A High Survivability Mesh Topology FBG Based Optical Sensing System with SDN Controlling

Jihh-Heng Yan[1], **Wei-Cheng Chen**[2], **You-Wei Chen**[1], **Kai-Ming Feng**[1,2], **and Chung-Yu Wu**[3]

[1]Institute of Photonics Technologies, National Tsing Hua University, Hsinchu, Taiwan
[2]Institute of Communications Engineering, National Tsing Hua University, Hsinchu, Taiwan
[3]National Chung-Shan Institute of Science and Technology, Taoyuan, Taiwan

Abstract— A FBG based optical sensing system with mesh topology is first demonstrated with SDN controlling. The design of FBG sensing sets and SDN-controlled remote node provides large sensing signal routing freedom and network survivability.

1. INTRODUCTION

Optical sensing techniques have been studied for decades and widely employed in many fields and infrastructures. In many proposed studies, fiber Bragg grating (FBG) based sensing systems can be built in large scale objects, infrastructures, and personal wearing devices [1–3] with their light weight and electromagnetic interference immunity features. Their high sensitivities and sensing accuracy always provide a clear picture of the monitoring objects. Also, in comparison with wireless sensing, FBG based optical sensing system eliminate the necessity of power management and sensing unit replacement. However, due to the weak structure nature, optical fibers are always threatened by environmental and human damages. On occasion of multiple link failures, conventional optical fiber sensing systems totally fail until the manual repair is finished. Therefore, to enhance the network survivability becomes a critical issue. Many proposed researches have been presented with their survivability enhancement, such as backup links and network topology designing [4–6]. Unfortunately, these system complexities usually grow when strengthening the network survivability. The sensing network deployment and consequently the ability of remote sensing are thus quite limited.

In our previous work, a FBG based optical sensing system with mesh network topology has been presented to largely enhance the network survivability [7]. With the design of periodic FBG sensing segment and network building block, the sensing network can be systematically implemented. With high network survivability, a self-healing function can be implemented in the sensing network. To efficiently utilize this function, the control of remote nodes and the calculation of alternative light path need to be organized. Hence, in this paper, we first introduce software-defined network (SDN) controlling [8] in the proposed sensing network. The regular sensing procedures can be operated with the routing table embedded in the central office (CO). Once the link/node failures occur, the SDN controller can re-calculate alternative light-paths and then reorganize the sensing procedures to avoid system failure. Furthermore, with the interconnected SDN controllers, this proposed sensing network can be organized as multiple regions where each is managed by a corresponding controller. For example, Figure 1 shows a 4-by-4 mesh network with a 4-CO scenario. Not only the power of sensing signal can be reduced, but also the available light-paths, as well as the network survivability, can be increased with multiple link/nodes failures.

2. EXPERIMENTAL DEMONSTRATION

The sensing network topology is designed to be a mesh network comprised of the designed remote node (RN) and four FBG sensing sets. First, as shown in Figure 2(a), a RN is built with three voltage-controlled optical latched switches (SWs). This RN design provides not only conventional bar and cross routing functions, but also a U-turn function, which largely relieves routing constrains. Second, each FBG sensing set includes three Bragg wavelengths in the demonstration. However, the wavelength counts can be scaled up if needed. As shown in Figure 2(b), the wavelength assignments of the four sets are λ_1: 1538.18 nm, λ_5: 1544.58 nm, λ_9: 1550.98 nm for S1, λ_2: 1539.78 nm, λ_6: 1546.18 nm, λ_{10}: 1552.58 nm for S2, λ_3: 1541.38 nm, λ_7: 1547.78 nm, λ_{11}: 1554.18 nm for S3, and λ_4: 1542.98 nm, λ_8: 1549.38 nm, λ_{12}: 1555.78 nm for S4. With these wavelength arrangement, we build the CO with a fiber ring laser (FRL) as the sensing signal generator, and a 100-GHz-grid eight-channel arrayed waveguide grating (AWG) as the receiver. Each of the sensing wavelengths belongs to a specific free spectrum range (FSR) of this AWG. Figure 2(c) shows the experimental

