Close-Packing based Sensor Node Deployment Schemes for AOFSN

Li-Mei Peng*, Chan-Hyun Youn
GRID Middleware Research Center of ICC
Korea Advanced Institute of Science and Technology, Taejon, 305, Korea
E-mail: aurora_plm@kaist.ac.kr
*Corresponding author

Wan Tang
Computer Intelligence Lab, College of Computer Science,
South-Central University for Nationalities, Wuhan, P. R. China
E-mail: tangwan@scuec.edu.cn

Xin-Wan Li
Department of Electronic Engineering,
Shanghai JiaoTong University, Shanghai 200240, China

Abstract: In this paper, we consider a hierarchical all-optical fiber sensor network (AOFSN) consisting of a number of passive sensor nodes. The sensor node deployment is considered for such kind of AOFSN, as sensor node deployment schemes are very important to its sensing efficiency in terms of their sensing accuracy and sensing cost, etc. High sensing accuracy requires high coverage ratio and low blind ratio, while low sensing cost requires the less number of sensor nodes/switches and low overlapping ratio. The above requirements drive us coming with the concept of close packing and we propose the Close-Packing based Sensor node Deployment (CPSD) scheme, and the Closest-Packing Sensor node Deployment (2-D CestPSD) scheme for two dimensional space. 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 reliability of AOFSN using 2-D/3-D CestPSD deployment is then discussed. We propose the switch deployment schemes and switch architectures for AOFSN using 2-D CestPSD and 3-D CestPSD respectively to gurarantee their reliability. The network performances of sensing accuracy are numerically analyzed and compared in terms of coverage ratio, overlapping ratio, blind ratio and node density. The reliability of AOFSN is evaluated in terms of the recoverability after link failure happening. Both of the proposed sensor node deployment schemes and the switch deployment schemes/architectures are shown to be efficient.

Keywords: AOFSN, Node deployment, Close-packing.

1 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 (Peng et al., 2008)(Peng et al., 2010). Regular arrays consisting of a large number of FBGs can be multiplexed into fibers to construct large-scale AOFSN. 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 forest are very important, because their damage or collapse will cause serious accidents. Recalling the fire disaster in Russia in July 2010, if we can distributed deploy this kind of large-scale AOFSN which is sensitive to the temperature and pressure within the forest, we believe that we can prevent such kind of fire disaster to some extent or can reduce the damage to some extent. Of course, this kind of large-scale sensor network should be highly reliable with high sensing accuracy as well as cost efficiency.

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 (Peng et al., 2003). 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 (Eduardo et al., 2007). In (Gillooly et al., 2004), 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 (Huang and Tseng, 2003),(Liu and Liang, 2005),(Zhang et al., 2007) and (Xing et al., 2009). 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 (Peng et al., 2008)(Peng et al., 2010), 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 (Stewart et al., 2003), 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. However, these results are all obtained under the assumption that the AOFSN is reliable and has no link failure or node failure. Then the reliability of AOFSN using CestPSD in two dimensions and three dimensions is considered by deploying a number of switches, as these switches can be adjusted to change their light path to scan the sensors besides the failed link after link failure happening.

