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A KOMUNIKAČNÍCH TECHNOLOGIÍ

DEPARTMENT OF TELECOMMUNICATIONS

ÚSTAV TELEKOMUNIKACÍ

FIBER OPTIC PERIMETER INTRUSION DETECTION SYSTEMS

SYSTÉMY DETEKCE NARUŠENÍ PERIMETRU VYUŽÍVAJÍCÍ OPTICKÁ VLÁKNA

BACHELOR'S THESIS

BAKALÁŘSKÁ PRÁCE

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VEDOUCÍ PRÁCE

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Bachelor's Thesis

Bachelor's study program **Information Security**

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Student: Karina Duisenbekova ***ID:*** 221540

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TITLE OF THESIS:

Fiber optic perimeter intrusion detection systems

INSTRUCTION:

The aim of the bachelor's thesis is a theoretical analysis of the of using optical fibers to detect violations of the secure perimeter. Both zone systems and reflectometric systems enabling precise localization of the event will be analyzed. As part of the practical part, an own zone sensor system based on the principle of interferometry will be designed. Subsequently, a measurement simulating a violation of the protected area (slow and fast walking, opening of the shaft, etc.) will be carried out on the BUT polygon. The evaluation will be performed in both the time and frequency domains.

RECOMMENDED LITERATURE:

[1] E. Udd and W. B. Spillman, Eds., Fiber optic sensors: an introduction for engineers and scientists, 2nd ed. Hoboken: Wiley, 2011.

[2] I. del Villar and I. R. Matias, Optical fiber sensors: fundamentals for development of optimized devices, Hoboken, New Jersey: Wiley-IEEE Press. ISBN 9781119534761.

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Chair of study program board

ABSTRACT

This bachelor's thesis focuses on the application of optical fiber sensors in perimeter security to prevent unauthorized access and intrusion. These systems can differentiate between various types of burglary and intrusion, enhancing the security of protected objects. The theoretical part of the thesis describes two types of sensors - distributed acoustic and interferometric sensors. The practical part relies on Mach-Zender interferometric optical fiber sensor; its sensitivity is tested by jumping and walking near the sensing cables.

KEYWORDS

Optical fiber sensors, distributed acoustic sensing, interferometric optical sensors, intrusion detection systems, optical fiber, oscillogram, spectrogram.

ABSTRAKT

Tato bakalářská práce se zaměřuje na aplikaci optických vlaknových senzorů v perimetrickém zabezpečení s cílem zabránit neoprávněnému přístupu a intruzi. Tyto systémy dokážou rozlišovat různé typy vloupání a narušení, čímž zvyšují bezpečnost chráněných objektů. Teoretická část práce popisuje dva prototypy senzorů - distribuované akustické a interferometrické senzory. Praktická část se opírá o Mach-Zender interferometrický optický vlaknový senzor, jehož citlivost je testována skákáním a chůzí poblíž senzorových kabelů.

KLÍČOVÁ SLOVA

Optické vláknové senzory, distribuované akustické senzory, interferometrické optické senzory, systémy detekce narušení, optické vlákno, oscilogram, spectrogram.

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ROZŠÍŘENÝ ABSTRAKT

0.1 Úvod

S rostoucími obavami o bezpečnost po celém světě se mezinárodní podniky a vlády rozhodly urychlit úroveň zabezpečení nejen v oblasti IT, ale také při narušení fyzické úrovně. Implementace perimetrického bezpečnostního systému může být skvělou investicí pro malou domácnost, středně velké sklady a kritickou infrastrukturu státu. Analytici očekávají, že poptávka po takových systémech bude v příštím desetiletí poháněna především rostoucími globálními obavami z narušení perimetru, krádeží, vloupáním, přeshraničním terorismem, nelegálním přistěhovalectvím a dalšími typy narušení. Výzkumníci tohoto trhu očekávají největší poptávku zejména v komerčním sektoru, a to v telekomunikacích, maloobchodu, pohostinství, zdravotnictví, médiích a zábavě, bankovnictví a finančním sektoru. Sofistikované systémy pro narušení bezpečnosti perimetru tvoří největší podíl na tomto trhu pro střední až větší podniky a vládní zařízení.

Díky široké škále schopností optických vláken došlo k jejich využití při vývoji senzorů pro fyzické zabezpečení objektů. Tržní podíl takové technologie je stále v raných fázích růstu, ale s tak rychlým pokrokem je na cestě k převzetí části zisku, alespoň v oblasti zabezpečení kritické infrastruktury. Trh mezi lety 2021 a 2022 vzrostl o více než 1 miliardu USD, a to zejména díky vnitřním (intrinsic) vláknovým senzorům.

0.2 Popis řešení

Cílem teoretické části této práce bylo zaměřit se na optické vlákno, senzory a výrobce systémů zabezpečení založených na optickém vlákně. Obsah prvních tří kapitol se soustředil na základy optické nauky, optického vlákna a kabelu. Byly popsány důležité pojmy pro další části této práce: koherence, koherenční délka, délka vlny, SMF, MMF. Bylo uvedeno rozlišení optického vlákna a optických kabelů.

Popis senzorů, jak bylo uvedeno výše, se soustředil na reflektometrické a interferometrické senzory. Byly uvedeny základní schémata nejpoužívanějších interferometrů, respektive senzorů založených na nich. Z každé kategorie bylo vypsáno několik výrobců technologií zabezpečení perimetru pomocí optických senzorů. U interferometrických senzorů byly popsány technologie firem Fiber Sensys, Bandwear, BEI security a Future Fiber Technologies. Všechny informace v této části byly čerpány z brožur a manuálů produktů. Byly také popsány podobné rysy při instalaci kabelů v sekci "cable installation" a byly nakresleny úvodní schémata instalace kabelů. Reflektometrické systémy byly popsány stejným způsobem jako interferometrické systémy.

Protože praktická část se soustředila více na interferometrické systémy, z vybraných produktů byly zjištěny používané interferometry. Tato informace se však nevyskytovala ve všech manuálech a proto nebyly zjištěny interferometry použité pro některé produkty uvedené v práci. V praktické části této práce pro veškerá měření byl použit Mach-Zenderův interferometr, u kterého referenční a snímací ramena byly umístěny v jednom kabelu v zemi mezi sportovní halou VUT a budovou T12. Zapojení laseru, fotodiod a osciloskopu probíhaly v kanceláři SD5.67. Pro grafický přehled osciloskopu byl využit software WaveForms, ve kterém se dala ukládat surová data. Dalším pokrokem bylo tato data zpracovat pomocí Matlabu a zobrazit oscilogramy a spektrogramy provedených událostí. Chůze po chodníku, pod kterým se nacházel kabel, nedala téměř žádnou změnu v oscilogramu, proto všechny události se prováděly kolem první šachty pro lepší citlivost.

0.3 Shrnutí a zhodnocení výsledků

Z teoretické části bylo zjištěno, že senzory založené na optických vláknech mají ve mnoha aspektech výhody oproti běžným senzorům. Avšak optické senzory jsou dražší a mají vysoké náklady spojené se zapojením systému, protože vyžadují vysokou úroveň opatrnosti a profesionalismu ze strany pracovníků. Samotné optické senzory jsou odolné vůči elektromagnetickému a radiofrekvenčnímu rušení, bleskům, nestabilním teplotám atd. S pomocí dalších zařízení, jako jsou kamery nebo specializovaná grafická rozhraní, například u firmy Future Fiber Technology, lze dosáhnout vylepšené přesné detekce.

Je důležité si však uvědomit, jak velkou hodnotu má chráněný perimetr nebo objekt pro vhodný výběr správného senzoru, ať už se jedná o optické vlákno nebo jiný typ. Je také důležité zjistit, v jakém prostoru budou kabely umístěny. Pokud jde o prostředí s vyšší aktivitou, je třeba zabezpečit ochranu před spontánními signály a rušením perimetru. Jinak mohou být optovláknové senzory cennou investicí pro bezpečnost perimetru pro mnoho klientů.

Z praktické části bylo zjištěno, že čím větší byl způsoben tlak na šachtu, tím lepší byl oscilogram a spectrogram. Při skákání nad šachtou byly generovány nejvýznamnější oscilogramy a spectrogramy. Avšak otevírání šachty nepřineslo významné výsledky ve grafech, protože tlak na šachtu při otevírání byl minimální.

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Author's Declaration

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Paper type:	Bachelor's Thesis
Academic year:	2022/23
Topic:	Fiber optic perimeter intrusion detection systems

I declare that I have written this paper independently, under the guidance of the advisor and using exclusively the technical references and other sources of information cited in the paper and listed in the comprehensive bibliography at the end of the paper.

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author's signature*

*The author signs only in the printed version.

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Additionally, I would love to thank my mother for her support and love during this academic journey.

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Introduction

With growing safety concerns worldwide, international businesses and governments choose to accelerate their security levels not only in the IT-sphere but also in physical level breaches. Implementing a perimeter security system can be a great investment for a small household, a middle-sized warehouse, and the state's critical infrastructures. Analysts expect demand for such systems over the next decade to be driven primarily by growing global concerns about perimeter intrusions, thefts, burglaries, cross-border terrorism, illegal immigration and other types of intrusions. Researchers of the given market expect the greatest demand in the commercial sector, particularly telecommunications, retail, warehouses, hospitality, healthcare, media and entertainment, banking and financial sectors. Sophisticated intrusion systems make the biggest share of this market for middle to bigger-sized businesses and government facilities. It is advised for vendors to keep intrusion systems under great observation in the upcoming years of their development.

Due to the wide range of optical fiber's abilities, this technology took place in developing the sensors for the physical security of the object. While competitors served the world for a long time, it also has many disadvantages compared to optical fiber sensors. The market share of such technology is still in the early stages of growth, but with such fast-paced advances, it is on the way to take over some of the profit, at least in critical infrastructure security. The market grew by over 1 billion USD between 2021 and 2022, dominated by intrinsic fiber sensors worldwide. [1]

Aim of the thesis

This bachelor's thesis will be mainly focusing on a particular technology in the perimeter security field - optical fiber sensors. The main goal of this work is to thoroughly research and understand the market of optic fiber sensor technology and how it is being applied to perimeter security systems. The practical part would be focused on interferometric fiber sensors and analysis of the collected data throughout the experiment in frequency and amplitude dimensions.

1 Optical Science

At the core of Optical science, short for Optics, exists light and how the light waves behave in different matters. Propagation of the light through a defined closed perimeter, such as cable, heavily relies on the internal reflection phenomena of the light wave. Every existing matter has its refractive index, which simply means how the light wave is reflected from this matter. Scientifically explained, *absolute refractive index* is a dimensionless physical quantity that shows how much faster is the speed of light in a vacuum than in any other material; it is always greater than 1.

$$n = \frac{c}{v} \tag{1.1}$$

The equation 1.1 illustrates relativity between $c-$speed of the light in vacuum and $v-$speed of the light in one particular medium, which is how refractive index n is calculated for different physical materials. [39]

Every light wave has its own wavelength. *Wavelength* is the distance between the two closest points in a light wave at which oscillations occur in the same phase, as shown in a picture below 1.1.

