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REVIEW ARTICLE

Can communications and sensors work together in one network?

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Abstract With the development of both optical fiber-based communication and sensation, one interesting topic has been pointed out. How to connect those mountains of sensors to detect the signal in a large area, and how to make the cost of sensing system lower enough should be studied. A network of sensors is a good option. All sensing equipments, including the interrogators and the sensors, will be internetworking together. However, fiber optic communication networks have been developed very well over the past two decades. Is it necessary to rebuild a new network for sensors? In this paper, some new technologies in the two areas of fiber optic sensors and fiber optic communication will be addressed. Then, the available overlay architecture of a fiber optic sensors network will be presented. Finally, a polymorphous optical burst switching (POBS)-based architecture will be proposed, which can support all kinds of services, including digital data optical circuit/burst/packet switching and analog fiber optic sensor signal circuit/burst switching, etc.

Keywords optical sensor network, optical communication network, polymorphous optical burst switching (POBS), optical circuit switching (OCS), optical burst switching (OBS)

1 Introduction

The development speed on optical fiber communications and networks has been so fast that it is beyond our expectations in past several decades. Even though the optical "bubble" burst at around 2001, the global market in optical components and networks keeps the stable increasing trend. Together with optical fiber communications, the field of optical fiber sensors has also progressed significantly over the past 30 years, taking advantage of the many innovations that have arisen in optical fiber communications systems and components. The advantages of optical fiber sensors have been documented in many places. Much of the effort in optical fiber sensors and their applications have been presented at the optical fiber sensor (OFS) conferences, which are series of international conferences, first held in 1983 and most recently in April 2008 (OFS-19) [1]. The advantages of optical fiber sensors include compact size; lower weight and high flexibility; excellent feature on electromagnetic immunity (EMI); and the superior ability to multiplex them along a single fiber. However, the sensing area is still limited due to the available multiplexing technologies, the cost is still high due to the expensive interrogator, and most importantly, the complication of sensing and interrogating technologies will lead to the compatibility of those sensing systems between different companies. In this paper, some comparisons on research and market between fiber optic sensors and fiber optic communications will be presented at first. Secondly, some key technologies in optical fiber sensor arrays will be summarized. In the third, the overlay architecture to support optical fiber sensor network (OFSN) will be discussed, and finally, the polymorphous optical burst switching (POBS)-based architecture will be proposed.

2 Academic and market trend on OFSA and OFCA

By searching publications in the ISI web of knowledge with the key words of optical fiber, and communications or sensors on http://isiknowledge.com, some differences between the optical fiber communications area (OFCA) and the optical fiber sensors area (OFSA) will be found. Figure 1 shows the relation between the publications for OFCA and OFSA in the past 10 years. The increasing speed of publications in OFCA was much fast than that of OFSA from 1997 to 2003. However, the situation changed

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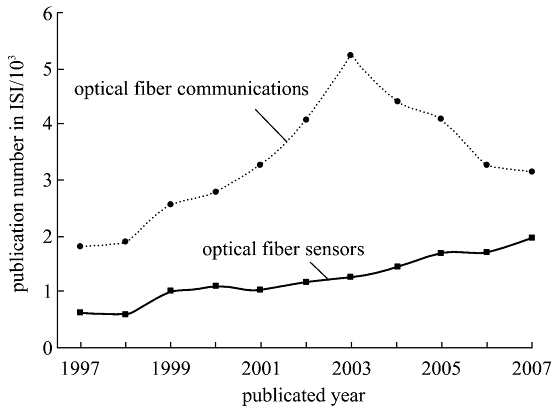

Fig. 1 Related publications trend in recent years

from 2003. The publications increased stably in OFSA, but decreased dramatically in OFCA. This is partially due to the breaking of the information technology (IT) "bubbles". The main reason is the limited financial support from government and industry.

