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Analysis of Video Transmission Capabilities in a Simulated OFDM-Based Supplementary BPL-PLC System

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Abstract: The design and maintenance of a reliable communication system, especially in harsh working conditions for the oil and mining industry, brings many challenges. With the use of a video transmission system, one can monitor the crew and their working environment. Broadband over power line–power line communication (BPL-PLC) seems an ideal medium for such a service, since it enables the use of the existing wired infrastructure for supplementary applications. In this paper, we perform a set of simulations for a dedicated wired medium as well as analyses of a visual data transmission system, designed to deliver video content with quadrature amplitude modulation (QAM) and orthogonal frequency division multiplexing (OFDM). We investigate a set of video sequences at 480 × 270 resolution under varying network conditions, including signal-to-noise ratio (SNR) and bit error rate (BER). We perform a subjective evaluation study of video content transmitted over our simulated communication link. The results of this study may aid parties involved in designing additional services for portable devices and user terminals, including reliable means of contact, surveillance and monitoring. The obtained results may be of particular interest to researchers and professionals related to the Industry 4.0 and Internet of things (IoT) concepts.

Keywords: digital systems; electrical engineering; ICT; Industry 4.0; IoT; power cable; quality evaluation; reliability; video coding

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1. Introduction

The broadband over power line–power line communication (BPL-PLC) technology offers broadband transmission by reusing power lines for data communication at high speeds, usually up to around 200 Mb/s within the 2 to 30 MHz frequency range. BPL includes all technologies over power lines, particularly those for carrying broadband signals for computer networks and/or smart grid (SG) utilities.

At the beginning, BPL was designed for billing data acquisition from electricity meters (mainly at low voltage). However, one can find numerous examples in the literature of its effective application to control intelligent devices, including the Internet of things (IoT) concept, and/or to transmit various data [1–3]. BPL technology enables, among others, broadband Internet access via electrical sockets at home. It operates at speeds close to that of a digital subscriber line (DSL). Since BPL reuses the existing grid infrastructure [4–7], it can be used wherever DSL communication is not available.

Nowadays, its utilization in medium-voltage industrial networks seems to be of particular interest, especially in smart grids and the Industry 4.0 concept. The authors' experience also shows that there is a real chance of using the BPL technology in an existing medium voltage (MV) mine power grid infrastructure as an additional transmission medium, including various signals, e.g., audio and video [8–12], whenever an emergency situation occurs. This would surely contribute to a significant increase in work safety in the oil and mining industry. The main advantages of the BPL technology are as follows [13,14]:

- Low cost of implementation, comparable to the narrowband PLC technology;
- High transmission speeds;
- Easy installation.

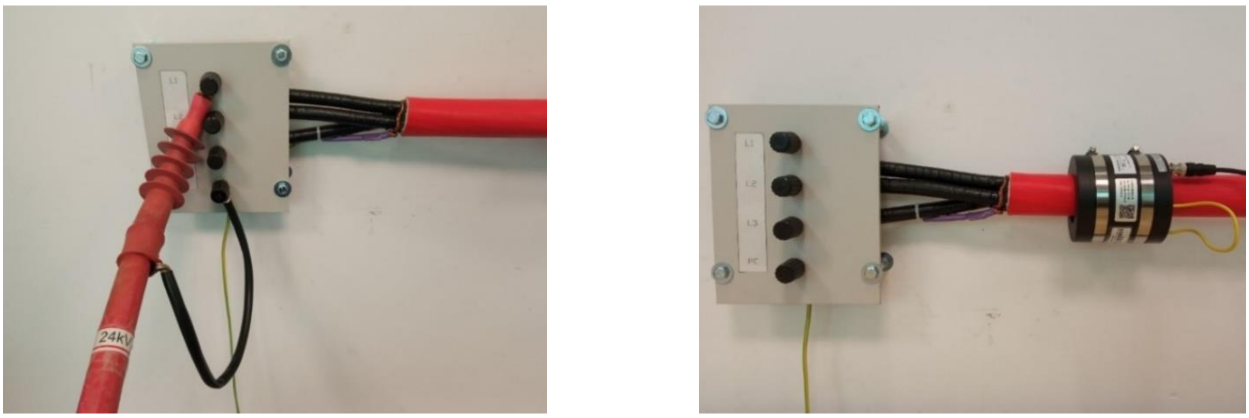
Furthermore, there is a possibility of extending the TPC/IP backbone network to medium voltage/low voltage (MV/LV) stations, as well as the coexistence of many other systems, not only smart metering (SM) or smart grid, including:

- Power grid supervision system;
- Control of street lighting and traffic lights;
- Access systems control and monitoring, etc.

However, it should be noted that despite a number of advantages, BPL technology is not resistant to various types of electromagnetic compatibility (EMC) disturbances (both induced and conducted). As a result, a decrease in the efficiency of this technology can be observed. Data transmission speed decreases, whereas errors increase [15,16]. It must be added that the BPL is not welcomed by amateur broadcasters and other users due to noise production. BPL becomes a source of radio waves and causes interference with other technologies. Power grids are not intended, and therefore also designed and constructed to transmit high-frequency signals.

