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Efficient Sensor Node Deployment Schemes for AOFSN

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Abstract-**In this paper, the sensor node deployment schemes are studied for the all optical fiber sensor networks (AOFSN). Sensor node deployment strategy is very crucial to the sensing efficiency in terms of the high sensing accuracy and low sensing cost, etc. High sensing accuracy requires high coverage ratio and low blind ratio, while low sensing cost requires fewer amounts of sensor nodes/switches and low overlapping ratio. Given the above requirements, we apply the concept of close packing and propose two-dimensional Close-Packing based Sensor node Deployment (2-D CPSD) scheme, and the two-dimensional Closest-Packing Sensor node Deployment (2-D CestPSD) scheme. Then the CestPSD scheme is extended to a three-dimensional application and is named as 3-D CestPSD. The AOFSN applying the 2-D/3-D CestPSD schemes can obtain the maximum coverage, minimum blind ratio under the premise of maintaining no overlapping ratio between any two nodes' sensing range. The network performances are numerically analyzed and compared with some other node distribution schemes in terms of coverage ratio, overlapping ratio, blind ratio, and node density.**

Keywords-AOFSN; Node deployment; Close-packing; Introduction

I. INTRODUCTION

Optical fiber sensor networks, which are multiplexed with arrays of passive optical fiber sensors, have received increasing attention due to their attractive advantages. They are immune to electromagnetic interference, harsh or hostile environments, and power-efficiency, therefore can be deployed in areas where electrical-based sensors would fail or require expensive protection. A number of similar or different sensors can be attached along a single optical fiber, and remote data over kilometers can be processed without corruption. One kind of FBG-based all optical fiber sensor networks (AOFSN) has been studied in our previous research [1, 2]. The applications of AOFSN are diverse, such as in environment monitoring, home caring, etc. Another application, called structural monitoring is becoming very important as ever more high buildings, large mansions and huge bridges are built. Structural monitoring for such as tunneling, building and bridge health are very important, because their damage or collapse will cause serious accidents. In order to monitor their security status, large-scale sensor networks with high reliability and high sensing accuracy are necessary.

Lots of researches about the network reliability for optical fiber sensor networks have been studied. A novel fiber-laser based sensor networks with a self-healing function is proposed in [3]. It is based on adding switches to self-healing ring architectures. Some novel designs of wavelength multiplexed fiber sensor networks that are tolerant to one or more cable failures are proposed in [4]. In [5], a star-bus-ring architecture for optical fiber sensor networks was proposed. The survivability and capacity of a multipoint sensor system are enhanced by adding remote nodes and 2x2 optical switches. In view of the sensing coverage, various works has been done for the wireless sensor networks in [6, 7, 8 and 9]. Generally, the node deployment schemes can be classified as the full coverage and the partial coverage, or deployments with overlapping and without overlapping. Lots of researchers have elaborated on the former strategy to consider full coverage, which can guarantee high accuracy. However, the former scheme sometimes produces too much redundancy which may not be necessary and exhaust WSN quickly. It may not be necessary to provide full coverage at the cost of high redundancy, and partial coverage deployment that can guarantee the coverage requirement to some degree is enough.

However, the coverage problem which affects the sensing efficiency has not been discussed for the optical fiber sensor networks. Great efforts on sensor node deployment have been made for wireless sensor networks (WSN), mostly aiming at achieving full coverage as well as a tradeoff in connectivity. Comparing to the mostly used random deployment strategy in WSN, simple and regular sensor node deployment strategies are preferred in AOFSN. Since AOFSN is consisted of passive sensor nodes and the scanning signals are processed by the limited expensive interrogation, simple but efficient node deployment schemes are needed to alleviate the burden of the limited and expensive interrogations. Two kinds of polygon-based deployment schemes have been studied in our previous research [1, 2], mainly considering the network reliability in cases of link failures and the network scalability when extended to larger scale.