With the similar comparisons between OFCA and OFSA in the global market, we can also find some interesting phenomena. According to the recent report by BCC Research [2], the total global market (as shown in Fig. 2) for OFCA purchases was more than \$2.1 billion in 2005 and over \$2.2 billion in 2006. At a compound annual growth rate (CAGR) of 3.5% (here, CAGR is calculated by $(P_n/P_1)^{1/n}-1$, where n is the number of years from the first reference year, P_n is the value in the nth year, and P_1 is the value of the first year), this market will reach almost \$2.7 billion by 2011. However, the global market of OFSA [3,4] was over \$500 million in 2006, and will reach almost \$1.2 billion by 2009 at a CAGR of 37%. So, the CAGR of OFCA is less than that of OFSA from 2003.

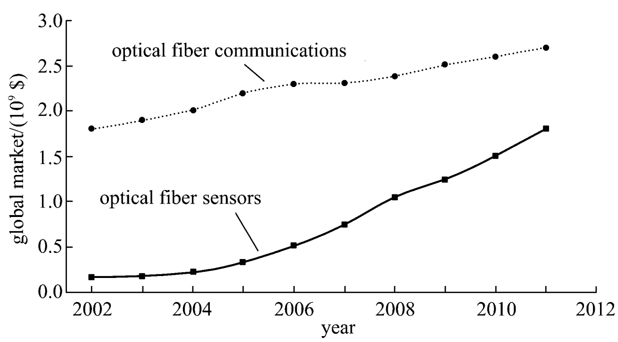

Fig. 2 Global market in fiber optics in recent years

From the above academic and market studies, it can be seen that the status of OFSA and that of OFCA have changed since 2003, and it can be expected that the purchase and publications of OFSA will surpass that of OFCA in no more than 10 years from the trend lines of OFSA and OFCA as shown in Figs. 1 and 2.

3 Multiplexing and switching technologies in optical fiber sensor array system

Basically, optical fiber sensors can be classified into two types by physics structures: interferometric and non-interferometric, as shown in Fig. 3. The non-interferometric-type optical fiber sensors normally detect the signal via the change of amplitude $A(\alpha)$, frequency ω, propagation constant β, time t, or transmission length z in $I(\omega,t,\beta,\alpha)=A(\alpha)e^{j\omega t-j\beta z}$ of lightwave in the sensing system by the kinds of physics effects, such as attenuation, scattering, dispersion, polarization walk-off, etc. Here, the optical fiber can be used as a transmission or sensing medium. In comparison with the non-interferometric type, the interferometric-type optical fiber sensors, in particular, offer a high sensitivity and wide dynamic range. Optical fiber sensors can also be classified as continuous sensing and discrete sensing by application method in Fig. 4 [5]. The continuous method uses the light backscattering effects, like Rayleigh scattering, Brillouin scattering, Raman effect, fluorescence, etc., to sense the signals. The discrete method uses kinds of techniques, such as optical delay, wavelength multiplexing, etc., to detect the