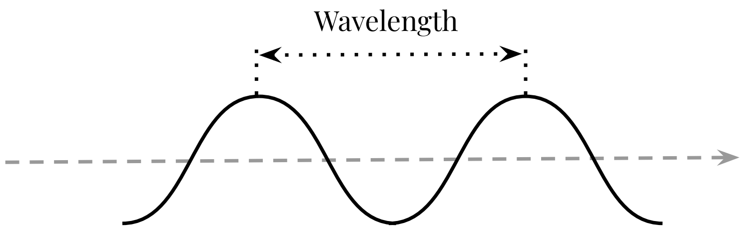

Fig. 1.1: Wavelength shown on sine wave [3]

Due to the heavy usage of lasers in modern optics, it is important to understand *coherence* and what it means to have a coherent light source. A light bulb or normal light from the sun is not quite of the right nature to possess such qualities as coherence, but lasers excel in it. [39] Two light sources can be coherent only when their phases (differences in phases) and frequencies are constantly the same throughout a time period, as illustrated on 1.2. Such a light source as a laser requires a defined phase difference between photons in a wave to be coherent. *Coherence length* is a defined length between different photons in a light beam past which coherence degrades. [5]

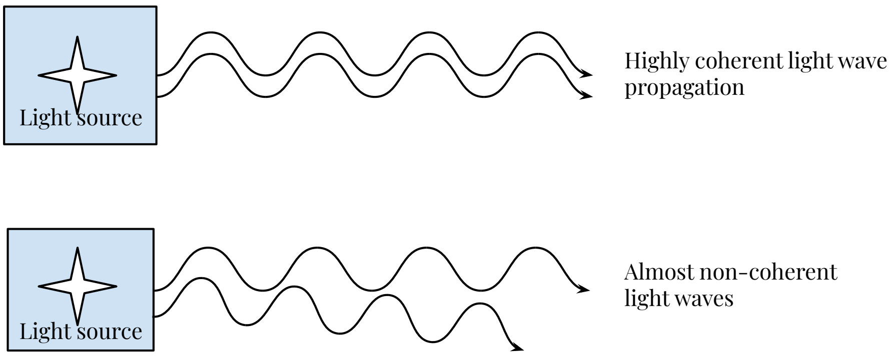

Fig. 1.2: Coherent and non-coherent light sources [42]

Bandwidth as a term serves to show the range/"band" of optical power between two limits, in which the optical power decreases by those limits, like illustrated on 1.3

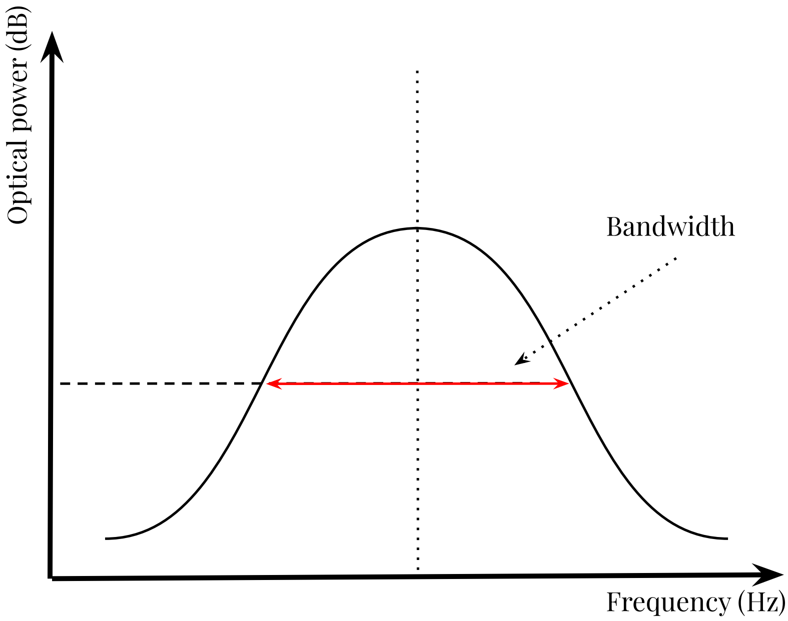

Fig. 1.3: Bandwidth [43]

2 Optical Fiber

Early days of optical fiber were mainly focused on their ability to transfer data with accelerated speed, but with thorough research, other properties of fiber technology were brought out. Fiber optics are commonly used in dentistry and surgery to brighten up a surgery area of a body; the automotive industry uses fiber optics in the safety and lightning features of current vehicles. [4]

Fiber optic technology can be used as a sensor for vibrational, deformational, and other types of mechanical impacts, making them helpful in perimeter security and intrusion systems. Vibration and temperature sensors are heavily used in industrial applications for monitoring and security purposes. Simple point sensors require much maintenance and continuous power supply, making them less appealing to clients. Fiber technology covers plenteous flaws of normal sensors; fiber cable itself can be a sensing element (intrinsic), or sensors can be directly connected to the optic fiber (extrinsic). [4]

Before proceeding with the sensors, it's better to understand what optical fiber is. Optical fiber is a waveguide with a core of a small diameter that transmits a lightwave. Modern optic fiber is usually made of glass or plastic core, cladding, and polymeric film on the outside, as shown in the illustration 2.1. [4] To ensure the reflection of light in the core, the absolute refractive index of the core must be slightly higher than that of the cladding. The core is made of material with a refractive index of around 1.5 and has a diameter of 9 µm (for single-mode fiber), 50 or 62.5 µm (for multimode fiber). The cladding has a diameter of 125 µm and consists of a material with doping agents that change the refractive index. [2]

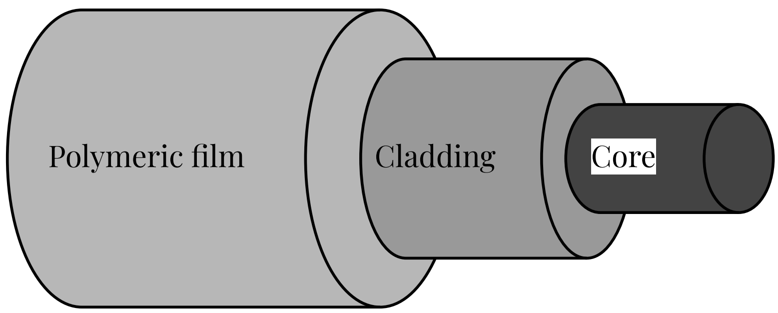

Fig. 2.1: Optical fiber structure [9]

To transfer any data using an optical fiber, at the very start of a system should be a transmitter or a sender of a light signal with a suitable wavelength for each designated purpose.

The light that is used in optical fiber is considered to be near-infrared or short-wavelength infrared (up to 1550 nm) waves. Depending on the qualities that need to be achieved, a light transmitter can be a light-emitting diode (LED) or a laser. LEDs have a much larger light-emitting area than lasers, making them less effective at long distances due to light fading. The market categorizes LED-based optic fiber as a cheaper version that is great for small to mid-sized communication lines. Laser-based optic fiber, on the other hand, is accustomed to communication lines where length is a major variable. [8]

Even if the core materials of fiber are pure, light loss is still persistent in this technology. Most light transmitters produce a loss of 4 to 6 decibels per kilometre at a wavelength of 850 nm (that is, 60 to 75% of the sent light). At a wavelength of 1300 nm, losses are reduced to 3-4 dB/km (50-60%), and at 1550 nm they are at the value of 0.5 dB/km (10%). The main causes behind light losses are inhomogeneities along the fiber lines that cause light absorption and scattering effect. Optic fiber is quite fragile due to the materials used to make it, so excessive bending of fiber can also cause light loss. [7]

Depending on the geometric quantities of the core and cladding, counting in the value of the refractive index in an optical fiber, only one (main) or a large number of spatial modes can propagate throughout the fiber. Therefore, all optical fibers are divided into two large groups: single-mode and multimode. Simply explained, the mode can be explained as a trajectory of a light beam propagating through a given fiber. The light signal can be inserted into the fiber under (Illustration 2.2) [4], [9]

- zero degree angle, which correlates with single-mode fiber technology;
- small angle, which is mostly used in multimode fiber. [9]

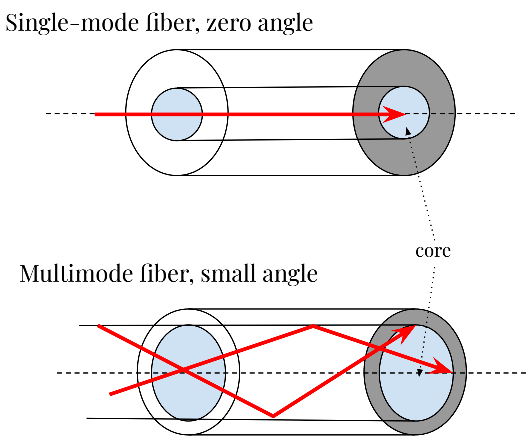

Fig. 2.2: Light propagation in the fiber [2], [9]

Standardizing optical fibers depending on their qualities, bandwidth, application properties, and more is a complex topic; optical industry categorizes some cables under ITU standards, as shown in the table below. 2.1.

Tab. 2.1: Optical fiber categories under ITU standard. [18]

Name	**Fiber type**	**Wavelength**	**Application**
ITU G.651.1	50/125 µm graded-index multifiber	850-1300 nm	Nework in a multi-tenant bulding
ITU G.652	8.6~9.5 µm single-mode fiber	1300-1625 nm	LAN, MAN, access networks and CWDM transmission
ITU G.653	dispersion-shifted single-mode fiber	1500-1600 nm	Long haul single mode transmission systems
ITU G.654	up to 13 µm fiber	1530-1550 nm	Submarine systems
ITU G.655	single-mode fiber	1550-1625 nm	Long-haul specific systems
ITU G.656	wideband optical transport fiber	1460-1625 nm	Long-haul systems
ITU G.657	bending-loss insensitive single-mode	1260-1625 nm	Fiber to the home networks

2.1 Multi-mode Fiber MMF

Multimode fibers are optical fibers with a core diameter larger than that of a Single-mode fiber, which results in multiple modes spreading along the fiber. Multimode fiber is inclined to intermodal dispersion due to its core's geometrical nature, which leads to shorter distances of fiber cables (up to 1000 m max). To generate light signals going through fiber, mainly LED and sometimes VCSEL transmitters are used, which makes the cost of the multimode optical fiber 2 to 3 times less expensive than that of a single-mode fiber.

Multimode fibers can be classified into two classes based on the material that is being used to make the core and cladding parts of the fiber. As described earlier, the diameter of the core is larger than that of the single-mode fiber, which allows using LED as light transmitters. The light signal coming from the LED transmitter has a larger beam divergence but a bigger core diameter helps optimise these imperfections. Quartz glass core and cladding are beneficial for multimode fiber, due to its higher dispersion rates. Such pure material forces light to travel through fiber in a more wave-like form, which leads to reducing in dispersion. This phenomenon is called gradient index multimode fiber; the refractive index in such fiber is higher at the axis and decreases gradually towards the core-cladding border. [4], [10] On the other hand, polymeric or plastic core and cladding provide less expensive cost to make and repair optic cables, but it brings bigger dispersion to the overall quality. Plastic-based fiber uses different phenomena to conduct light through fiber. For step-index multimode fiber, light propagates in a zig-zag form through the core. Such materials have an application in optical science to this day. Relating to this thesis, step-index multimode fiber is widely used in optical sensor production. [11]

2.2 Single-mode Fiber SMF

Single-mode fibers are optical fibers with a core diameter smaller than that of a mulltimode fiber core diameter, due to which only one light mode is transmitted within the fiber. Such fiber requires laser-based transmitter because an LED signal wouldn't be able to hold the same amount of transferred data. The purity of the production materials of the core and cladding plays a big role in smooth functionality. Quartz glass material is the most popular in the production of single-mode fiber cables. The suitable wavelength of a signal also should be considered nevertheless. Picking a shorter wavelength can result in multiplying of transmitted modes, which could lead to an unwanted number of modes. Standard single-mode fiber wavelength must be larger than that of a multimode fiber. [7] [10] In single-mode fibers, there is a phenomenon of chromatic dispersion. It has the greatest impact on high-speed signals of 10 Gbps and above. The essence of this phenomenon is that the greater the transmission distance, the greater the distortion level. There are different technologies to battle this phenomenon, such as dispersion compensators and error correction mechanisms.

