100km pipeline monitoring: record length for intrusion and leakage detection

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Abstract: We demonstrate a record length of distributed acoustic fiber sensing (DAS) for pipeline monitoring. Both intrusion (third party interference) and leakage can be detected. An ultra-sensitive architecture enables record length (100km for a single ended fiber sensing system or 200km for sensing from both ends) detection while advanced classification capabilities minimize both false and nuisance alarms. Targets are localized (high resolution of few meters) and classified.

While conventional DAS fiber sensing is limited to 20-50km, increasing the effective range to 100km can significantly decrease the number of systems and number of stations needed for long range pipeline monitoring.

1. Introduction

Fiber Sensing is an ideal solution for long infrastructure monitoring due to the following inherent advantage: “the fiber is the sensor”, i.e. passive, highly reliable, very long lifetime, “zero maintenance” and very attractive cost structure (in $/km). A single Optical Interrogator (OI) unit can be used to monitor tens of kilometers of standard single mode fiber optic cable.

One of the prominent applications is oil & gas pipeline monitoring, and the two main use-cases are intrusion (third party interference) and leakage detection. The effective detection range in this application is 20-50km per OI unit. In this paper we will present our recent results, demonstrating effective and reliable detection at range of 100km. There are strong drivers and motivation to increase the OI detection range, for example:

- Reduced complexity for installation and maintenance: reducing the number of OI systems along a pipeline by a factor of 2-5 can significantly simplified both installation complexity, cost and maintenance.
- Improving cost structure: the user’s cost calculation is based on $/km structure and not on the actual cost of the OI unit. Therefore, increasing detection range will decrease the number of OI systems and therefore it is one of the most effective approaches for an overall project cost reduction.
- Reducing False Alarm Rate (FAR): performance of existing DAS fiber-sensing technology at maximum range (the 20-50km range) is characterized by relatively high FAR. An architecture that can enable high-probability detection at very long range (100km vs 20-50km) can achieve a significantly higher signal to noise ratio (SNR) at the 20-50km range and therefore has the ability to achieve a substantially improved FAR.
- Reducing Nuisance Alarm Rate (NAR): in “real-life” application, one can find that the limiting factor in many cases, is not FAR but rather NAR (the limited ability to classify and differentiate

between relevant target and irrelevant/unimportant target). A richer data (as described below in Section 2) is the basis for advanced classification, the foundation for NAR reduction.

In the following sections we will present our recent results of high-quality (high SNR) detection at record length of 100km.

2. Prisma Photonics edge

One of the limiting factors in DAS is a typically low SNR. The total number of photons transmitted into the fiber is determined by the product of the pulse duration by the pulse power. The pulse power is limited by non-linear phenomena that can distort the signal as it propagates along the fiber [1]. Increasing the pulse width lowers the system resolution, and typically chosen to be around 10m, corresponding to a pulse width of 100ns. The maximal pulse energy is then in the range of 80nJ. Together with the low Rayleigh backscatter coefficient of -60dB for pulse width of 100ns [2], and round trip fiber attenuation of at least 0.4 dB/km along tens of km, the Rayleigh back-scattered signal is typically so small, that it limits the ability to observe acoustic signals at a large distance (higher than 50km).

Prisma Photonics novel Hyper-Scan technology enables transmitting more light into the fiber, thus increasing the signal. We combine this with a novel amplification scheme, that amplifies both the transmitted pulse and the back-scattered signal along over 50km [3]. This amplification process takes place within the standard single-mode (SM) sensing fiber, without the need to install any amplifier, repeater to specialty fiber along the fiber itself. The only access to the fiber is at the fiber end where the system is coupled to the fiber. The amplification enables sensing range to be increased to 100km.

Moreover, our technology supplies the real-time analysis system a much larger and richer data set, enabling full reconstruction of the entire vibrational signal at every point along the detection fiber. This information is used not only to enable the detection of very weak vibrational signals, but also to classify them accurately, and reduce false alarms dramatically.

3. Sensing using pre-existing optical cables

Many infrastructures have optical cables deployed alongside the infra-structure. It would be very beneficial to use these cables for fiber sensing. In such a case, turning the infrastructure into a monitored smart infrastructure could be done by installing fiber interrogators at the fiber ends without need for any additional sensor installation along the infrastructure.

