Address Challenges in Placing Distributed Fiber Optic Sensors

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Abstract *We are the first to investigate a novel problem, called distributed fiber optic sensor placement, in the context of Infrastructure-as-a-Sensor. We propose an ILP-based optimal solution and a close-to-optimal heuristic solution, both of which aim at minimizing the cost of sensors.*

Introduction

The recent advances in distributed fiber optic sensors (DFOS) technologies allow continuous long distance sensing over the existing telecom networks [1], enabling network carriers to provide not only communication services but also various sensing services, such as traffic/road condition monitoring and intrusion detection, using the same network. In other words, the entire telecom network is now acting as a large-scale sensor, which we refer to as “Network-as-a-Sensor” or NaaSr. Furthermore, other infrastructures with optical fibers installed, such as power distribution grid and highway system, can also be used as large scale distributed sensors to offer additional services and value, and to improve operation efficiency. This is referred to as “Infrastructure-as-a-Sensor” or IaaSr.

A critical challenge for IaaSr is: where to deploy the DFOS sensors and how to determine the sensing fiber route such that all the required fiber links in the given network infrastructure can be covered to provide IaaSr services. We name this problem as the DFOS placement problem.

As shown in Fig. 1, an IaaSr network consists of a set of nodes connected by a set of fiber links that need to be monitored (or sensed) by the DFOS sensors. Network carriers can place one or more DFOS sensor hardware at a network node, and connect them to one or more fiber links linearly to form a sensing fiber route. The total distance travelled by a sensing fiber route should be within the sensing range limit (e.g., 80km [1]), given the existing sensing techniques. In Fig. 1, sensing fiber route *A-G-H* has a DFOS sensor deployed at node *A*, traverses two hops then terminates at node *H*. The measured data on sensing fiber routes can be stored and processed locally, or can be sent to the remote centralized controller for analysis. When all the required links in the network are performing sensing function continuously, the IaaSr function is achieved. Due to the hardware cost and operational expense, the DFOS placement aims at minimizing the number of DFOS sensors used to fully monitor all the required fiber links.

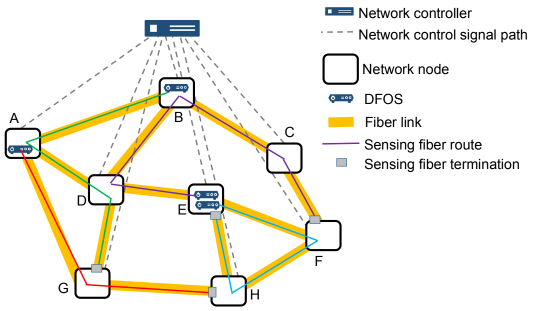

Fig. 1: Distributed fiber optic sensor placement

The DFOS sensor placement problem is novel and challenging. It is different from the coverage problem in wireless sensor networks [2], because the latter considers the coverage in terms of circle areas while DFOS placement considers the coverage on a network topology. It is also different from the regenerator placement problem [3], as the latter considers to place regenerators to ensure the reachability of the established lightpaths, while DFOS considers to monitor all the required physical fiber links. The most similar problem is the classical vertex cover problem [4]; however, in vertex cover, a selected node can only cover its attached links, while in DFOS, a sensor can cover one or more fiber links over multiple hops. So far, to the best of our knowledge, there is no existing solution for addressing the DFOS placement problem.

In this work, for the first time, we define and investigate the DFOS placement problem. To address this problem, we propose an Integer Linear Programming (ILP) based optimal solution that can minimize the cost of sensors. As the ILP solution may be intractable when network size is large, we propose a fast heuristic algorithm, called Explore-and-Pick (EnP), which can achieve a close-to-optimal performance. We evaluate the performance of these solutions through comprehensive simulations.

Problem Statement

The DFOS placement problem can be defined as: given a network infrastructure, the goal is to find out (1) where to place the sensors and (2) how to determine the sensing fiber routes, with the objective of minimizing the number of sensors used while all the required fiber links in the given network infrastructure can be covered.

In this work, we focus on the basic DFOS placement problem that considers the following conditions. First, each sensor has the capability to sense data in a single-direction with a limited sensing range. Secondly, each sensing fiber route is considered to be a linear route, in which splits (e.g., tree-like route) is not allowed. Finally, each sensor is coupled with only one sensing fiber route, while concurrently sensing multiple routes is not considered.

The Integer Linear Programming Solution

We use ILP to formulate the DFOS problem to facilitate the optimal solution.