For the complex topology of electricity network, the BPL channel presents frequency selection, multi-path effects, high susceptibility and high attenuation. Owing to the good characteristics of anti-multi-path fading, orthogonal frequency division multiplexing (OFDM) [17] is often adopted as a preferable modulation technique in BPL. As for the possibility of using BPL technology in medium voltage (MV) lines, it must be noted that it is an alternative to much more expensive fiber-optic systems (lower costs, greater ease, and higher speed of implementation). In many cases it is the only option, e.g., in highly urbanized areas.

In low voltage applications, the BPL modems are connected directly to 230/400 V networks. However, in case of MV applications, modems must be joined via appropriate couplers, either capacitive (Figure 1a) or inductive (Figure 1b). They isolate from high voltage and allow safe transmission of the high-frequency signal over the power line.



(**a**) (**b**)

Figure 1. Different types of couplers connected to a physical MV cable: (**a**) Capacitive coupler; (**b**) Inductive coupler.

The distances over which data can be transmitted via medium voltage lines using BPL technology range from several hundreds of meters to about 1.5 km. This of course depends on many parameters affecting the signal, including: type of cable/line, presence of cable box, busbars, type of couplings, etc. However, these distances can be extended by using the well-known repeaters, installed in convenient locations. They are designed to receive the signal from the transmitter, amplify it and forward it further. The leading companies producing transmitting/receiving devices for the BPL-PLC technology utilize solutions that enable the implementation of transmission in one of three hardware configurations:

- With time access, using time division duplex (TDD), as shown in Figure 2;
- With frequency access, using frequency division duplex (FDD), as shown in Figure 3;
- In a combined access configuration, using both TDD and FDD.

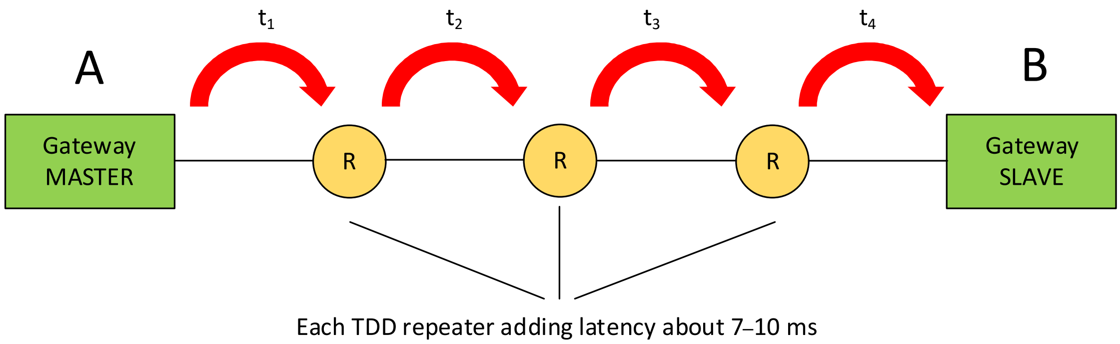


Figure 2. Data transmission from point A to point B using repeaters (R) in a TDD scenario.

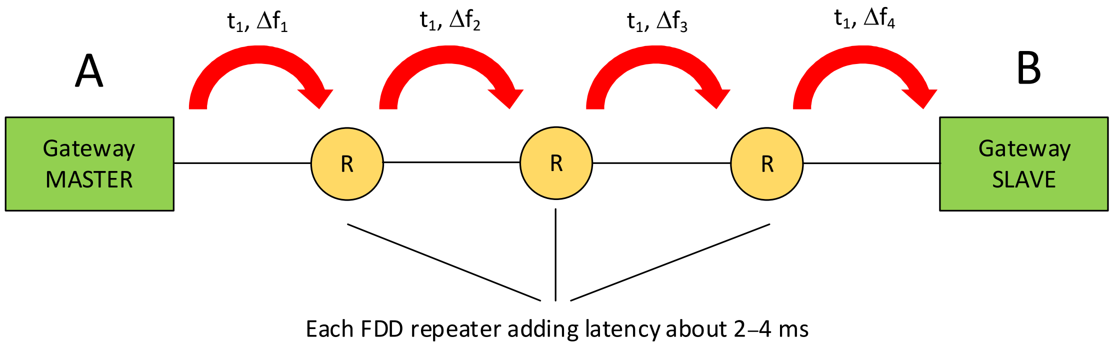


Figure 3. Data transmission from point A to point B using repeaters (R) in an FDD scenario.

