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# Simultaneous transmission of accurate time, stable frequency, data, and sensor system over one fiber with ITU 100 GHz grid

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## ARTICLE INFO

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## ABSTRACT

Optical fiber is the most used medium for current telecommunication networks. Besides data transmissions, special advanced applications like accurate time or stable frequency transmissions are more common, especially in research and education networks. On the other hand, new applications like distributed sensing are in ISP's interest because e.g. such sensing allows new service: protection of fiber infrastructure. Transmission of all applications in a single fiber can be very cost efficient but it is necessary to evaluate possible interaction before real application and deploying the service, especially if standard 100 GHz grid is considered. We performed laboratory measurement of simultaneous transmission of 100 G data based on DP-QPSK modulation format, accurate time, stable frequency and sensing system based on phase sensitive OTDR through two types of optical fibers, G.655 and G.653. These fibers are less common than G.652 fiber but thanks to their slightly higher nonlinear character, there are suitable for simulation of the worst case which can arise in a real network.

## 1. Introduction

Networks built up on optical fibers are very suitable for the fast, reliable, and efficient transfer of a big amount of data. Technical specifications for the passive optical network including 40 Gbit/s and 100 Gbit/s for downstream and 10 Gbit/s for upstream, which has been developed by IEEE (Institute of Electrical and Electronics Engineers) as the IEEE 802.3ca specification is still continuously updated [1,2].

According to [3] and other big telco market players, the increasing trend of the data transfer all over the world will rise even more steeply. There is not actually any other technology or a transmission medium which could compete with optical fibers. New specification for 100 Gbit/s wireless is known [4] but, it is still not designated for a common use.

Telecommunication access networks highly contribute to the overall size of the data being transmitted over the passive optical networks. The results of current research in the field of optical packet switching can facilitate to the additional utilization of bandwidth. Used optical switching technology still relies on the OEO (Optical-Electrical-Optical) [5] and other conversion mechanisms. Those devices have a major problem with optical buffers and QoS and they face the processing of queues and any commercial method or technology is not available yet. Researchers use optical fibers to prolong the length to affect it, but it increases the transmission delay [6].

The WDM (Wavelength Division Multiplex) technology is designed for use of a single fiber to transfer tens or hundreds of wavelengths. Nowadays, data transfer is not only one application of fiber networks. New applications like accurate time transmission, stable frequency transmission or sensing are still more common. Especially NREN (National Research and Education Network) may be one example of such network. Sensing using standard optical fibers represents an important part of a research in the field of industry, perimeter security, and the coexistence of sensing signal with data transmission is necessary to be evaluated, and is the issue of this paper.

The rest of this paper is structured as follows. In the next section we get an overview of the related works. Section 3 presents the infrastructure for accurate time and stable frequency transmission, sensing stem, and data system for our research. Section 4 describes the measurement setup and results discussion. Section 5 concludes this paper.

## 2. Related works

Accurate time and stable frequency are special applications of transmission through optical networks and are used e.g. for metrology. Researchers around the world widely study these fields for improving system parameters, like total reach, accuracy or stability. Authors [7] transfer accurate time by passive listening in a 10 Gbit/s optical fiber transmission. In other words, the proposed technique listens data in 10

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Gbit/s fiber optical network with double clock comparison. They reached ~300 ps accuracy over 5 km distance. The work [8] extends a distance up to 500 km of optical fiber link. Although, they have RMS accuracy better than 1 ns for several months, the results show that there is no linear degradation of accuracy with increasing distance. On the other hand, temperature dependence may have a huge impact on time accuracy, according to [9]. Nowadays, the total reported distance of a high-accuracy time transfer was more than 2000 km [10]. CESNET system allows transmit accurate time (with a accuracy 10–100 ps) over 1000 km. To demonstrate the accuracy clearly, a signal in an optical fiber travels a distance to 3 cm in 100 ps (vacuum space). Accurate time transfer is done by own developed TTAs (Time Transfer Adapters) [11].