However, there are a few challenges in this approach. The cables themselves may have been deployed with the intention of communication rather than fiber sensing and hence are not optimal for coupling to the vibrations. In addition, the cables are usually deployed in a conduit, which further suppresses the coupling. Attenuation of up to 20 dB have been measured when comparing communications cable deployed in a conduit to a designated fiber sensing cable [4]. In addition, the fiber-optic cable will not typically be buried in the best location for fiber sensing. It may be located up to a few meters away from the monitored infra-structure, reducing the signal even more.

Using both the Hyper-Scan technology and our Smart Amplification scheme, we overcome these challenges. The combination of the very high SNR, rich data, and novel classification algorithms enable us to detect and classify different events at distances of up to 100km, using a pre-existing optical cable in a conduit deployed along a pipeline.

4. Medium range sensing data

In this section we will present real-life generated data gathered and processed in real-time along a pipeline infrastructure. The pipeline is buried at a depth of 1.5-2m, varying according to ground conditions. The sensing fiber is a standard SM fiber, originally deployed for the purpose of optical communication, buried in a plastic conduit at a distance of 1-2m from the pipeline. The data below shows a 9km section, out of the hundreds of kilometers of pipeline infrastructure.

The pipeline passes near roads, railways and settlements. The environment is thus noisy and includes many sources of different acoustic signals. Many of them are harmless events that do not require special attention, such as cars passing, humans walking, farm animals grazing and such. The high quality of the gathered data enables our advanced algorithms to detect and classify correctly all the targets in the vicinity of the pipeline, both the harmless background sources and sources that are threats to the pipeline, such as machine digging and even human digging with a hoe. Once all the targets are classified correctly, the system clears the nuisance alarm (harmless targets) and alerts the user only when a pre-defined target is detected. In our case, the pipeline crosses agricultural and rural areas. It is buried under and parallel to highways and train tracks. These busy areas are fruitful grounds to numerous different strong and weak background signals. If the classifying algorithm would not disregard them, the high nuisance alarm rate of the system would deem it useless.

The following figures show data examples recorded in real time by the system. In these graphs, the x-axis presents the location along the interrogated fiber and the y-axis presents the time. Figure 1 shows the trace of a car driving back and forth at a varying distance of 10-50m from the pipeline, around the 7^{th} km of the fiber. One can also clearly see the acoustic noise (at 5.5km) generated by cars passing on a road that crosses the pipeline route.

