Field Implementation of Fiber Cable Monitoring for Mesh Networks with Optimized Multi-Channel Sensor Placement

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Abstract: We develop a heuristic solution to effectively optimize the placement of multi-channel distributed fiber optic sensors in mesh optical fiber cable networks. The solution has been implemented in a field network to provide continuous monitoring. © 2024 The Authors

1. Introduction

In recent years, distributed fiber optic sensing (DFOS) technologies have been adopted in optical communication networks [1,2]. By utilizing these existing communication fibers as the sensing media (so-called "Network-as-a-Sensor" or NaaSr), no new dedicated fiber needs to be deployed for sensing purpose, which significantly reduces the deployment cost and the implementation time. This new way of NaaSr not only improves the efficiency of the optical network operations, such as providing accurate geophysical information of the fiber optic network [3] and preventing potential cable damage [4], but also adds values to the existing network infrastructure, since it enables new functions such as traffic monitoring [5] and security monitoring [6] while performing the conventional communication function. Therefore, it has great potentials for practical applications.

In traditional DFOS applications such as perimeter intrusion detection, oil well operation monitoring, or civil infrastructural health monitoring, a dedicated DFOS sensor (usually called an interrogator) is paired with a dedicated sensing fiber optic cable, and the cable is in a single-ended straight-line configuration because of the operation principle of the backscattering-based sensing. But in real-world NaaSr applications, the sensing fibers from the existing communication networks are typically not in a straight point-to-point configuration. Instead, they can be in the forms of various topologies, such as ring, star, or mesh [7]. It is not efficient to assign an interrogator to each link in the network since each sensor can detect multiple spans connected in series, as long as the overall route is within the sensing distance limit. How to optimally place the sensors and determine the sensing fiber routes is a novel network optimization problem that cannot be solved using existing networking solutions.

In our previous works, we defined the DFOS sensor placement problem, performed theoretical analysis, conducted ILP-based study, and proposed a fast heuristic algorithm called Explore-and-Pick (EnP) [8,9]. Recently, multi-channel DFOS interrogators have been introduced to the market, each of which can monitor multiple routes in a concurrent or round-robin manner. This leads to a new problem, namely the multi-channel sensor placement problem. In this work, we develop a novel heuristic algorithm to address this problem, analyze its performance and verify its effectiveness through simulation. Furthermore, this technology was developed into a network management solution and deployed on a Verizon field network for continuous network-wide anomaly detection.

2. Multi-channel sensor placement problem and algorithm

In the previous EnP algorithm, the goal of minimizing the number of sensors is the same as minimizing the number of sensing routes, since each sensor can only sense a single route. However, for multi-channel sensors, these two goals are no longer the same. To reach the goal of minimizing the number of sensors (i.e. to minimize the hardware cost), more sensing routes might actually be required. As shown in the example below, the 5-node network could be covered using 2 single-channel sensors and 2 sensing routes ABEC and CADE (Fig. 1a). With multi-channel sensor, only one sensor is required, but the number of sensing routes becomes 3 (ABE, ACE and ADE in Fig. 1(b)).

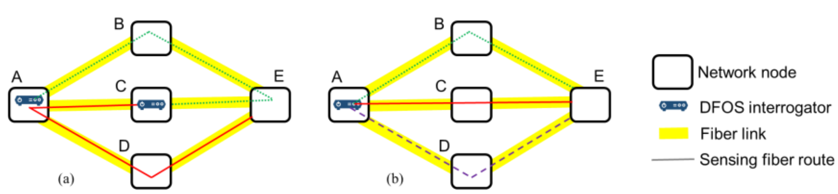

Fig. 1. Example of (a) single-channel sensor placement vs. (b) multi-channel sensor placement

The multi-channel sensor placement problem is defined as follows. Given a network infrastructure that has *V* nodes interconnected by *E* (optical fiber) links, the goal is to determine the optimal placement of multi-channel sensors and the corresponding sensing routes assignment with the objective of covering all the links using the minimum number of multi-channel sensors. Compared to the single-channel sensor placement problem, the multi-channel sensor placement problem is more challenging, since we need to determine not only the optimal combination of sensor placement, but also the optimal combination of sensing routes per sensor.

