Efficient use of expensive components of optic vibration sensor

Vít Novotný, Petr Sysel, Aleš Prokeš, Pavel Hanák, Karel Slavíček

***Abstract*—This paper studies possible utilization of fiber optic switches for more efficient utilization of expensive electronic components which are the core of long range fiber-based sensors systems. Complex architecture of such systems starting to be used for monitoring of events along various linear objects like railway lines, product lines or object defense perimeters, are based on rather expensive ultra narrow band laser source and interrogation electronics. Possible sharing of these expensive components for sensing on more fiber optic lines is discussed in this work.**

***Keywords*—optical fibre, distributed sensor, mechanical vibrations, -OTDR.**

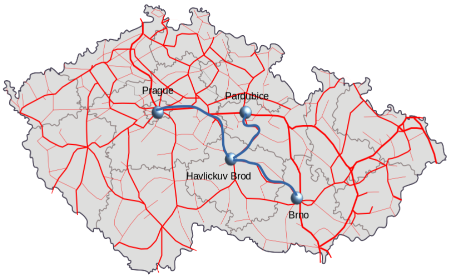

Fig. 1. Early field test of sensor system alongside the railways.

I. INTRODUCTION

Fibre optics has undergone a rapid ramp-up and has been widely deployed during the past two decades. Wide deployment of installed base of fibre optic allowed further research on utilization of the fibre not only for data and voice transport but for sensing applications as well. One of the sensing systems utilizing fibre optics is the Long-Range Optical Fibre Based Distributed Mechanical Vibration Sensing System developed in terms of project VI20202017078.

The most common solutions of this problem are based on the reflectometry principle, [5], [4]. Localization of the physical quantity incidence is based on the transmission of short-time and high power pulses that go through the fibre and the portion of the light is scattered due to elastic or inelastic effects that are influenced by a physical quantity (temperature, pressure, radiation, strain, etc.), which can be measured by processing of scattered signal. There are several attempts to utilize the OTDR principle for construction of a distributed sensor like [1], [2], [10] and [7]. Some of them are intended to be used for scientific purposes like seismic activity monitoring [3] and also several results in sensor data processing are present [6]. Intention or the above mentioned project was to construct a long-range distributed sensor and test it in real environment. The sensing system developed in terms of the above mentioned project has a reach up to about 100 km on fibre optics cable installed in standard telecommunication manner, 80 to 150 cm under the surface inside a legacy HDPE tube with spatial resolution 100 m. The sensing system is described in detail in [8].

The electronics used for this sensing system is a bit expensive as it needs a very narrow signal source. This paper analyses abilities of the electronics to be shared for measurement on more fiber optics lines. Currently there are several types of fibre optics switches available, namely MEMS based switches and magneto-optics switches. In case of utilization of fiber optics switches the switching time is yet another variable which should be taken into account for sensor reach and resolution analysis.

This paper explains this optional sensor system enhancement on top measurements performed in real environment.

II. FIELD MEASUREMENT

We have performed a set of early field tests in several locations: railway road, high voltage transformer station and firing range. In all cases, the measurement electronic was placed in a location where several fiber optic cables coming from more directions were available. This fact led us to the idea of sharing the expensive electronics equipment for sensing on more fiber lines. Detailed information on the above mentioned early field tests are documented in [8] and [9]. A brief summary of experience in the field measurement serving as inspiration for this paper is summarized here.

The longest fiber optic lines used for sensor system field testing are lines alongside the railway. The measurement system was installed in the city of Havlickuv Brod where three railroads are meeting: one towards Brno (our city) one towards Prague (our capital) and one towards Pardubice. All of the lines are about 100 km in length. Using our current model of sensor system, we were able to measure these lines one by one with manual reconnecting. The situation is described in figure 1.

Using the sensor system, we developed, we were able to identify basic events like movement of the train or movement of cars which were stopping at the railway crossing and waiting till the train passed. The waterfall image of the train going alongside the fiber line is in figure 2.