Single-mode fiber is generally designed for long-distance operation thanks to its transmission capabilities. These characteristics, combined with the need for finer alignment and stronger connectors, result in significantly higher module costs and overall higher costs for single-link fiber optic connections than that of a multimode fiber. [10], [4]

2.3 Optical Fiber Attenuation and Losses

There are two main parameters on how optical fiber losses can be described: dispersion and optical loss. Each of these parameters could greatly affect the speed of transferred data and the overall quality of the optical fiber. [12]

The attenuation is a ratio between input and output signals, which using simple words, describes how much signal was lost over the propagation length of the optical fiber. The sum of absorption, scattering, bending of a fiber, and dispersion shows overall attenuation, which is measured in dB/km. [12]

Dispersion is an important parameter of an optical fiber. In multimode optical fibers, the main factor limiting the transmission rate is the *modal* dispersion. In single-mode fibers, as well as in gradient index multimode fibers, there are two more types of dispersion: material dispersion and waveguide dispersion. These two dispersions are combined and called *chromatic* dispersion. [15]

Modal dispersion, how described on the table 2.2, is more prominent in multimode fiber. Multimode fiber can carry out up to 17 modes that all would enter fiber under different angles, with different trajectories. It makes the propagation time of each mode through fiber non-identical to other modes, which results in different delay times upon reaching the finish. [16]

Chromatic dispersion is mainly persistent in single-mode fiber. This type which was described before, is dependent on waveguide and material components. The laser signal which is used in single-mode fiber is very thin but not monochromatic (since it is hard for a wave to be completely monochromatic), which causes different spectral components of a wave to travel at different velocities. *Material* dispersion is dependent on the silicon dioxide (SiO2) of the core, also called silica is sensitive to frequency, which makes different frequencies in a beam of light travel at different speeds. Light does not only travel in the core but in the cladding too. With a bigger wavelength, the bigger part of the light is distributed toward the cladding. This is what's called a *Waveguide* dispersion. [15]

2.4 Optical signal receivers

To get any data from an optical signal, a detection system should be at the end of every cable, which helps convert an optical signal consisting of photons into an electrical signal consisting of electrons. Receivers are made to convert such signal into a signal that electronic devices can later handle. Some receivers in optical fiber sensors are also used to control the sensors' optical power or track the spectrum's intensity. The often-mentioned material in making optical receivers is a semiconductor. Its ability to conduct electricity lies between materials that are not able to conduct and materials that are considered to be conductors. Those are mostly germanium, silicon, gallium arsenide (GaAs), and so on. [4]

Optical fiber sensors require such receivers that need to be small, consume little power and have great reaction time and sensitivity. Choosing the right one imposes a great challenge from the wide variety of signal receivers. For example, for extrinsic sensors that use fiber optic cable as a propagation element only, requirements are higher than those that use the cable as a sensing element. [39]

Tab. 2.2: Attenuation types in optical fiber [12] [39]

Attenuation	**Types**	**Description**
Absorption - convertion of optical energy into different types of energy	Intrinsic	Minimum level of absorption, even if OF materials would be completely pure [14], [12]
	Extrinsic	Energy level changes due to the existing dopant ions like chromium, nickel and iron
	Imperfections in the atomic structure	Mising molecules in the structure or oxygen defects in the core
Bending loss, [13]	Macroscopic bend	For example when an acceptable bending angle is surpassed while cable installations
	Microscopic bend	Could happen when fibers are put together into optic cable
Dispersion	Chromatic	occurs more in SMF
	Modal	occurs in MMF
Scattering		*DAS chapter*

3 Fiber optic cables

Fiber optic cable is a cable, that contains optical fiber in it. The optical fibre cabling gives it protection from damage and easy handling and installation. Sometimes bare optical fiber could be more than enough, for example, in some fiber optic sensors and laboratory use. But most of the time, cabling is a must thing to do.

As shown in illustration 3.1 besides core, cladding, and film, there are more layers to make a fiber optic cable. An important thing to remember is that for indoor and outdoor fire-hazard safety, UV resistance, tight cabling of fiber, and different types of layering are implemented. [17]

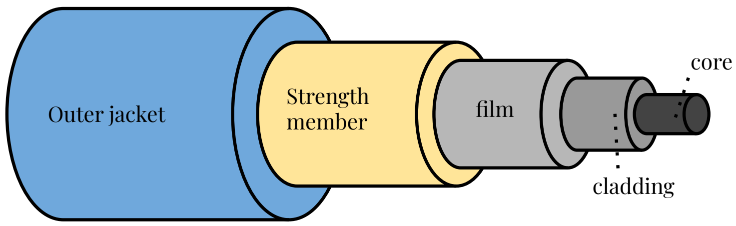

Fig. 3.1: Simple fiber optic cable structure [10]

3.1 Tight buffered Cable

This approach of cabling is widely used in indoor construction. These cables are used to connect outside cables with inside terminals and also for connectivity in the local network. The structure is on illustration 3.2. [19]

3.2 Loose tube cable

Loose tube cables are mostly used for outdoor installation due to their structure that separates the fibers from the cable. This cabling method is usually used in aerial, duct, or direct-buried applications. Cable structure is on illustration 3.3.[19]

3.3 Connectors of the optic fiber cables

Due to the sensitive nature of the optical fiber, connectors that are meant to be used repeatedly to achieve the best possible outcomes, like minimum noise interference

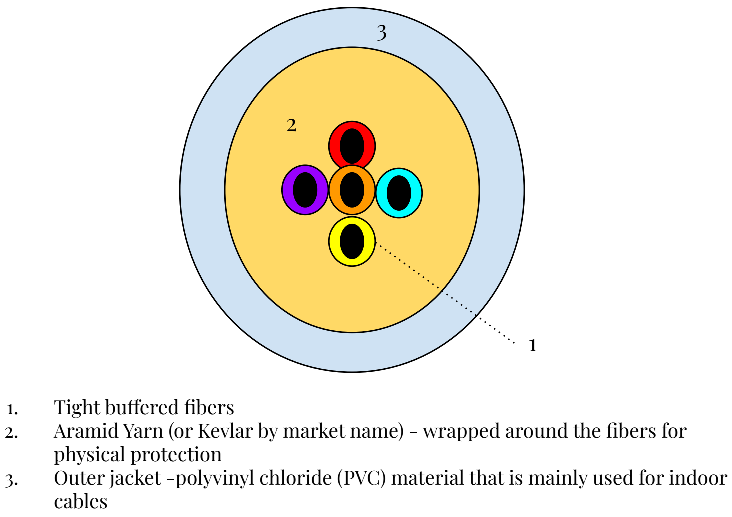

Fig. 3.2: Tight buffered cable structure for indoors [19]

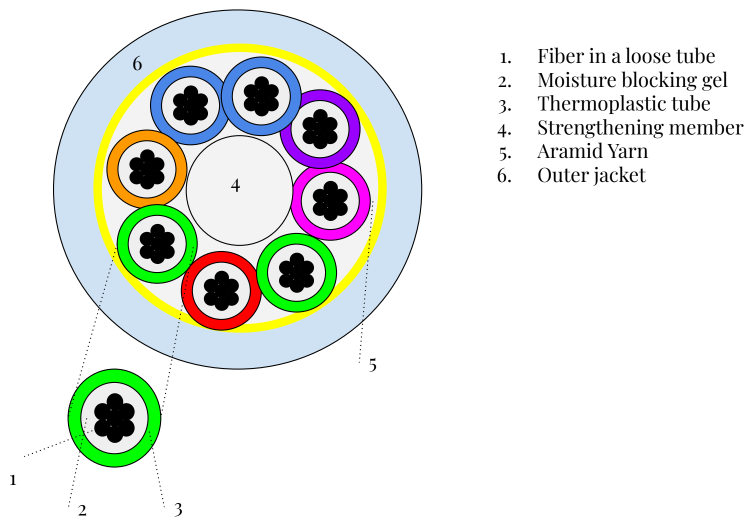

Fig. 3.3: Tight buffered cable structure for indoors [19]

on the signal, are made under standardized criteria. Those are SC, FC, and ST connectors. *SC connector*, popularly called square connector, has its name due to the simplicity and alignment of the connection because of the square form it possesses. In the optical industry, this connector is a popular choice for highly precise signals and simple connection performance. *LC connector* is a smaller version of the SC connector; these connectors are popular choices for highly used applications, where SC would be too bulky and an unreasonable choice. *FC connector* is a round-shaped connector used for vibrating environments, but in the modern world, it has become less popular. [42]

4 Fiber Optic Sensors

How it was described before, fiber optic systems are not only useful for telecommunications but also as local measuring sensors. Physical measurement quantities such as temperature or pressure as well as tensile forces can affect the optical fiber and change the properties of the light at a particular location in an optical fiber. Due to scattering and light damping in fiber, the place of external physical influence can be accurately determined which makes optic fiber technology a suitable competitor for perimeter security. [4]

Fiber optic sensors (FOS), as a type of detector, have been formalized as one of the technical directions quite recently: in the early 80s of the 20th century. At the same time, the term "fiber optic sensors" was formed, in other words, FOS is a rather young field of technology. [4]

Fiber optic sensors can be divided into two groups: sensors with fiber as a transmission line and single-mode fiber itself as a sensing element. The most developed in theoretical and technological terms and gradually mastered in industrial production are fiber-optic sensors of the first type. There are different types of fiber optic sensors and parting of this technology might become lengthy. This thesis work will mainly be focused on 2 different types of fiber sensor systems: the interferometric method and DAS (distributed acoustic sensor). [4]

5 Interferometric fiber optic sensors

Interference itself is a sum of the "combination" of two or more waves. For interference to happen, the light source should be of a coherent nature. [22] The process behind interferometers is based on the separation of a beam of light to obtain two or more mutually coherent beams that pass through different optical fiber paths, and then come together, and the result of their interference is observed. The separation and combining of light arms is executed with the help of a fiber coupler. *Fiber coupler* connects fiber ends together in order to propagate light through many paths. This device helps manage and distribute energy, which is being flowed into the fiber, between separated fibers.[42] [23] In most interferometers, there is a sensing arm and a reference arm of the divided light wave. In the case of an interferometric sensor, the sensing arm that contains an object to be tested is a light wave that undergoes different physical phenomena, which then affects the object wave.[39] Measurements are mainly dependable on the phase difference between these separated light waves and their interference pattern. Therefore sensors that are based on this technology are called interferometric or phase-modulated sensors. Due to the fact that there is a broad spectrum of interferometers and sensors that are based on them, optical science highlights four interferometers. The next section will explain the principle behind them.[20]

5.1 Fabry-Perot optical fiber interferometer

From the interferometers described in this chapter, the Fabry-Perot interferometer is the only one multibeam interferometer, which means that the light wave is separated into more than two light wave arms. [39] Fabry-Perot consists of two parallelly set reflectors (highly reflective mirrors) which are separated by a cavity (Fabry-Perot resonator or cavity). Two different functionality types can be seen in Fabry-Perot interferometers. In one type light is propagated through the fiber, and in another light is reflected by the mirror on the light's propagation path. [20]

Fabry-perot interferometer sensor is made of two parallel mirrors separated by a distance or a gap. Interference occurs based on beams that are reflected and transmitted at the mirrors. Mirrors can be placed outside or inside the fiber cable. The sensor can be divided into two groups: extrinsic and intrinsic, as shown in illustration 5.1. Extrinsic type is effective at getting high finesse interference signal. But it has low coupling efficiency. The intrinsic type has a reflective material inside of the fiber. [21]

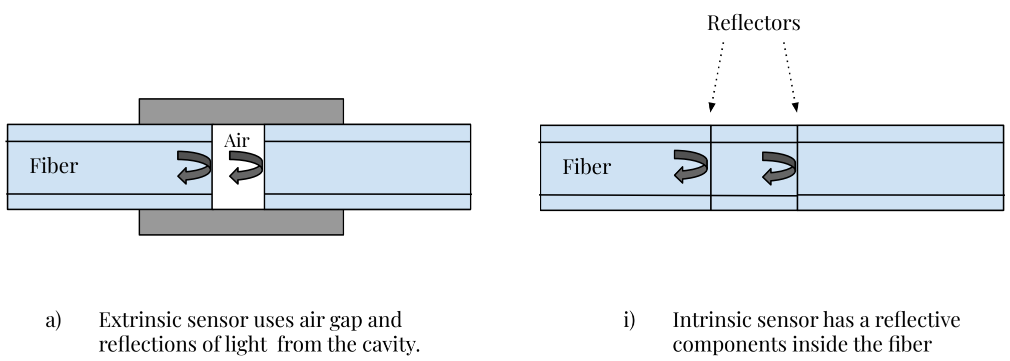

Fig. 5.1: Fabry-Perot Optical Interferometer construction [21]

5.2 Mach-Zender optical interferometer

Mach-Zender interferometer has two fiber couplers. The light signal from the transmitter hits coupler 1, which separates a beam of light to have two light paths. One light path is delayed by a special optical delay element to get a clear interference picture after coupler 2. Mach-Zender interferometer has two receivers that help generate an interference picture. With the help of two couplers, the Mach-Zender interferometer could be turned into an N-path interferometer, which would have higher sensitivity. [20]