We develop a novel algorithm called *maximum coverage-based* (MCB) heuristic algorithm to solve this problem. It first uses depth-first search to enumerate all the available sensing routes that are within the sensing range limit for each network node. Secondly, the algorithm greedily selects the network node, which is associated with sensing routes that has the maximum overlapping with the uncovered links, for deploying multi-channel sensor. Thirdly, the algorithm sorts all the available sensing routes originated from the above selected sensor location, according to the number of overlapping links between a sensing route and the uncovered links. After that, the algorithm selects the top *N* sensing routes for deployment. Here, *N* is the smaller number between the maximum number of channels a sensor can support and the number of available sensing routes found at the selected node. The algorithm will repeat the above three steps to deploy multi-channel sensors and allocate sensing routes until each network link is covered at least once by a sensing route. The pseudocode of the algorithm is shown in Algorithm 1 as below.

Algorithm 1. Maximum Coverage-Based (MCB) Algorithm

```
initialize an empty dictionary called dfos_assignment, keys: <network nodes>, values: <sensing fiber routes>
initialize a set called uncovered, which consits of all the network links in E
applies depth-first search to enumerate all the available sensing routes for each network node
while uncovered is not empty do
    for each network node do
        find out the non-duplicated links that are on the remaining sensing routes, add them to coverage
    end for
    select node whose coverage has the maximum overlapping with uncovered, namely max_node
    create a new entry in dfos_assignment, e.g., dfos_assignment[max_node], with an empty list as value
    (if max_node's node ID already exists in dfos_assignment, then create the new entry with a hashed ID)
    sort the remaining sensing routes on max_node based on the number of overlapping with uncovered
    for each route in the sorted remaining sensing routes on max_node do
        if there still exists available sensing ports on the multi-channel sensor then
            add route to dfos_assignment[max_node]
            remove route from the remaining sensing routes on max_node
            decrement sensing port by one on the multi-channel sensor
        end if
    end for
end while
return dfos_assignment
```

3. Simulation and analysis

Simulations are conducted to validate the proposed solution using four regional or metro fiber optical networks from real-world datasets [10]. Since the average node degree in these networks is only 2.4, a 4×4 mesh network with average node degree of 3 is also considered for comparison. The network parameters are listed in Table 1. To make the condition closer to the actual field operation, the sensing range is changed from distance to optical power budget, since fiber conditions in the field are non-uniform and therefore the interrogator's specification is typically associated with the optical power level instead of the distance. Also, a loss is added to each bypassing node to better represent the real condition.

We compare three single-channel solutions (namely ILP, Random-Fit, and EnP [8]) with the new multi-channel MCB solution in terms of the number of sensors used. The number of channels is set to 16, the node loss is 1.5 dB, the fiber attenuation is 0.2 dB/km, and the optical power budget for the sensor is 20 dB. The results are shown in Table 2. We can see that the MCB solution can achieve fewer sensors for all cases with saving up to 67%, and the computation is very fast (within a second on a regular computer) even for large networks. The amount of sensor saving from the multi-channel feature varies among these networks. This is related to the network topology, which can be generally represented by the average node degree. For ION network whose average degree is only 1.94, the improvement is only 53%, but for the 4×4 network with an average degree of 3, the improvement reaches 67%.

Table 1. Simulation network parameters [10]

Network	Oxford	Palmetto	ION	USC	4×4
No. of nodes	19	43	95	150	16
No. of links	24	63	92	166	24
Ave. degree	2.53	2.93	1.94	2.21	3
Ave. link att.	10.29	11.37	7.76	10.09	9

Table 2. Simulation results

Network	Oxford	Palmetto	ION	USC	4×4
Single-channel ILP	17	52	*	*	24
Single-channel R.F.	21	59	76	155	24
Single-channel EnP	19	54	60	130	24
Multi-channel MCB	7	19	28	54	8

*: unable to yield a result in a reasonable amount of time

We then study the effect of sensor channels. We vary the number of channels per sensor from 1 (i.e. single-channel case) to 16. As shown in Fig. 2(a), the sensor saving is significant at the beginning, then gradually reduces, and eventually reaches an optimal level, indicating that sensor with more than 6 channels is generally not required for this application. The optimal number of channels is higher for larger networks (6 for ION and USC) compared to smaller networks (4 for Oxford and 4×4).