For a hardware solution with TDD access, the signal is sent from point A to point B at subsequent time intervals (between the transmitter, repeaters, and receiver). Only after receiving a signal at the destination point (that is point B), the transmitter can send a new data packet. However, in case of FDD access, the data transmission time is much shorter, compared to TDD. It is caused by the fact that multiple devices operate simultaneously, thus can transmit and receive information at the same time. Therefore, when a signal is transmitted from point A to the first repeater in the frequency range Δf_1, in other parts of the network, signals can be transmitted at the same time but only in other frequency ranges. However, what is also concluded in the literature is that the FDD approach requires twice as many modems as in the case of the TDD transmission. As a result, the investment costs can increase significantly. The technical and economic analysis of BPL systems indicates that the optimal solution for an MV wide power electric grid is the use of combined TDD and FDD transmission technology.

After a careful and throughout analysis of available literature, including journal papers as well as conference proceedings, we did not encounter any previous works that would focus on and describe a supplementary video transmission system based on the well-known BPL-PLC wired technology. Therefore, we have initialized joint cooperation in order to contribute to the development of such a system. First, we focus on simulating the parameters of a dedicated physical communication link that would offer stable and reliable communication and exchange of visual content.

The paper is organized as follows: Section 1 provides an introduction to the topic of research along with a review of available literature. Section 2 presents materials and methods, including the methodology of evaluating different types of coupling and wired media, as well as the designed transmission link along with simulation parameters. Section 3 discussed the procedure of video content processing and ranking by human individuals. Section 4 summarizes this paper and provides further research directions for upcoming studies.

2. Related Work

The current development of communication systems applicable to the mining industry is very dynamic. However, most advancements in this field are focused on wireless systems, such as WLAN, ZigBee and Bluetooth, and also on mobile telephony [18–24]. The authors of these works show the great development of communication systems used, i.e., in open pit as well as underground mines. They describe the use of wireless media mainly for the purpose of monitoring the mining process in a typical miner's work cycle.

More difficult aspects to analyze are safety and support systems for mine rescuers. Once again, available literature mainly relates to wireless systems and solutions [25–33]. Initially, they were based on the so-called dripping cable technology, and then moved to popular wireless means of communication. Of course, the main advantages of using wireless communication interfaces in mines are the following:

- Relatively quick way to build the telecom infrastructure;
- Low weight and portability of user terminals;
- Easy integration with sensor systems connected to the rescuer's equipment.

However, wireless technologies suffer from many disadvantages, such as:

- Relatively low bandwidth; therefore, in most cases, only voice transmission is possible;
- Communication protocols are most often based on TDD;
- When transmitting a signal over long distances, it is required to utilize signal amplifiers and repeaters, which reduces the throughput of data transmission and lowers QoS for multimedia services, particularly those in real-time;
- The matter of developing efficient algorithms, network scaling issues, as well as ways of deploying network nodes, etc., is also problematic, especially whenever a malfunction or unexpected event occurs.

Therefore, all of those factors make it necessary to look for other solutions, e.g., using the already available power lines for communication purposes as the main backbone system for the exchange of supplementary information. The literature review indicates that scenarios related to the management of rescue teams in the event of, i.e., rock falls, earthquakes and rock mass movements that cause the collapse of escape corridors for miners working underground, have been relatively rarely analyzed. As shown, this issue is therefore very poorly recognized. In our opinion, the BPL-PLC technology has a potential to serve as a transport network for multimedia services, which can effectively support the work of a mine rescuer while performing his job with the aid of, i.e., video signals. This conviction became the starting point for conducting this research.

3. Materials and Methods

Considering the importance as well as practical aspect of the analyzed problem, we intended to determine the impact of various factors on the transmission of video signals. In our case, we utilized the OFDM technique along with quadrature amplitude modulation (QAM).

The resultant resistance of the cable plays a fundamental role, limiting both the quality and distance of the transmitted signal. It depends both on the structure of the utilized cable and the physical quantity of its materials. Due to this fact, the value of the signal-to-noise ratio (SNR) factor is significantly reduced because of the relatively high value of the cable's attenuation. It should be noted that the SNR is also related to other physical cable quantities, such as its capacitance and/or inductance. Additionally, it does change with frequency as well. The methods of approaching this problem and respective results are presented in [11]. In this paper, we focus on investigating the influence of numerous factors, which may affect the quality of video data transmission.

3.1. Methodology

The resistance has been calculated taking into account the skin effect in the conductors, the screen, as well as the armor. The skin depth (δ) is defined as a function of frequency (f) and can be calculated as:

$$\delta = \sqrt{\frac{1}{\pi f \mu_c \sigma_c}}, \tag{1}$$

where σ_c and μ_c are the conductivity and permeability of the conductor, respectively.

When analyzing the structure of the 3-phase cable, the resistance of one solid phase can be calculated as:

$$R_{soild} = \frac{1}{\pi a \delta \sigma_c}(\Omega/m), \tag{2}$$

where a is the radius of the conductor.

