

Influence of phase-sensitive optical time-domain reflectometer on community antenna television transmission

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Abstract. Multiple studies have been carried out to analyze the mutual interaction of a phase-sensitive optical time-domain reflectometer (Φ -OTDR) and parallel digital data traffic. However, interactions with analog transmission, e.g., community antenna television (CATV), have not been addressed. Our study examines and presents the influence of a developed sensing system Φ -OTDR when operated simultaneously on parallel fibers with the transfer of data from an analog CATV system. Three scenarios are suggested and discussed for the measurements and optimization of the data network in the analog CATV data transfer. These scenarios are suggested to enable the verification of the mutual interactions between data networks with the analog data transfer and suggested sensing system and to determine how the data network with the analog data transfer may or may not be influenced by the sensing system. The optimization and measurements prove that the analog CATV data transfer was negatively influenced by the sensing system Φ -OTDR, and the channel bit error rate increased by nearly half. The implementation of the sensing system Φ -OTDR was realized for a data network, followed by the testing and optimization, which proved that the safe spectral distance between the CATV and the sensing system is 150 GHz and higher. © The Authors. Published by SPIE under a Creative Commons Attribution 4.0 Unported License. Distribution or reproduction of this work in whole or in part requires full attribution of the original publication, including its DOI. [DOI: [10.1117/1.OE.60.2.026103](https://doi.org/10.1117/1.OE.60.2.026103)]

Keywords: sensing system; analog data transfer; influence of system; Rayleigh; high-power amplification; signal quality.

Paper 20200855 received Jul. 14, 2020; accepted for publication Jan. 13, 2021; published online Feb. 17, 2021.

1 Introduction

Existing fiber distribution systems utilize fiber integrity self-monitoring for the immediate localization of fiber cuts. This feature is often implemented using a built-in optical time-domain reflectometer (OTDR) subsystem.^{1,2} A proactive approach is the detection of vibrations along the fiber to detect and localize fiber tampering or factors that can lead to future fiber breaks.

These effects (mainly mechanical vibrations along the fiber) can be monitored via measuring changes in the properties of light (phase, amplitude, or polarization) that propagates through the fibers, measured at the transmission³ or in the back reflection^{4,5} modes. The Φ -OTDR^{2,6} system has been implemented and improved based on the phase detection of back-reflected signals in the fiber. The principle is based on Rayleigh backscattering⁷ and is described in the following section. This phenomenon is weak in standard telecom fibers (it contributes to transmission losses, which are generally pushed to be low), and therefore, it is necessary to utilize high-power pulses and very sensitive detection. These high-power pulses have a strong potential to negatively influence community antenna television (CATV) transmission.⁸

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2 Test Scenarios

Different scenarios on the test preparation of data networks with a parallel analog data transfer and sensing system have been suggested. Examining all three scenarios presented below allows for the verification of possible mutual interactions between the analog transmission and the designed sensing system Φ -OTDR, particularly if or how the sensing system influences the data network and how large such an influence is. For the data network with analog transmission, we used the CATV system with a hybrid distribution, which utilizes a combination of coaxial and optical fibers. This CATV system performs direct modulation of a distributed feed-back laser. The transmit laser contains an output isolator to minimize the influence of reflection from the fiber. An optical line is realized by spools of the standard single-mode optical fiber type G.652 at different lengths (5, 10, 25, and 50 km). Attenuation of the fiber for 1550 nm is ≤ 0.21 dB/km and chromatic dispersion is ≤ 17.8 ps/(nm km). The optical spools have a pigtail with the SC/APC optical connector (attenuation of connector is < 0.3 dB). The worst interaction between the signals can be expected when signals are spectrally close. This is due to non-linearities of fiber and will be discussed later. For this reason, for the CATV (fixed 1550.12 nm) signal, spectral distances of the Φ -OTDR were selected at 50, 100, and 150 GHz apart. For radio frequency (RF) connections, patch cords based on a 75 Ω RG59-U cable (attenuation at 500 MHz not worse than 2 dB/10 m) were used.

The proposed scenarios are presented as follows.

1. Setup with antenna distribution

- *Scenario 1.* Passive antenna + CATV transmitter + optical line (5, 10, 25, and 50 km standard single-mode fibers) + CATV receiver + DVB-T/T2 tester Televés.
- *Scenario 2.* Active antenna + set-top box + CATV transmitter + optical line (5, 10, 25, and 50 km standard single-mode fibers) + CATV receiver + DVB-T/T2 tester Televés (compared with scenario 1, the signal level in scenario 2 is stabilized).

2. Setup for a precise measurement

- *Scenario 3.* Generator + CATV transmitter + optical line (5, 10, 25, and 50 km standard single-mode fibers) + CATV receiver + DVB-T/T2 tester Televés.