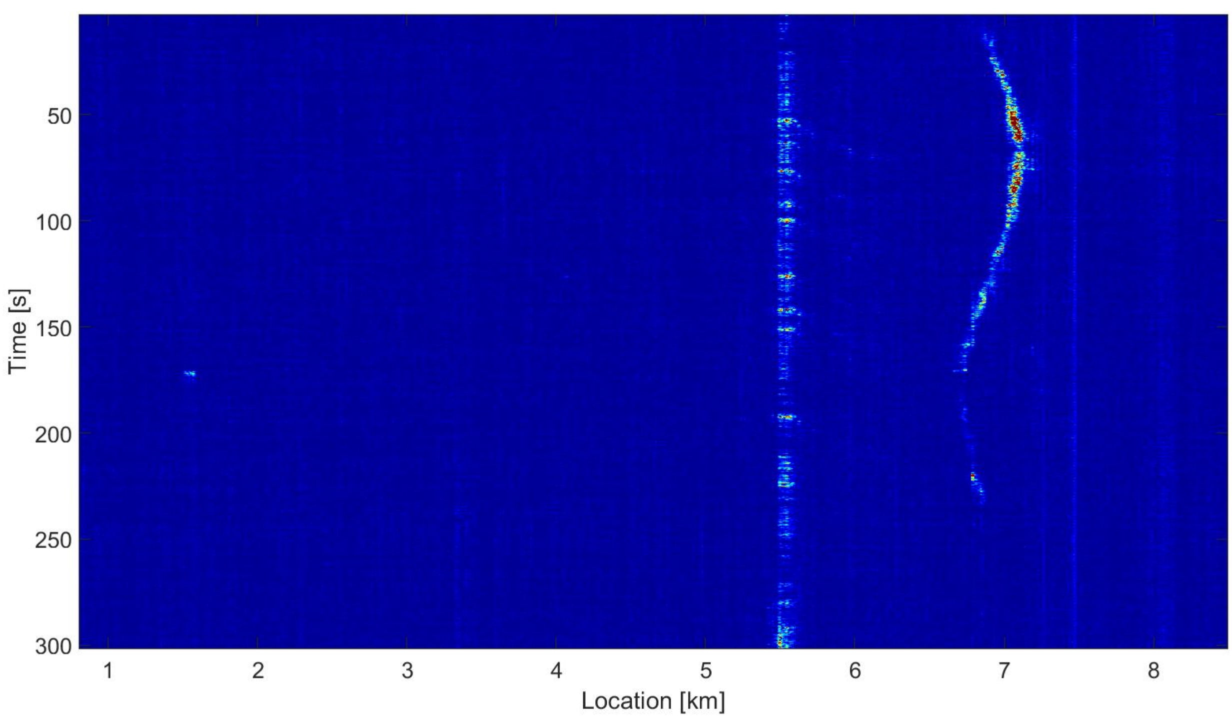

Figure 1: Vehicle trace at 7km

Figure 2 below shows human digging activity, comprised of 20 hits to the ground with ah hoe at a distance of 10 m from the pipeline. In Figure 3 machine digging activity at the same location is presented, over a much longer time.