Besides the high reliability/recoverability in view of link failure, the sensing efficiency in terms of the coverage ratio and sensing cost is also very important to AOFSN. In this paper, the sensing cost is evaluated in terms of the required number of sensor nodes/switches, which is also decided by the node deployment. And the problem of minimizing the cost can be generalized to minimize the overlapping ratio in the sensing area, optimally no overlapping ratio. Therefore, the sensor node deployment schemes considering the sensing efficiency of AOFSN will be discussed in this paper. Considering the regular sensor node deployment requirement and inspired by the close-packing concept from the greengrocer [10], the simple, regular and efficient close-packing concept will be applied to the sensor node deployment in this paper. The deployment strategy applying the close-packing concept can obtain the maximum coverage, minimum blind ratio while maintaining no overlapping ratio between any two nodes' sensing range. Close-Packing based Sensor node Deployment (CPSD) scheme and Closest-packing based Sensor node Deployment scheme (CestPSD) are firstly proposed for the two-dimensional sensing space. The network performance of the AOFSN applying the 2-D CPSD and 2-D CestPSD strategies are numerically analyzed and compared to AOFSN using the deployment scheme proposed in our previous paper. The scheme shows the best sensing efficiency. Then the 2-D CestPSD scheme is extended to three dimensions and named as 3-D CestPSD, which also achieves the optimal network performance considering the sensing accuracy and the sensing cost.

The rest of the paper is recognized as follows. Section II has a brief view about the related work and our previous work. In section III, the proposed 2-D/3-D CPSD schemes will be discussed. In section IV, the numerical results of the proposed deployment strategy are discussed. Section V gives some concluding remarks.

II. PRELIMINARY WORKS

A. Previous works

In this section, our previous works on AOFSN in [1, 2] are briefly reviewed. Hierarchical AOFSN networkss consisting of three levels have been studied. The first two levels consist of the active interrogation and remote nodes (RN), and the third level called the sensor subnet (SSN), consists of passive Fiber Bragg Gratings (FBG) and a few switches. The switch architectures in the RN and various SSNs to improve the reliability and scalability have been studied. Furthermore, Two SSNs with regular have been studied by topology using the polygon architecture: square-based sensor cell (SSC) and pentagon-based sensor cell (PSC). The hierarchical AOFSN networks applying the polygon-based sensor cell can achieve high reliability even when multiple link failures happen simultaneously. The lost sensing coverage area can be recovered in most of the cases when applying the SSC-based architecture. It can also maintain high self-similarity while being scaled to larger-scale networks, which simplifies the routing process and reduces the processing complexity of interrogation after been extended to larger scale.

B. Related works

In this paper, we still apply the three-level hierarchical architecture considering its high reliability and scalability. The sensor node deployment strategies in the third level will be continuously studied, aiming at achieving good network performance in the sensing efficiency. Lots of works about the coverage problems in the WSN has been elaborated on. In [6], full coverage problem has been discussed. The authors formulated the problem as a decision problem with the goal of determining whether every point in the service area of the sensor network is covered by at least K (predefined) sensors. Distributed polynomial-time based algorithms have been proposed. In [7, 8, and 9], the partial coverage/connectivity algorithms have been considered for WSN, as all of them thought that full coverage and connectivity may not be possible or necessary due to the resource/energy constraints, high excessive redundancy and energy conservation. In [7], the connected coverage problem with given coverage guarantee was studied. The concept of partial coverage was introduced and analyzed, and a heuristic algorithm considering the partial coverage and sensor connectivity simultaneously was proposed. In [8], a configurable coverage protocol (CCP) was proposed. CCP can be configured such that at least k portion of the required area will be covered by active nodes with high probability, where k is a tunable parameter. In [9], under a certain coverage and/or connectivity requirements, a square region based coverage and connectivity probability model (SCCP) has been proposed to estimate the relationship among the coverage and connectivity rates, the number of sensor nodes, the sensing and communication ranges of sensor nodes, and the network sizes.