We connected the sensing system Φ -OTDR to the line using a three-port optical coupler with a coupling ratio of 50:50 to maintain consistent attenuation conditions for all scenarios. Another three-port optical coupler with a splitting ratio of 50:50 was used for the measurements of both signals by the high-resolution optical spectrum analyzer (OSA) type FTB-5240B from the supplier EXFO. Its optical parameters are a wavelength range of 1250 to 1650 nm, resolution bandwidth [full width at half maximum (FWHM)] of 0.033 nm, channel spacing of 12.5 to 200 GHz, dynamic range of -80 to $+18$ dBm, maximum total safe power of $+23$ dBm, and OSNR dynamic range > 35 dB.

The following sources of the signal were selected for the CATV: passive rod type antenna (omnidirectional, ranges 87.5 to 230 MHz and 470 to 790 MHz, 4 dB antenna with LTE/4G filter for signal suppression of mobile networks) to receive a digital terrestrial signal DVB-T/T2. Further active commercial panel antenna (ranges 174 to 230 MHz and 470 to 790 MHz with built-in amplifier max gain of 40 dB and LTE/4G filter) with a set-top box for the amplification of a weak terrestrial signal, and an ideal source of the signal as a suitable generator of analog

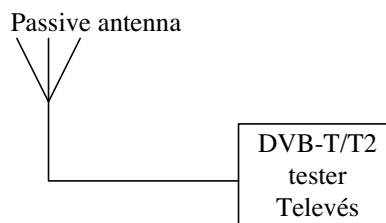


Fig. 1 Signal quality measurements with a passive antenna.

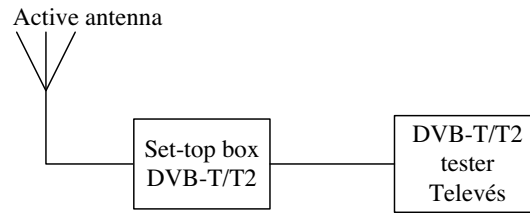


Fig. 2 Signal quality measurements with an active antenna and a set-top box.



Fig. 3 Signal quality measurements with an appropriate signal generator.

signals. Figures 1–3 illustrate the possible scenarios for verifying the quality of the signal strength from individual sources. For the verification of signal quality and evaluation of the channel bit error rate (CBER), Viterbi bit error rate (VBER), and modulation error ratio (MER) parameters in the above-mentioned scenarios, the tester DVB-T/T2 Multimeter FSM 450 Televés was used.

The received signals will have low quality in the following cases.

- Multipath transmission happens because of reflections of the surrounding terrain.
- The above-ground objects or their recent construction causes shading of the signal or degradation in the reflections.
- The receiving device (antenna, amplifier, antenna lead-in, and receiver) is of low quality or its installation is inappropriate.
- The receiving device has insufficient resistance against a strong signal from a nearby transmitter for the Global System for Mobile Communication, Universal Mobile Telecommunications System, and ultrashort-wave radio and radars.
- Exceptional conditions of other radio wave transmissions for distant receivers work on the same channel.

When a digital TV is operated and error correction codes are used, the various levels of quality deterioration of the image and sound are almost not present; rather, only two states exist: the image and sound are perfect or they are deteriorated completely. The quality of the received image and sound directly reflects the quality of the signals being transmitted. Image jamming and sampling and sound interruptions show that the receiver gets signals within the limits of its detection possibilities. A disturbed or low-quality signal presents itself as an image jamming or image sampling, a short outage or distortion of the sound, a lost image and sound, and a non-synchronized image and sound.

2.1 Description of the Setup with Antenna Distribution

- Scenario 1

Scenario 1, shown in Fig. 4, consists of a passive antenna for DVB-T/T2 terrestrial digital signal reception, CATV system, variable optical line, and tester DVB-T/T2 Multimeter FSM 450 Televés. The coaxial cable from the passive antenna is connected to the RF input of the CATV system (transmitter part) for the analog transmission of data. The data are modulated with a wavelength of 1550.12 nm. The analog transmission enters the modular optical line, and various lengths of the optical line are engaged. The receiver part of the CATV system is connected at the end of the optical path, where conversion from the optical part to the RF part takes place for the subsequent measurement of the analog signal quality. The functionality of this proposed scenario depends on the quality and strength of the signals from the passive antenna. Here we observe possible pitfalls of scenario 1.

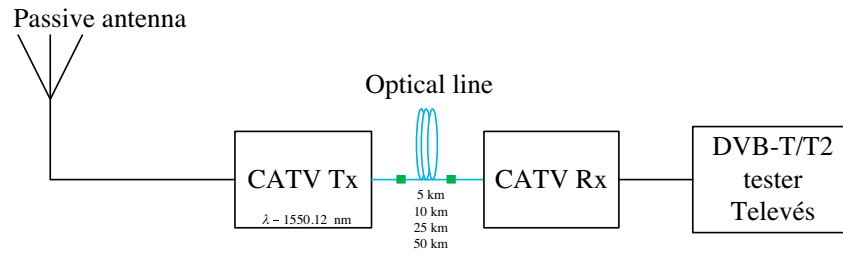


Fig. 4 Block scheme of scenario 1.