Another service, stable frequency transmission may be utilized, besides metrology, also for remote calibration of lasers. Authors [12] deal with a comparison of two Cesium beam frequency standards connected via optical fiber network. Furthermore, a comparison with GPS link is proposed too. The results prove frequency stability for fiber and GPS method in a range from $3 \cdot 10^{-15}$ to $1 \cdot 10^{4}$. Another article [13] presents stable frequency transmission over 920 km distance. Frequency of the signal after transmission over 920 km can be expected with deviation values less than $4 \cdot 10^{-19}$. The work [14] presents simultaneous transmission of stable frequency and Internet data over standard optical telecommunication network. Digital stream uses channel 34 of DWDM grid (1550.12 nm) and ultra-stable frequency signal uses channel 44 (1542.14 nm). The gap between both services is high enough to eliminate interference. The article [15] demonstrates the ultra-stable frequency transmission over 300 km long real fiber network. Furthermore, parallel transmission with data communication by DWDM technology is done. Ultra-stable frequency transmission uses channel 44 (1542.14 nm) and Internet data channel 43 (1542.94) and 42 (1543.73 nm), respectively. But there is not presented any interference measurement or analysis. In our work, we use 4 services in consequent channels with 100 GHz channel spacing. Moreover, sensing signal uses high-power pulses which may cause nonlinear phenomena in the fiber. The results presented in [16] describe measurements for three different pulse durations (200, 500, 1000 ns) through 2 fibers (G.652, G.655). Current paper describes measurements for pulse durations 200, 500 and 800 ns through G.653 and G.655, and also their combination.

## 3. Infrastructure for accurate time and stable frequency transmission

The presented research in this article and the topic have many related works with articles and research done by CESNET, a.l.e. It is an association of universities of the Czech Republic and the Czech Academy of Sciences. It operates and develops the national e-infrastructure for science. The first project about the accurate time and stable frequency transmission was introduced by [17] in 2011. The authors used the CESNET infrastructure, which consisted of over 5000 km of optical fiber lines.

The first experiment with the bidirectional transmission of the accurate time and stable frequency was performed between Prague and Brno (the optical path over 300 km) in the Czech Republic. Two important organizations, namely Institute of Photonics and Electronics (IPE) in Prague and Federal Office for Metrology and Surveying (BEV) in Vienna were connected over the CBF (Cross-border Fiber) between the Czech Republic and Austria over a pair of fibers.

Since 2016, CESNET has upgraded optical filters with own developed bidirectional amplifiers CLA BiDi (Czech Light Amplifier Bidirectional) between Prague and Brno. Nowadays, CESNET operates more than 6 lines for accurate time and stable frequency transmission with total length over 900 km.

### 3.1. Sensing system

For a long time, the main use for standard optical fibers was only high capacity data transmission over long distances. However, the current trend is to use the fiber capacity as much as possible to optimize the number of leased fibers and therefore reduce costs. Moreover, thanks to decreasing price of optical components such as stable lasers or modulators, distributed sensing for fiber self-protection is more desirable. Optical fibers are sensitive to acoustic vibrations (although this is backgrounder for case of data transmission) and in appropriate configuration sensing system can monitor activity along fibers (also in case the optical cable is buried more than 70 cm underground). Especially in case of critical infrastructure which connects e.g. bank or government, the cable interruption may have enormous consequences. Another issue is there are always some shared risks in dense localities in cities, i.e. even the back-up lines (circuits) might be located nearby, so some larger failures (constructions, infrastructure repairs etc.) may affect the complete circuits and break the connection. That is why CESNET started the development of own sensing systems, as a possible unique instrument for precise care of own infrastructure. Current sensing system (so-called phase sensitive OTDR or Φ-OTDR) is based on optical time domain reflectometry and uses the Rayleigh backscattering. The system total distance reach is in order of tens of kilometers with a resolution of tens of meters. Main advantage of the system is one end solution and relatively easy localization of detected events compare to other methods. On the other hand, power level of measured backscatter is very low and hence high power pulse signal is necessary to be used. If simultaneous transmission of multiple applications is considered, it is necessary to analyze possible interaction and evaluate optimal channel spacing between signals. CESNET has started testing and evaluating parallel services transmission (accurate time/stable frequency transfer, high-power sensing signal, and 100 Gbit/s DP-QPSK data) in 2017.