C. Coverage requirements for AOFSN

The sensing coverage problem is also very important to the AOFSN networks, and the partial coverage deployment schemes discussed in sub-section B are considered in this paper. Besides the absolute sensing coverage and recoverability discussed in our previous works, the guarantee of sensing coverage while maintaining low switching cost for a required field is crucial to evaluate the efficiency of AOFSN and to guarantee the sensing accuracy and security. While in view of connectivity problem, as most of the AOFSN networks are based on passive sensor nodes, the connectivity may be not a main problem in AOFSN, because optical signals are just passively emitted and reflected, and their communication ranges do not rely on the passive sensors themselves. Therefore, efficient algorithms considering the sensing coverage are more meaningful and will be considered for AOFSN in this paper, comparing to both of the coverage and connectivity problems in WSN.

D. 24-dimensional greengrocer Problems

The requirements of simple and regular topology construction in AOFSN and the optimization requirements between sensing coverage and blind ratio, overlapping ratio, etc, inspire us to apply the 24-dimensional greengrocer concept [10], into the works in this paper. In [10], it gave a two-dimensional example of packing handful of coins, and the case when each coin is surrounded by six others, saying with the 'kissing number' of six, is the closest packing arrangement. This can be applied to the two-dimensional sensing applications and each coin can be seen as the sensing range of a sensor node in two dimensions. It then gave another three-dimensional example of packing handful of oranges. It said that 'greengrocers do it instinctively, but mathematically it is proven that the closest packing in the three dimensions is achieved with a kissing number of 12, i.e., each orange enclosed inside this stack is in contact with 12 neighbors.' This can be applied to our three-dimensional sensing applications and each orange can be seen as the sensing range of a sensor node in three dimensions.

III. SENSOR NODE DEPLOYMENT ALGORITHMS

In this section, we will discuss two node deployment algorithms applying the close-packing concept for two dimensions, and they are called 2-D Close-Packing Sensor node Deployment (2-D CPSD) and 2-D Closest-Packing Sensor node Deployment (2-D CestPSD) algorithms. Then, 2-D CestPSD scheme is extended into the three dimensions.

A. Close-Packing based Deployment in two dimensions

As what have been discussed before, the full coverage may not be necessary, the partial coverage deployment schemes will be considered. The close-packing based sensor node deployment algorithm for two dimensions is discussed in detail. In our research, each sensor node is supposed to have the identical sensing range. In view of the 2-D AOFSN application, the sensing radius of each sensor node is assumed to be identical with the value of r, and the sensing range of each sensor node is supposed to represent by a circle with the area of πr^2.

In this section, we will discuss three kinds of square-based node deployment schemes: one overlapping based scheme which was proposed in our previous research and two non-overlapping based schemes. The square-based deployment scheme proposed in our previous research is shown as in Fig. 1, and it is a square-based sensor sub-network. Twenty FBGs are embedded in one fiber to construct a sensor network. Each circle presents the sensing range of each FBG. The dashed square in the periphery presents the required sensing coverage. The full coverage requirements cannot be satisfied and the overlapping ratio is high. If we try to satisfy the full coverage requirement, more sensors and switches are required. As well, more overlapping and redundancy will be generated. The sensor network may need more energy or cost to pick up the useful sensing signal among the overlapping raw sensing signals to guarantee the sensing accuracy. Moreover, more sensor nodes and switches are required and this will increase the cost of the sensor network. In order to reduce the redundancy while guaranteeing the sensing coverage to some significant degree, two close-packing based node deployment schemes are proposed. Now, considering the example of packing handful of coins in [7] again, the sensor node deployment problem in our research can be generalized to the packing of circles representing the sensing range of sensor nodes. We discuss two packing schemes, one is the close-packing and one is the closet-packing which are differed in the kissing number of each node. The proposed close-packing based deployment strategy is further classified into the 2-D close-packing sensor node deployment (CPSD) and 2-D closest-packing sensor node deployment (CestPSD), differing in their kissing number. The 2-D CestPSD strategy can achieve maximal coverage ratio while maintaining the minimal sensing cost/overlapping. The 2-D CPSD scheme without overlapping is shown in Fig. 2. It is so called close packing because each sensing circle is packing closely with its four neighbors, i.e., the kissing number is four. Given the same coverage field, the sensor node deployment scheme shown in Fig. 2 can obtain better coverage ratio than the scheme in Fig. 1 does, but it has zero overlapping ratio and much less node density as well as sensing cost.