However, taking into account the reduction in the resultant cross-section of the phase due to the wiring stranding, a correction factor X_R must be included:

$$X_R = \frac{cos^{-1}\left(\frac{r_{wire}-\delta}{r_{wire}}\right) \times r_{wire}^2 - (r_{wire} - \delta)\sqrt[2]{r_{wire}^2 - (r_{wire} - \delta)^2}}{2 \times r_{wire} \times \delta}, \tag{3}$$

where r_{wire} is the radius of a single wire in the stranded conductor, and δ is the skin depth. With this correction, the resistance for the single phase can be expressed as:

$$R = X_R \cdot R_{soild}(\Omega/\text{m}). \tag{4}$$

Therefore, the final resistance for the 3-phase cable is calculated according to:

$$\delta R_{Cable} = \frac{R}{3}. \tag{5}$$

When considering the effects of the screen R_{Screen} and the armor R_{Armor}, their resistance values were calculated from Equation (2). In case of the screen, a represents its radius. However, for the armor, we must take into account both its different radius as well as the magnetic permeability of iron. The resultant resistance R_t of the 3-phase power cable constitutes the parallel connection of all components and therefore should be calculated as:

$$\frac{1}{R_T} = \frac{1}{R_{Cable}} + \frac{1}{R_{Screen}} + \frac{1}{R_{Armor}}. \tag{6}$$

3.2. Type of Coupling

In order to develop a reliable simulation model of a dedicated power cable, it was necessary to perform a series of theoretical analyses. The analyses of the transmission properties of the cable, including its attenuation, characteristic impedance, group delay [11], etc., showed that in the frequency range from 2 MHz to approx. 7.5 MHz, the measured SNR values are within the regression error, regardless of the cable model adopted for the analysis. Obtained results for inductive–inductive and mixed capacitive–inductive coupling are shown in Figures 4 and 5, respectively.

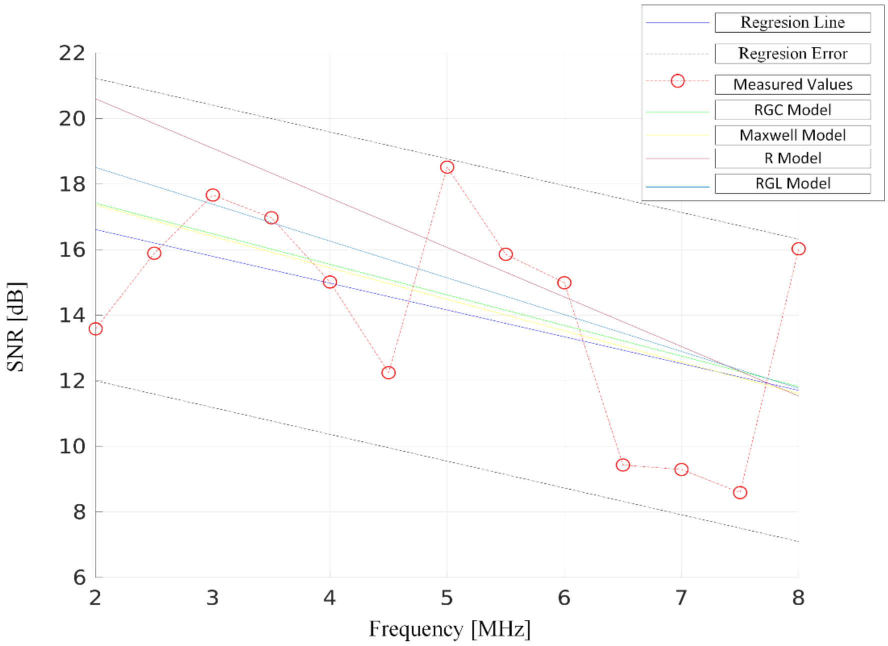


Figure 4. Relation between SNR and frequency for different cable models for inductive–inductive coupling.