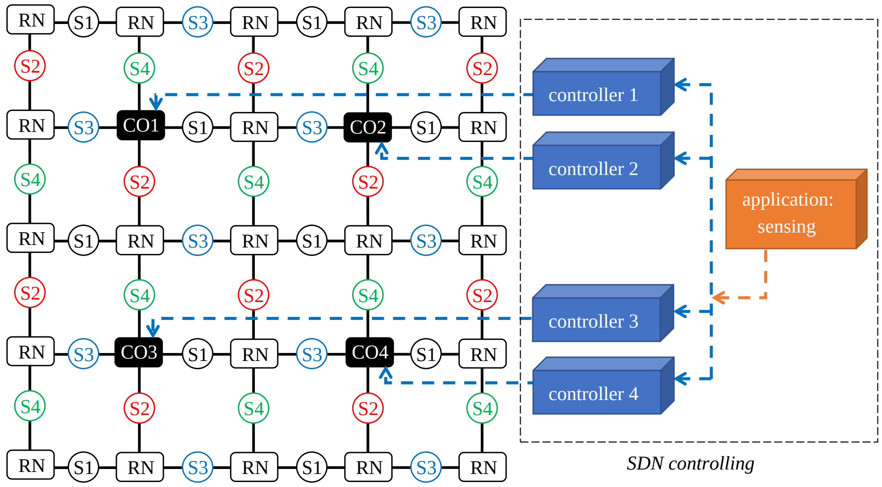

Figure 1: The proposed mesh topology sensing system with software-defined network (SDN) controlling (RN: remote node)

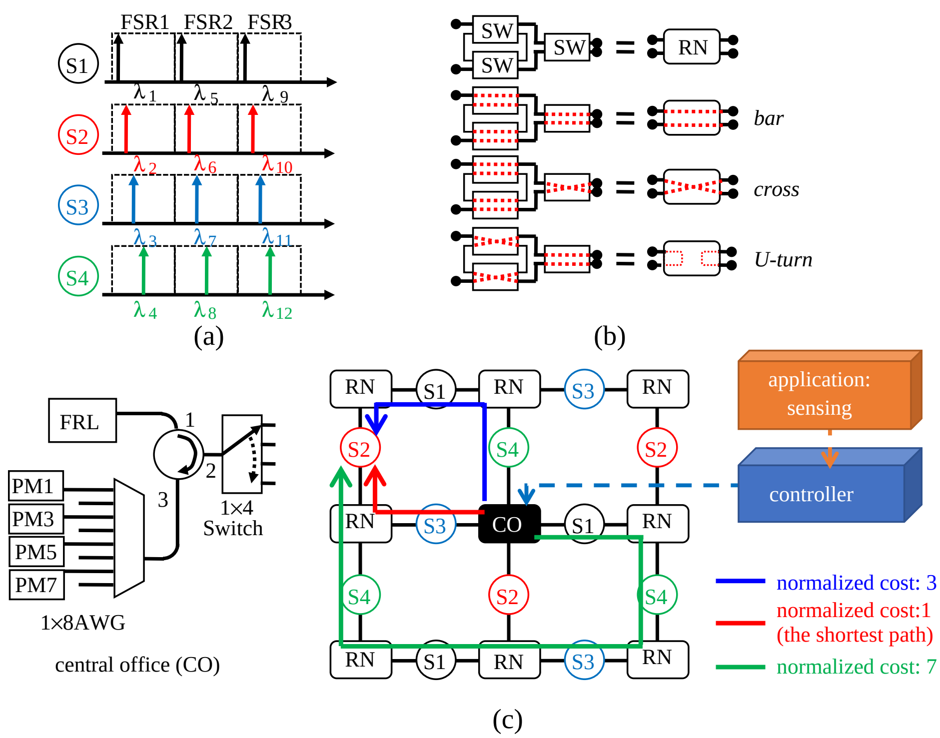

Figure 2: The experimental setup. (a) The wavelength arrangements; (b) the remote node; (c) the experimental system setup.

setup which consists of a 2-by-2 mesh network and the designed CO as well as the SDN controlling.

