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A Survey on Optical Technologies for IoT, Smart Industry, and Smart Infrastructures

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Abstract: In the Internet of Things (IoT), a huge number of sensors, actuators and other equipment for data acquisition and processing will be interconnected by means of an omnipresent communication network able to efficiently support heterogeneous transmission technologies and applications. On the one hand, advanced optical communication systems, which already play a significant role in modern networks, are currently evolving to meet very high requirements of modern applications. On the other hand, there are already many ways to utilize optical components and effects for building precise, efficient, and reliable sensors. Thus, optical technologies have the potential to greatly help in realizing future smart infrastructures and systems. This paper gives an overview of currently available and emerging optical technologies for sensing and communication applications and reviews their possible application in the context of the IoT for realizing smart systems and infrastructures.

Keywords: optical technology; Internet of Things (IoT); optical sensors; optical communication systems and networks

1. Introduction

The main prerequisite for implementing future smart city applications and systems is the existence of an efficient and reliable smart infrastructure. Such an infrastructure integrates in an efficient and reliable manner various basic infrastructures such as (i) water distribution systems, (ii) electricity grids, and (iii) transport infrastructure (roads, railways, trams, and metro) together with information technologies, distributed smart sensing systems, and communication networks. Another prominent application is the smart healthcare, which has the potential to improve the quality of patient care and how health care is delivered, for example, through a better and faster diagnostics, better treatment of patients, and improved operational efficiency. In production environments, recent developments in the area of control systems in conjunction with modern information and communication technologies (ICTs) are the main drivers for the fourth industrial revolution. In the coming decades, this trend may lead to a radical change in industrial processes. A broad penetration and widespread implementation of machine-to-machine (M2M) communication and the Internet of Things (IoT) will erase the traditional boundaries between the manufacturing and telecommunication sectors. Thus, a huge number of sensors, actuators, and various other smart devices interconnected with each other by means of an omnipresent, high-performance, and highly reliable communication network are the main building parts of an effective and ubiquitous IoT. An optimal combination and integration of these devices and technologies together with intelligent and efficient data acquisition and processing are key factors in realizing integrated and smart infrastructures and systems.

The Role of Optical Technologies in the IoT

Photonic technologies have played and will play in the future a significant role in the development of the IoT and its application in smart infrastructures. There are countless examples of using photonic devices and systems in smart infrastructures such as imaging sensors and sensors for measuring various physical and chemical quantities such as temperature, strain, force, acceleration, tilt, rotation, vibration, velocity, fluorescence, luminescence, absorbance, refractive index, and humidity. Other well-known examples are fiber-optic communication systems and networks, as well optical positioning systems. An example of the positioning of optical technologies within the layered IoT architecture is shown in Figure 1. It is evident that optical technologies mainly relate to the device layer (sensors and actuators) and the network layer (transport capabilities). While optical effects and structures are one of the possible candidates for implementing various sensors and actuators, the modern transport network infrastructure is based mainly on optical communication systems. Thus, optical communication and switching technologies will continue to play the central role in providing ubiquitous, high-performance, and reliable transport networks for IoT systems.

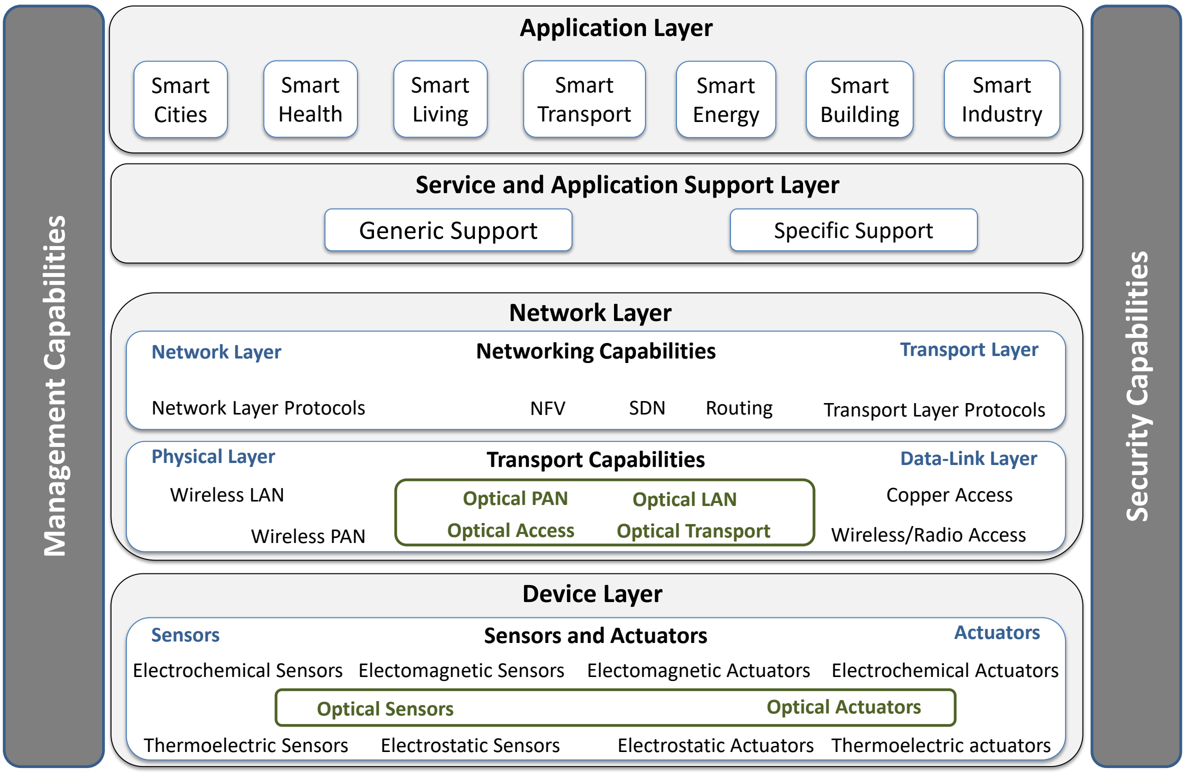

Figure 1. Layered architecture of the Internet of Things with an emphasis on the role of optical technologies—adapted from the International Telecommunications Union—Telecommunication Standardization Sector (ITU-T) [1] (NFV: Network Function Virtualization, SDN: Software-Defined Networking, PAN: Personal Area Network, LAN: Local Area Network).