The following parameters are given:

- $G(V, E)$: the network infrastructure, where V is the set of nodes, E is the set of links;
- R: the sensing range limit;
- $d_{i,j}$: the distance of the link (i, j);
- $w_{i,j}$: the distance weight of link (i, j), which is obtained by $d_{i,j} / R$;

The following Boolean variables are to be determined:

- $\theta_{s,d}$: 1 if a sensor is deployed at node s, with termination point at node d, where $s, d \in V$; 0 otherwise;
- $r_{s,d,i,j}$: 1 if the sensing fiber route between s and d passes through link (i, j), where $s, d, i, j \in V$; 0 otherwise;

The objective is to minimize the number of sensors used, which is defined as:

$$\min: \quad \sum_{s,d \in V} \theta_{s,d} \tag{1}$$

The following constraints are considered:

$$\sum_{i,j \in V} r_{s,d,i,j} \cdot w_{i,j} \le \theta_{s,d}, \quad \forall s, d \in V \tag{2}$$

$$\sum_{s,d \in V} r_{s,d,i,j} + \sum_{s,d \in V} r_{s,d,j,i} \ge 1, \quad \forall i, j \in V \tag{3}$$

$$\sum_{i,j \in V} r_{s,d,i,j} - \sum_{i,j \in V} r_{s,d,j,i} = \begin{cases} \theta_{s,d} & i = s \\ -\theta_{s,d} & i = d \\ 0 & otherwise \end{cases} \quad \forall s, d \in V \tag{4}$$

Here, Eq. (2) represents the sensing range limit constraint that the distance of any sensing fiber route must be less than the sensing range limit R. Eq. (3) ensures that each link (i, j) can be sensed at least once from either direction. Eq. (4) makes sure that each sensing fiber route is a linear route.

The Fast and Efficient Heuristic Solutions

In this section, we propose two fast heuristics, Random-Fit and Explore-and-Pick (EnP).

Random-Fit: This algorithm serves as a baseline heuristic solution for addressing the DFOS placement problem. The overview idea is to first randomly select a node that is attached with an uncovered link for placing the sensor. Secondly, a sensing fiber route is set to start from the selected node, traverse to its neighbor node through one of its remaining uncovered links, and continues to explore the next-hop until the sensing range limit is reached. The above two steps will repeat until all the links are marked as covered. The detailed steps of Random-Fit are shown as below.

The Random-Fit Algorithm

Step 0: Run shortest path algorithm to find out the distance between each node pairs in the given network.

Step 1: Initialize a list *assignment* to store the assignment of DFOS sensor placement and the corresponding sensing fiber routes. Initialize a set *uncovered* that contains all the fiber links in the given network.

Step 2: Randomly select a node *s* that is attached to an uncovered fiber link from *uncover* to place a sensor.

Step 3: Among all the neighbor nodes that are within the sensing range limit of *s*, randomly select one as termination point *d*. The shortest path between *s* and *d* serves as the sensing fiber route *r*. The above is stored in *assignment*.

Step 4: Remove all the links traveled by *r* from *uncovered*.

Step 5: Repeat Step 2 to Step 4 until *uncovered* is empty. Return *assignment* and terminate.

Explore-and-Pick (EnP): Although Random-Fit can generate a valid solution for DFOS placement, it is not cost-efficient. Hence, we propose another fast heuristic, EnP, which can achieve a close-to-optimal performance. EnP consists of two procedures. The first procedure is to explore all possible sensing fiber routes for the given network infrastructure, through a novel distance-limited route exploration based on depth-first search. The second procedure takes all the possible sensing fiber routes *S* as input, and consider all the fiber links in the given network infrastructure to be universe set *U*. Then, the goal is to find a minimum subset of sensing fiber routes *M* from *S* whose union equals *U*. This is actually transformed to the classic minimum set cover problem, which can be solved by a greedy algorithm [4] with simple modification to consider the sensor placement. The detailed steps of EnP are shown below.