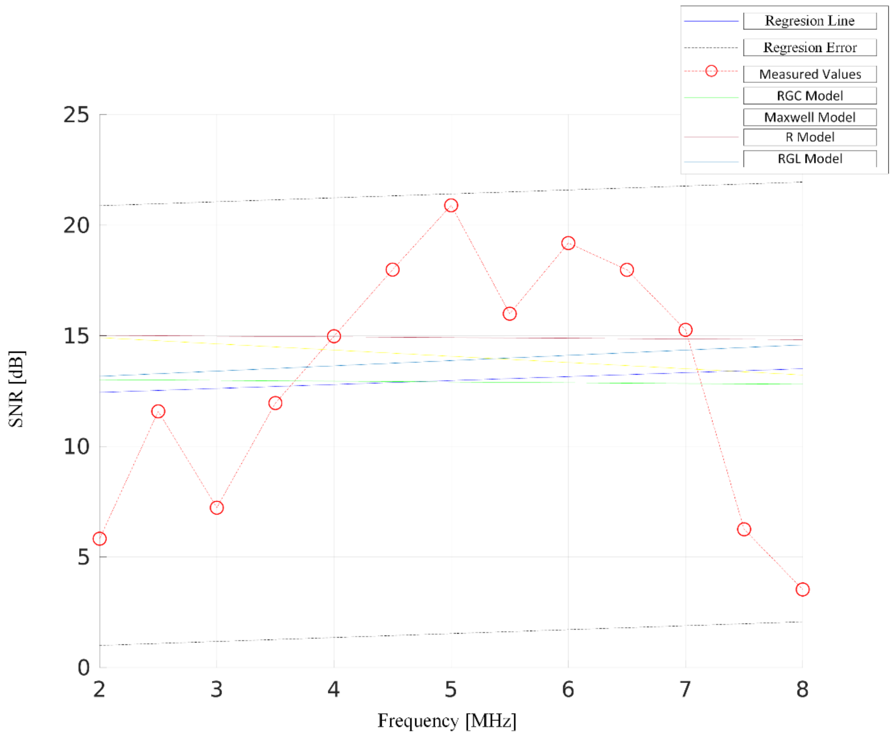


Figure 5. Relation between SNR and frequency for different cable models for capacitive–inductive coupling.

The methodology for performing verification measurements is shown in Figure 6. As observed, the Gwinstek frequency generator was connected to the input coupler (in this case, the inductive coupler) on one side, and the USB-SA44B SignalHound spectrum analyzer was connected to the output coupler (in this case, the capacitive coupler) on the other side.

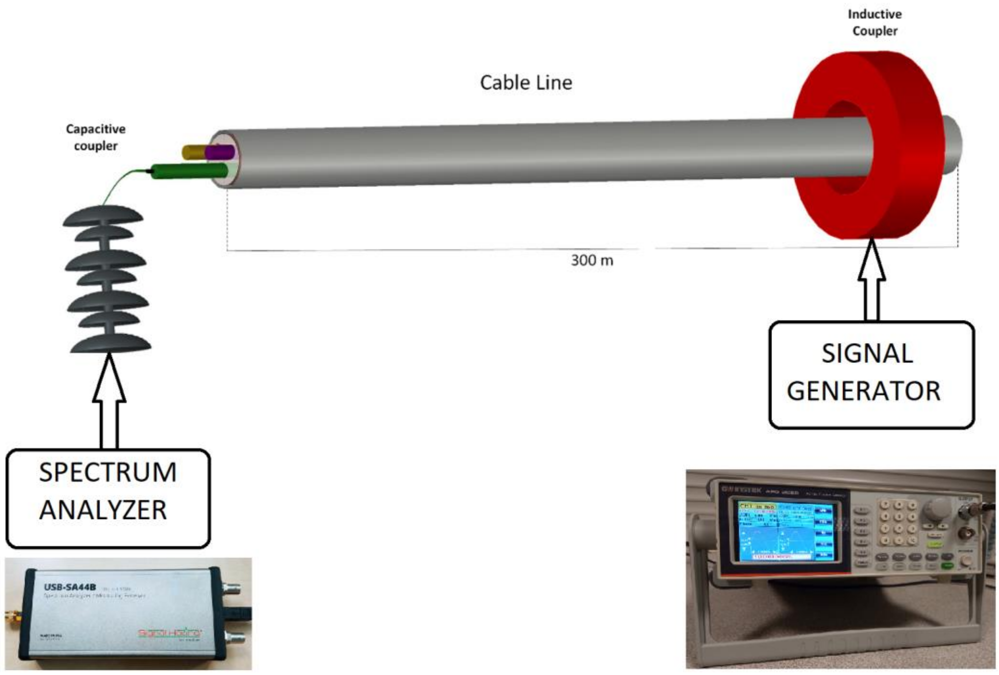


Figure 6. Methodology of performing verification measurements for mixed (capacitive–inductive) coupling.

By measuring the signal levels at both input and output, it was possible to determine the relation between attenuation and frequency. Next, by evaluating the noise level, the SNR value for a given frequency could be determined.

3.3. Transmission Link

The transmission quality has been investigated in the Matlab/Simulink environment. The simulated model enabled to determine the resulting bit error rate (BER) in case of video files, as shown in Figure 7.