We also compare the number of sensors needed under different power budgets from 20 dB to 40 dB, while keeping the number of channels at the optimal level. The results in Figure 2(b) show that the number of sensors required reduces as the power budget increases, which is as expected. The saving is from 50% for ION to 75% for 4×4 network. Comparing with 20 dB single-channel case, the saving is between 76.7% and 91.7%. With 40 dB power budget, the saving of multi-channel sensor over single-channel sensor is between 63.2% for ION and 81.8% for 4×4 network. Therefore, improving the sensor capability, such as increasing the dynamic range of the sensor receiver, can better utilize the multi-channel sensing scheme.

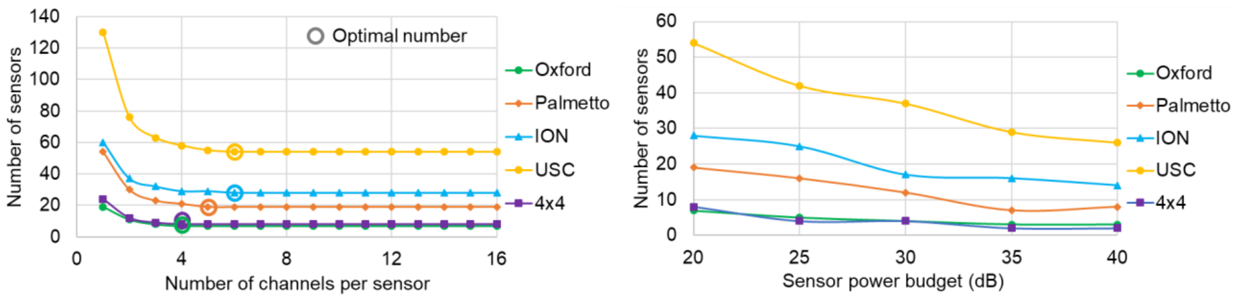

Fig. 2. Sensor placement analysis (a) sensor number vs. channel number, (b) sensor number vs. power budget

4. Field deployment of the multi-channel sensor placement solution

The MCB multi-channel sensor placement algorithm is developed into a sensing network planning tool, which takes the text-based network configuration file as input and calculates the total number of required sensors, the node (or location) for deploying each sensor, and the path of each sensing route. It has been used in a Verizon metro field network in the USA. This network has a meshed ring topology, consisting of 50 nodes. The node degree ranges from 2 to 6, with an average node degree of 2.46. The attenuation in each fiber span ranges from 1.5 dB to 11.4 dB, and the loss at each node is 1.2 dB on average. NEC SpectralWave LS Distributed Acoustic Sensor (DAS) interrogators are used as the sensors, each interrogator has 16 sensing channels. In less than 1 second, the planning tool determines that 8 interrogators will be sufficient to monitor the entire network, and the corresponding sensor placement and sensing routes are generated. According to this arrangement, DAS sensors have been partially deployed since August (deployment will be completed by the end of the year), and are continuously monitoring the fiber cut, attenuation variation, and other anomaly events such as construction event near the buried cable.

5. Conclusions

We defined a novel network optimization problem to address the multi-channel sensor placement challenge, and developed a fast and effective heuristic algorithm. The performance is verified via simulations on real-world networks. The solution is implemented in a Verizon field mesh fiber cable network to optimize the sensor placement and routing for continuous network anomaly monitoring.

[1] G. A. Wellbrock, et. al., OFC 2019, Th4C.7.
[2] Y. Aono, et al., OFC 2020, W3G.1.
[3] T. J. Xia, et al., OFC 2020, Th3A.5.
[4] M.-F. Huang, et al., OECC 2021, T5A.8.
[5] P.N. Ji, et al, OSA Optical Sensors and Sensing Congress 2021, SM2A.7.
[6] J. Fang, et al., OFC 2022, W4D.3.
[7] G.A. Wellbrock, et al., ECOC 2020, Th2H-1.
[8] Z. Ye, et al., ECOC 2020, We2K-4.
[9] Z. Ye, et al., Photonic Network Communication, 44, 90-101 (2022).
[10] http://www.topology-zoo.org/dataset.html