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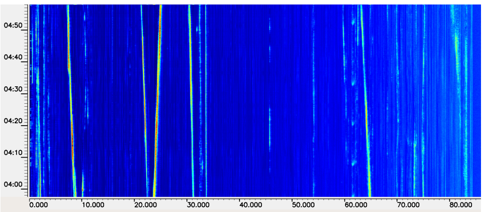

Fig. 2. Waterfall image of moving trains.

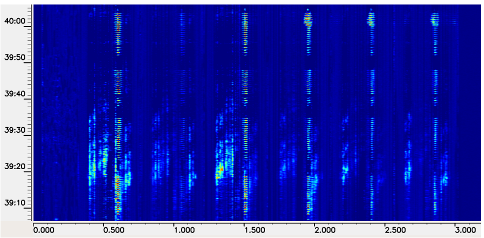

Fig. 3. Waterfall image of people walking alongside the fence of transformer spot . The measurement was performed on three optic lines connected in a loop.

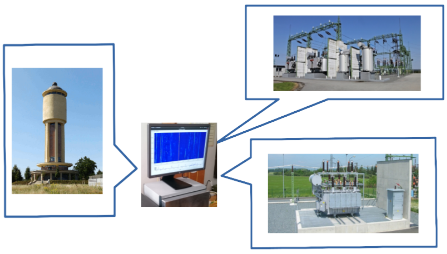

Fig. 4. Structure of defence perimeter monitoring for utilities technology installations estates.

Another sensor system testing was in a form of perimeter monitor, where the system was tested on a fiber going alongside the fence bordering the estate of a high voltage transformer station. In this case the fiber length was only about 1 km, but there were more fiber optics lines in the same cable available. This field test served as a model of a typical defence perimeter monitoring situation, where several fiber loops terminated at the same location should be monitored. Waterfall image reflecting a group of three persons walking alongside the boundary fence of a high voltage transformer cell is present in figure 3. In this case it might be interesting to use the sensor system in a pseudo parallel way measuring on the same fiber loop by turning in counter-propagating directions and of course, in more general case to share the electronic part of the sensor system for measurement on more fiber loops. An expected deployment of our sensor system in this kind of application is presented in figure 4. There are many possible applications of the type defense perimeter protection like estates of transformer stations, water sources or gas compressing or pressure transforming stations.

Another early field test was performed on a shooting range. Here the fiber is laid alongside the access roads and the sensor system is intended to be used to prevent unauthorized persons entering the shooting range during the live firing. In this case there were fiber lines of length about 1 km available. Here we have tested measurement with a 20 km launch fiber simulating remotely connected fiber of interest. The waterfall is presented in figure 5.

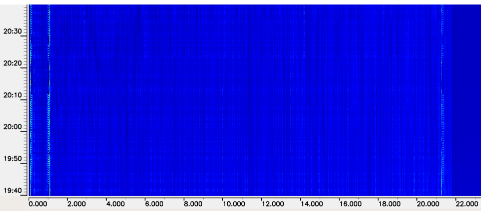

Fig. 5. Driving a wood stick into ground. Sand type of earth. About 1 km measurement fiber looped back through a 20 km spool of launch fiber.

III. TIMING ANALYSIS OF A SINGLE FIBER SYSTEM

In case we plan to share measurement electronics for more then one fibre path, we need to analyse timing of the measurement process. To be able to detect short duration events or sparse events, it is necessary to be able to perform measurement in appropriate frequency. Localization of the physical quantity incidence is based on the transmission of short-time and high power pulses that go through the fibre and the portion of the light is scattered due to the measured physical effect. According to the time delay d between instances of light pulse transmission and the instances of the response sample reception the location x of response generation can be calculated using formula

$$x \approx \frac{d v_g}{2} \tag{1}$$

where v_g is the he group velocity of the light. In case of common telecommunication fiber whose index of refraction is $\eta = 1.47$ the group velocity of the light is about $v_g = 200000 km.s^{-1}$. In case of planned reach y of the sensor system, the time delay d which can be expressed as

$$d \approx \frac{2y}{v_g} \tag{2}$$

, in out case where the planned reach of the system is about 120 km

$$d \approx \frac{2 \cdot 120 km}{2 \cdot 10^5 kms^{-1}} = 1.2 ms$$

This time delay d determines the duration of events recognizable or not recognizable by the sensor system.