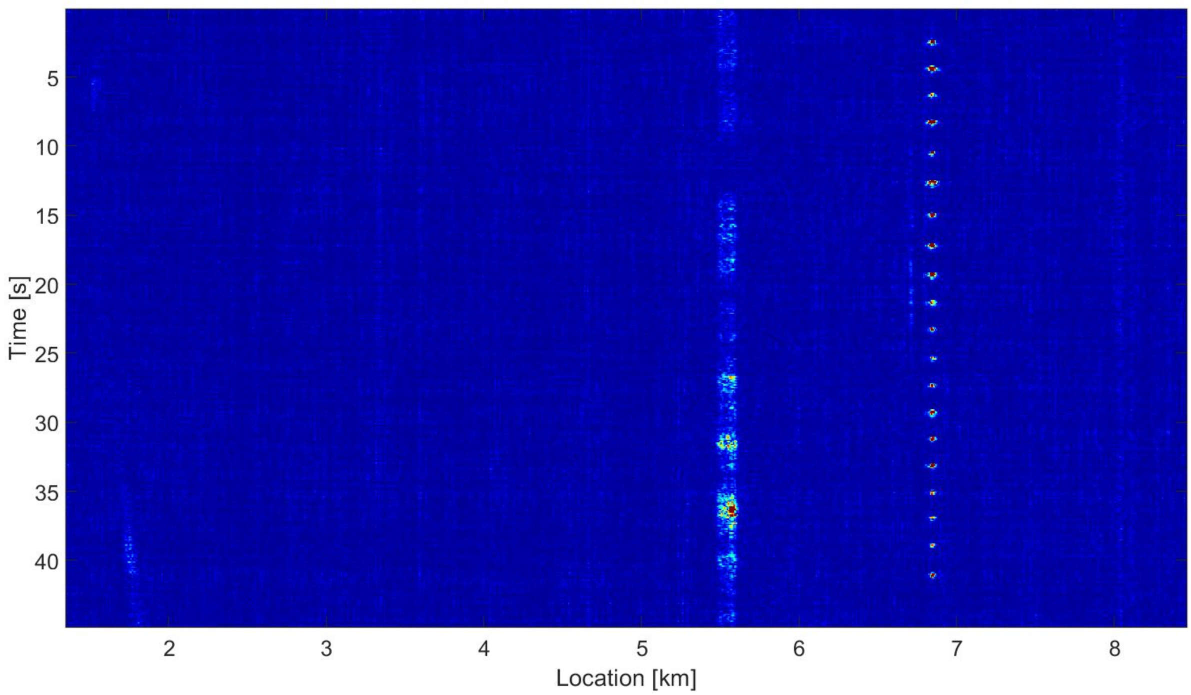

Figure 2: Human digging activity at 7km

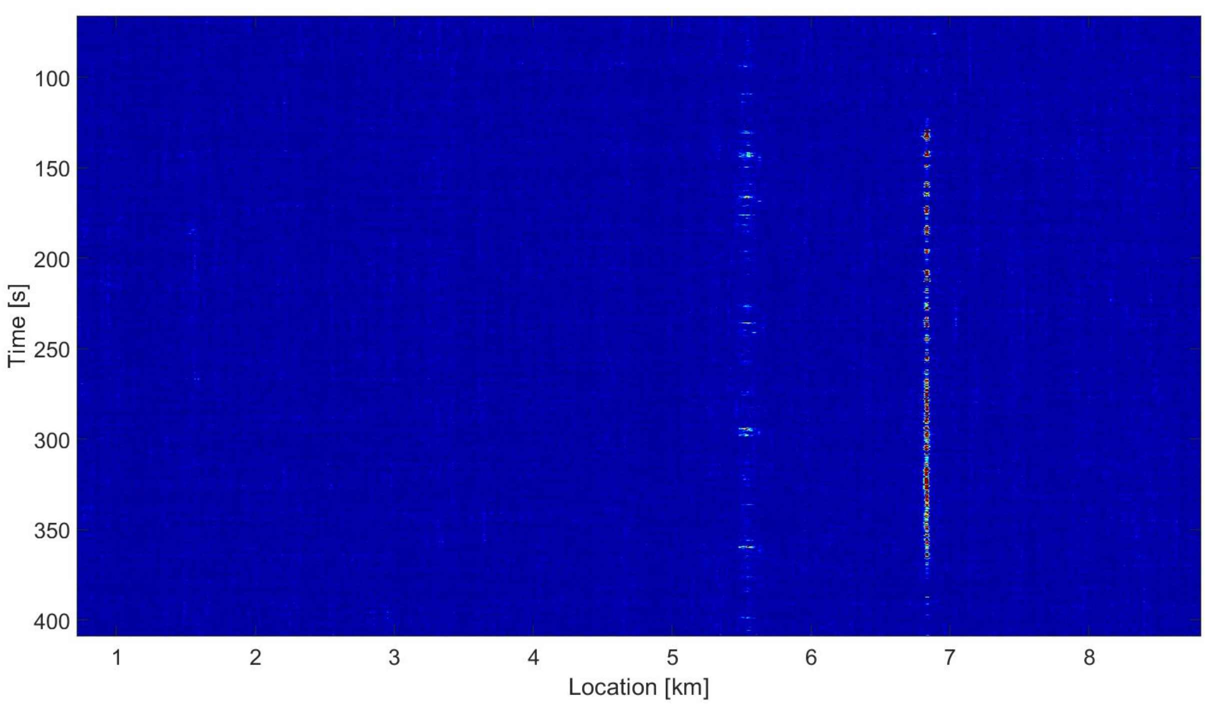

Figure 3: Machine digging activity at 7km

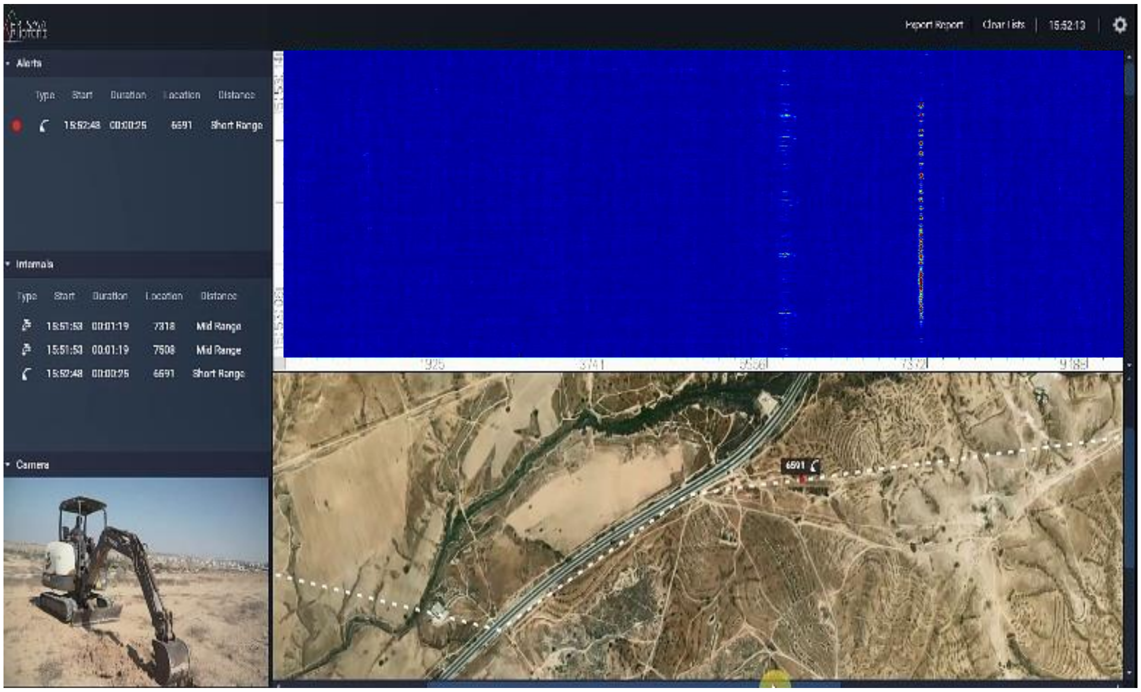

Figure 4: System user interface

Figure 4 is a snapshot of the PrismaSense™ graphical user interface. The presented snapshot is of the machine digging of Figure 3. The detected and classified events are presented both on a map, and in a table, providing the user with additional detailed information about the event. According to user supplied rules, part of the events are classified as threats and appear in a table of alerts. An additional, optional table presents all the events, including both alerts and harmless events. Here, the system detected and classified two irrigation water pumps which are presented only in this table, as they pose no threat to the monitored pipeline, and only the digging is presented as a threat.

5. Extending the sensing range to 100km

This section demonstrates the unique PrismaSense™ system capability of monitoring a record length of 100km, in a distributed manner, with a single interrogator. Figure 5 and Figure 6 show a closeup of a fiber section starting 93-94km away from the interrogator. As briefly described in Section 2, the combination of the unique Hyper-Scan technology and tailored Smart Amplification, improve SNR significantly, enabling us to extend the sensing range to 100km. The expected SNR degradation is apparent in the 100km data, remains sufficient for detection and classification of the events of interest, in this case, human and machine digging.