Within this scenario (see Fig. 4), the sensing system Φ -OTDR was implemented for further verification of the mutual interactions and for the examination of any degradation in the analog transmission of the data. This modified scenario is shown in Fig. 5. As mentioned above, the Φ -OTDR was connected within this scenario via a three-port optical coupler with a splitting ratio of 50:50. Both signals were merged in this coupler, i.e., the CATV (1550.12 nm) and sensing system (1550.52 nm). Both wavelengths were set to be as close to each other as possible (50 GHz wavelength grid) to show the possible interactions between them. There is a high possibility that the sensing system influences the CATV transmissions as the former uses relatively high-power signals. Such an assumption can be proved or disproved through testing, verification, and measurements of either of the scenarios (see Sec. 3).

In following text, the principle of the Φ -OTDR is briefly described and the need for pulses of high intensity to launch into fiber under test is shown. The Φ -OTDR injects high-power optical pulses into the optical fiber at one end, and a small fraction of light is continuously backscattered as it propagates along the fiber. This setup is very similar to a standard telecommunication OTDR, but an ultra-narrow line-width laser source is necessary.^{2,6,9} This technique is called Φ -OTDR because it detects phase changes along the fiber. The spatial resolution of two close events is dependent on the pulse duration.¹⁰ For example, for a pulse duration of 50 ns, the spatial resolution is ~ 5 m. In a typical case, we focus on a high resolution; hence, short pulses are used. The backscatter power is described as follows:^{6,11}

$$Pr(t) = \frac{P_i \cdot S \cdot R \cdot W_0 \cdot v_g \cdot e^{-\gamma \cdot v_g \cdot t}}{2}, \quad (1)$$

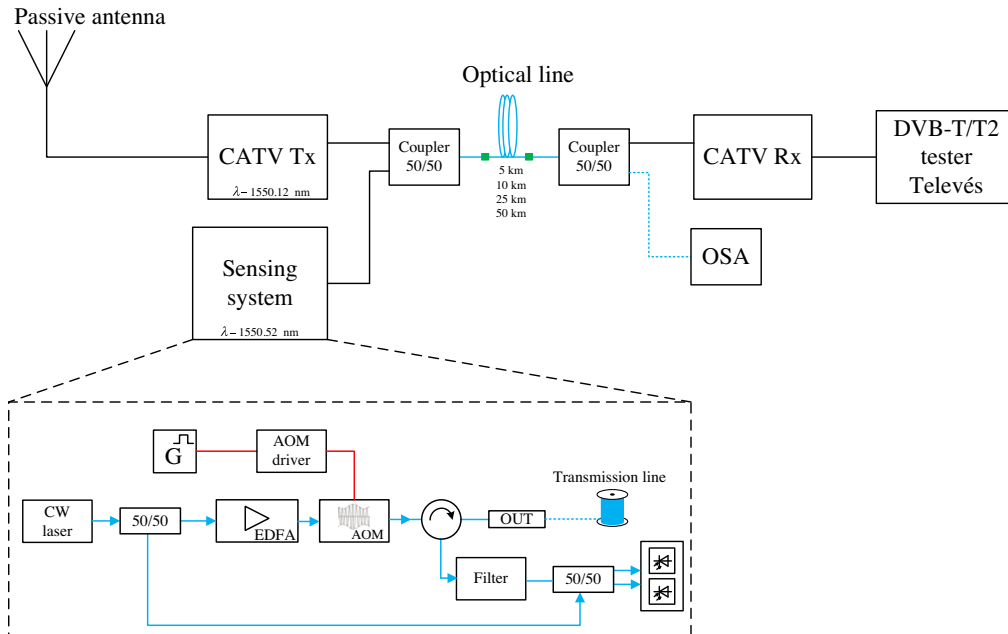


Fig. 5 Block scheme of scenario 1 with the sensing system.

where $P_i \cdot W_0$ represents the input pulse energy in joules, S is the fraction of the captured optical power, R is the Rayleigh scattering coefficient, v_g is the group velocity, and γ is the attenuation coefficient and is equal to 1/20th of the plot gradient of the Rayleigh backscatter attenuation in decibels (dB). For a standard step-index telecommunication fiber, Eq. (1) is simplified as follows:^{6,11}

$$Pr(t) = 7.8 \cdot P_i \cdot W_0 \cdot e^{-\gamma \cdot v_g \cdot t}, \quad (2)$$

where for an average power of 150 mW and pulse duration of 50 ns, $P_R(0)$ will be 58 nW only. This shows the main disadvantage of backscatter-based sensors, i.e., a low level of received optical power.^{6,11} Thus to achieve reach long enough together with requested resolution, high-power sources need to be used.