The Explore-and-Pick (EnP) Algorithm

Step 0: Initialize a list *assignment* to store the assignment of DFOS sensor placement and the

Table 1: Network parameters

	Oxford	INS	ValleyNet	Palmetto	ION	US_carrier
No. of nodes	19	24	31	45	98	150
No. of links	24	28	33	70	97	171
Ave. node degree	2.53	2.33	2.13	3.11	1.98	2.28
Ave. link distance	51.44	59.06	44.78	54.96	38.02	49.80

Table 2: No. of sensors used

	Oxford	INS	ValleyNet	Palmetto	ION	US_carrier
Random-Fit	21.42	26.7	27.06	61.38	80.9	151
Explore-and-Pick	19	26	23	55	60	132
ILP	18	26	23	*	*	*

corresponding sensing fiber routes. Initialize a set *uncovered* that contains all the fiber links in the given network. Initialize a set *all_routes_set* to store all the possible sensing fiber routes from each node in the given network.
Step 1: For each node *n* that has not been explored yet, repeat Step 2 through Step 9. If all the nodes have been explored, go to Step 10.
Step 2: Initialize three data structures as follows. First, a stack *next_hop* is created to store all the candidate nodes for the next hop of a sensing fiber route that originates from *n*. The stack will be initialized with *n*. Secondly, a list *visited* will be created to keep track of the nodes that have been visited. This will ensure that there exist no duplicated links in the sensing fiber route. This list is initialized with *n*. Finally, a set *route_set* is created to store all the possible sensing fiber routes that originate from *n*. It is empty at first.
Step 3: While *next_hop* is not empty, repeat Step 4 through Step 8; otherwise, go to Step 9.
Step 4: Pop the last-in node from *next_hop* and denote it as *current*.
Step 5: For each sensing fiber route *r* in *route_set*, if the very last hop of *r* is *current* or if *route_set* is empty, repeat Step 6 through Step 8. If all the sensing fiber routes have been checked, go back to Step 3.
Step 6: For each neighbor node *nn* of *current*, generate a new sensing fiber route *r_new* by extending the existing route *r* from its last hop *current* to *nn* (if *route_set* is empty, *r_new* will be initialized with a route with only one hop from *current* to *nn*). Repeat Step 7 and Step 8 until all the neighbor nodes of *current* have been processed, then go back to Step 5.
Step 7: If *r_new* is a linear route, and in the meantime, if the distance traversed by *r_new* is less than the sensing limit range, then add *r_new* to *route_set* and continue to Step 8; otherwise, go back to Step 6 and check the next neighbor node.
Step 8: If *nn* is not in *visited*, add *nn* to *next_hop* and add *nn* to *visited*; otherwise, go back to Step 6 and check the next neighbor node.
Step 9: Add *route_set* to *all_routes_set*.
Step 10: While *uncovered* is not empty, go to Step 11; otherwise, go to Step 12.
Step 11: From *all_routes_set*, select the sensing fiber route *r_max* that has the maximum number of overlapping links with *uncovered*. Select the source node of *r_max* to deploy a sensor and the other end as termination point *d*. Remove the fiber links traveled by *r_max* from *uncovered*. Add *r_max* to *assignment*. Back to Step 10.
Step 12: Return *assignment* and terminate.

Numerical Results

We conduct comprehensive simulations to validate the proposed solutions. The fiber optic sensing range limit is set to be 80km, given the existing fiber optic sensing technique [1]. Due to this constraint, the network infrastructures we selected are regional or metro fiber optical networks using real-world datasets [5]. The key network parameters are shown in Table 1. Note that we performed pre-processing that clips the links that are greater than the sensing range limit to be 80km, so that those links can also be covered by DFOS sensors.

We compare Random-Fit, EnP and the ILP solution in terms of the number of sensors used. The results are shown in Table 2. We can see that the ILP solution provides the lower bound; however, as the network scale becomes large, it is not able to yield a result in a reasonable amount of time. In addition, we can observe that EnP can achieve a performance that is close to the lower bound set by the ILP solution. EnP outperforms Random-Fit by 13% in average and 25% at best, respectively. We can conclude that EnP is a fast and cost-efficient solution for addressing the DFOS placement problem.

References

[1] G. A. Wellbrock, et. al., “First Field Trial of Sensing Vehicle Speed, Density, and Road Conditions by using Fiber Carrying High Speed Data”, Proc. of IEEE/OSA OFC 2018, Th4C.7

[2] C. Huang, Y. Tseng, “The Coverage Problem in a Wireless Sensor Network”, Springer Mobile Networks and Applications, Vol. 10, 2005, pp. 519-528

[3] G. Shen, R. S. Tucker, “Translucent Optical Networks: The Way Forward”, IEEE Communication Magazine, Vol. 45, No. 2, Feb. 2007, pp. 48-54

[4] T. H. Cormen, et. al., "Introduction to Algorithms", MIT Press, 3rd Edition.

[5] http://www.topology-zoo.org/dataset.html