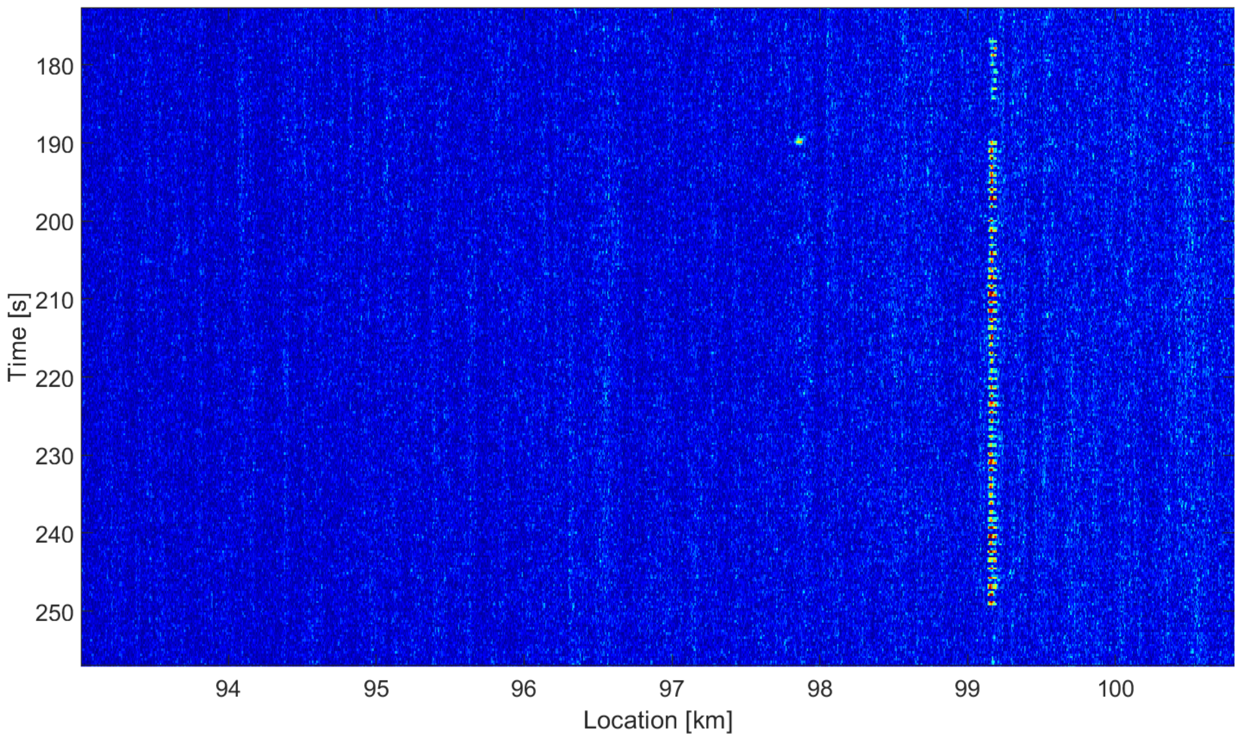

Figure 5: Human digging activity at 99km

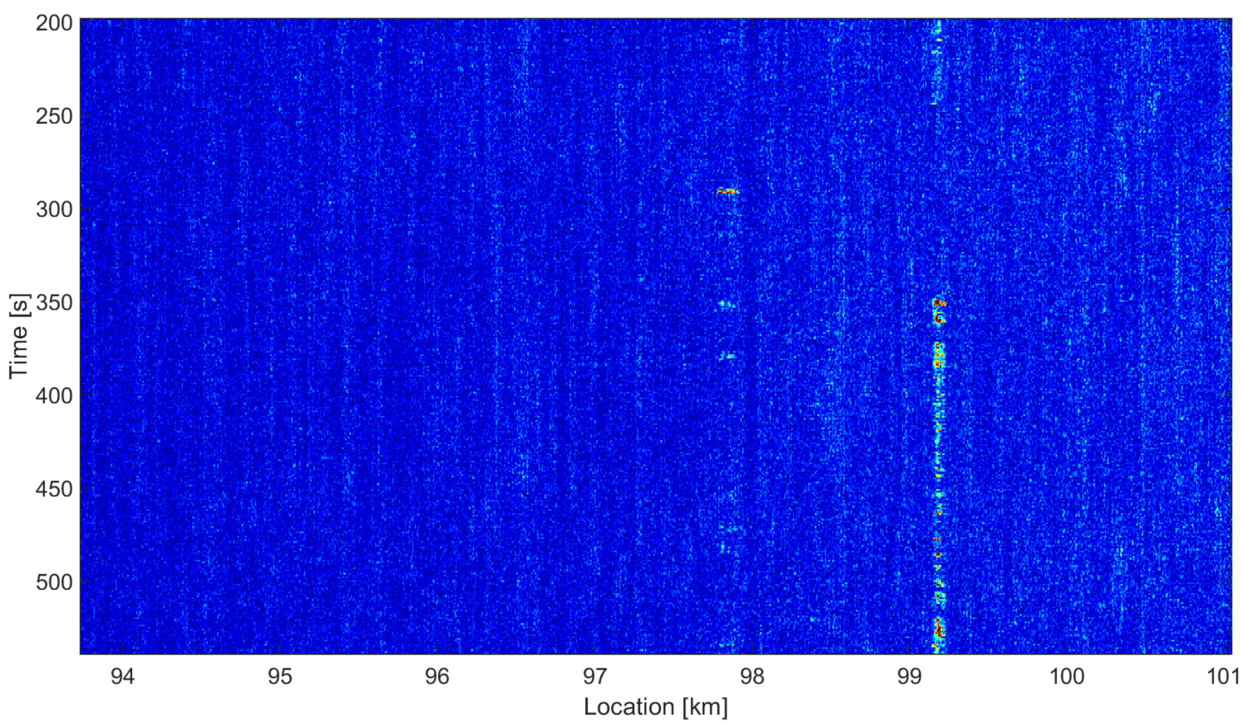

Figure 6: Machine digging activity at 99km

6. Summary

We presented fiber-sensing DAS detection capabilities at record length of 100km. A high-quality (high SNR) data was achieved even for relatively weak targets (for example: human digging 10m away from the fiber). The testing scenario was even more challenging since all those measurements were taken using “pre-existing” optical communication fibers (fiber optic cables in conduit, which, based on [4], reflects additional 20dB of signal attenuation).

The high signal to noise ratio (SNR) and very rich data is the foundation for FAR (false alarm rate) and NAR (nuisance alarm rate) reduction and performance optimization.

References

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[4] Riley S. Freeland et al., "Relative acoustic sensitivity of standard telecom and specialty optical fiber cables for distributed sensing," *Fiber Optic Sensors and Applications XIV,* vol. 10208, pp. 139-148, 2017.