As an improvement of the node deployment scheme in Fig. 2, 2-D CestPSD scheme is proposed and shown in Fig. 3. The node deployment in Fig. 3 is generalized from the packing of coins in [10], which has been proven to be the closest packing scheme in the two-dimensional space. Each sensing circle is packing closely with six other neighbors. As the packing of coins with a kissing number of six was proven to be the closest, the sensor node deployment shown in Fig. 3 can be seen as the optimal deployment strategy considering its maximal sensing coverage ratio and no overlapping. In Fig. 3, every four adjacent nodes construct an equilateral diamond with the acute angle of 45 degree.

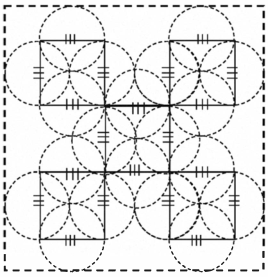

Figure 1. SSC

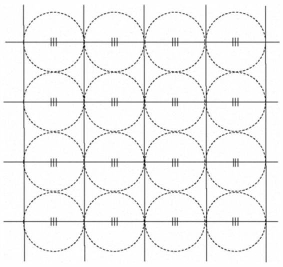

Figure 2. 2-D CPSD

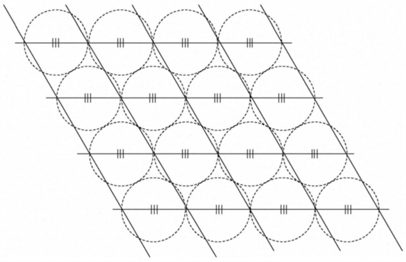

Figure 3. 2-D CestPSD

B. Closest-Packing Sensor node Deployment in three dimensions

As the closest-packing based node deployment strategy can obtain the optimal network performance while guarantee no overlapping, it will be extended to the three-dimensional AOFSN applications. In three dimensions, the sensing range of each sensor node is represented by a sphere. Therefore, the node deployment problem can be generalized to the closest-packing of spheres, and the location distribution of sensor nodes can be obtained from the packed spheres. In the closest packing of spheres, there are two simple regular lattices that achieve this highest average density. They are called cubic closest-packed (FCC) and hexagonal closest-packed (HCP) as show in Fig. 4 in [11]. They differ in how the sheets are stacked upon one another. In both arrangements, each sphere has twelve neighbors, i.e., their kissing number is 12. As it has been proved that both of the two deployment schemes can obtain the same coverage ratio, we only consider to apply the HCP based node deployment scheme in this paper.

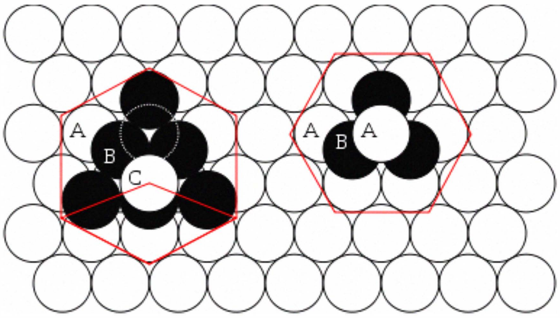

Figure 4. FCC and HCP

In HCP, every other layer is the same and alternatively consists of two layers shown in Fig. 5, saying A and B. The HCP based sphere packing shown in figure 6a is constructed by alternatively packing layer A and layer B, and can be described in the following form:

HCP = ABABABA……

The kissing number of HCP is 12 and its atomic packing factor (APF) is around 0.74 in [11] which has been proven to be the closest packing ratio. From the closest-packing construction of spheres, which represent the sensing range of a sensor node, we can get the location distribution of sensor nodes as shown in Fig. 6b. Each point on the hexagon column denotes a sensor node and is deployed in the center of each sphere. That is to say, if we deploy the sensor nodes according to the strategy shown in Fig. 6b, we can obtain an optimal sensing coverage of 74% while maintaining no overlapping.