Constrains and requirements set on IoT devices and systems greatly depend on the selected IoT application and considered layer. Some applications such as environmental monitoring or traffic control require a large number of sensors distributed over a large geographical area. Thus, extremely low energy consumption, long battery life, and large network coverage are very important requirements for such applications. On the other hand, in case of manufacturing process control and home automation, the requirements of energy consumption and battery size, as well as network reach, are much more relaxed since the area to be covered by the network is restricted and direct access to the electricity grid is mostly available. Also, the requirements of mobility, flexibility, and data rate can vary in a wide range, depending on the application and implementation approach used. As this is the case with most of the technologies and approaches that have already been developed or considered for use in the IoT, photonic communication systems and sensor devices are also not generally suitable for all IoT scenarios. Since optical sensors can be used for sensing a large number of quantities and properties in both a discrete and distributed manner, they are relatively universally applicable. The main advantage of optical sensors in comparison to electrical and electromagnetic ones is that optical sensors can be used in wet and harsh environments. Therefore, optical sensors can be used in underwater systems, for monitoring the structural health of energy generation and distribution systems, for in-situ and in-vivo applications, in hospitals and operating rooms, in hash production environments, etc. Regarding the transport and network capabilities, optical transmission technologies are able to provide very high data rates over long distances and a more secure and efficient signal transmission than radio transmission systems because of their guided/directed signal/beam transmission mode. There are several IoT applications requiring large bandwidth such as e-health, telemedicine, large software updates, video control and surveillance (e.g., closed-circuit television—CCTV), autonomous cars, and virtual reality. Once implemented and broadly used, these applications may generate enormous need for flexible and rapid providing of very high capacity paths in the network, which can only be satisfied by modern optical network technologies.

The aim of this paper is to provide a survey on optical technologies in support of applications for smart systems and infrastructures. While wireless systems have widely been considered and investigated for application in IoT systems, there is still less work on the importance and application of optical technologies. Thus, this paper draws attention to the role of optical technologies in the IoT. It extends the discussion presented in the conference paper [2] and gives some new insights.

The paper is structured as follows: The following section describes the recent developments in the area of technologies for optical sensors. Current work in the area of remote optical sensing and optical sensor networks are briefly addressed in Section 3. Section 4 reports on recent efforts at building an adequate network infrastructure that matches the needs of IoT applications and services with particular attention paid to optical communication technologies. The last section discusses possible future trends and concluders the paper.

2. Optical Sensors

Optical sensors have traditionally been used for hundreds of years in some applications such as, imaging and distance measurements. In the last decades, photonic materials and effects have been extensively exploited for sensing applications, so that a number of additional use cases have appeared. Optical sensors have already found a wide use in holography, automated mass manufacturing, transportation, and health applications, just to mention some examples. In sensitive environments such as those found in health systems, especially for in-situ and in-vivo applications, there are crucial advantages of optical systems because of their inherent properties such as short wavelength, small size, lightweight, absence of electromagnetic radiation, immunity to electromagnetic interference, and ability for remote and multi-position measurements. This applies analogously to harsh environments, in which the immunity to electromagnetic interference provides the crucial benefit.

Typical applications of optical sensors include: (i) measurement of physical quantities such as temperature, velocity, acceleration, strain, pressure, or shape of an object; (ii) monitoring the health of composite materials by detecting delamination, deformation, and cracking as well as measuring vibrations; (iii) measurement of various chemical properties; (iv) biomedical and biometric applications such as measuring blood flow, testing of skin irritants, blood perfusion measurements in the stomach and duodenum, long term health assessment, obtaining fingerprint image; (v) industrial applications such as characterization of products, real-time thermal imaging, composition analysis, detecting delamination and defects, surface inspection, and many more. Some more applications are shown in Figure 2.

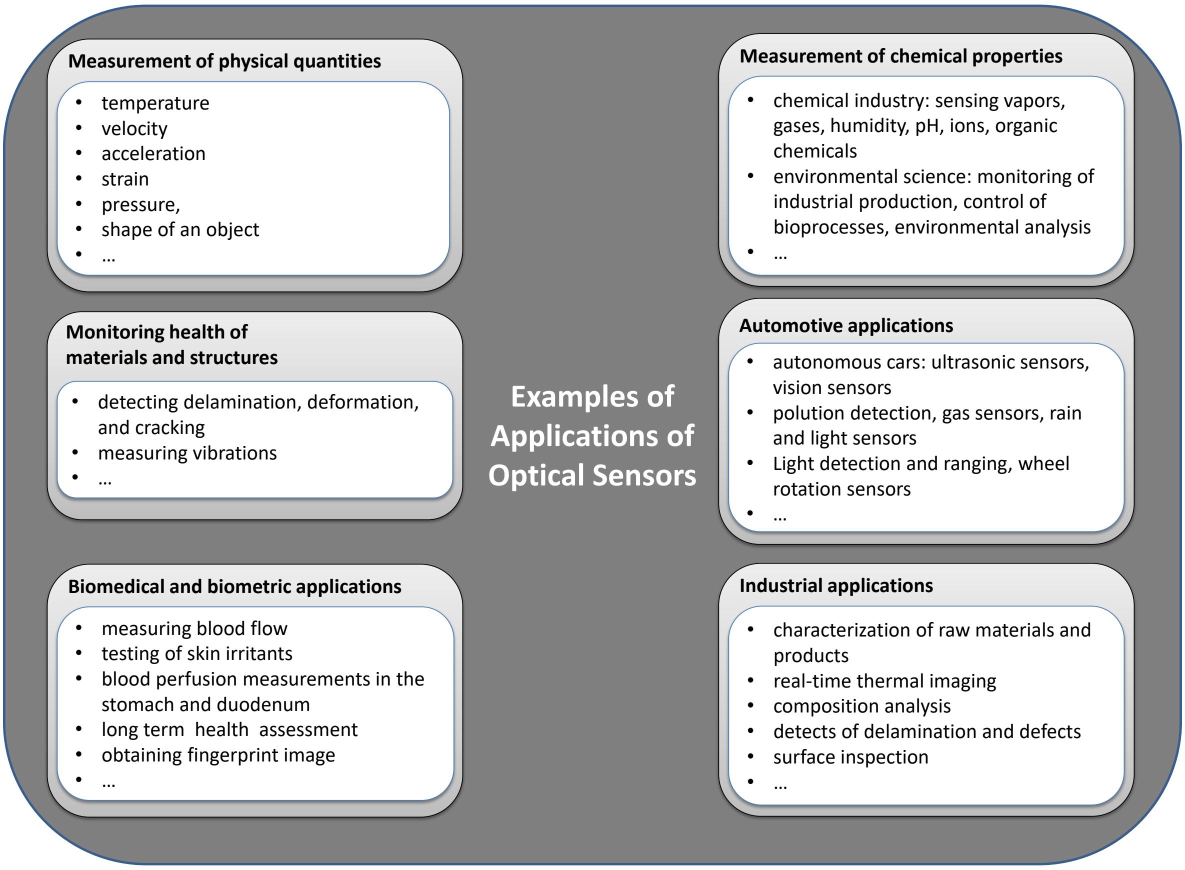

Figure 2. Some examples of possible applications of optical sensors.