Next, the possible sources of non-linear interactions will be briefly mentioned. When an intense optical signal propagates through the optical medium showing a third order of electrical susceptibility χ_3 , as shown in Ref. 12, it changes the refractive index of the dielectric media that, in return, changes its own phase; this phenomenon is called self-phase modulation. Furthermore, in the same way, it changes the phase of any present optical signal. Such an effect is called cross-phase modulation (XPM),¹² and for two signals with intensities I_1 and I_2 , this results in the modification of a refractive index experienced by the first signal:¹²

$$n(I_1, I_2) = n + n_2(I_1 + 2I_2), \quad (3)$$

where n is the refractive index of the dielectric media for a given signal frequency and n_2 is the non-linear part of the refractive index.¹³ n_2 is related to the third order of the electrical susceptibility of an optical fiber:¹²

$$n_2 = \frac{3}{8n} \chi_3. \quad (4)$$

If both signals are intensive enough, they will influence each other's phase, and the phase of the first signal will be the following equation:¹²

$$\phi_1(I_1, I_2) = \frac{2\pi}{\lambda} L(n + n_2 I_1 + 2n_2 I_2), \quad (5)$$

where L is the propagational length and λ is the wavelength. The constant 2 in the last term of Eqs. (3) and (5) is valid for the worst case of co-polarized signals. It becomes 2/3 for orthogonal polarizations. Optical signals can also interact in the dielectric media if their parameters are properly aligned. One such case is called four-wave mixing (FWM). Two signals at frequencies ω_1 and ω_2 interact in the media and create two new signals at ω_3 and ω_4 . This interaction must comply with the energy and momentum conservation conditions:¹³

$$\omega_1 + \omega_2 = \omega_3 + \omega_4, \quad (6)$$

$$k_1 + k_2 = k_3 + k_4, \quad (7)$$

where ω_{1-4} are the frequencies of the mixing signals and k_{1-4} are the respective wavenumbers.¹² Equation (6) determines the frequencies of the newly created signals, whereas Eq. (7) addresses the fact that mixed signals have to be reasonably close in frequency. Therefore, the main sources of parallel CATV signal transmission disturbances will arise from the products of XPM and FWM.

For the launching of sensing signals into the line under test, we chose a uniform approach with a spectrally non-selective wideband fused coupler instead of narrowband filters based on fiber Bragg gratings,⁷ which need to be especially prepared for each wavelength. This approach allows for uniform insertion losses for all scenarios with different spectral shifts between the CATV and sensing signal, despite having higher insertion losses.

- Scenario 2

After improving scenario 1, the previously mentioned active antenna with built-in amplifier and set-top box DVB-T/T2 were used for the amplification and improvement of the signals for

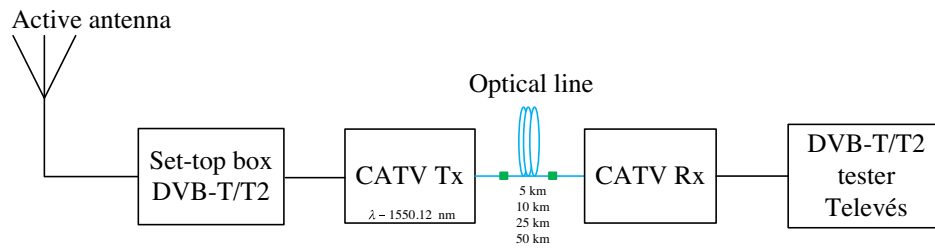


Fig. 6 Block scheme of scenario 2.

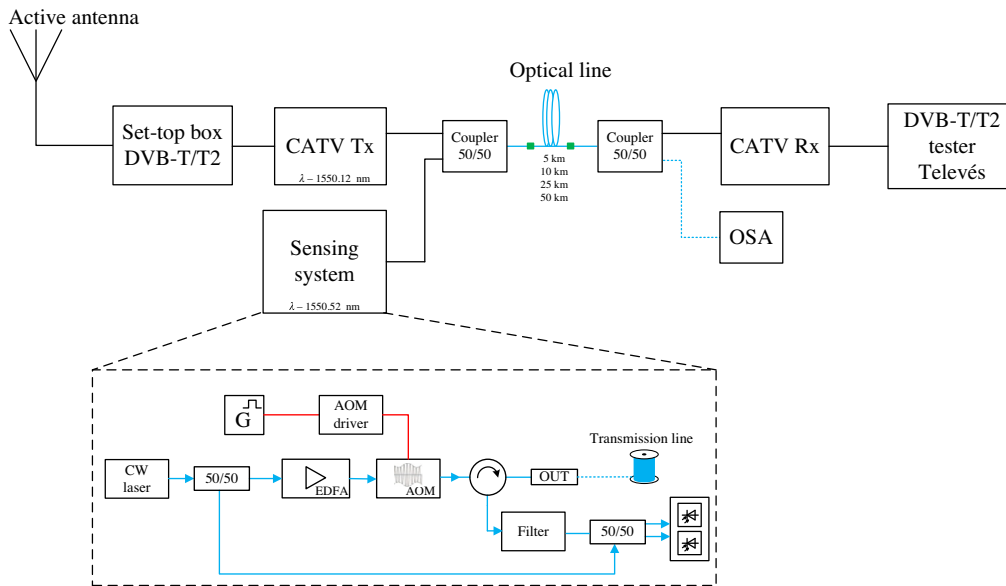


Fig. 7 Block scheme of scenario 2 with the sensing system.

the RF input of the CATV system in the analog transmission of data (Fig. 6). Within the three proposed scenarios, these settings will be retained for the CATV system, Φ -OTDR, and modifications in the lengths of the optical line, including the type of fiber. Such setups enable comparisons of various scenarios with one another.