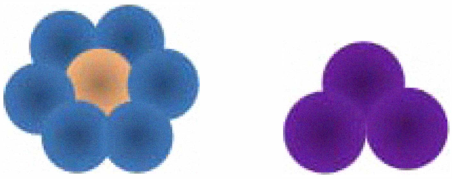

Figure 5. a) layer A; b) layer B

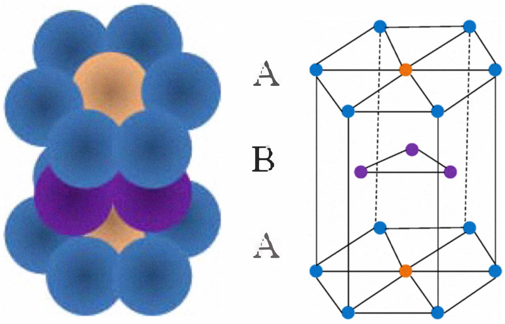

Figure 6. a) 3-D CestPSD based on HCP: ABABA…; b) Sensor node deployment in AOFSN

IV. RESULTS EVALUATION

In this section, we briefly discuss the network performances of AOFSN using the close packing strategy mainly in the two-dimensional space. Their results are compared with those of AOFSN applying different node deployment schemes. The network performances are evaluated in terms of coverage, coverage ratio, blinding ratio, overlapping ratio and node density. The definitions of the metrics are firstly introduced.

A. Definitions of metrics

(1) *Coverage (C)*: The sensing area of AOFSN.

(2) *Coverage Ratio(CR)*: Given a coverage area, the area ratio how AOFSN can cover using a node deployment scheme.

(3) *Blinding Ratio (BR)*: Given a coverage area, the ratio that AOFSN cannot cover using a node deployment scheme. In our paper, it can be generalized as the area ratio that cannot be covered by any circle/sphere (sensing range).

(4) *Overlapping Ratio (OR)*: The ratio of the sensing area that is covered by more than one sensor nodes.

(5) *Node Density (ND)*: Given the coverage requirement, the number of sensor nodes that are needed to satisfy the requirement.

B. Result analysis

We analyze and compare the network performances of AOFSN that apply SSC, 2-D CPSD, and 2-D CestPSD respectively. The sensing radius of each sensor node is supposed to be r, their sensing range in two dimension is πr^2. For the simplicity of comparison, we suppose the required coverage area is a square with the area of $64r^2$. The coverage area, the coverage ratio, the blinding ratio, the overlapping ratio and the node density for SSC-based node deployment scheme are calculated by (1), (2), (3), (4) and (5).

$$C_{SSC} = 5*(2r)^2 + 8\pi r^2 + 4*(\frac{4r^2 - \pi r^2}{2}) = (28+6\pi)r^2 = 46.84r^2 \tag{1}$$

$$CR_{SSC} = \frac{(28+6\pi)r^2}{64r^2} \approx 73.2\% \tag{2}$$

$$OR_{SSC} = \frac{20\pi r^2 - (28+6\pi)r^2}{(28+6\pi)r^2} = \frac{7\pi - 14}{14+3\pi} \approx 34.07\% \tag{3}$$

$$BR_{SSC} = 1 - 73.2\% \approx 26.8\% \tag{4}$$

$$ND_{SSC} = \frac{20}{(28+6\pi)r^2} \approx \frac{0.427}{r^2} \tag{5}$$

The coverage area, the coverage ratio, the blinding ratio, the overlapping ratio and the node density for 2-D CPSD based node deployment are calculated by (6), (7), (8), (9) and (10).

