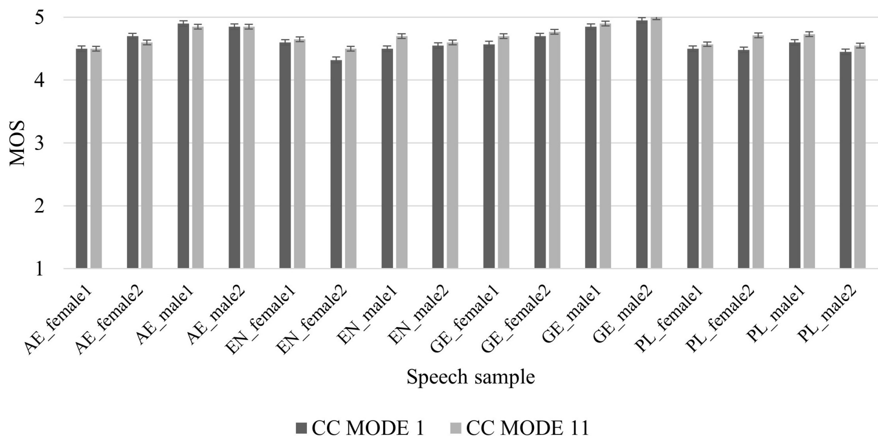

Fig. 9. CC – signal samples processed at 24 kbps.

As shown, the type of coupling, as well as transmission mode, has an observable effect on the end user quality. According to the obtained results, the lowest bit rate (8 kbps) proved to be insufficient to the extent that some individuals perceived these signals as simply annoying. On the other hand, the medium bit rate (16 kbps) was clearly ranked higher. However, not all samples were considered as acceptable. For the highest bit rate (24 kbps), all voice messages, regardless of the speaker, delivered clear and easily understandable commands.

6. Conclusions

As shown, the BPL-PLC wired system can be effectively used for various data transmission purposes, especially additional and/or supplementary voice communication. This fact becomes crucial in case of emergency situations, such as mine disasters. Since wired cable networks are very resistant to mechanical damage, the BPL-PLC technology, speech signal processing devices and voice communication terminals, together with battery-powered modems, could be implemented, regardless of electrical operating conditions.

This analysis has demonstrated that speech signals transmitted at 24 kbps are sufficient from a practical point of view. Lower bit rates, namely 8 and 16 kbps, did not provide clear and unambiguous statements. Generally speaking, regardless of the evaluated language and/or dialect (AE, EN, GE, PL) as well as the lector's gender (male or female), the level of 24 kbps may be considered as a break point necessary for conveying high-quality speech signal content. Similar results were obtained when changing the type of coupling and/or mode.

Furthermore, the displayed results clearly show the superiority of transmission mode 11 (2–7 MHz) over mode 1 (3–7.5 MHz). Additionally, CC most often provided higher MOS grades than IC. These remarks, observed regardless of the utilized bit rate, are particularly important for engineers responsible for designing and maintaining energy grids and related wired infrastructure.

The outcomes of this work provide practical insights for stakeholders in the mining and oil industry, not to mention researchers and professionals active in related fields. The obtained results may be of particular aid to researchers involved in the design and maintenance of a supplementary voice communication services in harsh environments, such as underground mines. They may be an interesting source of inspiration for engineers in other parts of the world as well. Future studies should consider, e.g., different types of dedicated wired media, a broader range of signal samples, and test scenarios involving listeners from various age groups and backgrounds.