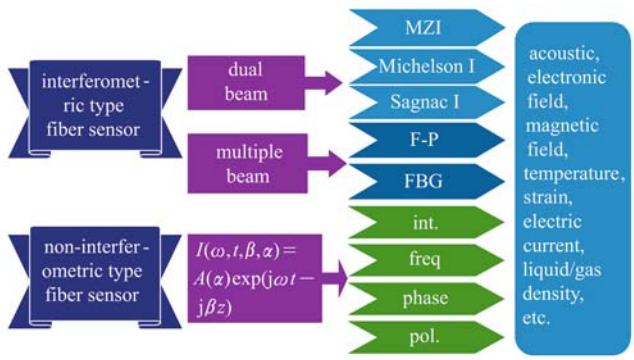

Fig. 3 Classification of fiber optic sensors by physics structures

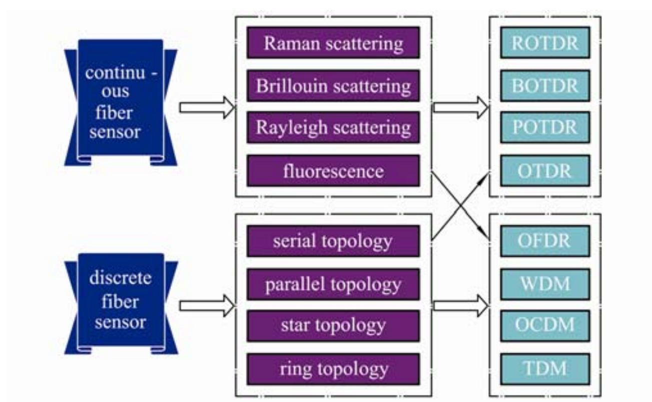

Fig. 4 Distributed fiber sensing methods

return light signal in a specific time or in a specific wavelength, or both of the discrete time and discrete wavelength from each sensor.

However, the difficulty in interrogation for kinds of sensors has led to a complicated sensing system architecture. Although optical fiber itself is a low-cost medium, and optical fiber sensors may also not be too expensive, the interrogation system should provide demodulation functions for all or most of the same types of sensors. This problem is especially acute in applications where large-scale sensor arrays are required to cover a large geographic area, for example, a community area, metropolitan area, national area, or even world wide area. Therefore, it is a challenge for all or most sensors to share one interrogation system cost, which leads to the requirement of lots of multiplexing technologies. Existing multiplexing techniques, based on time, wavelength, frequency, and code division schemes or the hybrid schemes among the above technologies are widely used in optical fiber sensor arrays as shown in Fig. 4, like time division multiplexing (TDM), wavelength division multiplexing (WDM), optical code division multiplexing (OCDM), etc. As one example, a large-scale fiber Bragg grating (FBG) sensor system with 60 sensors has been experimentally demonstrated by using a combination of WDM and TDM techniques [6].

Generally, the in-line topology, star topology, and tree topology adopted in an FBG sensor network need a broadband light source or a tunable laser source. Because the optical power reflected from an FBG far away is very weak, the capacity of sensors would be limited by the wavelength resolution of demodulator or of tunable laser, which lead to the limited topologies coverage ability. Recently, switching technologies were used to expand the size of the arrays further. The early aim in using an optical switch in an optical fiber sensor system was to enhance the survivability [7]. Now, extensive arrays of these strings may be connected through an optical switch to increase the number of sensors that can be interrogated by one interrogator. In practice, up to a few hundred sensors have found their expanding ways into it [8]. Figure 5 shows that a group of interrogation systems will demodulate the different kinds of fiber sensor arrays via one optical switching node. The role of the optical switch is to provide the functions of reconfiguration and protection of optical paths, which can support the mountains of sensor points. If more switches are induced to the optical fiber sensor arrays, it becomes necessary to study the management and architecture to control these switches well. The situation of the switches in sensor system is quite similar to that in all optical network (AON). At this time, How to manage those switches in the switched OFSN will have to be studied.

4 Architecture for OFSN

The concept of OFSN was coined around the 1980s [9], which is similar to that of optical fiber data transmission networks. In 1988, Chen, Leuing, and Chang [10] first presented the basic concept of hybrid sensing and communication systems. Since optical fiber sensors are mounted in a structure to monitor the health of structure, and since optical fiber can also provide communication function, it is possible to use the embedded fibers for sensing and for communications. The hybrid integration of sensing and communication functions can reduce the number of fibers needed in the structure, which reduces the cost of the system and simplifies the assembly and installation of the system, too. However, there have been few studies on how to integrate both of sensing and communication in one fiber system since then. The progress on optical fiber communication network was very fast at that time. The demand of communications is also very intensive in comparison with OFSN. From the beginning of this century, the network switching concept has been adapted to the sensor system. In 2002, Hiroshi presented his dream of tomorrow's photonic sensor networks picture [11].