2.1. Classification of Optical Sensors

Optical sensors are mostly based on optical fibers as waveguide, in which a certain effect takes place. Additionally, polymers or graphene with its derivatives are valuable candidates. Also, free-space optics can be used to sense properties of the environment.

Different realizations of fiber-based optical sensors can be classified according to several criteria. One can decide to make a classification according to the intended application or purpose. Fiber-based optical sensors can be classified as follows [3]:

- According to the modulation and demodulation process, sensors can be based on intensity, phase, frequency, or polarization modulation.
- Optical fiber sensors can be intrinsic or extrinsic. In intrinsic sensors, the sensing occurs in the fiber itself by the change of one or more physical properties of the optical signal (phase, intensity, wavelength, or polarization). Intrinsic sensors are mostly used to measure temperature, pressure, flow, or liquid level. They are mostly easy to use and less expensive. If the fiber is mainly used to guide the light into and out of the sensing region and the sensing essentially occurs outside of the fiber, then such a sensor is called extrinsic. The main applications of extrinsic sensors are the measurement of acceleration, strain, rotation, vibration, and acoustic pressure. They are more sensitive and expensive than intrinsic sensors and require a more complex signal processing.
- According to measurement points there can be point-based (discrete), multiplexed, or distributed sensors. In a point-based sensor, the sensing occurs at a single measurement point in the fiber. Multiplexed sensors are capable of providing several measurement points within a single piece of fiber. In distributed sensors, the sensing is taking place in a distributed manner at any point along the fiber.

- Regarding the intended application or physical property to be sensed, we can have (i) physical sensors, e.g., for measuring the temperature, magnetic field, concentration, humidity, strain; (ii) chemical sensors that sense chemical properties of, e.g., gas or liquid environments, pH factor, refractive index; and (iii) biological sensors, e.g., for sensing physiological parameters, glucose and thrombin detection, and blood flow.

2.1.1. Physical Sensors

The most widely used optical sensors are those measuring a physical property such as temperature, pressure, position, and flow. Probably the largest class of commercially available optical sensors is the temperature sensor. Although there are many different realizations of optical temperature sensors based on various effects and measuring methods, the optical fiber-based distribution ones have found the widest application in temperature monitoring. Especially for applications where making a temperature profile with a large number of sensing points is a crucial feature, the distributed temperature sensing shows enormous advantages. Examples of such applications are pipelines in refineries, tunnels, electrochemical processes, power cables, feed bands, and oil wells. The typical effect utilized in fiber-based distribution sensors is Raman scattering. To measure the temperature a laser generates short optical pulses that are injected into the fiber, which acts as the actual sensing element. Due to the interaction of the laser light with the material of the fiber the light is scattered and a part of the optical signal is transmitted back in the direction that is reverse to the propagation direction of the generated light. The backscattered light comprises a Rayleigh, a Brillion, and a Raman part. The information about the temperature can be obtained by measuring the Raman part of the backscattered light because it is created by thermally influenced molecular vibrations. The Anti-Stokes component of the Raman backscattered light shows a strong dependence on the temperature, while the Stokes component does not. By filtering out the two components (they have different wavelengths) and calculating the ratio of their intensities, we can obtain the information about the temperature. Due to the fact that very short optical pulses with a duration of only a few nanoseconds are generated and injected into the fiber, the exact position of the measurement along the fiber can be determined by measuring the arrival time of the backscattered light.

Pressure sensors are mostly based on movable diaphragms representing a pair of parallel partially refractive mirrors separated by an air gap. This structure essentially forms a Fabry–Pérot cavity. By exposing a diaphragm to pressure, the length of the air gap is changed, which leads to a change of the transmission properties of the Fabry–Pérot cavity. Thus, the pressure is sensed by measuring the retro-reflected intensity.

Flow is often measured by combining pressure sensors with the Venturi effect. The flow rate is obtained by measuring differentiated pressure between two segments of a Venturi tube with different apertures.

Position and displacement sensors have already been developed in early 1980s. These sensors rely on a very simple principle of the change in retro-reflectance of light injected into the fiber due to a movement of a proximal mirror surface. For strain measurements one can use different types of optical sensors such as those based on fiber Bragg grating (FBG) [4,5], polarimetric sensors [6], interferometric sensors [7], sensors based on Raman, Brillouin, and Rayleigh scattering [8,9], and hybrid sensors [10].

2.1.2. Chemical Sensors

Typically, optical chemical sensors are based either on a piece of fiber with a partially transparent mirror or on bifurcated fibers. Thus, chemical sensors are mostly extrinsic where the actual chemical sensor, i.e., the sample to be analyzed, is put very close to or integrated into the end of the fiber, depending on the measurement strategy and fiber type. Optical properties that are typically measured are fluorescence, luminescence, phosphorescence, reflectance, absorbance, evanescence, refraction index, and Raman dispersion.

Additional to the fiber and the sample to be analyzed, optical sensors usually comprise an optical source and an optical receiver, i.e., a photodetector. Typical device combinations and measurement methods for four examples of optical sensors are summarized in Table 1.

Table 1. Examples of typical configuration of optical sensors for sensing four quantities: fluorescence, phosphorescence, absorbance, and reflectance (LED: Light-Emitting Diode; LD: Laser Diode; PD: Photo Diode; APD: Avalanche Photodiode; PMT: Photomultiplier Tube; PL: Pulsating Lamp).

Quantity	Optical Sensor Principle		
	Optical Source	**Optical Receiver**	**Method**
Fluorescence	LED	PD	Frequency-domain measurement
	LD	APD	Impulse-response time-domain measurement
	PL	PMT	Intensity measurement
Phosphorescence	LED	PD	Frequency-domain measurement
	LD	APD PMT	Intensity measurement
	PL	APD PMT	Impulse-response time-domain measurement
Absorbance	LED LD	PD	Intensity measurement
Reflectance	LED LD	PD	Intensity measurement

When selecting the right device for a specific sensor application, particular attention should be paid to the characteristics of the quantity to be measured. For example, since phosphorescence generates a rather low intensity, the photodetector should have a high sensitivity. Thus, for phosphorescence sensors an avalanche photodiode (APD) or a photomultiplier tube (PMT) should be used. On the other hand, for fluorescence sensors utilizing the impulse-response time-domain measurement, a pulse source capable of generating very short optical pulses in combination with a high-speed detector should be selected. For sensing the luminescence, it is recommended to use a shaped fiber tip in order to reduce the noise at the photodetector caused by the reflected light. Additionally, selective membranes can also be used to improve the sensor selectivity. However, the membrane leads to an increase in the sensor's settling time because the light is diffused while passing through.