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References

1. 3rd Generation Partnership Project [3GPP] (2011), *Policy and charging control architecture*, Technical specification group services and system aspects, 3GPP Technical Specification 23.203, https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=810, access: 21.06.2023.
2. Bernacki K., Wybrańczyk D., Zygmanowski M., Latko A., Michalak J., Rymarski Z. (2019), Disturbance and signal filter for power line communication, *Electronics*, **8**(4): 378, doi: 10.3390/electronics8040378.
3. Boz E., Finley B., Oulasvirta A., Kilkki K., Manner J. (2019), Mobile QoE prediction in the field, *Pervasive and Mobile Computing*, **59**: 101039, doi: 10.1016/j.pmcj.2019.101039.
4. Debita G. *et al.* (2020), Subjective and objective quality evaluation study of BPL-PLC wired medium, *Elektronika ir Elektrotechnika*, **26**(3): 13–19, doi: 10.5755/j01.eie.26.3.25794.
5. Debita G., Habrych M., Tomczyk A., Miedziński B., Wandzio J. (2019), Implementing BPL transmission in MV cable network effectively, *Elektronika ir Elektrotechnika*, **25**(1): 59–65, doi: 10.5755/j01.eie.25.1.22737.
6. Delcroix M. *et al.* (2019), End-to-end SpeakerBeam for single channel target speech recognition, [in:] *INTERSPEECH 2019 – 21th Annual Conference of the International Speech Communication Association*, pp. 451–455, doi: 10.21437/Interspeech.2019-1856.
7. Ding S.Y., Liu J.L., Yue M.H. (2021), The use of ZigBee wireless communication technology in industrial automation control, *Wireless Communications and Mobile Computing*, **2021**: 8317862, doi: 10.1155/2021/8317862.
8. Dubey H., Sangwan A., Hansen J.H.L. (2019), Toeplitz inverse covariance based robust speaker clustering for naturalistic audio streams, [in:] *INTERSPEECH 2019 – 21th Annual Conference of the International Speech Communication Association*, pp. 416–420, doi: 10.21437/Interspeech.2019-1102.
9. Falkowski-Gilski P. *et al.* (2020), Subjective quality evaluation of speech signals transmitted via BPL-PLC wired system, [in:] *INTERSPEECH 2020 – 22th Annual Conference of the International Speech Communication Association*, pp. 4601–4605, doi: 10.21437/Interspeech.2020-1077.
10. Falkowski-Gilski P., Uhl T. (2020), Current trends in consumption of multimedia content using online streaming platforms: A user-centric survey, *Computer Science Review*, **37**(4): 100268, doi: 10.1016/j.cosrev.2020.100268.
11. Falkowski-Gilski P. (2020), On the consumption of multimedia content using mobile devices: a year to year user case study, *Archives of Acoustics*, **45**(2): 321–328, doi: 10.24425/aoa.2020.133152.
12. Fallgren P., Malisz Z., Edlund J. (2019), How to annotate 100 hours in 45 minutes, [in:] *INTERSPEECH 2019 – 21th Annual Conference of the International Speech Communication Association*, pp. 341–345, doi: 10.21437/Interspeech.2019-1648.
13. Fuchs G., Ashour C., Bäckström T. (2019), Superwideband spectral envelope modeling for speech coding, [in:] *INTERSPEECH 2019 – 21th Annual Conference of the International Speech Communication Association*, pp. 416–420, doi: 10.21437/Interspeech.2019-1620.

14. Gibson J.D., Berger T., Lookabaugh T., Lindbergh D., Baker R.L. (1998), *Digital Compression for Multimedia: Principles and Standards*, Morgan Kaufmann, San Francisco.

15. Hao S., Zhang H.Y. (2021), A cross-layered theoretical model of IEEE 1901 power-line communication networks considering retransmission protocols, *IEEE Access*, **9**: 28805–28821, doi: 10.1109/ACCESS.2021.3059246.

16. Held G. (2016), *Understanding Broadband Over Power Line*, Auerbach Publications.

17. Helmrich C.R., Marković G., Edler B. (2014), 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*, pp. 6954–6958, doi: 10.1109/ICASSP.2014.6854948.

18. Hoßfeld T. *et al.* (2014), Best practices for QoE crowdtesting: QoE assessment with crowdsourcing, *IEEE Transactions on Multimedia*, **16**(2): 541–558, doi: 10.1109/TMM.2013.2291663.

19. International Telecommunication Union [ITU] (2003), *General methods for the subjective assessment of sound quality*, ITU Recommendation BS.1284, https://www.itu.int/rec/R-REC-BS.1284/en, access: 21.06.2023.

20. International Telecommunication Union [ITU] (2017), *Test signals for telecommunication systems*, ITU Recommendation P.501, https://www.itu.int/ITU-T/recommendations/rec.aspx?id=14271, access: 21.06.2023.