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

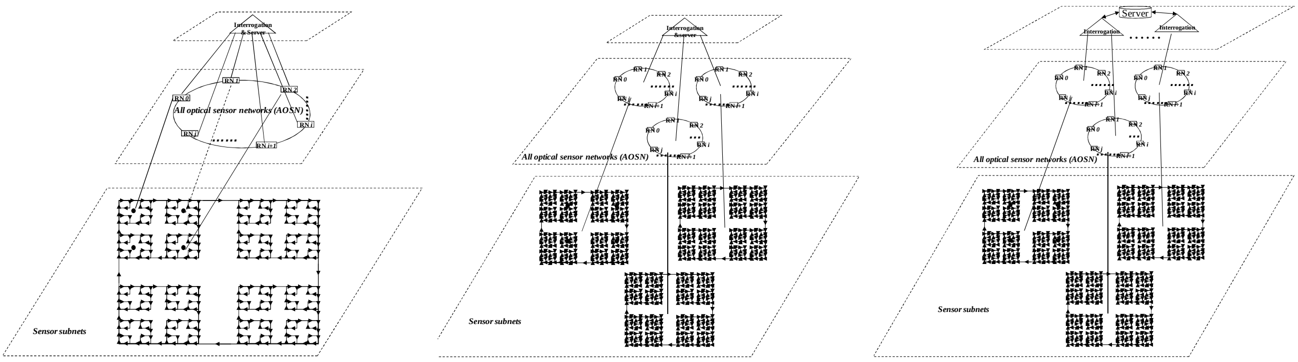
2 Related Work

2.1 Hierarchical AOFSN Architectures

In this paper, we discuss a hierarchical based AOFSN network. The considered AOFSN consists of three levels: the first interrogation/server(InS) level. It manages the second and third levels to check for link failure between RNs and InS or sensor cells, by sending and collecting scanning signals from RNs; the second level is the interface/RNs (Remote Nodes). Several RNs comprise the self-healing ring architecture. Each RN manages its own sensor subnet to collect scanning signals from the third level and then they provide feedback to the first InS level. The third level is the sensor subnet (SSN). It consists of some passive FBG sensors, executing the scanning request and providing feedback to their upper RN level.

The cost of hardware in AOFSN is mainly due to the interrogation and switches and the interrogation is the most expensive device. In order to reduce the cost of the most expensive interrogation device and utilize it efficiently, three different types of hierarchical AOFSNs are proposed. They mainly differ in terms of whether the second communication network level and the first interrogation level are grouped. By grouping them, the cost due to interrogation and the burden of interrogation for demodulating large numbers of signals can be reduced in order to utilize resources efficiently. The architectures are discussed in detail and shown in Figure 1.

The first type is shown in Figure 1. The first level is composed of one interrogation/server for signal recognition. The second level is the interface level between the interrogation/server and sensor subnets. It is composed of a self-healing



(a)

(b)

(c)

Figure 1: (a) No grouping in the first two levels; (b) Grouping in the second level; (c) Grouping in the first and second levels.

unidirectional ring consisting of N RNs. Each RN manages its own sensor subnet. All RNs are centrally controlled by the only interrogation and are responsible for collecting data and providing feedback to it. Thus, the RNs can simultaneously receive the scanning requests from a common interrogation, and they execute the scanning process to provide feedback of the scanning results to the interrogation. Finally, the interrogation selects the signals useful for recognition and decides the sensing results from all the feedback signals by the below RNs. The second type is shown in Figure 1(b). Of all the sensing signals collected by the RNs in the second level, the useful ones can be quite rare. Many researches on wireless networks apply a three-point location mechanism. Only three sensor nodes are activated for sensing and they provide useful sensing signals each time. In the AOFSN, we apply a similar candidate mechanism in the second level in order to reduce the burden of the only interrogation. That is, the RNs in the second level are grouped according to their geographical positions instead of providing all the raw sensing signals to the only interrogations directly. Each time the interrogation sends the scanning request to its below RNs, it estimates the approximate geographical scanning region from the results of the last scanning process. Then it first selects one or several specific groups to do the scanning process and collects the feedback signals from these specific groups. Thus, the burden of the interrogation is further reduced and the scanning speed is improved. This screen-out mechanism can be realized by selecting nearby regions with higher strength signals according to the last scanning results. The third type is shown in Figure 1(c). It is an alternative from the second type. The interrogation level is further grouped according to the interrogating techniques. This architecture is applicable for heterogeneous sensor networks, as each interrogation can interrogate different types of feedback scanning signals. This type has high flexibility compared to the first two types but there is a higher cost, because more interrogations are used. The three types of hierarchical architecture were proposed based on the cost or burden of the first two levels. The construction of the SSN will be discussed in the next section.