2.1.3. Biological Sensors

In practical applications, biological sensors mostly measure a chemical or a physical quantity, which is directly related to a biological parameter. A biological system produces a change of a chemical or physical variable, which can then be indicated by measuring a change of a property of the generated light such as intensity, phase, or frequency, leading to a very similar measuring principle as already shown in Table 1. A classic example of a biosensor is to use the luciferin-luciferase method for measuring adenosine triphosphate (ATP) content—an energy coenzyme found in the cells of all living organisms—which acts as the common energy currency. The chemical reaction used here is [11]:

$$\mathrm{ATP} + \mathrm{luciferin} + \mathrm{O_2} \rightarrow \mathrm{oxyluciferin} + \mathrm{PP_i} + \mathrm{CO_2} + \mathrm{AMP} + \mathrm{light} \tag{1}$$

Adenosine monophosphate (AMP) is one of the results of the reaction and emits light. This phenomenon is referred to as bioluminescence. Due to the fact that the concentration of ATP is proportional to the emitted light, the ATP content can easily be measured by measuring the intensity of the bioluminescence.

2.2. Examples of Optical Sensors

There is a long list of possible applications of optical sensors. Intensity-based optical sensors are one of the first and most used optical sensor types. They have been mostly used to detect vibrations, position, pressure, temperature, or strain [12]. Even though this type of sensor is quite simple to realize, they have a number of limitations imposed by the change in losses without any direct relation to the measured quantity. This variation in losses can be due to the imperfections of connectors and splices, misalignment of light sources and detectors, as well as mechanical creep. Another option is to utilize phase modulation or an interferometric structure. Table 2 shows a summary of optical sensors and typically measured quantities by different sensor types.

Table 2. Examples of optical sensors and their typical utilization (WDM: Wavelength-Division Multiplexing; TDM: Time-Division Multiplexing).

Type of Sensor		Typically Measured Quantity	Ex. Ref.
Intensity modulation	Numerical aperture	Closure or vibration	[13]
	Flexible mirror	Position, vibration, or displacements	[14]
	Reflectance	Rotary position	[15]
	WDM based	Linear position	[16]
	TDM based	Linear position	[17]
	Total internal reflection based	Pressure	[18]
	Evanescence based	Temperature, pressure, or strain	[19]
	Microband based	Temperature, vibration, or pressure	[20,21]
	Grating based	Vibration or acceleration	[4,22]
	Raman or Brillouin scattering	Distributed measurement of strain or temp.	[8,9]
Frequency modulation	Back body sensor	Temperature	[23]
	Absorption based	Temperature	[24]
	Fluorescence based	Temperature, viscosity, and humidity	[25]
	Fiber grating based	Strain	[5,26]
	Etalon based	Pressure, temperature	[27]
Phase modulation (Interferometric sensors)	Mach–Zehnder interferometer	Vibration, acoustics, or strain	[28]
	Sagnac interferometer	Optic gyros, vibration, acoustics, or strain	[29,30]
	Michelson interferometer	Vibration, acoustics, or strain	[28,31]
	Fabry–Pérot interferometer	Strain, temperature, displacement	[7]

3. Optical Sensor Networks

A more complex sensing system with extended reach is realizable by combining optical sensors with optical fibers and network components such as optical multiplexers/demultiplexers and switches. The main applications of remote fiber-optic sensing and optical sensor networks envisaged so far are remote and continuous monitoring of structural health, environmental monitoring and surveillance, home security, agriculture, medical monitoring, monitoring of transport systems, and industry applications. Many types of optical sensors can be used in a remote configuration including both distributed and discrete ones. The discrete remote configurations are mostly based on Fabry–Pérot or fiber Bragg gratings (FBG) while the distributed ones mostly exploit Brillouin or Raman scattering. An example of such a remote sensing system is presented in Figure 3a.

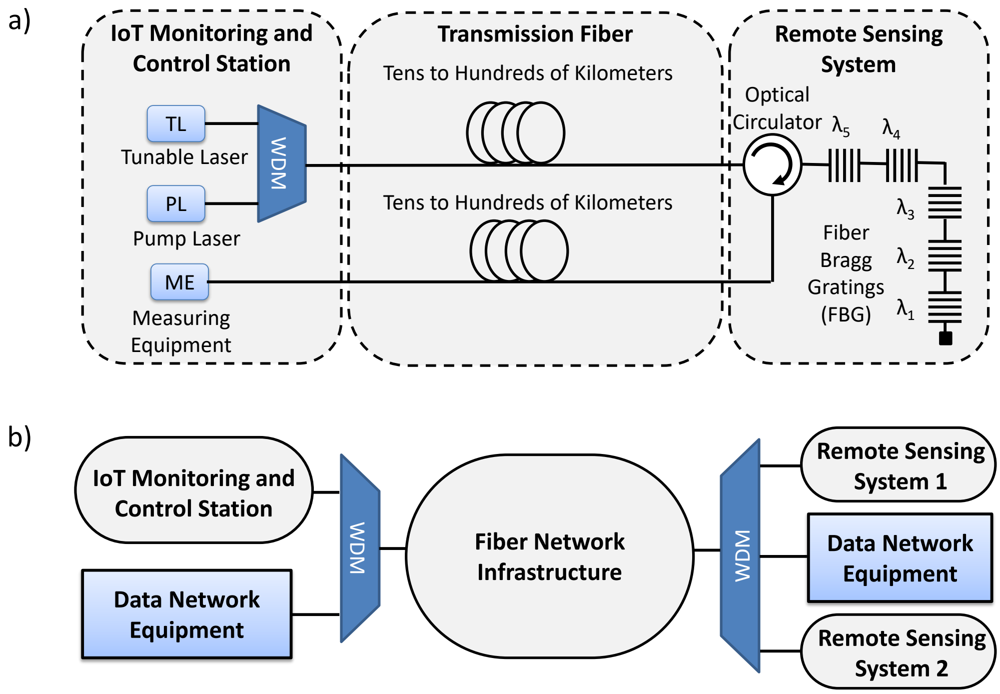

Figure 3. Remote sensing: (**a**) the main components of a discrete remote sensor network based on fiber Bragg gratings (FGB) and Raman amplification, (**b**) integration of a remote sensor network together with an optical data transport network by sharing the same fiber network infrastructure. The sensor and data signals are separated by using the wavelength-division multiplexing (WDM) technology.