The sensing system Φ -OTDR, shown in Fig. 7, was again connected with the optical coupler. We suppose that the influence of the suggested sensing system Φ -OTDR on the CATV transmission may be more visible, especially with the higher quality and more powerful signal entering into the RF input of the CATV system. This assumption will be proven by testing, verification, and measurements, which are described in Sec. 3.

2.2 Description of the Setup for a Precise Measurement

- Scenario 3

The largest disproportion in the previous scenarios is at the RF input to the CATV system, where there is no receiving device, such as an antenna. Instead, the generator of the appropriate analog signal is used, as shown in Fig. 8. Such a solution actually yields maximal benefits. The Φ -OTDR interconnects over the three-port coupler to prove the potential interactions with the CATV system, as shown in Fig. 9. If the ideal power source is used, then the influence of the suggested sensing system to the CATV is visible at its best.

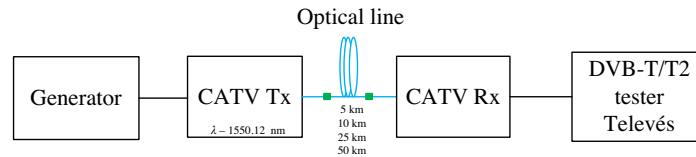


Fig. 8 Block scheme of scenario 3.

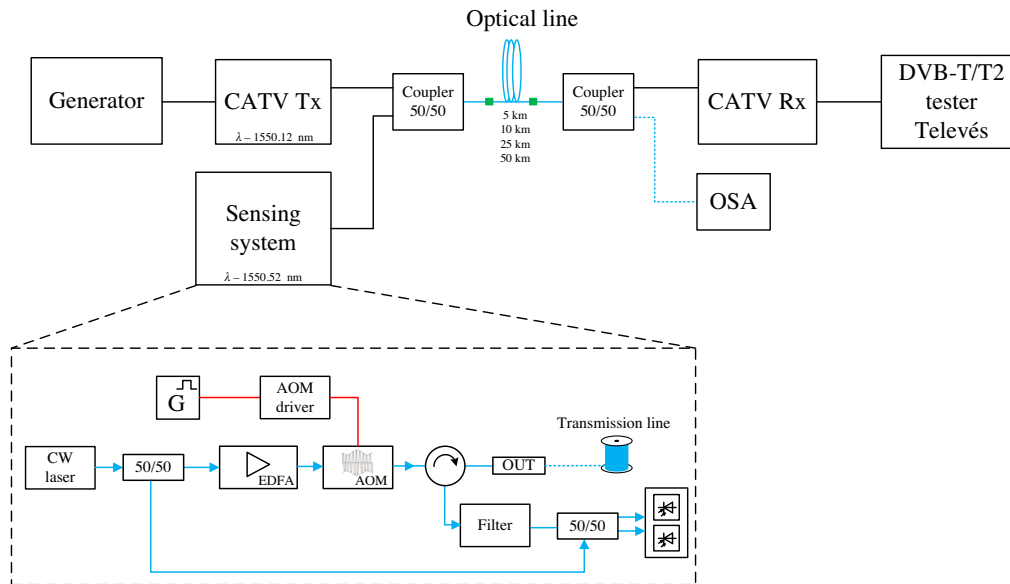


Fig. 9 Block scheme of scenario 3 with the sensing system.

3 Results

3.1 Optimization and Network Measurement with Analog Transmission

3.1.1 Verification of the signal quality for each source

First, before the measurements of each suggested scenario (as shown in Figs. 1–3), a measurement reference for the signal quality of each signal source was established and is shown in Table 1. For verification, we used the measuring instrument and the tester DVB-T/T2 Multimeter FSM 450 Televés, which evaluates the CBER, VBER, and MER parameters.

The minimal required value of the MER is in the range of 22 to 24 dB, and the optimal value is ≥ 25 dB. The crucial value for a stable and quality DVB-T/T2 signal without image jamming

Table 1 Measured reference values.

Parameter	Measured reference values		
	Passive antenna	Active antenna with a set-top box	Appropriate signal generator
Signal quality (%)	43	77	86
CBER	4.5E-3	1.7E-5	3.4E-6
VBER	<1.0E-8	<1.0E-8	<1.0E-8
MER (dB)	23	26	26

and sampling is represented by the VBER. The minimal parameter of the VBER is 2.0×10^{-4} . The safe value of the VBER is at least $\leq 9.0 \times 10^{-5}$. The VBER is closely related to the CBER and MER. Practical application shows that it is suitable to optimize the antenna settings according to the CBER bar graph, in which the lower the value is, the better the situation is. The value of the CBER for stable DVB-T/T2 signals should be $\leq 5.0 \times 10^{-4}$.