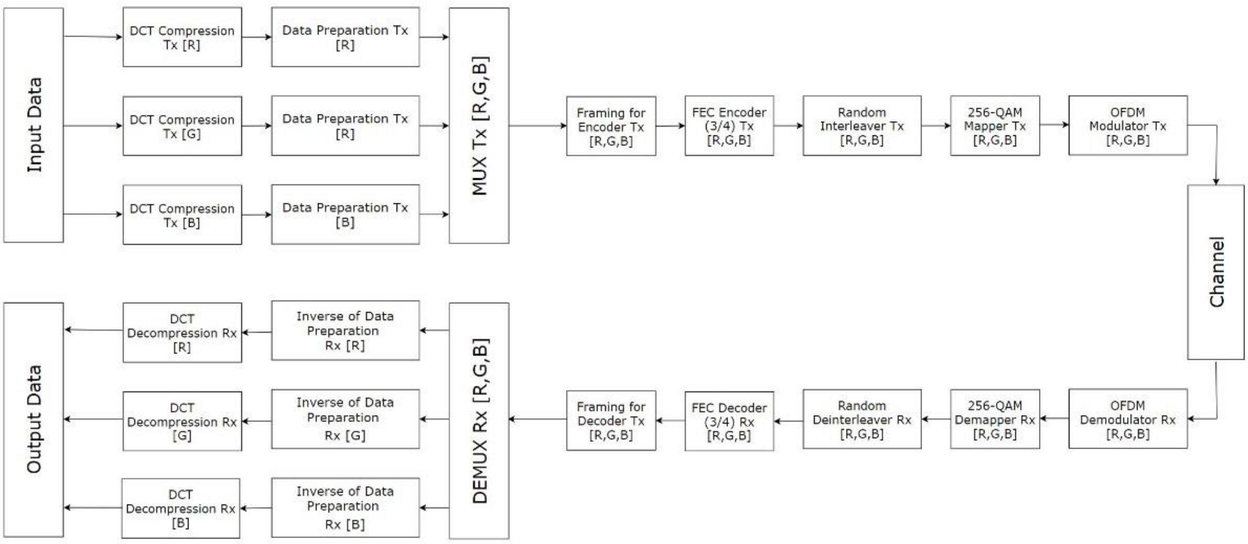


Figure 7. Simulated video transmission system.

The principal parameters of the simulated system are described in Table 1.

Table 1. Basic parameters of the simulated video transmission system.

Parameter	Description
Resolution and refresh rate	480 × 270, 24 FPS
Color model	RGB
Compression algorithm	8 × 8, DCT, quantization, lossless compression
Protection coding	FEC 3/4 (BCH + LDPC 3/4)
Modulation and coding scheme	256 QAM, OFDM
No. of subcarriers	81
Carrier spacing	42 kHz
Channel bandwidth	3.4 MHz
Channel model	AWGN

The video content utilized during the study was available in color and therefore split into different streams in the red, green and blue (RGB) model, just before multiplexing, as shown in Figure 8.

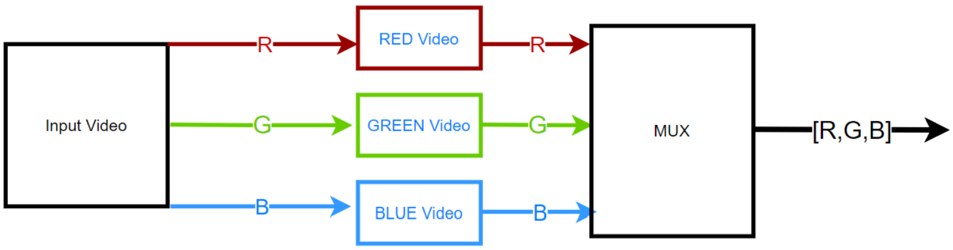


Figure 8. Handling of the video content in the RGB mode.

At the beginning, the input file was compressed into smaller blocks of 8 × 8 pixels. Next, those blocks were transformed one by one as an image *f* of size $[M \times N]$, representing a single frame from the input video file. In the two-dimensional pixel domain (*x*,*y*), it would be expressed as $f(x,y)$. In order to transform the image in the frequency domain, the 2D discrete cosine transform (DCT) was utilized. Thus, the output image would be given by:

$$F(m,n) = \frac{2}{\sqrt{MN}} C(m)C(n) \sum_{x=0}^{M-1} \sum_{y=0}^{N-1} f(x,y) cos\frac{(2x+1)m\pi}{2M} cos\frac{(2y+1)n\pi}{2N}, \tag{7}$$

where:

$$\begin{cases} C(m) = C(n) = \frac{1}{\sqrt{2}} & for\ m = n = 0 \\ C(m) = C(n) = 1 & \forall m,n \in C : m,n \neq 0 \end{cases}. \tag{8}$$

Such an operation was realized in the transmitting part. In case of the receiving part, a reverse operation, namely, the 2D inverse discrete cosine transform (IDCT), was performed on the image *F* in the pixel domain (*m*,*n*). This inverse transformation converted the *F* image into the time domain according to:

$$F(x,y) = \frac{2}{\sqrt{MN}} \sum_{m=0}^{M-1} \sum_{m=0}^{N-1} C(m)C(n) f(m,n) cos\frac{(2x+1)m\pi}{2M} cos\frac{(2y+1)n\pi}{2N}, \tag{9}$$

where:

$$\begin{cases} C(m) = C(n) = \frac{1}{\sqrt{2}} & for\ m = n = 0 \\ C(m) = C(n) = 1 & \forall m,n \in C : m,n \neq 0 \end{cases}. \tag{10}$$

The compressed channels were multiplexed in order to adapt them into a single transmission medium. Such an operation was required so that the forward error correction (FEC) could be performed, just like in a typical terrestrial video broadcasting system [34,35].