Mach-Zender interferometer sensor's working scheme will be illustrated on illustration 5.2. A beam of light is split into two arms by a coupler and then reconnected by another coupler. Interference is therefore of two recombined arms of light. In sensing applications, the reference arm is isolated from any external signals, while the sensing arm is exposed to them. Newer versions of couplers only send another arm into the cladding and then back to the core. This sensor has a flexible configuration, so it is popular among many sensing fields. Newer versions of the sensor only split the light into the core and cladding and then combine the light into the core again. This version happens to be the most compact one. [21]

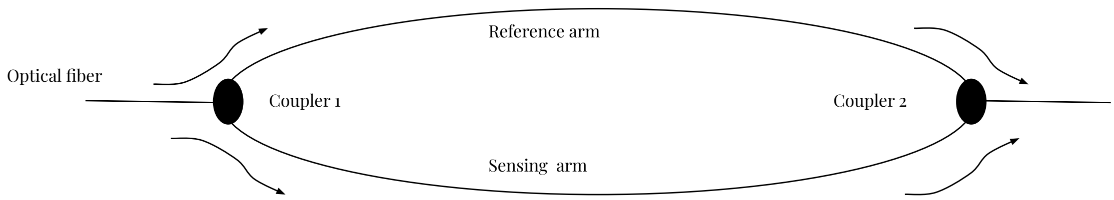

Fig. 5.2: Mach-Zender Optical Interferometer construction [21]

5.3 Michelson optical fiber interferometer

In optical science, the Michelson interferometer is called to be one of the simplest interferometers. Like a scheme 5.3 Michelson interferometer sends highly coherent light towards a coupler, which then splits it into two beams that are mirrored back at the end back towards a coupler and a receiver, so an interference picture can be produced. [20]

Michelson interferometer sensor is quite similar to the Mach-Zender optical sensor. It is possible to couple light into the core and cladding, as long as the fiber length difference is adjusted between the two arms. Michelson sensor is quite popularly used in temperature sensing or flow velocity. [21]

5.4 Sagnac optical fiber interferometer

Sagnac interferometer uses a single-mode coherent semi-conductor or Erbium dopant-based laser as a light transmitter. After the light beam is transmitted, it enters the

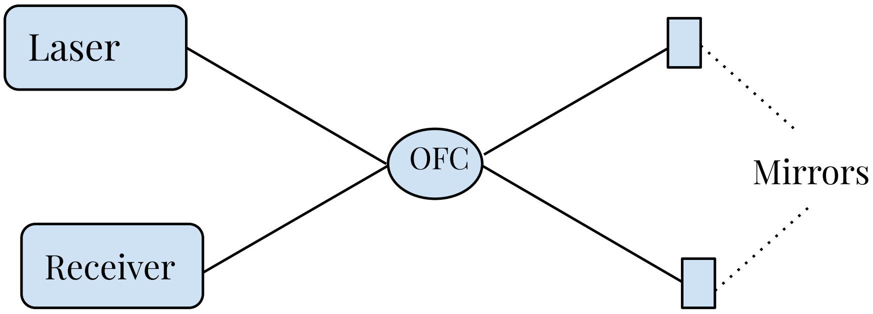

Fig. 5.3: Michelson Optical Interferometer construction [20]

fiber coupler (OFC), after the light is split into two counter paths, the light beam undergoes some changes. The light beam arrives at a detector. Popular Sagnac interferometers have a routing type of scheme as shown in illustration 5.4. The analysis is based on the frequency difference of two split beams: counter-clockwise and clockwise.[20]

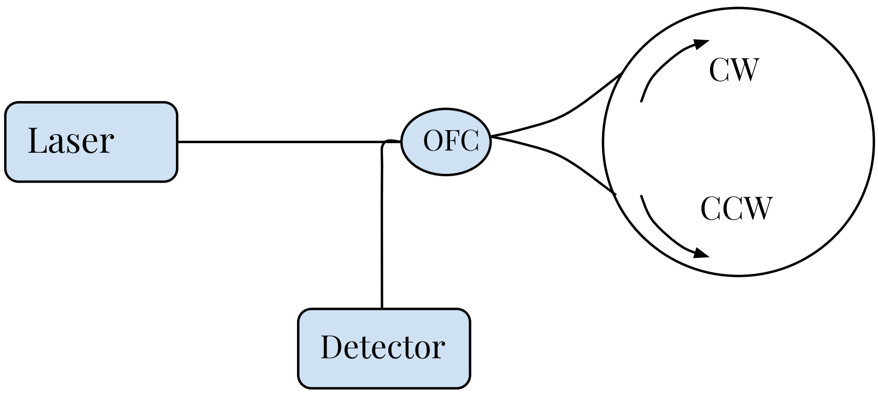

Fig. 5.4: Sagnac Optical Interferometer construction [20]

Sagnac interferometer sensor has an identical construction scheme. As a sensing fiber in a loop, it is chosen to use birefringent fibers (fibers that preserve the polarization state of a light [24]). [21]

5.5 Lasers used in interferometers

As it has been described before, optical fiber systems require a highly coherent source of light that would produce somewhat monochromatic waves, which is crucial for successful results. Lasers provide must needed characteristics for interferometers and their sensors. *Laser* itself is an abbreviation of **L**ight **A**mplification by **S**timulated **E**mission of **R**adiation. This thesis work won't focus on complex theory correlated with laser technology, since the topic is relatively broad.

5.5.1 Noise of optical light sources in interferometric systems

Due to the extensive options of the light sources in optical fiber and their different characteristics and used materials, the light signal isn't consistently clear. The noise parameter in optics plays a big role in many applications. Scientists note the importance of two types of noise in optics: **intensity noise** and **phase noise**. [39]

Intensity noise

Intensity noise shows how much the power output of a light source fluctuates and is described by special coefficient RIN(*relative intensity noise*):

$$RIN = \frac{\delta \mathrm{P}}{\overline{P}} \tag{5.1}$$

which shows relativity of δP (power fluctuations) to the $\overline{P}$ (overall average of output power). Extrinsic and intrinsic forces can affect the intensity noise of a light signal, like, for example, electrical power fluctuations and mirrors in resonators. There are ways to reduce this parameter, for example, by using two optical receivers. [40] [41]

Phase noise

Just like the name, phase noise is associated with the optical phase of the signal output. Due to the scientific nature of phenomena, only single-frequency laser is considered to undergo phase noise effects. Optical sensors use these lasers in practice. In theory, single-frequency means that a laser should be able to generate light of one-valued frequency, but in practice, no laser is able to do that. Optical science considers lasers to be able to get very close to the value of one frequency light wave. So, even a single-frequency laser can't be used to show a perfect sinusoidal graph of a wave, and a phase noise parameter is used to determine exactly that. Phase noise value could be greater than that of an intensity noise value. This parameter can be minimized by, for example, unbalancing two interferometric arms. [40] [41]

5.6 Polarization

For light waves to interfere, they need to propagate on the same axis. If, for example, one light wave propagates on the x-axis and another - on the y-axis, there would not be any interference pattern visible at the finish line. [44] There are three major polarization states: linear, circular, and elliptical polarization. Lasers usually emit light with a linear polarization nature, which basically means propagation of the electrical field of the light wave in a 2-dimensional state on the given axis. [6]

5.7 Fiber zone optic security systems

By doing market research, it is clear that a lot of fiber zone intrusion detection systems base their technologies on fiber interferometer sensors. Intrusion detection systems are understandably made for perimeter security. Fiber optic cable acts as a sensing element that is being implemented around the whole perimeter. Since this chapter focuses on fiber zone systems, it is clear that each desired to secure perimeter object can be divided into many zones depending on the chosen marketed system. Those types of systems are able to sense a lot of intruder dangers at once. [21]

Since fiber optic technology is being used, those systems are resistant to the harshest world environments, like extremely humid or hot weather, electromagnetic interference coming from outside, material corrosion, etc. One more property that zone systems have is that the power supply or controlling unit can be placed away from the secured object itself. In that lead-in cables make a good choice to connect the controlling unit and sensing cables. Lead-in cables do not react to any physical contact or vibration, they are specifically made to be either covered with armored finish or configured by software to be insensitive towards any outside world. [25]

Since zone systems are based on interferometers, the principle behind them stays the same as for the interferometric sensors. Each system should have some type of alarm processing unit which in this situation would play not only as a processor but as a light transmitter too. After light is sent, it splits into two beam paths that are led to sensor cables around the perimeter. A portion of the light comes back (reflected) to the processing unit. A speckle pattern or an interference image is analyzed constantly by the processing unit. Every vibration, motion, and pressure towards the system contributes to the change of the wave of light, which also changes the interference image. [25], [21]

Software that is a part of the intrusion system constantly monitors the whole perimeter for any unauthorized entry with the help of digitized reflected light signals from the sensing cables. Important to keep in mind that software mechanisms should be calibrated upon every secured object differently. Understandably secured objects are all located in very different faunas; some might be located too close to highways and railroads, so the application is supposed to be immune to any artificial noise. Some objects are located in vegetative or windy places. An intrusion detection system must ignore small vibrations coming from inconsistent movements from plants. The best possible solution to generate software like this is with the use of artificial intelligence or machine learning merged with the detection system itself. [25] Regarding sensing cables, they can be multimode or single-mode fiber cables dependent on the chosen system. Sensor cables use light instead of electricity, so they are unaffected by EMI, RFI, and lightning. Next, this work will go through some overall system deployment, as shown in illustration 5.5. What is shown on this system deployment scheme is four secured independent zones that can be configured differently and are connected by a trunk cable and a breakout box that interconnects every two zones. The sensing cable in each zone is fastened toward the fence to achieve a physical zone. The processing unit and the system as a whole are connected with the help of a lead-in single-mode cable. Each of the zones transmits a reflected light signal. [25]

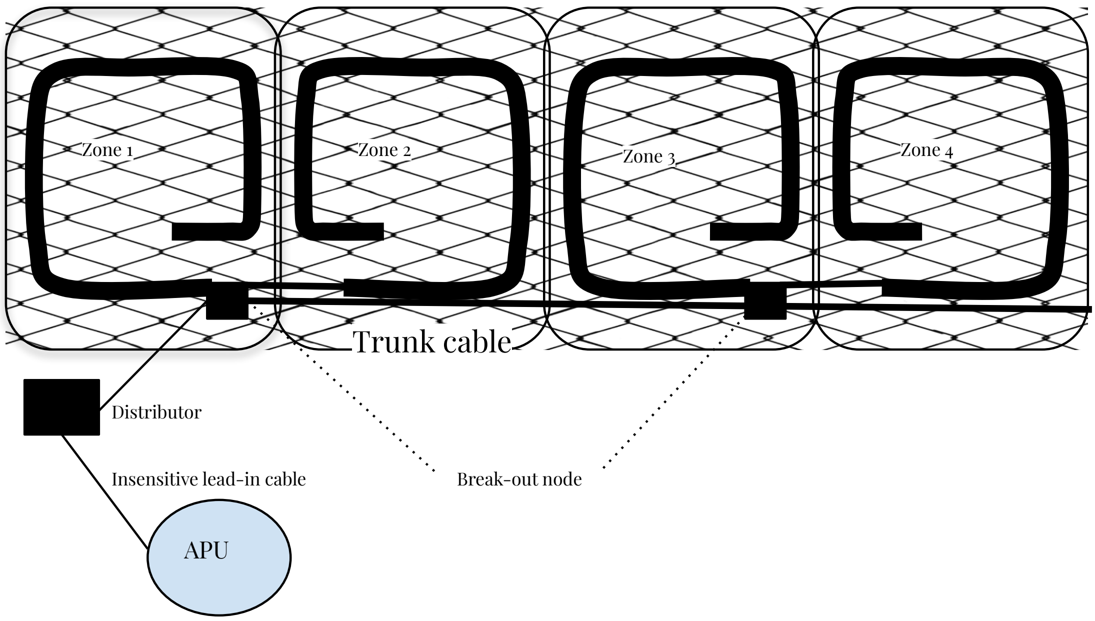

Fig. 5.5: Fiber Defender system deployment [25]

5.7.1 Cable installation of fiber zone systems

Planning the security system outline, calibrating zones, and focusing on fence quality are significant steps in securing the object. Clients of the fiber zone security systems should consider zone and processing unit placements, system resolution, and overall length and quality of an existing barrier before installing it.