From the measured reference values, it can be deduced that the scenario using only the passive antenna has the worst parameters, and consequently, the worst signal quality and CBER. This could be caused mostly by the localization of the receiving antenna (the CESNET Laboratory is located in the basement of the building). Despite optimizing the position and direction, a better reception of the signals was not obtained. The other two scenarios resulted in nearly ideal values of the signal quality and CBER. Therefore, we can consider these values a reference for our measurements.

Obtaining better values of the parameters for scenarios 1 and 2 would have been feasible if the antenna system was positioned on the roof of the building, but this was not possible with the local situation and conditions.

3.1.2 Measurements and optimization of the suggested scenarios

In all of the subsequent scenarios, the method was performed as follows. First, only the CATV system of the proposed scenario was measured (obtaining reference values). The measurements were realized with the optical line of various lengths constructed with a standard single-mode fiber type G.652. Thereafter, within each scenario, the sensing system was connected to a three-port optical coupler with a splitting ratio of 50:50, and the influence of the analog transmission system was verified. Both signals, i.e., CATV (1550.12 nm) and sensing system (1550.52 nm), were merged in the optical coupler. Such a spectral distance according to the 50 GHz grid was chosen as the worst possible scenario. The spectral spacing is shown in Fig. 10, where the measurements were performed using an OSA. In all of the subsequent scenarios, the measured values of VBER and MER did not change radically. VBER was the same for all scenarios, being $< 1.0 \times 10^{-8}$, and MER was in the range of 23 to 26 dB.

For scenario 1, the measured values of the signal quality and CBER (as shown in Table 2) show that the quality of the received signals is very low. This is verified by the impossibility of measuring all of the various lengths of the optical line in scenario 1. Figure 11 shows a large increase in CBER when simultaneously measuring the CATV and the sensing system with a 50 GHz spacing.

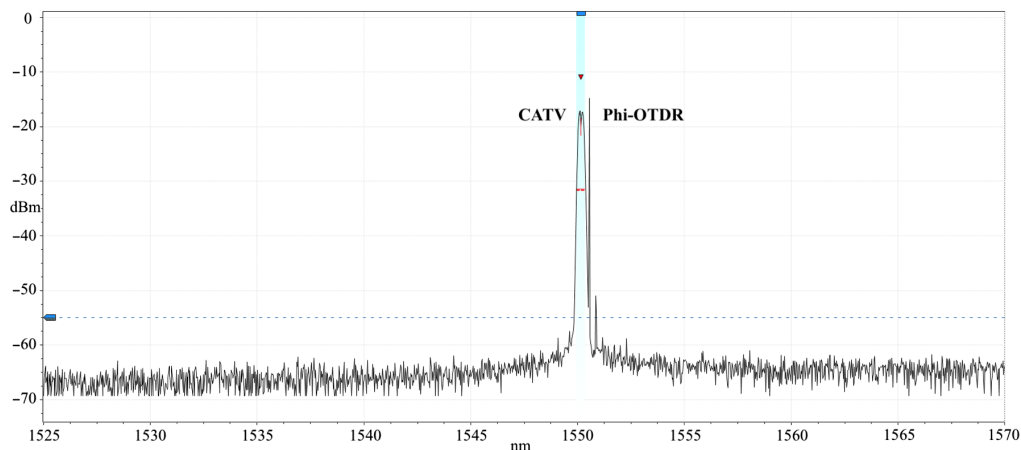


Fig. 10 Measurement results by the OSA in the CATV (1550.12 nm) and sensing system (1550.52 nm).

Table 2 Reference values for scenario 1.

Path length	Reference values		50 GHz grid (with the sensing system)	
	Signal quality (%)	CBER	Signal quality (%)	CBER
5 km	33	6.2E-3	15	1.2E-2
10 km	17	1.3E-2	Immeasurable	Immeasurable
25 km	Immeasurable	Immeasurable	Immeasurable	Immeasurable
50 km	Immeasurable	Immeasurable	Immeasurable	Immeasurable

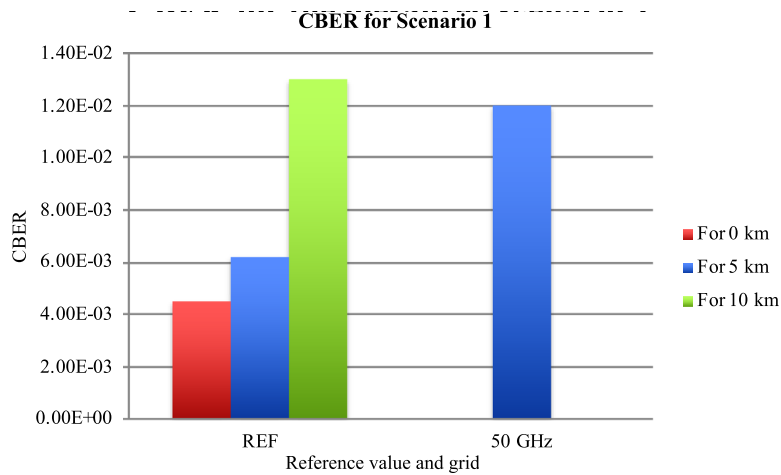


Fig. 11 CBER graph for scenario 1.