In our case, the FEC encoding was identical to that used in the well-known DVB-T standard [36]. According to available literature, this standard utilizes a combination of the Bose–Chaudhuri–Hocquenghem (BCH) code, which is a subclass of cyclic error correction codes build over finite bodies with linear low-density parity check (LDPC) correction coding. The simulated FEC encoder had the following parameters, as described in Table 2.

Table 2. Basic parameters of the coding procedure.

Parameter	Description
Code rate	3/4
n_{ldpc}	64,800 bits (normal frame)
k_{bch}	48,408 bits
k_{ldpc}	48,600 bits

First, the binary message of length k_{bch} was encoded with the n_{bch} BCH-bit code word. Then, the BCH code word k_{ldpc} equal to n_{bch} was coded into an n_{ldpc} LDPC-bit code word. The code word n_{ldpc} was equal to 64,800 bits in length. The lengths of k_{bch} and k_{ldpc} were variable and depended on the code rate. In case of our system, the efficiency was equal to three-fourths.

Later on, the data were subjected to the interleaving mechanism. The designed interleaver transformed the data according to a random permutation based on a fixed initial state. The permutation table was selected randomly using the specified input parameter. In case of the de-interleaver, knowing the initial state, it was possible to undo the interleaving operation and restore the original data.

In the next step, data were converted to symbols by a 256-QAM baseband modulator and then subjected to OFDM [37,38]. OFDM preserved the orthogonality of the subcarriers, which reduced the risk of interference. It also transformed a single transmission into several data streams that were less prone to corruption. For a stream at the input of the OFDM modulator $X(k)$, this signal was first split into N parallel streams. Then, for each symbol the inverse discrete Fourier transform (IDFT) was calculated as:

$$x(n) = \sum_{k=0}^{N-1} X(k) e^{j\frac{2\pi}{N}nk}, \tag{11}$$

where:

$$\mathrm{V}_{n\epsilon N} \qquad n = 0, 1, \ldots, N-1. \tag{12}$$

Such an operation was performed in the OFDM modulator. In case of the OFDM demodulator, a reverse operation was performed, namely, the $x(n)$ subcarrier symbol was transformed by the discrete Fourier transform (DFT) algorithm according to:

$$X(k) = \sum_{k=0}^{N-1} x(n) e^{-j\frac{2\pi}{N}nk}, \tag{13}$$

where:

$$\mathrm{V}_{k\epsilon N} \qquad k = 0, 1, \ldots, N-1. \tag{14}$$

Data prepared in such a way were passed through an additive white Gaussian noise (AWGN) communication channel. This channel also inherits the sampling rate from the input signal. In order to adjust the noise level, as well as check various quality aspects, one can modify the SNR parameter as required.

4. Results

Since the MPEG-4 is one of the most popular coding formats for content processing and distribution, regardless of whether talking about terrestrial or online services [39–41], we have decided to source the video material from Netflix [42]. This repository offers numerous files in varying formats, as well as different pixel (from standard definition up to high definition) and color (8-bit or 10-bit) resolutions. Each video file consists of five sequences, where the fourth and fifth resemble the same scene, as shown in Figure 9. However, sequence no. 5 was recorded in slow-motion (with a much higher framerate per second).

Figure 9. Transmitted sequence of video content.

The sequences were ordered as follows:

1. Walking man—static background with a single man walking along the street;
2. Windmill—static angle with numerous fast moving (rotating) windmills;
3. Traffic—static angle with cars passing along the road, at various speeds.
4. Toddler fountain—playful child walking around a fountain, with lots of movement in the background;
5. Toddler montage—similar material with a playful child recorded in slow-motion (much higher framerate).

These were available in a number of bitrates (qualities), from standard definition (SD) up to Full-HD (1920 × 1080). After a careful examination, we have selected one video file, available in the 480 × 270 resolution, 8-bit color variant. This resolution, being exactly one fourth of 1920 × 1080 is easily scalable and popular among many portable devices and user terminals, including media players, consoles, etc. [43]. Next, the video transmission performance was tested in a quality evaluation study.

According to the 3rd Generation Partnership Project (3GPP) [44], video services can be divided into two main categories, depending on delay and bit error rate, as described in Table 3.

Table 3. Basic video transmission services with their technical requirements.

Service	Acceptable Delay [ms]	Acceptable BER
Live streaming (real-time video)	150	10^{-3}
Buffered streaming (non-real-time video)	300	10^{-6}

In our scenario delay may be neglected; therefore, in this particular study, we focused on BERs ranging from 10^{-3} to 10^{-6}. During the experiment, the MPEG-4 video file with a resolution of 480 × 270 pixels was fed into the simulator. The input (original) as well as output (processed) format remained unchanged. Overall, the test involved six different SNR levels, ranging from 24 to 29 dB, that is: 24, 24.4, 27, 28.3, 28.7 and 29 dB, as well as monitored BER before and after forward error correction (FEC). As observed, FEC had a significant impact on the final error rate only for SNR equal to 27.5 dB and above. The initial range of approx. 10^{-4} and 10^{-3} was reduced by tens or even hundreds of times. However, the efficiency of transmission should be evaluated in a subjective manner on the end-user side.