If the barrier is a chain-link fence, for the system to be successful, the fence must be composed of a steel chain with openings that are not bigger than 25 cm, and the fence must be higher than 2 meters (so it is not so easy to climb over) and of the same quality along the perimeter. Corner posts around the fence are less likely to transmit any physical disturbance, so it is advised to place two place extra sensing cables, place sensing cables in a serpentine-like form on a fence. This way, sensitivity rises to detect physical vibrations. Placing more cabling material around the corners and fence posts makes it easier to take up sensing cable distance while repairing the systems. [25]

For underground security against walking across areas, crawling, and tunnelling, some fiber zone systems allow the burying of the sensing cables underground. Sensing cable is usually paced underground with service wells along the way, some security companies advise placing the sensing cable in the serpentine pattern for better results. Fiber Defender sensing cables, for example, of model 525, are not advised to be put under asphalt or concrete. When sensing cables are buried underground, placement depth and type of land play a big role in fiber zone system sensing capabilities. [25], [26]

5.7.2 Fiber SenSys | Fiber Defender 525

The FD 525 APU units can detect many intruder dangers at once along the perimeter with a maximum of two kilometres of distance. FD 525 or model 525R can support up to 25 secured zones on the chosen perimeter. Advised for small to mid-sized areas such as correction facilities, warehouses, and communication centres that need high-end security technologies. Some basic characteristics are on a table 5.1 [25]

Tab. 5.1: Fiber Defender technical specifications [25]

Parameter	**Specification**
Application	Perimeter fence (also suitable for indoor security applications)
System Type	Vibration-sensing intrusion detection system
Maximum number of zones per APU	25
Maximum protected perimeter length	5 km
Maximum sensing cable per zone	800 m
Maximum insensitive lead-in cable length	12km for up to 15 zones; 5km for up to 25 zones
Operating Temperature	0° C to 55° C
Humidity	0 to 95% non-condensing

5.7.3 Bandweaver | ZoneSentry

ZoneSentry is a zonal fiber optic sensing perimeter security solution. Per one object the system allows 8 zones in total. Each zone can be expanded up to 1 km long with an insensitive lead-in cable of 10 km. Every zone can be configured differently depending on their location and its proximity to high physical interference objects (like roads, highways etc.). ZoneSentry is an ideal option for small remote sites like power utilities, telecommunication and construction areas.

ZoneSentry is based on Sagnac interferometer technology, using Sagnac fiber optic loops, the system provides the same physical path for two opposite light waves. This helps to eliminate signal fading that happens to other types of interferometers. [26]

Tab. 5.2: ZoneSentry specifications [26]

Parameter	**Specification**
Optical Fiber Type	Single mode fiber compliant to ITU-T G.652
Measurement Range	1km per zone / 4km or 8km per unit Insensitive lead-in length up to 10km
Operating (Storage) Temperature	-20°C ~ +70°C (-10°C ~ 85°C)
Operating Humidity	10% ~ 95% relative humidity

5.7.4 BEI security | FiberSensor

One of the market's most prominent manufacturers BEI Security has made some progress with phase-modulation sensors, which led to the development of Fiber Sensor. This particular technology relies on a speckle pattern of light that is received at the end of a connection. Relying on the speckle pattern of the light being transmitted over sensing cables, an overall analysis of the perimeter and potential intrusion can be noticeable through the company's software or alarms in case of any marked intrusion. The indicated technology claims to be one of the cost-effective solutions due to the usage of interferometric sensors. [36]

5.7.5 Future Fiber Technologies | Secure Point

Future Fiber Technologies' dual zone interferometric sensor disturbance system is suitable for smaller to mid-sized properties that are physically protected by chain-link, weld-mesh or palisade fences. The great thing about this particular product is

Tab. 5.3: FiberSensor's specifications. [37]

Parameter	**Specification**
Application	Perimeter fences or buried underground
System Type	Vibration-sensing or cut detection security system
Maximum number of zones per APU	up to 2 zones
Maximum protected perimeter length	2 km of sensing cables
Maximum sensing cable per zone	762 meters
Fiber optic sensing cable	Multimode fiber, 820 nm.
Operating Temperature	-30° C to +70° C

that it has advanced signal processing, making it exceedingly better at nuisance/false alarm minimization. Like many interferometric sensor-based systems, it is expandable by adding more processor units for every zone. The indicated product has been used on properties like solar farms, storage yards, construction sites, pumping stations, and many more infrastructures that are smaller perimeter-wise. [38]

Tab. 5.4: Secure Point's specifications. [38]

Parameter	**Specification**
Application	suitable for aboveground
System Type	high sensitivity interferometric sensor system with single mode fiber optic
Maximum number of zones per APU	2 independent zones per controller
Maximum lead-n cable length	10 km for remote configuration
Maximum sensing cable per zone	500 meters
Fiber optic sensing cable	UV stabilized single mode fiber
Operating Temperature	-40° C to +70° C

6 Distributed Acoustic Sensing (DAS)

Distributed sensing itself is a mechanism in which a sensing cable is able to collect continuous or quasi-continuous data while it (data) is distributed over many measurement points along the cable. There are various methods of distributed sensing: a point sensor only picks up data from one point; a quasi-distributed sensor collects data from discreet sensors and a fully distributed sensing mode analyzes data from the whole fiber along the cable line. [27]

Today, distributed acoustic sensors are in large demand for various scientific and practical industrial applications. The sensitive element in such sensors is an optical fiber itself, upon acoustic action its parameters change, and, consequently, the parameters of propagating light through the fiber change too. The operational principle behind distributed optical sensors is that as the light pulse propagates through the fiber, it is subjected to *Rayleigh*, *Brillouin*, and *Raman scattering*. The last two of them are directly related towards the vibrational state of the optical sensing fiber. [28] [29] *Raman scattering* is used in distributed temperature sensors, distributed sensors based on *Brillouin scattering* by spectral shear can measure fiber tension and lastly *Rayleigh scattering* is used for determining the distribution of losses in the fiber in reflectometers. Rayleigh scattering is a linear process since scattered power is proportional to incident power. The frequency of the scattered light doesn't change either. That is why it is so widely used since the scattered light is powerful and doesn't come with a frequency change. [28] [39]

The Distributed Acoustic Sensor (DAS), which uses the light scattering effect, continuously monitors optical fiber. It is based on a phase-sensitive optical reflectometer (coherent reflectometer), which operates on the same phenomenon as the most common optical reflectometer - Rayleigh backscattering, but with its own characteristics [29]:

- each second the reflectogram of mirrored back signal and change of reflectogram in time are being analyzed,
- the measuring pulse is longer, with a strictly synchronous phase, in order to record not only the power of the reflected signal, but also the change in the phase of the electromagnetic oscillation. Hence the name - phase-sensitive reflectometer (OTDR). [27]

An *optical reflectometer (OTDR)* is a measuring device designed to determine the distance to inhomogeneities in the optical fiber: splicing of the cables, macro bends, connector points, breaks, etc. Its operation is based on the detection of reflected signals due to Rayleigh scattering. During the diagnostics of an optical fiber, an optical reflectometer sends a probing pulse into it. The probing pulse is a light pulse of a certain amplitude and duration. Its characteristics largely determine the maximum length of the measured line and the achievable resolution of the measurement. Simultaneously with the start of the probing pulse, the reflectometer starts counting the time. While propagating along the optical fiber, the pulse encounters various obstacles (damages, inhomogeneities), from which part of the signal is reflected. The reflected signal propagates in the opposite direction and the time of its arrival at the input of the reflectometer is fixed.

DAS technology is a popular choice not only for perimeter security companies, but also for pipeline maintenance, road and highway observations, and many more. This thesis work will be focusing on the biggest perimeter security companies and technologies in the market right now. Concentrating on existing systems helps to better understand the installation process, different clientele, and their expectations of marketed systems. [28]

6.1 Distributed acoustic sensing security systems

These systems are heavily reliant on Rayleigh backscatter and are phase-sensitive and OTDR-based. The sensing cable in the DAS system works as a microphone along the whole length of a fiber. By using a coherent laser, a light signal propagates through the whole fiber, and Rayleigh scattering causes some portion of it to be reflected back to the transmitter. [30], [4]

DAS-based security systems are highly sensitive to any disturbance, and they can pinpoint almost the exact spot of the intrusion happening on the premises. Mainly sensing cables are almost always single-mode fiber cables, that are of longer lengths than interferometric systems.

Just like fiber zone-based systems, DAS systems can be differentiated by zones too. Not all marketed systems are able to do it, since it involves more software configuration rather than cable configuration instalment. [30], [27]

6.1.1 Cable installation of DAS security systems

DAS sensing cables' most popular uses are that which use mounting to iron fences. Burying of the cables isn't as popular for these systems. Overall system installation would be reviewed with the scheme of Future Fiber Technology Aura system on the illustration [30] 6.2. The overall installation of the FFT Aura doesn't involve any loop cabling, the sensing cable is mounted to the fence with UV-resistant ties. The processing unit can be placed far away from the secured system itself with the help of single-mode lead-in insensitive cables. [30]

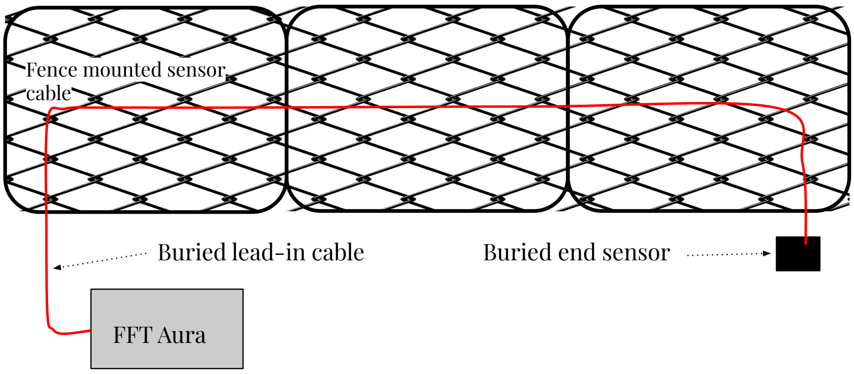

Fig. 6.1: Future Fiber Technology Aura system deployment [30]

The serpentine pattern of the sensing cables is implemented only when stable corners arise to insure more sensitivity around those places. Like shown in illustration 6.2.

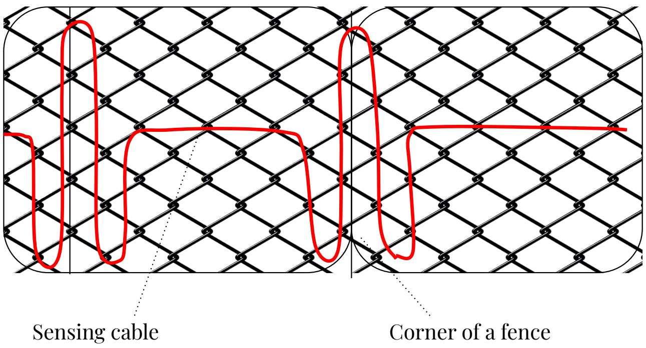

Fig. 6.2: Future Fiber Technology Aura system deployment around the corners[30]

6.1.2 Future Fiber Technologies | Aura

Future Fiber Technologies development focuses on fiber optic sensing solutions for the protection of critical assets. FFT's core products include:

- FFT Aura
- FFT Cams
- FFT Secure Fence
- FFT Secure Pipe
- FFT Secure Point
- FFT Secure Zone

FFT Aura is a highly cost-effective intrusion detection system that uses distributed fiber optic sensors for fences. It was mainly developed by the company to be used on chain-link fences due to their elasticity and installation simplicity. Aura might be installed on other types of fences, but it can lead to the loss of some technology's advantages. Implementation of other FFT products like FFT Cams and Secure fences leads to the prolongation of distance covered by fiber up to hundreds of kilometres. [30]

Tab. 6.1: Future Fiber technologies Aura specifications [31]

Parameter	**Specification**
Optical fiber type	Standard singlemode optical fibre (ITU-T G.652)
Sensing Configuration	Distributed sensor with a sensor length of up to 16km (10miles) percontroller.
FFT Aura sensor cables	-30°C to +70°C
Optical Specifications	Optical output lasr 1550 nm
Application	Outdoors, chain-link fences, cut resilient

6.1.3 Senstar | Fiber Patrol 1150

FiberPatrol was invented to operate on most types of metallic fences up to 4 meters in height, including weld-mesh, chain-link, and expanded metal types. Not only that, but Senstar company technologies allow the sensing system to be buried underground for people, vehicles, and tunneling detection. The protective distance of a cable is up to 80km per processing unit. The protective distance of a cable is up to 80km per processing unit. The main difference from other competitors is that the sensing system includes two dedicated fibers that go around the perimeter in opposite or the same direction depending on configuration:

- Loop configurations in which the two sensors run in opposite directions in one fiber optic cable. That is the configuration that provides influential DAS cut immunity, so intruder tracking will continue over the full length of the damaged cable.
- Split configurations in which the two sensors run in opposite directions, in two fiber optic cables. Cut immunity is determined by the point of the cut only.
- Line configurations in which both sensors run in the same direction in one fiber optic cable.