### 3.2. Data system

The commercial solution of Coriant Groove™ system was used for a data transmission in the measurement. This system allows high-speed data transfer (up to Tbit/s) through tunable DWDM (Dense Wavelength Division Multiplexing) line interfaces with reconfigurable speed rate and modulation format. For example, the 100G specification uses DP-QPSK (Dual Polarization Quadrature Phase Shift Keying) modulation, the 150G specification uses DP-8QAM (DP Quadrature Amplitude Modulation) modulation, and the 200G specification uses DP-16QAM modulation. In our case, the 100G data rate for the measurement of interaction was used.

## 4. Measurement setup

The measurement scheme contains four services: accurate time transmission, stable frequency transmission, data transfer, and sensing signal. Detailed measurement scheme showing transmitted services is depicted in Fig. 1. As can be seen, each service is set with wavelength according to ITU DWDM 100 GHz grid [18]. The main aim was proving the possibility of simultaneous services in one fiber and with minimal channel spacing. Requirement on minimum channel spacing is because in some cases it is not possible to use whole spectrum but only dedicated CWDM channel for multiple services. Accurate time transfer (1550.12 nm), frequency transfer (1552.52 nm), and 100G data (1551.72 nm) were multiplexed together in a standard telecommunication multiplexer. Multiplexed signal from multiplexer is connected by patch cable with SC/APC connectors to sensing system. Setup scheme of sensing system is shown in Fig. 1 detail. In general, continuous wave signal from ultra-narrow linewidth stable laser is amplified by EDFA (Erbium Doped Fiber Amplifier) and modulated by pulse signal in acousto-optic modulator (AOM). Maximum available EDFA output power is 27 dBm but due to insertion loss of AOM and