The subjective part of this study was performed according to [45] on a 27-inch Full-HD (1920 × 1080) screen. The group of viewers consisted of 10 individuals without visual impairments. All of them could adjust the stand and viewing angle of the display according to their own preferences. The processed video content was presented in a randomized way. The results of this experiment are shown in Figure 10.

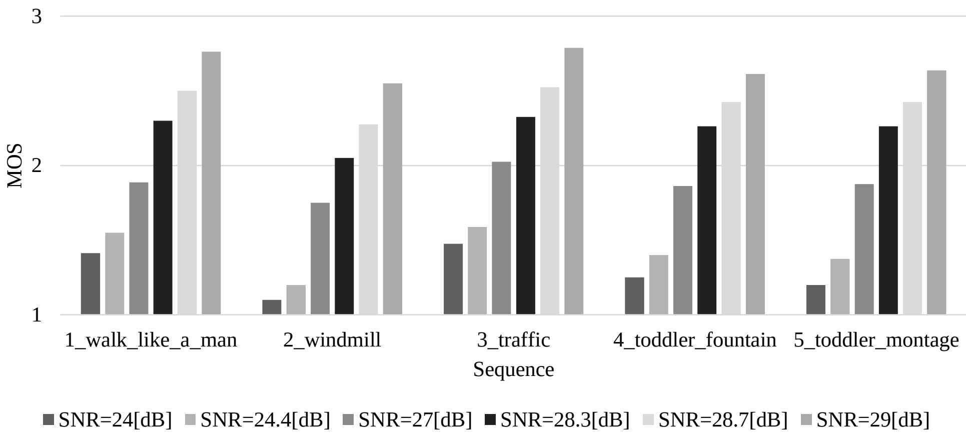


Figure 10. Subjective quality evaluation of processed video content with respect to SNR.

According to obtained results, the lowest SNR proved to be unacceptable (MOS score close to 1.0), whereas, in case of the highest value, the quality was ranked between 2 and 3, resembling a poor or fair quality (annoying or slightly annoying). As observed, the degree of distortions and interference was at the threshold of acceptability. Yet, as pointed out by the group of viewers, for higher SNR values, the most important visual information could be pinpointed out and tracked effectively.

To sum up, for the lowest SNR equal to 24 dB, the quality was very poor. No details were visible, colors were distorted and numerous elements did not have sharp edges (grainy and/or blurred). For instance, the first (walking man) and second (cars) sequence was easily interpreted, whereas the third one (windmill) presented something hard to determine. In the case of the fourth and fifth sequences (toddler), people reported not knowing whether it was just noise or not.

The second level of the SNR equal to 24.4 dB provided similar observations, as no changes were noticeable. The third level of the SNR equal to 27 dB was ranked definitely better compared to previous ones. Yet, the quality was still unacceptable, as many pixel artefacts occurred. As reported, there was a visible decrease in the level of noise, the shapes were more precise, i.e., the windmills were adequately labeled, just like the fountains. In the fourth level of SNR equal to 28.3 dB there was a noticeable upgrade; however, the color mismatch and artefacts among many pixels were still present.

For the second highest level of SNR equal to 28.7 dB, the level of noise, artefacts and color distortions was smaller. The highest level of SNR equal to 29 dB was ranked evidently better than the previous ones.

5. Conclusions

As shown, in case of our custom-designed OFDM-based transmission system, BPL-PLC technology has shown the potential for becoming a reliable supplementary video communication system. According to the quality analysis, a noticeable difference was only observed from a particular breakpoint in case of SNR: in this case, higher than 28 dB, where the level of noise, color distortions, etc., was acceptable and enabled to determine characteristic elements in the video sequence.

It should be pointed out that a similar solution has not yet been described in available literature so far. Such activities require a wide range of interdisciplinary skills from many fields of science and technology, with particular emphasis on computer science, telecommunications, coding and transmission techniques, as well as processing and analysis of multimedia content. For this reason, in the near future, we would like to focus on the practical and final implementation of our solution in the form of physical devices and proprietary software. Similar research, carried out by other authors and research centers from around the world, would certainly contribute to accelerating this process and the exchange of information.

Undeniably, it would be interesting to examine a broader range of video content, including different resolutions as well as file formats. Such an investigation, including, i.e., various technical and subjective quality aspects, would be particularly interesting for a broad group of scientists. Professionals from the oil and mining industry would surely welcome any novel reliable and dependable services [46]. Furthermore, it would be stimulating to broaden the range of research scenarios and interested third parties involved in similar studies. Due to the current situation, and with the aid of modern ICT solutions, it would be fascinating to carry out new studies utilizing, i.e., crowdsourcing methods [47–50]. A source of inspiration for further studies, including content storing and processing mechanisms, wired and wireless communication media and standards, etc., may be found in [51–57].

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