21. King M., Nirav D., Arvind A. (2012), Automatic generation of hardware/software interfaces, [in:] *Association for Computing Machinery*, **47**(4): 325–336, doi: 10.1145/2248487.2151011.

22. Korycki R. (2012), Detection of tampering in lossy compressed digital audio recordings, [in:] *NTAV/SPA 2012 – New Trends in Audio and Video/Signal Processing: Algorithms, Architectures, Arrangements and Applications*, pp. 97–101.

23. Kostek B. (2019), Music information retrieval – The impact of technology, crowdsourcing, big data, and the cloud in art, *Journal of the Acoustical Society of America*, **146**(4): 2946, doi: 10.1121/1.5137234.

24. Kostek B., Odya P., Suchomski P. (2016), Loudness scaling test based on categorical perception, *Archives of Acoustics*, **41**(4): 637–648, doi: 10.1515/aoa-2016-0061.

25. Kotus J., Szczodrak M., Czyżewski A., Kostek B. (2012), Distributed system for noise threat evaluation based on psychoacoustic measurements, *Metrology and Measurement Systems*, **19**(2): 219–230, doi: 10.2478/v10178-012-0019-6.

26. Maijala P., Shuyang Z., Heittola T., Virtanen T. (2018), Environmental noise monitoring using source classification in sensors, *Applied Acoustics*, **129**: 258–267, doi: 10.1016/j.apacoust.2017.08.006.

27. Marciniuk K., Kostek B. (2015), Creating a numerical model of noise conditions based on the analysis of traffic volume changes in cities with low and medium structure, [in:] *Postępy Akustyki – Progress of Acoustics*, Opieliński K.J. [Ed.], pp. 347–358, Polskie Towarzystwo Akustyczne, Wrocław.

28. Meng Z., Gaur Y., Li J., Gong Y. (2019), Speaker adaptation for attention-based end-to-end speech recognition, [in:] *INTERSPEECH 2019 – 21th Annual Conference of the International Speech Communication Association*, pp. 241–245, doi: 10.21437/Interspeech.2019-3135.

29. Miśkiewicz K., Wojaczek A. (2010), *Radio Communication System Using Leaky Feeder in Mines Undergrounds* [in Polish: *Systemy radiokomunikacji z kablem promieniującym w kopalniach podziemnych*] Silesian University of Technology Publishing House, Gliwice.

30. Miśkiewicz K., Wojaczek A. (2016), How to assess and improve the quality of voice services in telephone communication and alarm systems in mines, *Mining – Informatics, Automation and Electrical Engineering*, **2**(526): 40–47.

31. Morello R., Mukhopadhyay S.C., Liu Z., Slomovitz D., Samantaray S.R. (2017), Advances on sensing technologies for smart cities and power grids: A review, *IEEE Sensors Journal*, **17**(23): 7596–7610, doi: 10.1109/JSEN.2017.2735539.

32. Möller S., Raake A. (2014), *Quality of Experience. Advanced Concepts, Applications and Methods*, Springer Cham.

33. Počta P., Beerends J.G. (2015), Subjective and objective assessment of perceived audio quality of current digital audio broadcasting systems and web-casting applications, *IEEE Transactions on Broadcasting*, **61**(3): 407–415, doi: 10.1109/TBC.2015.2424373.

34. Szczodrak M., Czyżewski A., Kotus J., Kostek B. (2014), Frequently updated noise threat maps created with use of supercomputing grid, *Noise Mapping*, **1**(1): 32–39, doi: 10.2478/noise-2014-0004.

35. Une M., Miyazaki R. (2020), Musical-noise-free noise reduction by using biased harmonic regeneration and considering relationship between a priori SNR and sound quality, *Applied Acoustics*, **168**: 107410, doi: 10.1016/j.apacoust.2020.107410.

36. Zamlynska M., Debita G., Falkowski-Gilski P. (2022), Quality analysis of audio-video transmission in an OFDM-based communication system, [in:] *Mobile and Ubiquitous Systems: Computing, Networking and Services. MobiQuitous 2021*, Hara T., Yamaguchi H. [Eds.], pp. 724–736, Springer Cham, doi: 10.1007/978-3-030-94822-1_47.