There are several kinds of architectures to build a sensor network. One popular approach is the overlay architecture, in which the sensor network is over the optical telecommunication networks or Internet as shown in Fig. 6. The sensor interrogation has the relative network interface to access the public Internet, and the relative

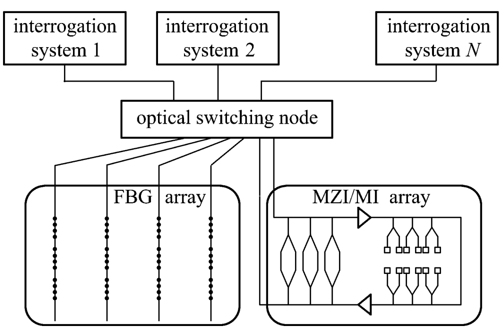

Fig. 5 Switched topology of fiber optic sensor arrays

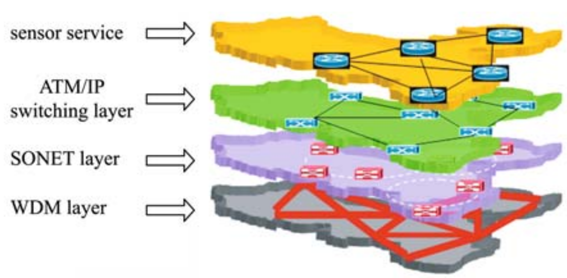

Fig. 6 Overlay architecture of optical sensor network

sensing interface to connect the sensor arrays. For example, SM125 is one commercial model of FBG interrogator made by Micron Optics, Inc., which provides one RJ45 interface to connect local area network (LAN) or access Internet. Together with it, the interrogator of SM125 also provides several fiber optic FC/APC ports to connect one sensing fiber per port. Up to 125 FBGs can be cascaded in each fiber. The FBG sensors' signal will be interrogated by SM125 into data, and these data will be sent to the destination personal computer (PC) via transportation control protocol/Internet protocol (TCP/IP) across the Internet. From the sensor network layer, the data from the sensor interrogator will be packed into IP datagram and further TCP datagram/user datagram protocol (UDP), and it can be switched/routed by the asynchronous transfer mode (ATM) router or IP router in the ATM/IP switching layer from source router to destination router. During this communication, the synchronous optical network (SONET) and WDM layers may be used for data transportation. Figure 7 shows one example of overlay fiber optic sensor networks in specifications of optical sensing interrogator SM125 by Micron Optics, Inc. (http://www.micronoptics.com.cn). Each interrogator will only demodulate those connected sensors, e.g., there are only four fibers that can be supported by SM125-500. Up to 125 FBGs can be multiplexed in wavelength on one fiber. So, in total, one interrogator SM125-500 can demodulate 500 FBG sensors. All the sensing signals will be demodulated into digital data electronically, and then those data will be transmitted to the remote PCs via Ethernet. It can be seen that the link among any sensors is opaque, and the data transferred among sensor interrogators is similar to the data across the all optical networks. Both of them are digital data.

From Fig. 7 we can see that the maximum of 500 FBG sensors for SM125-500 can be designed to cover a sensing area. It will need more modules if more sensors are to be supported. In the following part, one hybrid of communication and sensing network architecture based on

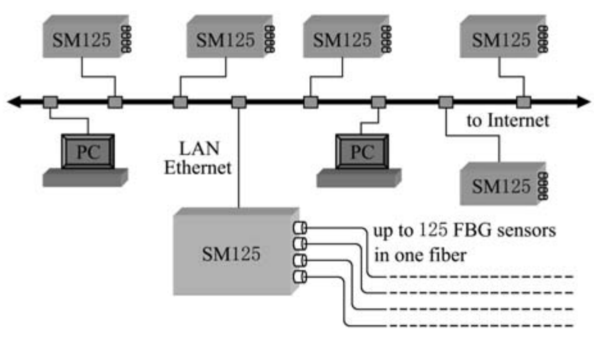

Fig. 7 One example of overlay fiber optic sensor networks (specifications of optical sensing interrogator SM125 on http://www.micronoptics.com.cn)

polymorphous optical burst switching (POBS) will be presented, which permits all sensors in the network to share one interrogator and permits all PCs in the network to communicate with each other.