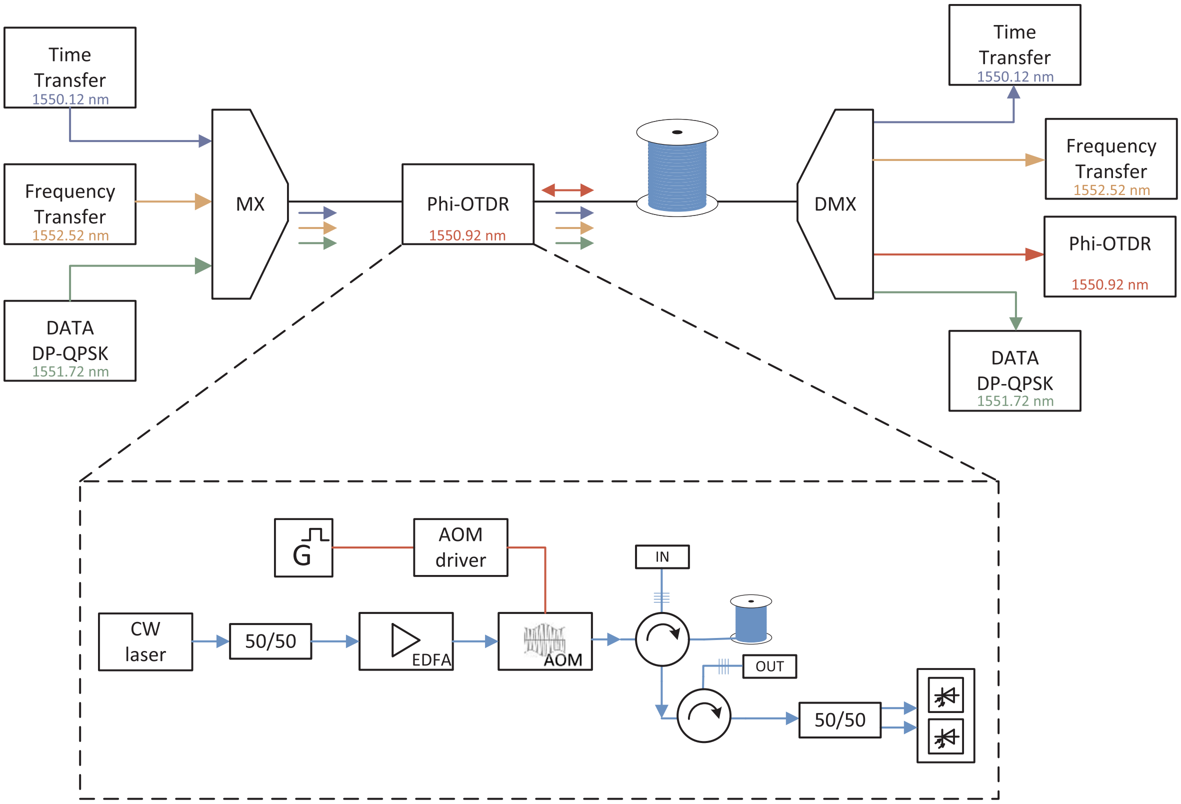

**Fig. 1.** Measurement setup for services interferences.

circulators (necessity of using two circulators is described below), the maximum power launched into the fiber is about ≈23 dBm. While the pulse propagates within the fiber, the backscatter signal is continuously measured on photodetector. This enables us to receive profile of the refraction index from each point of the fiber. Each local temperature change or interaction between photons and phonons from acoustic wave cause local refraction index change. Finally, all changes along the fiber can be evaluated by the system. As mentioned before, backscatter signal is very low. Hence it is necessary to minimize insertion loss (IL) of all components after amplification. In our case AOM has IL ≈2 dB, next ≈2.5 dB has circulator in which signal passes from port 1 to port 2, then is reflected (FBG has reflectivity ≈90%) to port 3. Multiplexed signals are launched into the fiber through port 2 and then continue together with sensing signal to port 3. In comparison with standard setup where all signals (including sensing signal) are combined in multiplexer, the loss of pulse signal is more than 1 dB lower because in the second case the IL of multiplexer is ≈3 dB and IL of circulator ≈1 dB which is ≈4 dB in total. Evaluated fiber link contained various lengths of optical fibers: G.653 (7 km) and G.655 (10 km), which were first tested separately and then together.

For the accurate time transfer, the own developed TTAs were used (for more details see [11]). According to the results [16,19], possible transfer of all services in the same fiber was verified (tested separate fibers G.652, G.653, and G.655) with 100 GHz channel spacing. On the other hand, if longer pulse duration and higher output power of sensing system is used more nonlinear phenomena can occur in the fiber. Especially in case of dispersion shifted fibers.

The spectrum of the DWDM signals is depicted in Fig. 2.

### 4.1. Results and discussion

The measurement was divided into two main parts. First part of the measurement provides the comparison of results for both fibers and the second part describes results for both fibers in combination. For data evaluation of the measurement pre-FEC-BER and Q factor were saved. In case of TTAs, accurate time values were observed. Pre-FEC-BER and Q factor were evaluated by Coriant system. Graphs in Fig. 3 contain evaluation of Q factor for both types of fibers (G.653 and G.655) for different pulse durations. It is necessary to mention here that pulses with higher durations have higher energy and hence longer distances can be achieved. On the other hand, the spatial resolution of two close events is also higher. However, the fiber G.653 is not very common in the Czech Republic. Japanese ISPs (Internet Services Provider) still use it in their networks. The second fiber type, fiber G.655, is widespread all around the world. In left graph of Fig. 3, it is obvious fiber G.653 has almost linear dependence of Q factor for increasing EDFA output power of sensing system. The situation is similar for all tested pulse durations. Graph on the right side of Fig. 3 shows results for fiber G.655. In this case the situation is different, Q factor is approximately same for EDFA output power up to 22 dBm (this corresponds approx. 18.5 dBm at the beginning of the fiber link). For higher output powers the Q factor value starts decreasing. The obtained results confirmed our assumptions because G.653 fiber is more nonlinear than G.655.