Sensitivity rounded cables due to the corners and rigid structures are not the only loops empirically advised by the company. Existing service loops are there to provide extra cable length for future repairs and fusion splices. Therefore, every 300 m there should be a service loop of up to 10 m of on-fence installed sensor cable, as shown in illustration 6.3 [32]

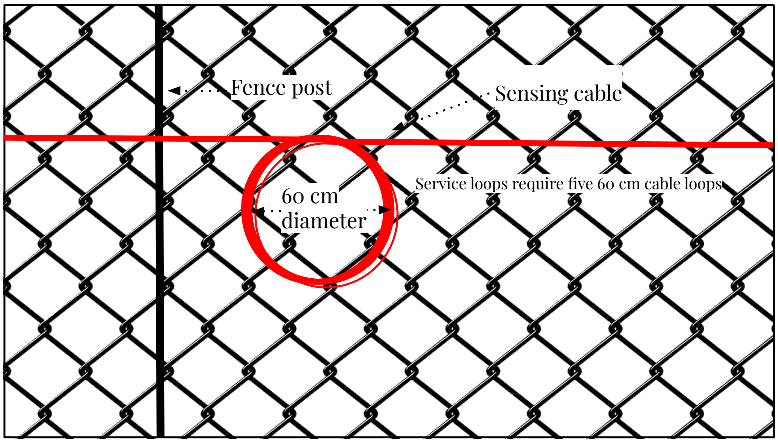

Fig. 6.3: Fiber Patrol service loops installation[32]

Tab. 6.2: Senstar Fiber Patrol 1150 specifications[33]

Parameter	**Specification**
Application	Detect and locate perimeter intrusions over a distance of up to 80 km, cut-resistant
Optical fiber type	single-mode fiber
Optical Specifications	Optical output laser 1550nm
Maximum cable attenuation	0.25 dB/km @ 1550 nm
Temperature ratings (installation)	-30 to 60ºC
Temperature ratings (operation)	-40 to 70ºC

6.1.4 T8 sensor | DAS | Danube

T8 sensor company is one of the biggest and most successful companies in the optic fiber field among the post soviet countries. The software and hardware complex "Danube" allows clients to detect acoustic vibrations at a distance of up to tens of kilometres along the optical fiber cable. Installation of T8 sensors is done underground up to 100 km, or along the fence (weld-mesh wire with a bar diameter of 2-7 mm, chain-link stretched over a metal frame) up to 50 km. For a better detection system, it is advised to use several security lines throughout a perimeter. Monitored objects are tied with graphical maps like Google, Yandex (Russian-owned searching software), or individually formatted maps, for graphical placement of intruders. API integration is done with the help of XML, JSON, and Modbus software. DAS technology of the T8 sensor is used to protect perimeters objects such as: [34]

- airports and seaports
- large industrial and regime enterprises
- specially protected zones of cultural heritage

- state institutions
- pipelines and other long distance objects

Tab. 6.3: T8 sensor Danube specifications [34]

Parameter	**Specification**
Optical fiber type	Single-mode G.652 or G.657
Maximum sensing cable length	75 km (or up to 100 depending on chosen configuration)
Wavelength	1550 nm
Length proximity detection of human steps	5-10 m from the sensing cable
Length proximity detection of a car	50-60 m from the sensing cable

7 Practice

For the practical part, I have worked on Brno university of technology owned interferometric system. After thorough research on interferometric systems, I have chosen to work on a designated Michelson interferometer. 5.3 The sensing cable is located between building T12 and the sport's hall of the university. The lead-in cable is laid from the SD5.67 office until the well right in front of T12 parking. After connecting cables using ports numbered 41, 42 in the office according to Michelson interferometer scheme, I have gotten to work and understand sensing technology behind this system.

How it has been described before, interferometric systems usually have digital graphic panel that represents the data that has been collected from the sensing cables. The one I have used is WaveForms software that is connected to Windows supported machine and USB portable oscilloscope.

With the help of a logging instrument I have collected a few oscilloscope acquisitions while testing the sensing cables. The graphs below will show signals in the time domain versus amplitude. An oscilloscope function in the WaveForms allowed me to view a signal's waveform in a two-dimensional graph. Maximum allowed logging data was set at 10 000, with a rate of 1 kHz. It is about 8 000 measurements of time and amplitude for each graph used in this thesis. Basically, an oscilloscope depicts how the electrical signal changes over time. The benefit of using an oscilloscope is that it can almost accurately reconstruct a signal and what changes it underwent during the propagation time. Sensor cables in this practical work were able to convert any vibration, temperature or power be converted to a voltage form, so it can be represented graphically. [35]

Graph 7.1, for example, shows us how a "still" state looks like on an oscilloscope. Interestingly, it still shows a lot of fluctuations even if the sensing cable doesn't pick up "anything" moving or vibrating. That is not exactly the truth here since the system picks up many vegetative vibrations and even the noise from the processing unit room. 3

On the other hand, graph 7.2 shows how oscilloscope reacts to the knocking vibration on the hard surface near the sensing cable. We can clearly see that a density of a waveform of a signal started to be more noticeable from the 0.289 s point. Light signal was going through more vibration from the knocking while propagating, hence the change of density.

Figure 7.3 depicts how the waveform of a signal changes while the sensing cable is being manipulated directly. Not only the graph became denser, but due to undergoing more vibrational power, amplitude values rose too.

Now for the actual buried sensing cable located outside of the building, it in-

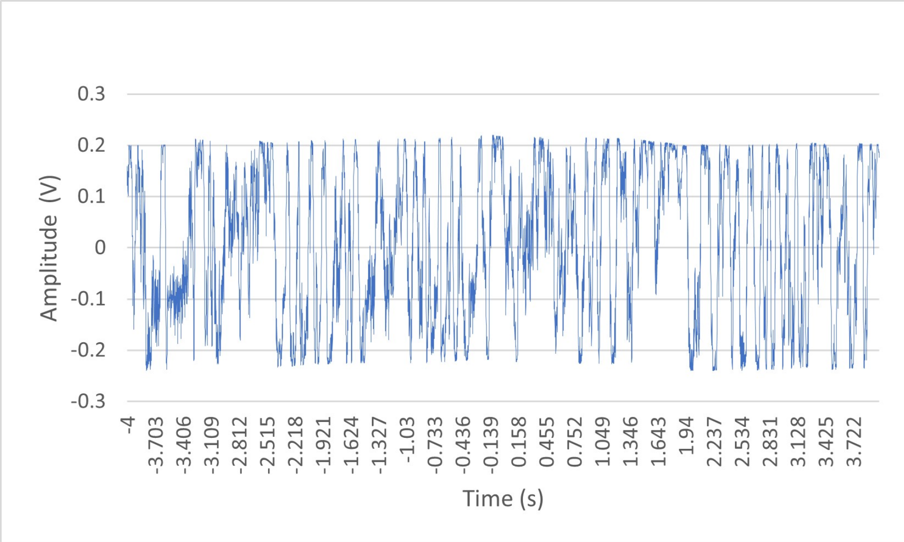

Fig. 7.1: Still state of an oscilloscope

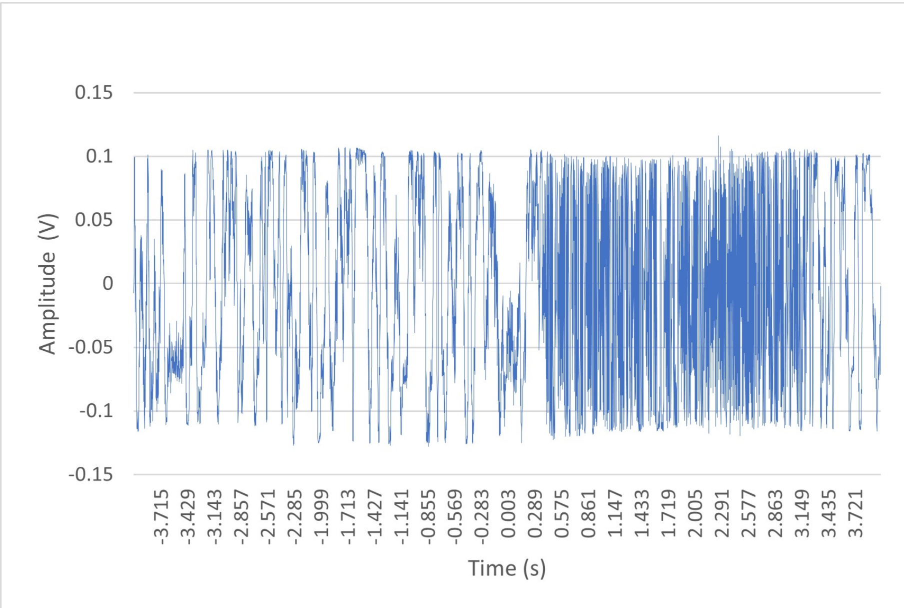

Fig. 7.2: Knocking on the hard surface near the sensing cable

dicates a lot of noise that is common for the outside. In theory, the sensing cable should be able to pick up vibrations from passing by cars and people walking on the premises. In practice, I have tried walking and jumping near the sensing cable. Due to the logging settings I have set for the experiment, vibrations from jumping seemed to play a much bigger role in the signal wave. The graph 7.4 shows how the signal changed with every jumping vibration sent down the sensing cable. If we consider that every graph depicts somewhat of 8 seconds of the signal form changes, it is clear that every density change correlates with the jumps made in this period.