The central monitoring and control station incorporate, among others, a tunable laser for generating light with different wavelengths, an optional pump laser for amplification or remote pumping, and measurement equipment for analyzing the response of the sensing devices located at the remote location. In the example shown in Figure 3a, the remote sensing system comprises fiber Bragg gratings (FBG). The reach of such a system can be from several kilometers to hundreds of kilometers. Amplification must be applied to make long-distance systems possible. For example, a remote sensing system with an extended reach of 230 km can be implemented by using erbium-doped fiber amplifiers (EDFA) [32]. An important benefit of remote fiber-optic sensing is the possibility of multiplexing several sensors on a single fiber. A system incorporating four FBG sensors and Raman amplification to provide a reach of over 250 km has been reported in [33]. Recently, a double-pumped random distributed feedback (DFB) fiber laser has been used to achieve remote interrogation of an interferometric sensor over 290 km [34]. Additionally, the optical fiber link can be used not only for sensing, but also simultaneously to carry signals for data transmission and power distribution to remote sensor nodes [35] as depicted in Figure 3b.

A number of network arrangements and topologies including simple sensor arrays, serial and ladder arrangements as well as tree and partially meshed topologies have already been considered for sensor networks [36–40]. To enable various topologies and increased reliability, optically transparent switches and routers can be used [39].

In addition to fiber-based sensor networks, optical wireless sensor networks have also gained particular attention in the research community [37,40–46]. The proposed systems consider both terrestrial free-space and underwater communication as well as those based on visual light communication. An interesting approach is to integrate optical wireless with radio technology in a hybrid/aggregated sensor network [47]. Such an aggregated optical/radio sensor network could combine the best of both worlds in a single system in an optimal and efficient way. In this way, an extended frequency spectrum [45], better coverage, and support of mobility as well as high data rates could be achieved. An overview of different optical sensor network types is shown in Figure 4.

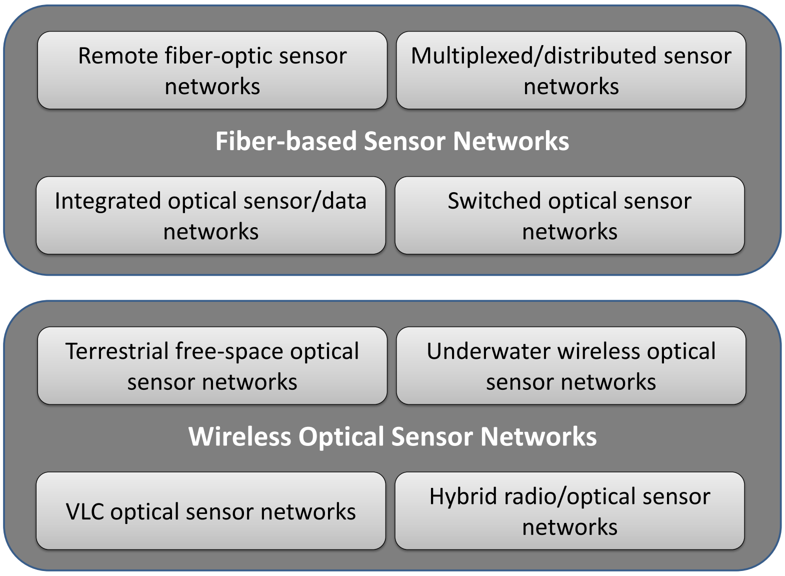

Figure 4. Different types of fiber-based and wireless optical sensor networks (VLC: Visual Light Communication).

The data measured and sometimes partially processed within a sensor network are mostly sent to either a central unit or a distributed system for further processing. In both cases, the interconnection of sensor networks with other sensor networks and data centers is a crucial function for realizing effective, reliable, and large-scale applications. As already discussed in Section 1 and indicated in Figure 1, transmission and networking capabilities represent an important middle layer between the device layer and the application layer. Therefore, the communication network infrastructure will play a significant role in future development of IoT systems and applications. Thus, the next section provides a brief review of current developments and future trends in the optical network infrastructure with a particular focus on its capability to support the demands of IoT applications.

4. Optical Network Infrastructure

Optical transmission technologies and networks have made huge progress in the last few decades towards a high-capacity, high-performance, and flexible network infrastructure. Many new technologies and network concepts have evolved recently [48]. One of the main drivers of this development is the rapid growth of applications such as machine-to-machine communication and smart infrastructures. These new applications set very high, and even more important, different requirements on the network infrastructure than the traditional communication application and services. In particular, low end-to-end latency, high availability, data consistency, and security are important requirements of many IoT applications. A new concept is needed to cope with this trend in order to provide high flexibility, adaptability, and reliability together with a high level of security and efficient separation of different network slices. Thus, flexible and adaptable network concepts are needed for all network areas and layers.

Traditionally, optical networks have been developed and operated in a quite static manner. Even though both capacity and topology have been continuously adapted to increasing requirements, the flexibility and adaptability features have not been supported at all. The capacity requirements have mostly been met by step-wise increasing the line data rate and using the dense wavelength-division multiplexing (DWDM) technique with the fixed wavelength grid. The topology of choice was mainly either a double counter-rotating ring or a partially meshed topology. Especially with regard to providing high capacity, optical transmission systems have made huge progress through increasing the spectral efficiency and using advanced multiplexing techniques and multi-level modulation formats as well as special types of fibers such as multi-core and multimode fibers. As an example, in recent laboratory experiments, an aggregate capacity of more than 100 Tbit/s over a single standard single mode fiber (SSMF) have been reported [49] or even more than 1 Pbit/s when using space-division multiplexing (SDM) over multicore fibers [50].

Similar to the development of radio communication systems, the evolution of optical communication systems and networks can also be represented by five technological generations as shown in Table 3. The recent developments of optical communication systems are promising to provide sufficiently high capacity for supporting all current and emerging applications within the area of smart systems and infrastructures. However, without an improvement in flexibility, adaptability, and manageability of optical networks, the network infrastructure will not be able to adequately respond to the very different and dynamically changing requirements of various emerging applications and services.

Table 3. Evolution of optical network capacity and functionality represented by five network generations.