POBS was first proposed by Qiao from New York State University at Buffalo around 2006 [12]. POBS supports different types of traffic using one integrated signaling datagram to support both optical circuit switching (OCS) and optical burst switching (OBS) seamlessly. The bandwidth utilization of OCS is lower due to its one wavelength resource occupied by one channel only during the communications among any two users. Optical packet switching (OPS) has high bandwidth utilization, but it has problems of high packet loss and acute contention due to the shortage of fast optical variable buffers or fast wavelength converters. Due to the difficulty on balance between the above two technologies, OBS has been proposed as a competitive hybrid switching technology between OCS and OPS [13,14]. The basis of the OBS architecture is the separation of control information from the data payload. Traffic is assembled in bursts with variable size and a burst header packet (BHP) is emitted per burst at an offset time in advance, to pave the burst's way among the core routers optical transparently. In OBS networks, the burst contention is resolved either by dropping or deflecting one of the contending bursts. The OBS makes bandwidth utilization more efficient and flexible in comparison with OCS and OPS. POBS can support OCS and OBS efficiently. Further, POBS can also support optical sensor services as shown in Fig. 8 because it provides the all optical channels at different granularities level, like one wavelength, or a burst of several IP packets, etc. The reference model in Fig. 8 shows five layers, including the sensor/communications application layer (S/CAL), application adaptation layer (AAL), POBS layer, medium access control (MAC) layer, and physical layer (PHY). In comparison with the digital service of optical communications channel, the optical sensor signal is a kind of "analog" channel. The POBS based burst photonic network will support different formats of optical signal, no matter it is digital signal with different kinds of encoding formats, like return-zero (RZ), non-return-zero (NRZ), or it is analogue signal with different kinds of modulation formats, like amplitude modulation (AM), frequency modulation (FM), etc. Due to the above specific performance, the POBS based photonic burst network is a new concept of all optical slot channels to carry anything. The slot could be a variable time or fixed time. The content in the slot is only recognized by the terminal users, thus it will be a high secure network. In the future, each user will has own slot identify number, like the IP address in Internet. In fact, it is expected that in the future there will be an evolution toward intelligent communication among person-to-person, person-to-sensor, and sensor-to-sensor, etc. Everything will be readily connected and disconnected no matter where you are, who you are, and when it is.

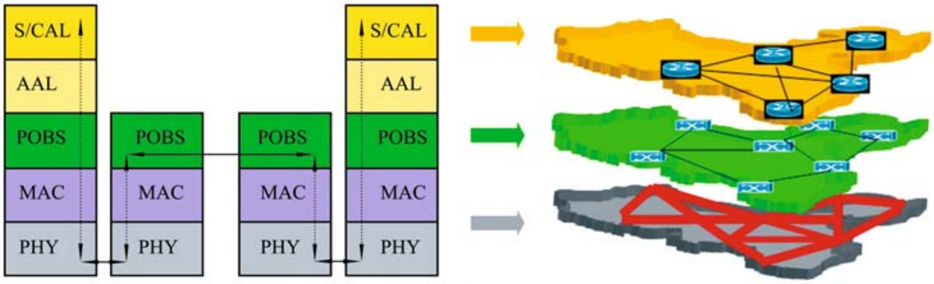

Fig. 8 POBS-based architecture

5 Conclusion

In this paper, we think, it is the time to consider the integration of OFCA and OFSA in one network. There are at least three reasons for this: firstly, the development speed on research and market on OFSA is faster than that of OFCA; secondly, the available multiplexing technologies for fiber optic sensors are limited to cover large sensing area; thirdly, the switching technologies were used in kinds of fiber optic sensor arrays to provide the protection and self-healing functions. The status of the overlay architecture for sensor networks was also discussed, but the limitation of the overlay architecture is also clear. So, a POBS-based architecture is proposed to support all kinds of services, no matter whether it is analog or digital optical data.

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