Left graph in Fig. 4 shows the influence of high-power pulse signal on bit error rate (BER) of 100G DP-QPSK. Dependence of BER is again almost linear for the G.653 fiber for all pulse durations. The green line in the graph represents power levels with no time transfer errors. Average delay of time transfer reached 34968.245 ns. After reaching some threshold (in this case 23 dBm) time transfer (represented by the red line) stopped working at all. In case of G.655, time transfer worked for all time without any error or losses. Average time of delay for this type of fiber was 50768.007 ns due to different lengths of the fibers. However, pre-FEC-BER values seem to be small for data transfer. Necessarily, it must be considered it is BER before repairing algorithms. Thanks to implementation of FEC algorithm the system is able to correct all lost data. Frequency transmission was stable for all measurements.

The last graphs (in Fig. 5) show results for a combination of G.653

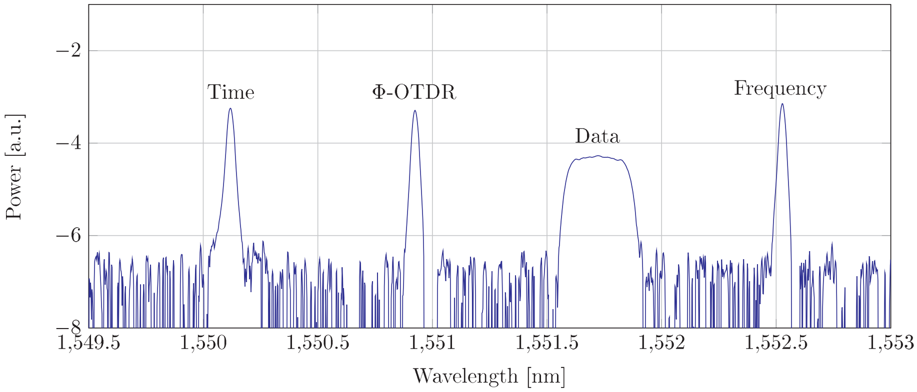

**Fig. 2.** Spectrum of the DWDM signals under evaluation.

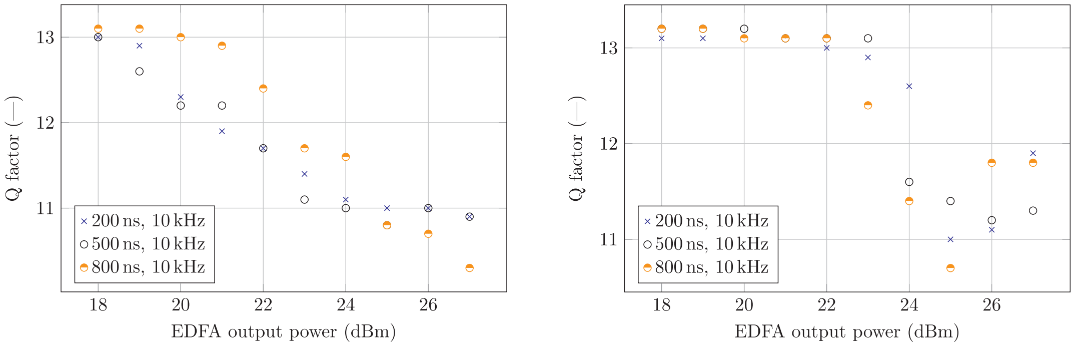

**Fig. 3.** Influence of high-power pulse signal on quality (Q factor) of DP-QPSK data signal for G.653 (left) and G.655 (right) fibers.