Fiber optics sensors of this type are planned mainly as a tool for defense perimeter monitoring. It should be able to detect movement of humans and commonly used vehicles as cars, trucks or motorbikes. E.g. a motorbike 2 m in length going at speed 180 km/h needs 40 ms to go over a given reference point. The reference point can be e.g. point on earth surface with shortest distance to the (underground) fiber optic cable used for sensing. This example can be taken as the shortest event we intend to recognize by the sensor system as cars and trucks are longer and usually not travelling at speed higher than motorbikes and walking or running humans need yet longer time to dismiss from reach of the sensor system.

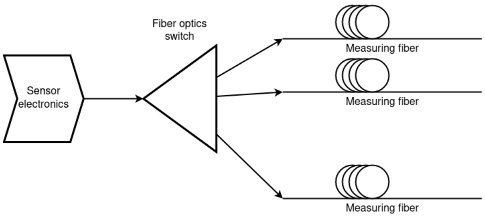

Fig. 6. Structure of a distributed sensor using more fiber optics lines.

In case of utilization of the maximal reach of the sensor system - 120 km - we have 40/1.2 = 33 pulses available to detect a motorbike from this example. Of course, it is not necessary to use so many pulses to detect the event of our interest. This sample calculation led us to the idea of sharing the electronic part of the sensor system for detecting events of interest on more fiber lines. Sharing of the electronics, especially the expensive high precision ultra narrow spectrum laser source, for more sensing fibers can make the sensor system more cost attractive and support its wider deployment in real environment.

The sharing of the electronic part of the sensor system is a kind of time division multiplexing. The proposed structure of a set of distributed sensors sharing the key electronic parts is presented on figure 6.

To share the signal source for measurement on more fiber optics lines, we have to consider several time constraints:

- The light propagation delay d which depends on the length yof the measuring fiber line according to equation 2. (1.2 ms in case of sensor system developed in terms of current project for fiber length up to 120 km). The time d is needed for light propagation throughout the fiber optics line. That means, once the signal is sent into the given output fibre optics line, we have to wait till we can retrieve the back-scattered signal at the receiver. Or, in case the first part of the line is not interesting for us, we can utilize the appropriate time slot for another line. At the first step, we are waiting for back-scattered signal retrieval and processing before switching to the next measuring fiber line.
- The minimal time duration t_E of events which should be detected by the sensor system. In case of intended applications, we like to detect moving persons or vehicles. The movement of persons or vehicles causes an event (mechanical vibrations) detectable by the fiber line for a certain time period only. During this time period a predefined number of impulses should pass through the point of presence of the event.
- The number p of impulses we need for reliable enough detection of the event.
- The switching time t_S needed by the optical switching element to switch the path from one output to another one. This time is determined by construction of the switch and in general depends on used technology (MEMS based switches versus magneto-optical switches) and in some cases on the number of output ports.

Time constraints mentioned above will be discussed in more detail in the following sections.

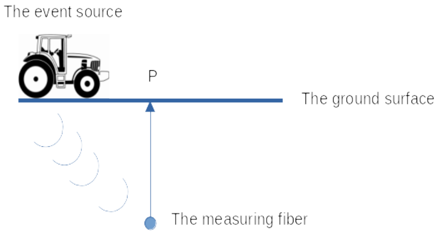

Fig. 7. Estimation of time of event detectability.

A. *Light propagation delay*

Let's have a sensing fiber of length y. The time needed for the light pulse to travel alongside the whole length of the fiber and for the back-scattered signal to return back is determined by equation 2. To this time is necessary to add yet the impulse length, which can be rather short, typically $100ns$ for short length measurement fiber and up to $1\mu s$ for longer fiber lines. For long enough sensing fiber the pulse length can be disregarded, but for shorter ones (about 1 km length fiber) we should take it into account even the impulse length is about 1% of the propagation delay. Commonly, we cover the impulse length influence with some time margin t_m.