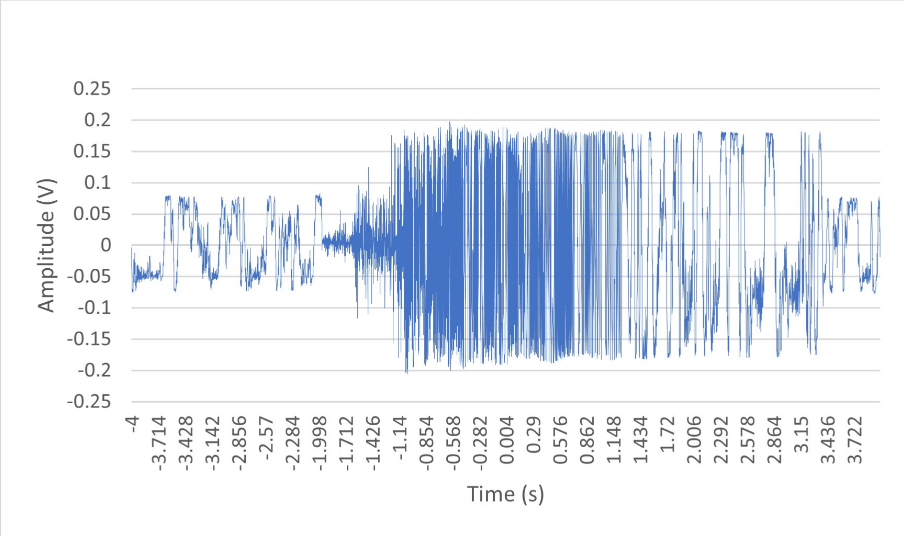

Fig. 7.3: Interfering with the sensing cable directly

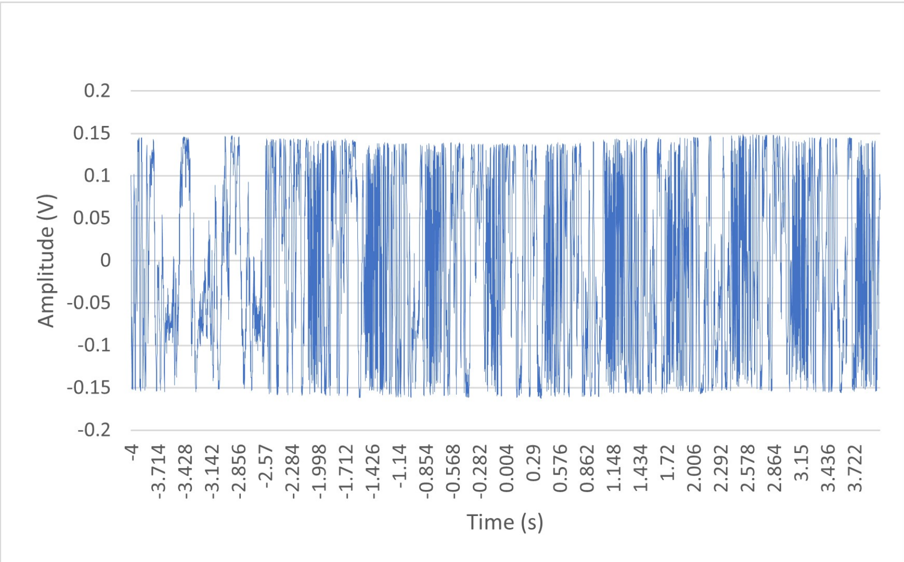

Fig. 7.4: Jumping on the ground where sensing cable is located

7.1 Proposal of an optical fiber zone security system

After the theoretical research, the practical deployment of the security system proposal was planned at Brno University of Technology polygon between the sports hall and building T12, as shown in illustration 7.5. Sensing cables are placed underground (sensing fiber and referencing fiber are in one cable); the lead-in cable is connected to the whole sensing system from a suitable rack in the SD5.67 office. The whole perimeter which is being monitored by sensing cables, is 600 m long; even though it consists of two wells, the main research was held around the first well (shown in illustration 7.5) due to allowed logging time with given settings. Overall, the location of the sensing cables is in mid to minimally occupied area with short lengthed vegetation and mildly used road on the side. This helps with analyzing interference patterns later on in work.

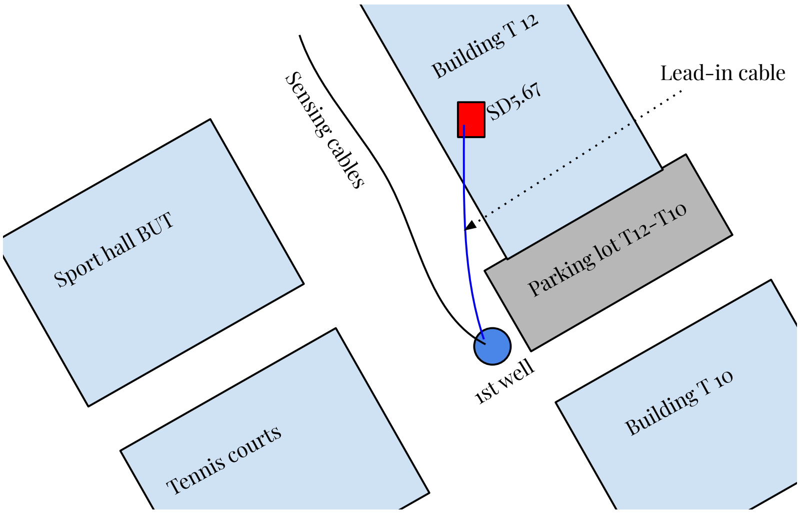

Fig. 7.5: Location of the deployment site

For this bachelor's thesis, the Mach-Zender interferometer was used for the sensing application, like shown on the scheme 7.6. The proposal consisted of choosing the right parameters for the laser, photodiode, and oscilloscope. A laser that had been chosen is the Pure Photonics ITLA model (number 1 on illustration 7.7), which has configurable frequency and output power. PP tunable laser has a built-in temperature control platform that helps operate demanding applications like sensors. The wavelength proposition was chosen to be around the range of 1550 nm, with the frequency resulting in 193 THz. Usage of the chosen laser product heavily relies on supported software that lets the controlling panel enable the laser from its machine. Two USB ports of the controlling unit are occupied for the laser control and oscilloscope GUI (WaveForms). The Analog Discovery 2 USB oscilloscope (number 3 on illustration 7.7) was chosen for the light wave observation and analysis. The controlling unit has to have WaveForms software installed on the machine. The mentioned software provides recording capabilities for this thesis to understand better the accidents happening on the premises. Data recording was a challenging part of this work since time accuracy plays a significant role in identifying suitable accidents with the data shown on the oscilloscope. Considering the semestral practical project, a small chunk of the sensing cable was placed right before the rack with ports for accessible analysis. However, this practical project focused on the actual perimeter; all sensing cables were outside. Therefore, the logging process of different actions that change the amplitude value of the light wave had to be video recorded on a portable device

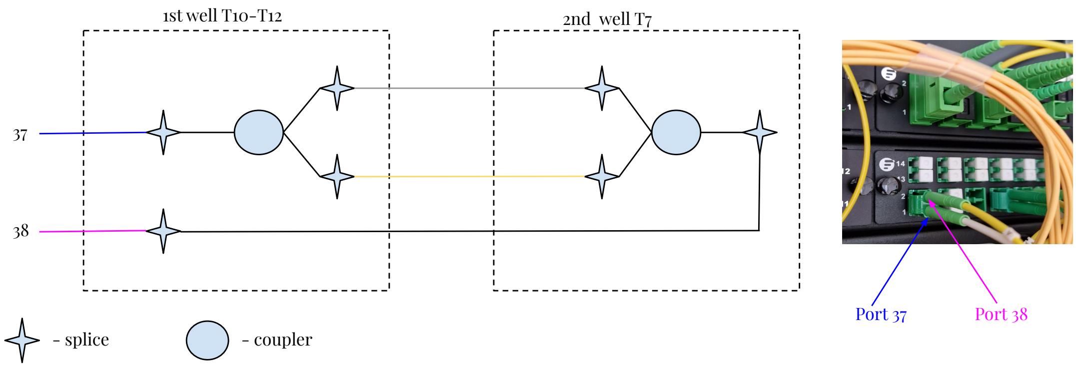

Fig. 7.6: Mach-zender interferometer-based system for the practical section

to get precise data later on. Before interconnecting the whole system, the optical fiber connectors had to be cleansed with a unique tool from any dust particles that could lead to additional noise in the signal. As described in the theoretical part, working with optical fiber requires cautious handling to avoid damaging anything.

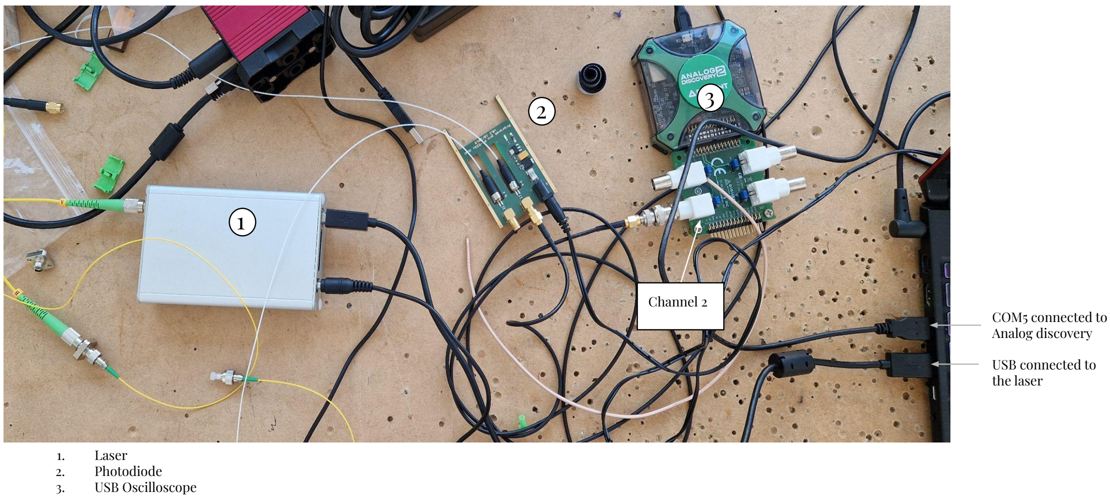

Fig. 7.7: Connection to the control unit

7.2 Processing of the recorded data in Matlab

With the help of WaveForms' recording mode, the control unit has acquired more than 2 million samples (exactly 2097152) from the Analog Discovery oscilloscope in 5 minutes. The rate for the recording mode was set at 1 kHz. In this experiment, the system's sensitivity has been analyzed regarding how it reacts to vibrational interactions, like walking, jumping, stomping, and even opening the 1st well.

7.2.1 Detection of walking on the premises

While walking on the pathway where the sensing cable lies didn't change the signal how on the oscillogram, and the same on the spectrogram, imitating walking around the 1st well while standing on it gave much better results. The pictures below show how the signal changes throughout the imitation. From the oscillogram, it is clear how amplitude fluctuates in a bigger range. This sudden change in the illustration 7.8 corresponds with standing up on the 1st well and remaining on it. Small sections of the amplitude fluctuations circled on the oscillogram fit the imitation of walking.

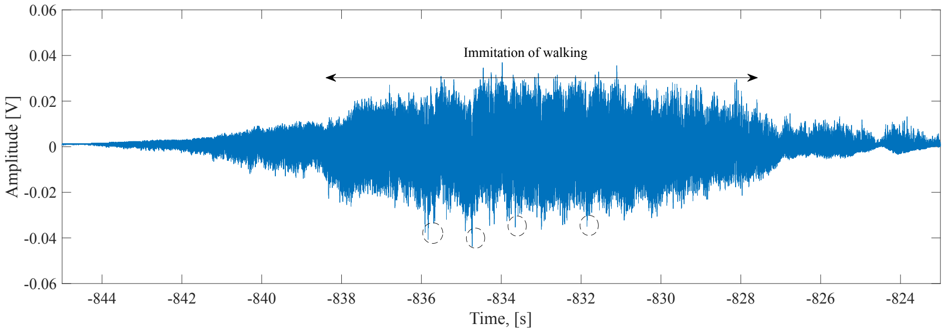

Fig. 7.8: Oscillogram of walking

From the spectrogram 7.9, standing on the well is also visible on the graph in the boxed section. But the imitation of walking is unclear; vertical lines would represent it here.

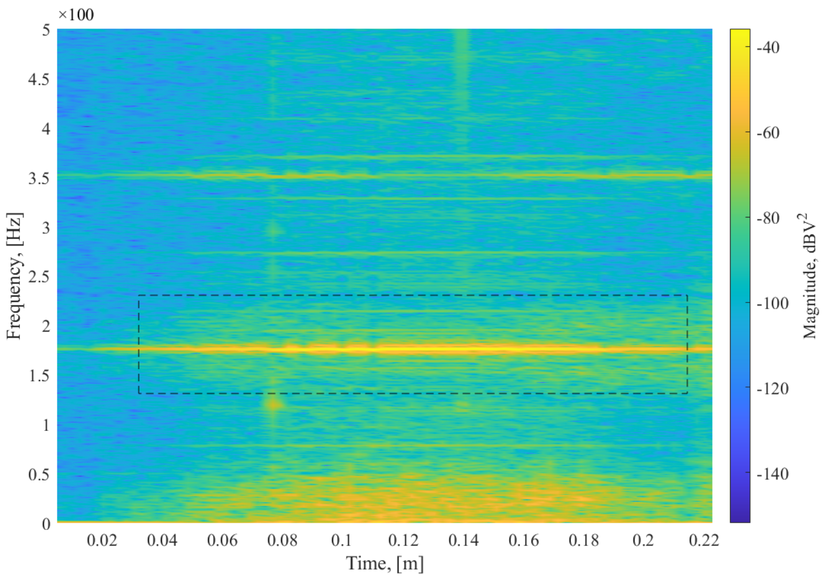

Fig. 7.9: Spectogram of walking

7.2.2 Detection of stomping on the well

Now if vibrational power is increased, the oscillogram 7.10 shows such changes in the circled areas. While remaining on the well with one foot, the second foot applied more pressure with stomping. Counting extensive fluctuation on the oscillogram would result in seven bigger fluctuations. The spectrogram 7.11 also shows seven

