Optical Sensor Networks

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Optical sensing that integrates communication and sensing functions is playing a more and more important role in both military and civil applications. Incorporating optical sensing and optical communication, optical sensor networks (OSNs) that undertake the task of high-speed and large-capacity applications and sensing data transmissions have become an important communication infrastructure. However, multiple failures and disasters in OSNs can cause a serious sensing provisioning problem. To ensure uninterrupted sensing data transmission, the survivability has always been an important research emphasis. This paper focuses on the survivable deployment of OSNs against multiple failures and disasters. It first reviews and evaluates the existing survivability technologies developed for or that can be applied in OSNs, such as fiber bus protection, self-healing architecture, 1 + 1 protection, etc. Then, the disaster-resilient survivability requirement of OSNs is elaborated. Moreover, a new concept of *k*-node (edge) sensing connectivity, which ensures the connectivity between sensing data and users is proposed. Based on *k*-node (edge) sensing connectivity, the disaster-resilient survivability technologies are developed. The key technologies of implementing *k*-node (edge) sensing connectivity are also elaborated. Recently, artificial intelligence (AI) has obtained rapid development. It can be used to improve the survivability of OSNs. This paper also elaborates the potential development direction of survivability technologies of optical sensing in OSNs employing AI.

Keywords: network survivability ; disaster-resilience ; optical sensor networks (OSNs) ; optical sensing ; optical networks ; k-node (edge) sensing connectivity ; artificial intelligence (AI)

1. Introduction

In recent years, new industries such as cloud computing, big data, data center, virtual/augmented reality (VR/AR), 5G, artificial intelligence (AI), Internet of Things (IoT), and optical fiber sensing have emerged. These developments have changed our way of life and simplified the completion of tasks that were difficult in the past. For example, the AI group in Tencent Corporation uses deep learning to successfully locate abducted children simply using photos from their childhoods [[1]]. In the past it was difficult to realize cross-age face recognition. Deep learning has benefitted society and humanity. Well-known companies such as Google, YouTube, Facebook, Alibaba, and Tencent have built a notable number of large-scale data centers to support those emerging industries [[2],[3]]. Data centers are designed to host massive storage and computing resources, and to support computing-intensive and storage-intensive applications. Requirements for data centers to deliver applications and services at high-speed and high-throughput have become greater. Therefore, it is necessary to achieve high-speed and large-capacity communication among data centers located in different geographical locations. Optical interconnection, which provides flexible interconnection reconfigurations for various topologies and supports transparent, large-capacity, and high-speed data transmission, is widely used [[4],[5],[6],[7],[8]]. Data center networking has evolved from hybrid optoelectronic networking to flex-grid optical networking [[9],[10],[11],[12]]. In addition, optical fiber sensing that integrates communication and sensing functions plays a more and more important role [[13],[14],[15],[16]]. It provides sensing solutions with optical performance for almost all kinds of applications and environments, such as monitoring of oil fields and large civil engineering structures, as well as natural environments [[17],[18],[19]]. In [[20]], the authors gave an overview of optical sensing technology for electromagnetic field measurement. They analyzed the principles of several types of sensors, including the probe-based Faraday effect, magnetostrictive materials, and magnetic fluids, discussed each advantage and disadvantage, and reviewed future outlooks on the performance improvement of sensors. In [[21]], the authors gave an overview of recent advances in optical fiber acoustic sensing systems in the domains of military defense, structural health monitoring, and petroleum exploration and development. It can be seen that optical fiber sensing is widely used.