Events shorter than the time resolution might not be recognized by the sensor system. In case of events shorter than the system time resolution, the event recognition is a matter of probability as it depends on the impulse length and on the phase shift between the light impulse insertion into the fiber line and the event occurrence. It can be modeled by geometric probability.

B. *The time duration of events to detect*

The event of interest lasts only for a certain period of time t_e. The duration of the fastest even we like to detect is denoted by t_E. For estimation of the time t_e we use the reference model denoted in figure 7. Commonly, we intend to detect a moving vehicle or person. As an estimation of the time t_e during which a moving vehicle can be detected we take the time the vehicle needs to pass over a predefined point, e.g., the vertical projection of measuring fiber to the ground surface. Of course, the moving vehicle can generate mechanical vibrations even for a longer time. That means since it is in a small distance in front of the point P till some distance behind it. The time the vehicle needs to pass over the point P is the worst case, that means the shortest time the vehicle can be detectable by the sensor. For this reason we use it as approximation of the time t_e.

An estimation of time needed by a motorbike is presented at the beginning of this section. Larger and slower vehicles are detectable for a yet longer period of time. We can use the time during which a speedy motorbike is detectable as calculated in the above mentioned example for estimation of the t_E, the minimal event duration.

C. The number of impulses needed to detect an event

The number of impulses needed to detect an event depends on the sensitivity of the receiver and the analog front end of the processing electronics. To properly determine this number, a lot of experimental measurements under varying conditions are needed. In case of measurement on one fiber line only, impulses are sent continuously. A large number of event responses received is used for statistical processing which can improve sensitivity of the system. For the current early stage of sensor system testing, we use predefined value for the number p of impulses used for event detection as $p = 5$. For fiber lines of shorter lengths we can use more impulses as the time of the flight of the light from the source to the end of measuring fiber line is much lower. If the measuring impulses are transmitted with time period d given by the length of measuring fiber line according to equation 2, the guaranteed number of impulses which can detect the event is given by

$$p_m = \frac{t_E}{d} \tag{3}$$

D. Switching time

We have studied properties of several types of fiber optics switches. The most widely available switches are MEMS (MicroElectroMechanical Systems) based. The times the switch needs to switch between various input/output ports are typically in the range 0.5 - 1 ms for MEMS switches operating on legacy single-mode fiber and arbitrary telecommunication wavelengths. For testing, we have used a four-port MEMS switch Fibermart (subject of availability). In case of long range sensing installations (lengths of fiber sensor lines about 100 km), the estimation of switching time t_S converges to the propagation delay d. For shorter measuring fibers, we'd like to have a more precise estimation of the switching time t_S as we want to optimize the number of lines we can share the sensor unit for.

E. Sharing the measuring electronic for more fiber lines

Lets have N measuring fiber optic lines of maximal length y and the shortest event to be reliably detected have duration t_E. The number of impulses meeting this event is given by simple equation 4

$$p = \frac{t_P}{N \cdot t_E} \tag{4}$$

where

$$t_P = d + t_S + t_M \tag{5}$$

is the time interval between two consecutive impulses launched into the given fiber line.

IV. LAB MEASUREMENT AND FIRST EXPERIMENTS

To verify the usability of fiber optics switches as for sharing of electronic part of the sensor system for more sensing fibers, we have performed a lab measurement of the time needed to switch from one fiber line to the next one. We have reused the preliminary lab model of the fiber optics switch module originally intended for manual reconnecting of the measuring fibers. This lab model is based on a simple four port MEMS based fiber optics switch equipped with a microcontroller development board Teensy 3.2. The module is presented in figure 8. To evaluate the time since the the optical signal is reconnected from one fiber line to another one we needed an analog based detector. As a best solution available we have identified reuse of a bit old fashioned transceivers used originally for ATM networks. These transceivers have a very simple interface: differential serial data communication (TX and RX) and in case of the receiving part a Carrier Detect (CD) pin signalling presence of an optical signal. We have used a pair of such transceivers to detect the optical signal and connected the CD pin to and oscilloscope. The module used for optical signal presence is presented in figure 9.