$$C_{CPSD} = 16\pi r^2 = 50.24 r^2 \tag{6}$$

$$CR_{CPSD} = \frac{16\pi r^2}{64 r^2} \approx 78.5\% \tag{7}$$

$$OR_{CPSD} = 0 \tag{8}$$

$$BR_{CPSD} = 1 - 78.5\% \approx 21.5\% \tag{9}$$

$$ND_{CPSD} = \frac{16}{16\pi r^2} \approx \frac{0.318}{r^2} \tag{10}$$

For the given coverage area requirement of $64r^2$, the node deployment of 2-D CestPSD should be constructed as shown in Fig. 7, where the periphery square means the requirement of $64r^2$. Therefore, the coverage area, the coverage ratio, the blinding ratio, the overlapping ratio and the node density for 2-D CestPSD are calculated by (11), (12), (13), (14) and (15).

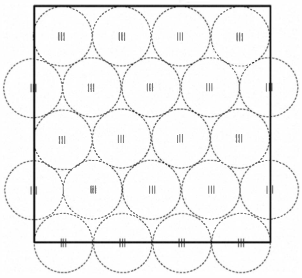

Figure 7. 2-D CestPSD to satisfy the required coverage;

$$C_{CestPSD} = 18\pi r^2 = 56.52 r^2 \tag{11}$$

$$CR_{CestPSD} = \frac{18\pi r^2}{64 r^2} \approx 88.3\% \tag{12}$$

$$OR_{CestPSD} = 0 \tag{13}$$

$$BR_{CestPSD} = 1 - 88.3\% \approx 11.7\% \tag{14}$$

$$ND_{CestPSD} = \frac{22}{18\pi r^2} \approx \frac{0.389}{r^2} \tag{15}$$

Finally, the network performance of the three node deployment schemes in AOFSN are compared and shown in Table 1. The results emphasized in bold and italic means the optimal results. From Table 1, we can see the close packing schemes achieves much better sensing efficiency comparing to the SSC based node deployment. The CPSD scheme achieves the best performance in view of the node density/sensing cost. The closet packing based node deployment, saying CestPSD, shows the best sensing efficiency as it achieves the coverage ratio as high as 88.3% when maintaining no overlapping ratio, at the cost of a little higher node density/cost than that of the CPSD scheme. The coverage ratio is significantly improved comparing to that of SSC and CPSD, with a little higher node density/cost than that of CPSD. However, need to mention that, as the required coverage area was supposed to be a square with the area of $64r^2$, so the CestPSD scheme required a little higher node density. It is of high probability that the node density for CestPSD would be better than that of CPSD if the given coverage is different. In view of the 3-D CestPSD scheme, we can get the coverage ratio as high as 74% while maintaining no overlapping ratio.

TABLE 1 Network performance comparison

Metrics **Schemes**	Coverage Ratio	Blinding Ratio	Overlapping Ratio	Node Density
SSC	73.2%	26.8%	34.07%	$0.427/r^2$
CPSD	78.5%	21.5%	***0***	***0.318/r²***
CestPSD	***88.3%***	***11.7%***	***0***	$0.389/r^2$

V. CONCLUSIONS

In this paper, we discussed several efficient node deployment schemes for AOFSN networks which require regular and simple sensor node deployment, so as to construct a simple but efficient sensor network topology. The efficiency of the node deployment schemes was mainly evaluated in terms of the sensing coverage ratio under the requirement of minimum overlapping ratio, so as to reduce the sensing cost. Considering the full-coverage may not be necessary, the mathematical close-packing concept was applied in our node deployment schemes to construct partial coverage deployment which can optimally approach the full-coverage requirement. The close-packing and closest-packing based node deployment schemes, called CPSD and CestPSD, were proposed for the two dimensional AOFSN applications. And CestPSD showed to have the highest sensing efficiency, with the highest coverage ratio, no overlapping, lower node density/cost. Then the CestPSD scheme was extended to the three dimensional AOFSN applications, and it can also achieve a high coverage ratio which approaches to the full-coverage while maintaining no overlapping ratio.

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