2. Influence and application

To improve quality of service (QoS) and guarantee uninterrupted traffic transmission, survivability remains an important part of network design. It represents the ability of a network to fulfill its mission of data transmission, in a timely manner, when threatened by attacks or large-scale natural disasters. In the case of an unavoidable link cut or a network node becoming ineffective due to misconfiguration or natural disaster, network survivability needs to quickly and effectively resume the interrupted traffic, thus keeping damage to a minimum. Due to wide distribution and high severity, natural disasters are big threats to the normal operation of optical sensor networks (OSNs). Therefore, the survivability of optical sensing and optical communication in OSNs in times of disaster is attracting wide-spread attention [[22],[23],[24],[25],[26]]. Moreover, optical sensing can help improve the survivability of optical networks [[27],[28]]. In [[27]], the authors proposed optical chaos and hybrid wavelength division multiplexing/time division multiplexing (WDM/TDM) based on large capacity quasi-distributed sensing networks. With WDM/TDM technology, hundreds of sensing units could be multiplexed in multiple sensing fiber lines. This sensing network could achieve real-time fiber fault monitoring. In [[28]], the authors used a distributed optical fiber sensor to improve the optical fiber cable condition monitoring system. A series of survivability technologies designed to ensure optical sensing and optical communication resist link/node failures already exist. For example, the classic p-cycle scheme ensures that there is at least one available light path between any node pair located in this cycle after a random single failure [[29]]. The traditional survivability techniques can be divided into two categories: protection schemes and restoration schemes. The protection scheme reserves backup resources for working flows and only needs to conduct protection switching at the source and destination nodes when failures occur [[30]]. The restoration schemes, such as link-based restoration and path-based restoration, attempt to establish recovery channels for interrupted working flows using the remaining available network resources after failures [[31]].

Both the protection and restoration scheme rely on network connectivity. In mathematics and computer science, network connectivity is one of the basic concepts of graph theory, which asks for the minimum number of nodes or edges that need to be removed to disconnect the remaining nodes from each other [[32]]. Since network connectivity, indicated by vertex (edge) connectivity, has a fixed upper bound for a given topology, the connectivity between a node pair can be easily destroyed by disasters. Merely relying on network connectivity to realize uninterrupted traffic transmission will cause bottlenecks. Fortunately, for some emerging services, such as high-definition TV, web searching, scientific computing, and cloud service, the required data can be replicated and maintained in multiple data centers through synchronization technology [[33],[34],[35]]. Therefore, service providing is no longer confined to one particular data center and any data center that hosts the required service can be designated a service provider. Moreover, the service can dynamically migrate to multiple data centers according to users' demands. For optical data center networks, traditional end-to-end connections are gradually replaced by end-to-content connections. The end-to-content connection means that the destination node is not fixed and can be any reachable data center where the required service is hosted. The user can obtain the required service along any available end-to-content connection. Even if a natural disaster breaks the optical data center networks into several disconnected parts, the service will not be interrupted as long as one reachable data center in each part remains. This new kind of connectivity is called content connectivity, which is defined as the reachability of the content from any point of a data center network [[36]]. It no longer merely ensures connectivity between source–destination node pairs but guarantees connectivity between users and their required services. Moreover, the k-node (edge) content connectivity concept, which indicates the minimum number of elements (nodes or edges) that need to be removed to disconnect the remaining nodes from the required service, was proposed [[37]].

In contrast to content connectivity and k-node (edge) content connectivity, a new k-node (edge) sensing connectivity concept, which ensures the connectivity between sensing data and users, was proposed. Based on k-node (edge) sensing connectivity, disaster-resilient survivability technologies have been developed. Recently, AI has become a hot topic and research focus. It has been applied in many aspects of optical networks, including failure localization and anomaly detection, routing and resource allocation, modulation level recognition, optical interconnection, network control and management, and quality of transmission (QoT) estimation [[38],[39]]. This paper first reviews and evaluates the existing survivability technologies that have been developed for or can be applied to OSNs, such as fiber bus protection, self-healing architecture, 1 + 1 protection and extension, p-cycle, the photonic millimeter-wave bridge scheme, p-polyhedron, multi-path protection, and restoration. Then, the k-node (edge) sensing connectivity concept is elaborated. Based on k-node (edge) sensing connectivity, disaster-resilient survivability technologies were developed. Moreover, the key technologies for implementing k-node (edge) sensing connectivity in elastic optical networks are elaborated.

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