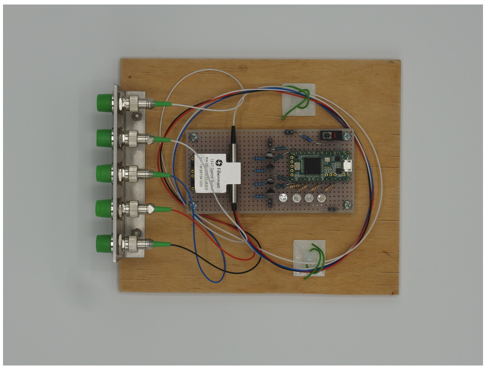

Fig. 8. Fiber optics switch used for lab measurement.

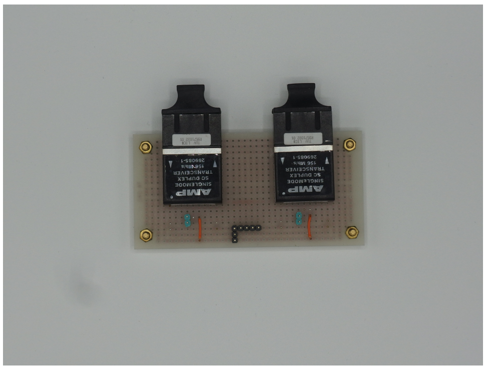

Fig. 9. Switching time measurement tool.

The switching time varies from 0.62 ms up to 0.85 ms depending on if the signal is switched to directly neighboring channel or not. The switching time was measured as the time interval since the electrical signal asking for light path switch was issued, till the signal on the requested output appeared. In common, fiber optic switches provide a signalling pins confirming that the light path is set to given direction. Reading of this signal by a microcontroller and then after by the computer controlling the whole sensor system means additional processing delay that in general will not necessarily be significantly shorter than the switching delay variation. However, this measurement gave us a reasonable estimation of the switching delay and allows to calculate the limitations of number of lines, which can be served by one electronics module while providing expected level of signal resolution.

Now let's recall the example from section III: The shortest

TABLE I
AN EXAMPLE OF MAXIMUM NUMBER OF FIBER USABLE IN PARALLEL TO DETECT EVENT OF LENGTH $40ms$.

Fiber length in km	20	40	60	80	100	120
Maximum number of lines	20	13	10	8	6	5

event which should be detectable by the sensor system has duration of $t_E = 40ms$. For better reliability of event detection we require at least the minimum number of impulses m to be incident with the event to be detected. A good estimation of m is $m = 5$. Now lets calculate the maximal number N of fiber lines which can be served by one shared electronic part of the sensor system. According to measurements realized, a good estimation of switching time plus necessary margin $T_S + t_M$ is $1ms$. The time needed to perform m consecutive measurements on a given fiber line is $m \cdot d$. To better imagine, the maximal number N of fiber lines of length y which can be used by the sensor system can be estimated by equation 6.

$$N = \frac{t_E}{m \cdot \frac{2y}{v_g} + t_S + t_M} \tag{6}$$

In case of events with minimal duration $t_E = 40ms$, the maximal number of fibers which can be used in parallel is summarized in the table I. In this example we assume the number of light pulses incident with the event $m = 5$.

It is clear, that for long length fiber lines the maximal number of fiber lines which can be server by one electronic part of the system is very limited. On the other hand, in case of very long fiber lines, the expected applications are monitoring of railways, oil or gas pipes and similar linear structures. Here the placement of the electronics is expected in the junction or crossing of several lines and the number of lines which meet at the given point is limited as well. In case of monitoring of defence perimeter, the theoretical number of loops which can be monitored by the system also corresponds to the number expected by the application.