Optical Network Generation	Description		
	Examples of Technologies	**Main Characteristics**	**Line Data Rates**
1st Generation	PDH, FC, Optical Ethernet	bit-wise multiplexing, p-t-p links	1–140 Mbit/s
2nd Generation	SDH, SONET	mainly ring topology, APS, byte-wise multiplexing, p-t-p links	50 Mbit/s–2.5 Gbit/s
3rd Generation	SDH, SONET over WDM	ring and mesh topologies, APS, fixed wavelength grid, byte-wise multiplexing, p-t-p links	50 Mbit/s–40 Gbit/s
4th Generation	OTN, DWDM, ROADM, 100G Ethernet	ring and mesh topologies, fixed wavelength grid, ODU switching	1–100 Gbit/s
5th Generation	HOS, EON, NFV, multi-layer SDN, 5G wireless backhaul, Optical cloud	mesh topology, adaptive modulation, flexible grid, adaptability, energy efficiency	10 Gbit/s–1 Tbit/s

FC: Fiber Channel; SDH: Synchronous Digital Hierarchy; OTN: Optical Transport Network; SONET: Synchronous Optical Network; PDH: Plesiochronous Digital Hierarchy; APS: Automatic Protection Switching; HOS: Hybrid Optical Switching; ROADM: Reconfigurable Optical Add/Drop Multiplexer; DWDM: Dense Wavelength-Division Multiplexing; ODU: Optical Data Unit; EON: Elastic Optical Networking; M2M Machine-to-Machine Communication; RAN: Radio Access Network; NFV: Network Function Virtualization; SDN: Software-Defined Networking.

4.1. Flexibility and Adaptability

One of the first steps towards greater flexibility of optical network infrastructure is to replace the fixed wavelength grid with a flexible wavelength grid, which makes a more effective utilization of the available optical spectrum possible. Two crucial components for realizing flexible optical networks are bandwidth-variable transceivers (BVT) and adaptive optical nodes based on flex-grid reconfigurable add-drop multiplexers (FG-ROADMs). The former makes it possible to encode and decode information on an optical carrier with an almost arbitrary center wavelength and using various modulation formats. Consequently, central wavelength, data rate, and bandwidth of the generated optical signal can be adapted to the actual needs and situation in the network. The latter component enables the formation of elastic optical paths through the network by establishing optically transparent connections in a flexible manner while supporting optical signals of different wavelengths and modulation formats. By putting them together and operating them in a coordinated, efficient way, these components can be used to implement the concept of elastic optical networking (EON) [51].

The main building block of an FG-ROADM is the bandwidth-flexible wavelength-selective switch (WSS) [52]. Within a WSS, the incoming light is firstly spectrally demultiplexed by using diffraction gratings and then sent to the space switching element through the angle-to-space conversion lens. A micro-electro-mechanical systems (MEMS) switch or a liquid crystal on silicon (LCoS) switch can act as the space switching element. LCoS is made as a large two-dimensional array of liquid crystal pixels, acting as an electrically-programmable grating. Thus, LCoS are capable of controlling the phase of the reflected light, and consequently, the reflected light beams are directed to the desired output port. Additionally, it is possible to change the passband width by selecting less or more pixel columns for each beam. Commercially available WSS are capable of supporting a relatively fine granularity of 12.5 GHz.

In an EON, optical paths can be realized using spectrum and rate adaptive superchannels. Optical superchannels consist of a number of closely spaced, adjacent optical subcarriers that propagate along the same optical path. Since superchannels can occupy different spectral widths, a bandwidth-flexible ROADM has to be used for switching along the path. For this purpose, flex-grid ROADMs based on LCoS WSS are suitable candidates because they are capable of providing adjustable bandwidths and making spectrally efficient resource allocation and efficient grooming possible.

The flexibility and adaptability enabled by the use of flexible and elastic optical components can be exploited by using network function virtualization (NFV) and software-defined networking (SDN). Although SDN was initially developed for packet-switched networks and mainly for applications in data center networks, it can easily be adopted for use in optical networks. Actually, the control plane of optical networks has traditionally been based on centralized concepts and there is a separation between the management, control, and data planes. The entire potential of SDN and NFV can only be exploited when implementing SDN in a cross-layer fashion. This results in an integration of the so-called optical SDN into the overall, multi-layer SDN concept. The main optical components that can be a part of an optical SDN network are software-controllable BVTs and FG-ROADMs incorporating bandwidth-flexible WSS [53]. Additionally, the use of different switching paradigms and a combined implementation of the switching elements in electronics and optics, often referred to as hybrid optical switching (HoS) [54], can lead to an even higher flexibility and better transmission efficiency due to the possibility of having lover granularities of data flows [55]. The parameters that can be directly controlled by software include modulation scheme, center frequency or wavelength as well as the number of optical carriers belonging to a superchannel. Additionally, switching bandwidth, symbol rate, data rate, and forward error correction (FEC) overhead can be adjusted. Controlling these parameters in a more or less dynamic manner would give great flexibility in providing efficiently various data rates, bandwidths and switching speeds adapted to the needs of different applications. Further, network slicing implemented directly in the signal transmission domain becomes possible, which can lead to both an increase in performance and a better separation of individual network slices.

4.2. Optical Cloud Infrastructure

Reliable and high-performance cloud infrastructures and services are key enablers of IoT and smart infrastructures. Optical transmission and switching technologies play a major role in further development of cloud infrastructure, both within and between large data centers. Within large data centers, novel optical interconnection solutions enable flexible and high-capacity interconnection of a huge number of servers and storage devices in an efficient manner [56,57]. Since applications such as mirroring and content distribution networks require highly available, and dynamically managed high-capacity connections between different data center sides, which can even be located on different continents, flexible and software programmable optical networks turned out to be best suited candidates to optimally meet these requirements [58].

4.3. Optical Access Networks and 5G Backhaul/Fronthaul

Current fiber-based optical access technologies already provide data rates up to 10 Gbit/s by utilizing both point-to-multipoint (p-t-mp) and point-to-point (p-t-p) topologies. Passive optical networks are widely deployed because they inherently support tree topologies and split ratios up to 1:256. An overview of current and emerging standards for passive optical networks (PONs) is presented in Table 4. The emerging standards NG-EPON (IEEE) and G.hsp.x (ITU-T) are considered to be supporting technologies for further development of 5G networks [59].

Table 4. Passive optical network (PON) standards.