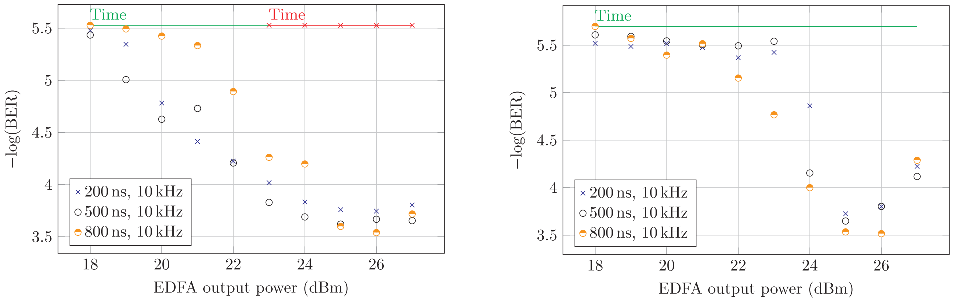

**Fig. 4.** Influence of high-power pulse signal on quality (BER) of DP-QPSK data signal for G.653 (left) and G.655 (right) fibers.

and G.655 fibers. The Q factor dependence has almost linear dependence for all pulse durations. We expected the worst results for 800 ns pulse duration but left graph in Fig. 4 provides worst results for 500 ns pulse duration. This was probably caused by limited length of measurement time. For basic idea how influenced the data is, it has no marginal impact but it has also showed that for future measurements it would be suitable to measure for longer and therefore more demonstrative time. The Graph on the right side provides pre-FEC-BER dependence and time transmission stability. However, pre-FEC-BER decreases with higher level of pulse signal still it is enough for stable data transmission thanks to FEC correction algorithm. Time transmission had no errors or losses until EDFA output power reached 25 dBm, then TTAs stopped working, according to Fig. 5. Average delay of time transmission had 85674.412 ns up to 25 dBm.

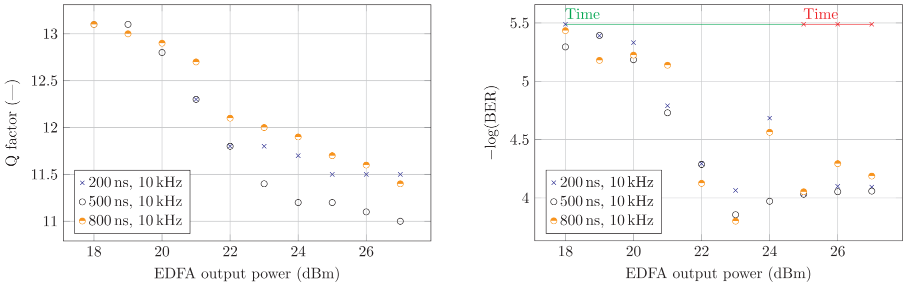

**Fig. 5.** Influence of high-power pulse signal on quality (Q factor – left and BER – right) of DP-QPSK data signal for combination of G.653 and G.655 fibers.

## 5. Conclusion

In this paper we shortly introduced current data transmission, represented by 100G DP-QPSK signal in our case, special applications like accurate time and stable frequency transmission, and new rapidly growing application, distributed sensing. All applications are represented by different types of optical signal and hence it is necessary to evaluate their possible interaction. Presented results confirmed the G.653 fiber cause more interference of signals. Even the accurate time transmission which is based on slow OOK modulation was affected and stopped working if some threshold of pulse power level was exceeded. Based on the results, it can be said that 100 GHz channel spacing is not high enough and to eliminate possible interaction the higher spacing must be used.

Commercial system for data transferring (Coriant GrooveTM) evaluates BER, Q-factor, and other parameters by itself. We did not consider a measurement in the long term. Limited time of measurement possibly caused increased BER values (G.655) as a measurement error. Long term measurement was not applied. The main purpose of our measurement scheme was not an emphasis on data BER but possible influence of fiber sensor on data transfer, and if, then how much.

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## Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.yofte.2017.11.016.

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