V. CONCLUSION

Utilization of fiber optics switches for price optimization of the Long-Range Optical Fiber Based Distributed Mechanical Vibration Sensor System seems to be viable and usable in real environment. The concept still needs further development and improvement, especially interconnection with an hardware frequency generator used for synchronization of impulse generator, fibre optics switch and back-scattered signal receiver. This synchronization will improve the number of impulses available for single event detection and this way improve the sensitivity as well.

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REFERENCES

[1] Eric UDD, William, B. SPILLMAN Jr. Fiber Optic Sensors: An Introduction for Engineers and Scientists (Second edition). John Wiley Sons, ISBN 978-0-470-1264-4, New Jersey, USA, 2011

[2] LEE, Byeong Ha, Young Ho KIM, Kwan Seob PARK, Joo Beom EOM, Myoung Jin KIM, Byung Sup RHO a Hae Young CHOI. Interferometric Fiber Optic Sensors. Sensors [online]. 2012, 12(3), 2467-2486 [cit. 2021-01-31]. ISSN 1424-8220. Available: doi:10.3390/s120302467

[3] FERNÁNDEZ-RUIZ, María R., Marcelo A. SOTO, Ethan F. WILLIAMS, Sonia MARTIN-LOPEZ, Zhongwen ZHAN, Miguel GONZALEZ-HERRAEZ a Hugo F. MARTINS. Distributed acoustic sensing for seismic activity monitoring. APL Photonics [online]. 2020, 5(3) [cit. 2021-01-30]. ISSN 2378-0967. Available: doi:10.1063/1.5139602

[4] ZINSOU, Romain, Xin LIU, Yu WANG, Jianguo ZHANG, Yuncai WANG a Baoquan JIN. Recent Progress in the Performance Enhancement of Phase-Sensitive OTDR Vibration Sensing Systems. Sensors [online]. 2019, 19(7) [cit. 2021-01-30]. ISSN 1424-8220. Available: doi:10.3390/s19071709

[5] HE, Haijun, Li-Yang SHAO, Zonglei LI, Zhiyong ZHANG, Xihua ZOU, Bin LUO, Wei PAN a Lianshan YAN. Self-Mixing Demodulation for Coherent Phase-Sensitive OTDR System. Sensors [online]. 2016, 16(5) [cit. 2021-01-30]. ISSN 1424-8220. Available: doi:10.3390/s16050681

[6] LIEHR, Sascha, Christopher BORCHARDT a Sven MÜNZENBERGER. Long-distance fiber optic vibration sensing using convolutional neural networks as real-time denoisers. Optics Express [online]. 2020, 28(26) [cit. 2021-01-30]. ISSN 1094-4087. Available: doi:10.1364/OE.402789

[7] THÉVENAZ, Luc. Brillouin distributed time-domain sensing in optical fibers: state of the art and perspectives. Frontiers of Optoelectronics in China [online]. 2010, 3(1), 13-21 [cit. 2021-02-01]. ISSN 1674-4128. Dostupné z: doi:10.1007/s12200-009-0086-9

[8] Novotný, V.; Sysel, P.; Prokeš, A.; Hanák, P.; Slavíček, K.; Přinosil, J. Long-Range Optical Fiber Based Distributed Mechanical Vibration Sensing. Preprints 2021, 2021040514 (doi: 10.20944/preprints202104.0514.v1).

[9] V. Novotný, P. Sysel, J. Přinosil, J. Mekyska, K. Slavíček and I. Lattenberg, ”Critical Infrastructure Monitoring System,” 2021 IEEE 17th International Colloquium on Signal Processing Its Applications (CSPA), 2021, pp. 165-170, doi: 10.1109/CSPA52141.2021.9377303.

[10] Wang, Z.; Lu, B..; Ye, Q. and Cai, H. Recent Progress in Distributed Fiber Acoustic Sensing with -OTDR. Sensors [online]. 2020, ISSN 1424-8220. Available at: doi:10.3390/s20226594

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