Scenario 2 (as shown in Figs. 6 and 7) shows the optimization of scenario 1 (Fig. 4), in which the active antenna and set-top box were used instead of the passive antenna. Such an optimization is supposed to provide more precise results for the evaluation of the parameters of the signal quality and CBER (as shown in Table 3). Figure 12 shows the verification of the functionality of scenario 2 with the sensing system Φ -OTDR implemented for an optical line of 5 km.

The measured and reference values for the various scenarios show that the sensing system Φ -OTDR influences the analog transmission in the CATV system. This is verified as the measured parameters, namely, signal quality and CBER, become worse (as shown in Tables 2–4). Through these measurements, our theoretical assumptions were confirmed and the cause was

Table 3 Measured values for Scenario 2.

Path length	Reference values		50 GHz grid (with the sensing system)		100 GHz grid (after the first optimization)		150 GHz grid (after the second optimization)	
	Signal quality (%)	CBER	Signal quality (%)	CBER	Signal quality (%)	CBER	Signal quality (%)	CBER
5 km	72	1.9E-5	68	8.1E-5	71	2.6E-5	72	2.0E-5
10 km	70	4.3E-5	56	1.3E-4	68	4.7E-4	70	4.4E-5
25 km	68	6.0E-5	47	2.2E-4	66	6.8E-5	67	6.1E-5
50 km	61	7.6E-5	41	2.6E-4	59	8.6E-5	60	7.7E-5

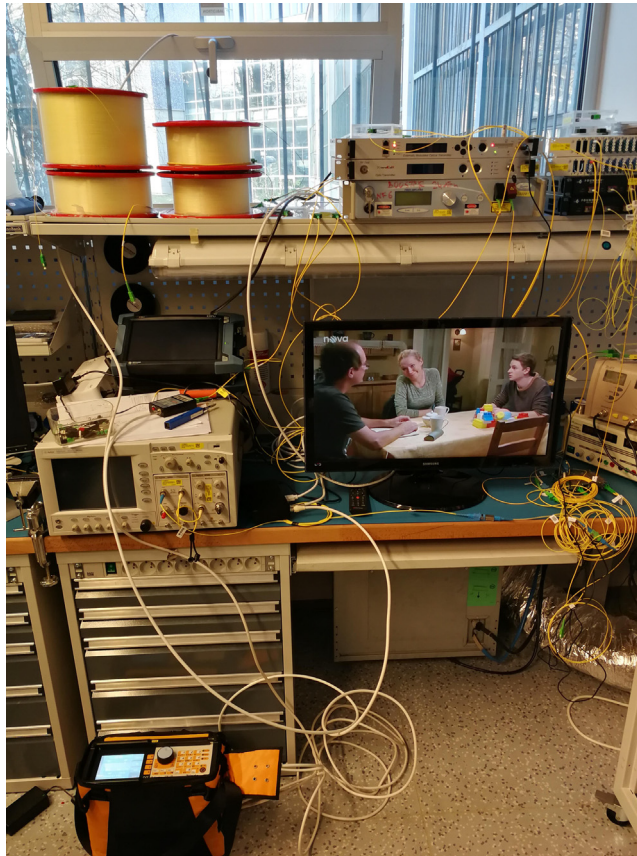


Fig. 12 Verification of the functionality of scenario 2 with the sensing system Φ -OTDR implemented for an optical line of 5 km.

Table 4 Measured values for Scenario 3.

Path length	Reference values		50 GHz grid (with the sensing system)		100 GHz grid (after the first optimization)		150 GHz grid (after the second optimization)	
	Signal quality (%)	CBER	Signal quality (%)	CBER	Signal quality (%)	CBER	Signal quality (%)	CBER
5 km	83	4.8E-6	81	1.1E-5	82	6.6E-6	83	4.9E-6
10 km	80	7.9E-6	78	2.3E-5	79	9.7E-5	80	8.0E-5
25 km	76	1.2E-5	73	4.1E-5	74	1.7E-5	75	1.3E-5
50 km	69	1.7E-5	58	6.5E-5	67	2.1E-5	68	1.7E-5

identified to be the low spectral distance (50 GHz grid) obtained at the sensing system signal with 1550.52 nm and CATV signal with 1550.12 nm.