Name	Characteristics			
	Standard	Data Rates		Comment
		Upstream	Downstream	
BPON	ITU-T G983.x	622 Mbit/s	155 Mbit/s	based on ATM
GPON	ITU-T G984.x	2.5 Gbit/s	1.25 Gbit/s	based on ATM
EPON	IEEE 802.3ah	1 Gbit/s	1 Gbit/s	based on Ethernet
10G-EPON	IEEE 802.3av	10 Gbit/s	10 Gbit/s	based on Ethernet
XG-PON	ITU-T G987.x	10 Gbit/s	2.5 Gbit/s	based on ATM
NG-PON2	ITU-T G989.x	10 Gbit/s 10 Gbit/s	10 Gbit/s 2.5 Gbit/s	TWDM, 4 λ p-t-p WDM, 8 λ
XGS-PON	ITU-T G9807.1	10 Gbit/s	10 Gbit/s	Symmetric GPON
NG-PON2 Amd1	ITU-T G989.x	10 Gbit/s	10 Gbit/s	TWDM, 8 λ p-t-p WDM, 16 λ
NG-EPON	IEEE 802.3ca	25 Gbit/s 50 Gbit/s	25 Gbit/s 50 Gbit/s	future standard
G.hsp.x	ITU-T SG15	50 Gbit/s	50 Gbit/s	future standard

BPON: Broadband Passive Optical Network (PON); ATM: Asynchronous Transfer Mode; GPON: Gigabit PON; EPON: Ethernet PON; XG-PON: 10-Gigabit-capable PON; NG-PON: Next Generation PON; TWDM: Time- and Wavelength-Division Multiplexing; WDM: Wavelength-Division Multiplexing; p-t-p: point-to-point; XGS-PON: 10-Gigabit-Symmetrical PON.

Traditionally, base stations of a radio cellular network are mostly connected to the core network by either microwave links or time-division multiplexed (TDM) leased lines (e.g., E1/T1) or digital subscriber lines (xDSL) or asynchronous transfer mode (ATM). However, these conventional methods for implementing fronthaul/backhaul to base stations are hardly capable of providing very high data rates in the order of Gbit/s or even several tens of Gbit/s, which will probably be required by future 5G networks. On the other hand, optical access networks are able to provide very high data rates and support long-reach links. Additionally, they can provide high energy efficiency. However, the main prerequisite for using optical fiber-based transmission is the existence of installed fiber, which is not always available or practical to install. Hence, optical access technologies in combination with moderate-speed and high-speed radio links (e.g., microwave and E-band), for exceptional cases in which the fiber rollout is not practical enough, seem to be the most suitable option for realizing a high-capacity and future-proof wireless backhaul network.

Recent developments towards a centralized, cloud-based radio access network (C-RAN) envisage a spatial separation of baseband units (BBU) and remote radio heads (RRH). However, assuming an exemplary 5G scenario with 100 MHz channel bandwidth and 32 antennas, one can calculate the required common public radio interface (CPRI) bandwidth to be about 157 Gbit/s [60]. Additionally, the requirement of low roundtrip latency of 250 µs has to be met [61]. In 4G networks, this requirement is not a concern because RRH and BBU are closely spaced and connected with each other directly by a short piece of fiber. However, in the centralized, cloud-based network architecture, the BBU pool can be implemented on a server, which can be located far away from the base station site, which makes it very difficult to fulfil the stringent low-latency requirement. A new concept divides the data transmission and processing units into four new functional elements, namely into radio unit (RU), distributed unit

(DU), centralized unit (CU), and next generation core (NGC). Depending on the selection of the split option, i.e., the potential placement of fronthaul and backhaul interface, the expected required capacity for the fronthaul connection regarding downlink/uplink vary from about 4 Gbit/s/3 Gbit/s (option 2, interface between CU and DU) and about 22 Gbit/s/86 Gbit/s (option 7, interface between DU and RU) [62]. This fact underlines the need for new optical access technologies and standards capable of supporting very high data rates in both downstream and upstream directions.

Another emerging and promising optical technology that can be used in the access, local area, and personal area networks as well as for proximity communication is optical wireless communication systems. There have been a lot of research efforts recently to propose, investigate, and develop optical wireless systems using both the infrared and the visible parts of the optical spectra and in combination with radio frequency (RF) systems [63,64]. In particular, visible light communication (VLC) and light fidelity (LiFi) as specified in the standard IEEE 802.15.7 have the potential to address a number of smart systems and smart infrastructure applications [65,66]. Some examples are communication and positioning applications in smart offices, smart buildings, smart factories, warehouses, transportation systems, and hospitals. A summary of various advanced networking technologies and approaches is shown in Figure 5.