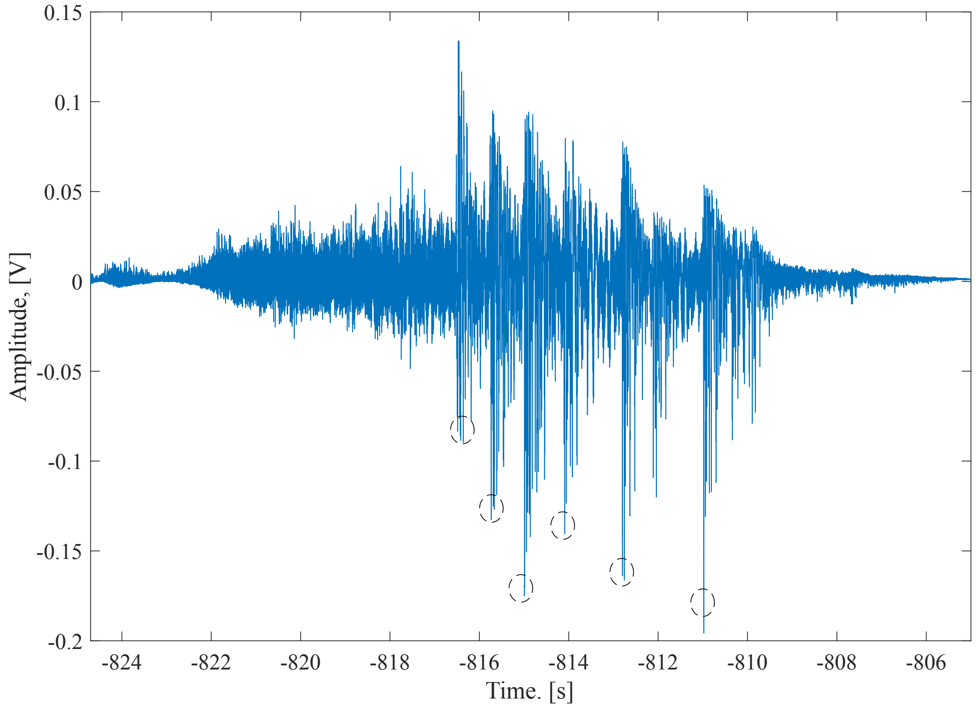

Fig. 7.10: Oscillogram of stomping

vertical lines that correspond with the oscillogram and conclude, in fact, 7 bursts, while the horizontal line remains and represents standing on the well, as on spectrogram 7.9.

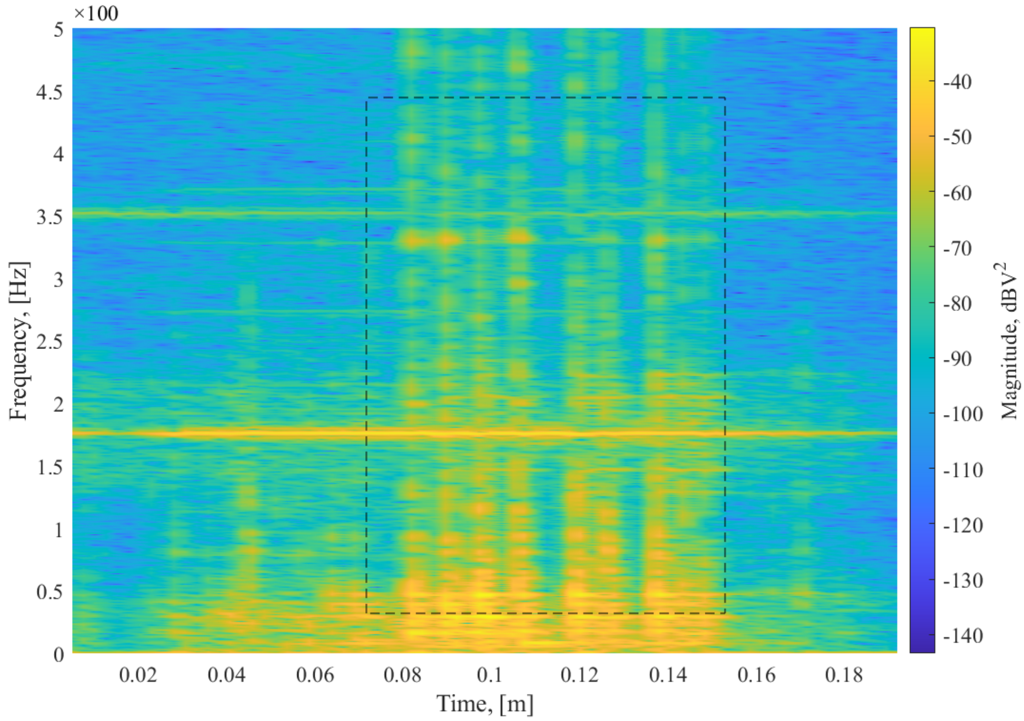

Fig. 7.11: Spectogram of stomping

7.2.3 Detection of jumping on the well

Logically jumping would put much more pressure on the physical object than just walking. From the oscillogram 7.12, boxed areas show the exact moment feet were placed on the well. This oscillogram differs from the other two since it doesn't show any noise on the graph between 3 jumps. As described earlier, the fluctuations throughout oscillograms 7.10, 7.8 were caused by standing on top of the well.

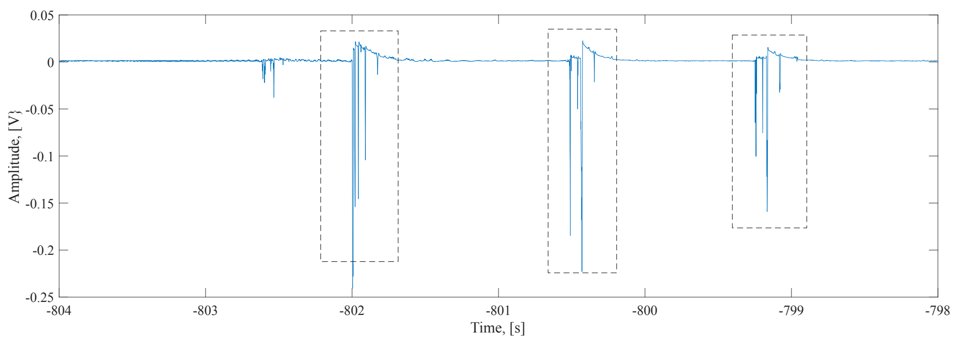

Fig. 7.12: Oscillogram representing jumping

Spectrogram 7.13 represents the same action that is on the oscillogram 7.12. Three vertical lines are much more visible than before with a greater magnitude quantity since they are almost fully covered in yellow.

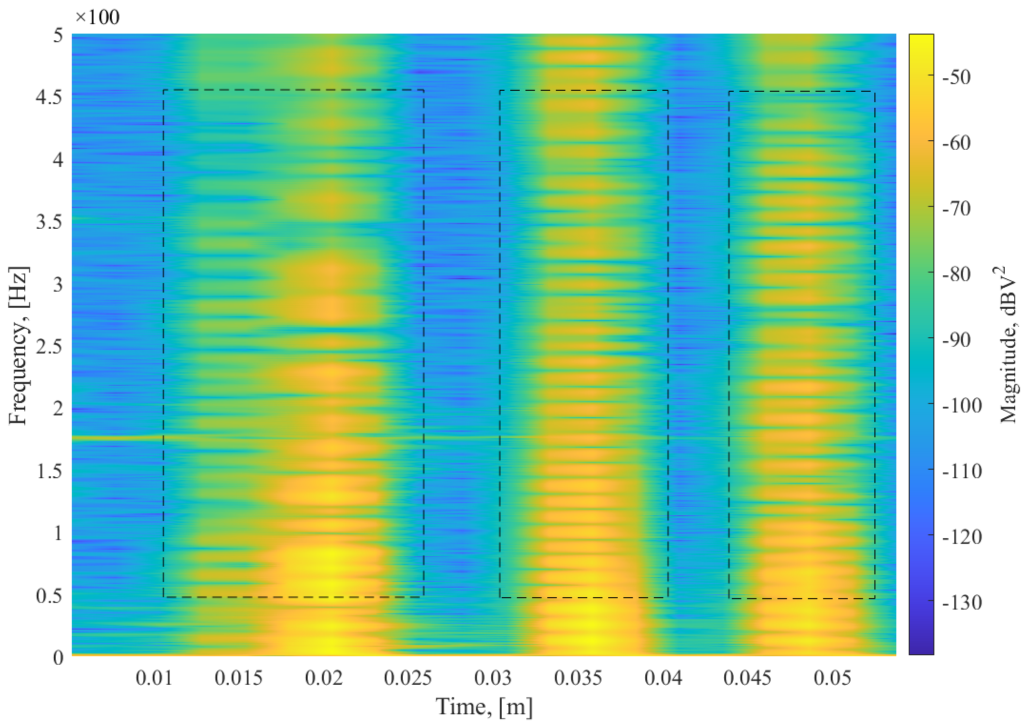

Fig. 7.13: Spectogram representing jumping

7.3 Analysis of the recorded data

Although WaveForms software provides its own wave analysis, Matlab software was chosen to represent all the graphs in this thesis. Every scenario shown here is about 20 to 25 thousand samples out of 2 million. Considering that, it is easy to spot differences between those scenarios. It was mentioned that walking on the pathway where sensing cables are located didn't give a clear picture of what was happening; all the scenarios happening near the 1st well were far superior in amplitude change. It could be the problem of cables lying underneath the soil, which can take away some vibrational power; there is also a possibility of wrong settings for this experiment that took away sensitivity in this area. Cables lying underneath the soil should not exceed the depth underground. What is understandable is that with more pressure put on the 1st well, more the spectrograms and oscillograms changed in time, frequency and amplitude dimensions. That might be the cause why opening the well didn't give the same results, since pressure from the opening is minimal to none.

Conclusion

In this bachelor thesis, the theory around optical fiber sensors and optical fiber itself was explored. From the theoretical research, optical sensors still don't play a big role in the sensor industry. However, the stakes at which its popularity grows change yearly with exceeding interest in such technology. Long-distance security systems, aggressive and difficult electromagnetic environments, and areas with high lightning activity have no equivalent alternative to fiber-optic technologies. Optical security systems also offer the advantage of preventing accidental or deliberate equipment failure. Additionally, they boast high reliability, a long service life (thanks to the fact that optical fiber does not oxidize), and infrequent maintenance requirements during operation (withstanding temperatures ranging from -45 to 75 degrees Celsius).

Installing and splicing optical fiber systems requires great expertise and precision in the optical fiber area. The process involves connecting cables and integrating the various components of the system, which demands a higher level of skill. Many precautions should be taken to work with such technology; otherwise, it could damage the workers, cables, and system overall. Hence, the prices of fiber optic sensors and their instalment.

Choosing between DAS and interferometric systems also significantly affects satisfactory results. While DAS systems can secure longer distances and stay resistant to cable cuts, they are on the expensive side of the technology. interferometry based sensors are cheaper in one way but are sufficient for small to mid-sized areas. Since the object's security is the most important part, the monetary value of the intrusion into such an object should not be overseen in choosing the right technology.

Overall, optical fiber sensing systems have many advantages over competitors in this market and are gradually replacing traditional security systems applications. In the practical part of the thesis, interferometric sensors such as a Mach-Zender interferometric sensor were chosen to get data from. The deployment chosen for semestral and bachelor's work differed from one another, which also gave a comparison to look at. After the practical part, it is clear that optic fiber sensors are more than capable of detecting intrusions.

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Symbols and abbreviations

IT	Information technology
LASER	Light amplification by stimulated emission of radiation
SMF	Single-mode fiber
MMF	Multimode fiber
LAN	Local area network
MAN	Metropolitan area network
CWDM	Course wavelength division multiplexing
LED	Light-emitting diode
VCSEL	Vertical cavity surface emitting laser
SMF	Single-mode fiber
OF	Optical fiber
SC	Square connector
LC	Lucent connector
FC	Ferrule connector
FOS	Fiber optic sensors
DAS	Distributed acoustic sensing

OFC	Optical fiber coupler
RIN	Relative intensity noise
EMI	Electromagnetic interference
RFI	Radio-frequency interference
APU	Application processing unit
FD	Fiber Defender
OTDR	Optical time-domain reflectometer
API	Application programming interface
XML	extensible markup language
JSON	JavaScript object notation
USB	Universal serial bus