3.2 System Testing with the Concurrent Analog Transmission

The results presented in this section are closely related and connected to those in Sec. 3.1, in which the optimization and measurements of the CATV system with a parallel sensing system were realized with a signal distance of 50 GHz. Unlike the previous testing, the signals were now placed at spectral distances of 100 and 150 GHz, which corresponds to the standard

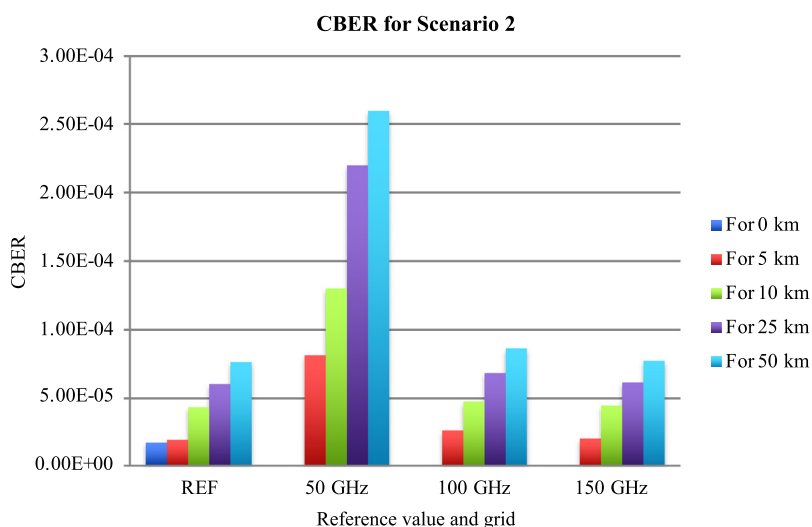


Fig. 13 CBER graph for scenario 2 after optimization.

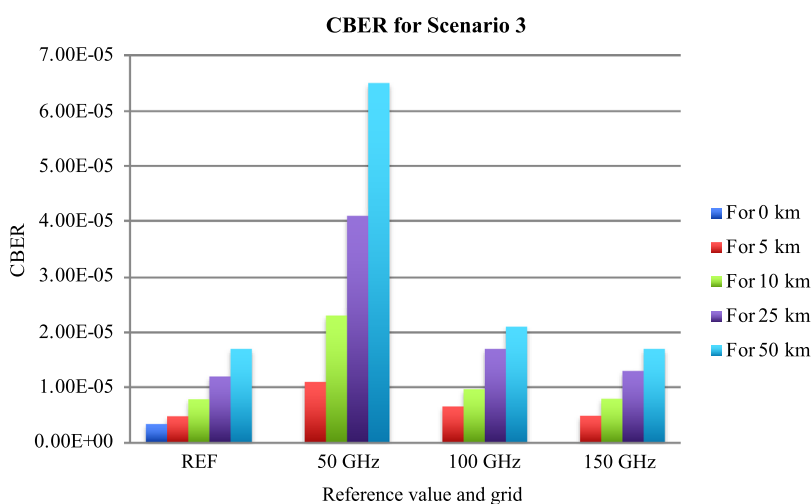


Fig. 14 CBER graph for scenario 3 after optimization.

telecommunication grid in the first case, and with a higher distance for the maximum suppression of interactions in the other case.

The reference and measured values presented in Sec. 3.1 were used for the comparison of the measured results. To ensure partial suppression or complete removal of the sensing system influence on the CATV system, the sensing system Φ -OTDR was retuned to another wavelength (spectral distances of 100 and 150 GHz from the CATV) in scenarios 2 and 3. Because of achieving maximal performance, the designed Φ -OTDR sensing system does not use a tunable laser; its functionality was represented by a tunable OTDR for dense wavelength division multiplexing (DWDM). The tunable DWDM OTDR was used for the measurement and verification, which allowed for operations at different wavelengths. After setting the DWDM OTDR wavelength to 1550.92 nm (100 GHz grid) and then to 1551.32 nm (150 GHz grid), the two scenarios were measured again.

The measurement results for testing and optimizing scenario 2 and scenario 3 are presented in Tables 3 and 4. The measured values and graphs in Figs. 13 and 14 show that, if the wavelength of the sensing signal is located at a sufficient spectral distance from the CATV signal, then only a minor influence on the CATV system occurs. If the sensing signal was located very close to the CATV signal (50 GHz grid), then the CBER graphs for scenario 2 and scenario 3 show a significant increase in the CBER before correction.

4 Summary

The measurement results show that the sensing system Φ -OTDR affects the analog transmission of the CATV system. In scenario 1 (for 50 GHz and optical path length of 5 km), the biggest increase in CBER could be due to the received signal from the passive antenna not being strong enough and having low quality for use in CATV transmission. Therefore, the measurement results of scenario 1 may be distorted. More relevant measurement results have been demonstrated for scenarios 2 and 3. For the 50 GHz wavelength grid in both scenarios, the CBER growth was evident, demonstrating that the Φ -OTDR affects the analog transmission of the CATV system. When using larger 100 and 150 GHz spacings, there was no longer a significant increase in CBER. In future work, we would like to address a significantly higher power of the Φ -OTDR signal in which the safe spectral distance between the CATV and sensing system can be expected to be higher than 150 GHz. In CATV distribution networks, passive splitting is often used, which leads to very strong signals leaving the distribution point. It will be very useful to verify the influence of launched CATV signal power signals to safe spectral distances.

Acknowledgments

This work was supported by the Ministry of the Interior of the Czech Republic under Grant No. VI20152020045. We would like to thank Editage for English language editing.

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