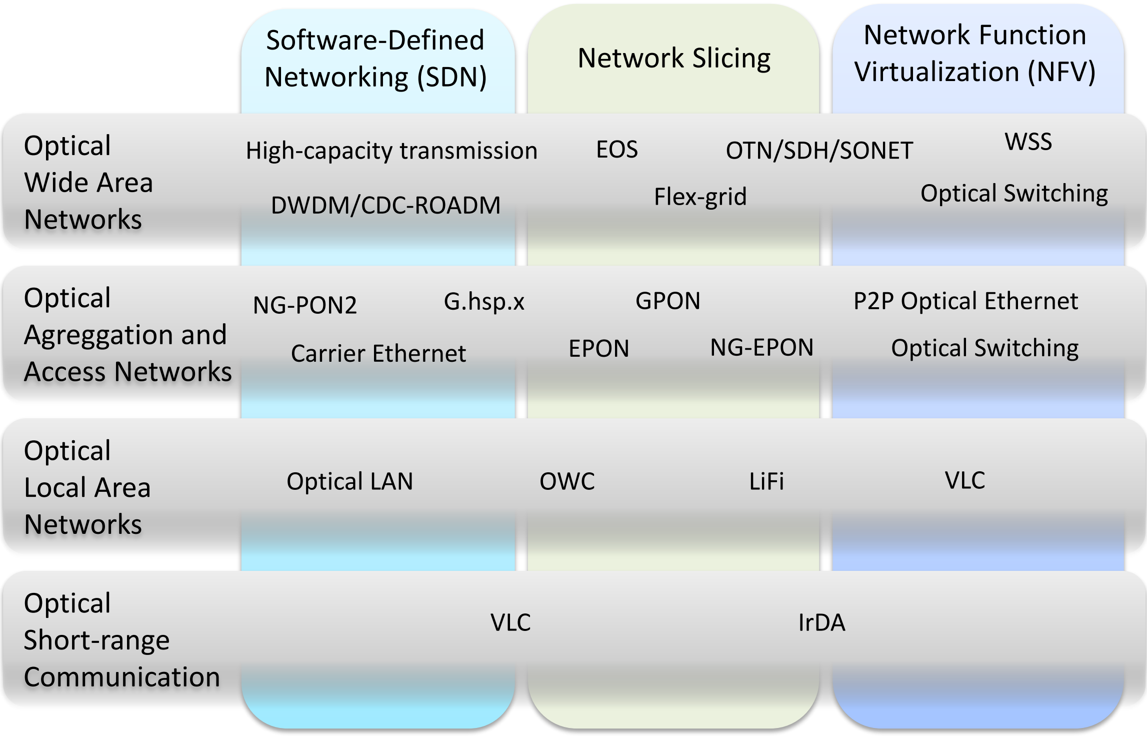

Figure 5. Summary of advanced optical communication technologies and approaches (DWDM: Dense Wavelength-Division Multiplexing, CDC-ROADM: Colorless Directionless Contentionless-Reconfigurable Optical Add-Drop Multiplexer, OTN: Optical Transport Networks, SDH: Synchronous Digital Hierarchy, SONET: Synchronous Optical Networks, EOS: Elastic Optical Networking, WSS: Wavelength Selective Switch, NG-PON: Next-Generation Passive Optical Network, NG-EPON: Next-Generation-Ethernet Passive Optical Network, P2P: Point-to-Point, OWC: Optical Wireless Communications, LiFi: Light Fidelity, VLC: Visual Light Communication, LAN: Local Area Network).

4.4. Energy Consumption

Low energy consumption is an important consideration when developing and implementing new sensing and communication systems, especially for IoT applications. On the one hand, sensor nodes implemented in the field without a direct access to the electricity grid have to manage with limited capacity of the battery for many years. On the other hand, large energy consumption of wireless and wired communication networks as well as data storage and processing systems are not only responsible for high energy bills, but also have a negative influence on the environment [67].

When analyzing energy consumption of a particular implementation of an IoT application one should take into account the energy consumed by all parts of the entire system, i.e., (i) sensor and actuator nodes; (ii) data transmission and networking devices within access and core areas; and (iii) data storage and processing devices such as network and application servers.

Energy consumption of sensor nodes depends greatly on the desired application and chosen architecture. The requirements set by the application will mostly influence the decision about the technology used for sensing unit and additional components and circuits needed for signal/data processing, power supply and management as well as data transmission (i.e., transceivers). A decrease of energy consumption, and thus, increase of battery lifetime, can be achieved through an optimized design of the sensor node. In many cases, different sensing principles require more or less complex signal processing. For a particular application, it could be justified to use optical sensors, depending on the requirements for performance, accuracy, and energy consumption. In some cases, such as in platforms based on optical spectroscopy for measuring various gas properties, the use of optical sensors leads to very precise and fast measurement results, at the cost of higher energy consumption and a more complicated design than when using, e.g., catalytic or semiconductor devices [68]. For some other applications such as those requiring underwater wireless sensor networks, optical technologies provide several advantages over acoustic or electromagnetic waves such as high data rates, low cost, and low power consumption as shown in Figure 6. However, in underwater conditions, optical beams have a relatively limited reach in comparison to the acoustic waves. This constraint can be relaxed by, e.g., using a hybrid acoustic-optical approach [69]. Another promising approach that is not constrained by the limited battery capacity uses an optical remote sensing method as discussed in Section 3 and shown in Figure 3. In such a system, there is no need for a battery or electricity supply in the field at all, which may turn out to be a crucial advantage for some applications, provided there is a direct access to fiber infrastructure.

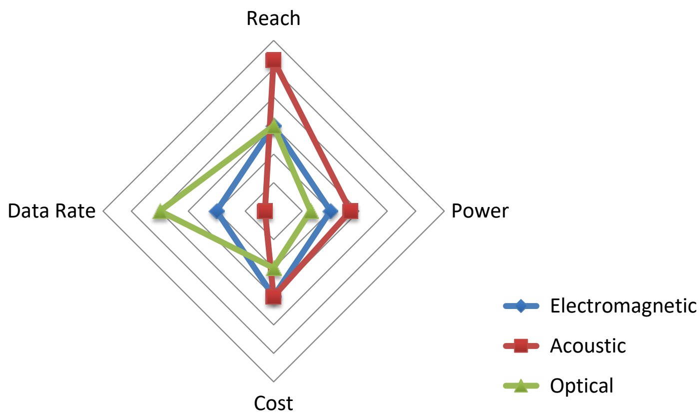

Figure 6. Comparison of electromagnetic, acoustic, and optical underwater wireless sensor networks [69].

The energy efficiency of optical communication technologies has already been extensively investigated. It has been shown that optical transmission systems, especially those using optical fibers, are able to provide higher energy efficiency than radio transmission or transmission over coper wires. A prominent example is the improvement of energy efficiency by more than six orders of magnitude by using modern optical submarine transmission systems instead of the formerly used wireless and coax cable-based ones [70]. Not only submarine transmission systems but also optical transmission and switching elements within various network areas, namely access, aggregation, and core network areas, together with sophisticated network concepts and energy management solutions, have the potential to greatly improve the energy efficiency of the network infrastructure [55,71,72]. Similar technologies and concepts can also be used for internal interconnection networks in large data centers in order to improve both their energy efficiency and scalability [73–75].

5. Conclusions

In conclusion, this paper provides a brief overview of various optical technologies in context of their potential application in future smart systems and infrastructures. Optical technologies have already played and will also play in the future an important role in developing and implementing a global, high-performance, and highly reliable Internet of Things (IoT). They provide fundamental components and functions at both device and network layers of the IoT layered model such as a variety of practical sensor implementations and high-performance communication and network capabilities. There are a number of examples of how introduction and wide use of optical devices and systems can improve the overall performance of the IoT. First, measurement accuracy can be increased by using high precision optical sensors. Second, the number of required sensors for some specific applications can be decreased by using distributed optical sensing that enables continuous monitoring of a certain physical or chemical quantity at different locations using a single sensor device. Third, remotely powered passive optical sensors are capable of providing high reliability and low maintenance cost. Because of their passive nature there is no need for a battery in the field. Additionally, sensor networks based on remote optical sensing can easily be integrated into existing optical network infrastructure. A certain level of mobility and flexibility can be provided by optical wireless sensor networks. They are also well suited for applications in sensitive and harsh environments, in which sensitivity to electromagnetic radiation and interference can be a problem. Systems that use the visible light spectrum (VLC) can reuse the light generated by existing lighting devices in rooms, offices, industrial halls, as well as street lighting and car lights for communication, sensing, positioning, and energy harvesting purposes. Last but not least, flexible and adaptive optical networks can provide a high-performance and highly reliable infrastructure for transmitting aggregated data originating from heterogeneous sensor devices and applications within the access and core network areas in order to help in realizing a global connectivity of large number of IoT devices and systems.

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