The CO will make the sensing light-path clear in advance by sending controlling voltages to all the related RNs with the build-in routing table. After the sensing signal is reflected by the target FBG, it traces the original path back to the CO, and then received by an eight-channel AWG. The sensing wavelengths correspond to the 1st, 3rd, 5th, and 7th channel respectively, where the even channels are leaved blank for wavelength interrogation function [9]. Here we demonstrate a wavelength interrogation function for sensing FBG strains. The shifted Bragg wavelength will make the reflected sensing signal interrogated by two adjacent AWG channels. As shown in Figure 3, the interrogation functions ρ refer to the evolution of the received optical powers in 3th and 4th

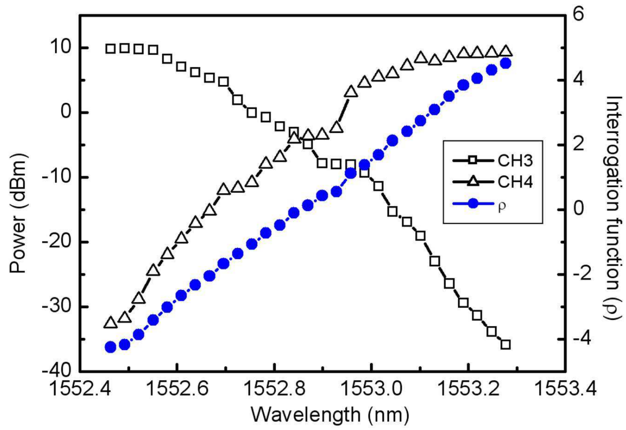

Figure 3: Demonstration of interrogation function.

channels with

$$\rho(S_K) = \log \frac{I_{2K}}{I_{2K-1}}, \tag{1}$$

where I_{2K} and I_{2K-1} are the received optical power at $(2K)$th and $(2K-1)$th AWG channel respectively, and S_K is the Kth FBG sensor set. The received optical power can be analyzed in the SDN controller without an optical spectrum analyzer based on the proven relationship between shifted Bragg wavelengths and the strains [10].

This proposed mesh network topology provides a large degree of freedom in sensing signal routing. For each sensing target, there are always multiple light paths available. Here we set a FBG set S2 on the east edge as the sensing target. As depicted in Figure 2(c), there are totally 3 available light paths to sense this target, which sensing traces are highlighted in blue, red, and green respectively. The shortest path obtained by Dijktras algorithm [11] has been defined in the routing table in advance while the network implemented. Once link/node failures occur, the shortest path re-calculation in the SDN controller will be activated to re-write the routing table in the CO.

3. MULTIPLE CO-SDN CONTROLLERS DESIGN AND A SIMULATION DEMONSTRATION

As the network growing up, the sensing signal needs more power for sensing round-trips. Also, the controlling of RNs will increase the system complexity. To mitigate these issues, applying multiple COs and the corresponding SDN controllers will be an efficient solution. Each CO corresponding to a SDN controller handles a specific sensing network region. This multi-region network design can largely reduce the power of sensing signal and the time of sensing round-trips. Also, SDN controllers can be interconnected with each other to share the network state information. Therefore, once a link/node failure occurs in a sensing region, these information will be notified to all the rest controllers. Both the present CO and the other COs can be in charge of the alternative sensing procedures.

Since the available devices are not sufficient for experiments, this multi-CO sensing system is demonstrated with a numerical simulation. A 4-by-4 and a 6-by-6 mesh sensing networks are respectively assembled in the same rule described in last section. The optimized CO location is the centroid of the corresponding network region, which minimizes the Euclidean distance between CO and all FBG sensors in a network region [12]. To demonstrate the relationship between the quantity of CO and the sensing network survivability, the simulation will examine the total available light paths with various link failures setting. A FBG set S2 at the network north-west corner is set as the sensing target. The link failures are set around the COs, which largely affect the network survivability. The evaluation of available light-paths versus link failures is shown in Figure 4. In the 4-by-4 mesh network, if no link failure exists, there are 60, 14, 14, and 10 available light-paths for the scenarios of 1-CO, 2-CO, 3-CO, and 4-CO respectively. However, if there exist 3 link failures, the quantity of available light-paths become 0, 7, 8, and 6. The main reason for the available light-path quantity drop is that the network loses some degree of freedom in routing sensing signals since many RNs are replaced by COs. But it is worth to note that available light-paths are still enough

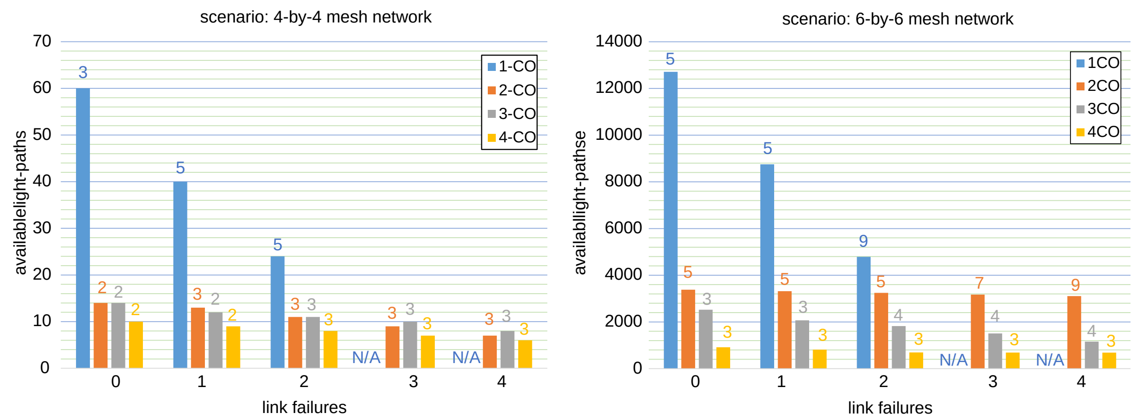

Figure 4: The available light-paths versus various link failures for a 4-by-4 and 6-by-6 meshed sensing networks.

to maintain a high survivability sensing network while 3 link failures. Similar results are obtained in the 6-by-6 mesh networks. We also examine the normalized linking costs, which is defined as the routing loss of the sensing signal, of the shortest light-paths for all CO scenarios, which are labeled on the top of bars in Figure 4. As we expect at first, the linking cost of the shortest path decreases with the CO increasing in the 1-CO scenario, while these costs remain low in multi-CO scenarios. As a result, for a large mesh sensing network, increasing COs and corresponding SDN controllers can largely reduce the sensing signal power consumptions.

4. CONCLUSIONS

In this paper, we proposed a FBG based optical sensing system with mesh sensing network topology. The design of four FBG sets and RNs makes the network construction an interleaved repeating manner, which keeps the system a relative low complexity while extending the network scale. Also, the RN comprised of three optical switches provides a large freedom in the routing of sensing signal. Consequently, to each FBG sensing set, the total available light paths is increased, which efficiently enhances the sensing network survivability. The SDN technique is first introduced to an optical sensing network in this proposed system. With the interconnection function between SDN controllers, a large sensing network can be reorganized to multiple partitions, where each of them is supervised by a central office and its corresponding SDN controller. Through the simulation result, for a specific sensing network, there exists an optimized deployment of central offices, which most efficiently enhances the network survivability.

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