2.2 Sensing Efficiency Problem of AOFSN

Considering the above Figure 1, we can see that the sensing accuracy and the reliability of AOFSN is mainly decided by sensor node deployment in the third SSN level. Therefore, the sensor node deployment strategies in SSN will be studied, aiming at achieving good network performance in terms of the sensing efficiency as well as high reliability. The sensing accuracy and cost is then mainly decided by the sensing coverage ability of a sensor network. Lots of works about the coverage problems in the WSN has been elaborated on. In Huang and Tseng (2003), 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 Liu and Liang (2005)Zhang et al. (2007) and Xing et al. (2009), 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 Liu and Liang (2005), 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 Zhang et al. (2007), 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 Xing et al. (2009), 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.

The sensing coverage problem is also very important to the AOFSN networks, and the partial coverage deployment schemes 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.

2.3 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 Stewart et al. (2003), into the works in this paper. In Stewart et al. (2003), 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.

3 SENSOR NODE DEPLOYMENT ALGORITHMS

In this section, we will discuss two node deployment algorithms applying the close-packing concept for two/three 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 and called 3-D CestPSD.

3.1 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. 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.

Then, 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 Figure 2, 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 Liu and Liang (2005) 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 Figure 3. 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 Figure 3 can obtain better coverage ratio than the scheme in figure 2 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 figure 3, 2-D CestPSD scheme is proposed and shown in figure 4. The node deployment in figure 4 is generalized from the packing of coins in Stewart et al. (2003), 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 figure 4 can be seen as the optimal deployment strategy considering its maximal sensing coverage ratio and no overlapping. In figure 4, every four adjacent nodes construct an equilateral diamond with the acute angle of 45 degree.

3.2 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

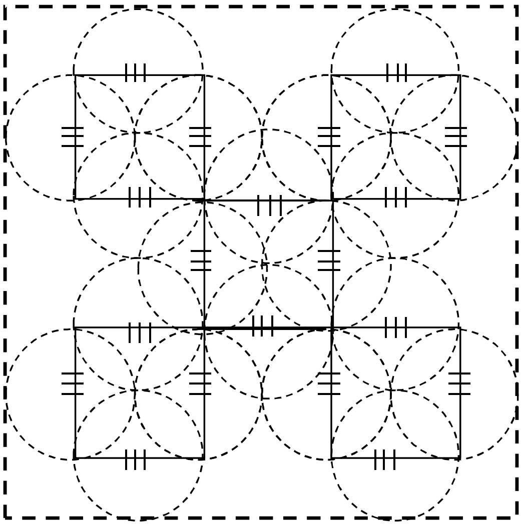


Figure 2: SSC

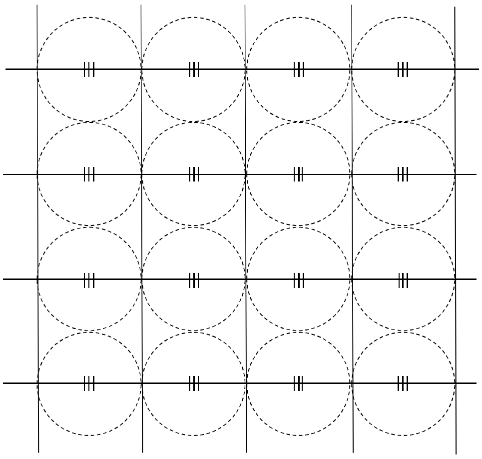


Figure 3: 2-D CPSD

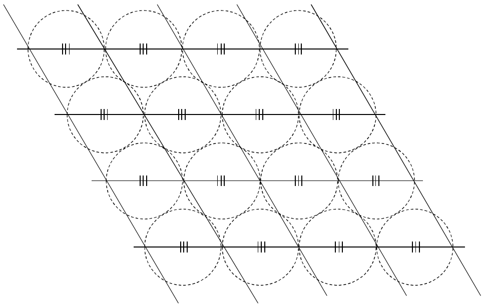


Figure 4: 2-D CestPSD

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 figure 5 in Close-packing-spheres (2010). 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.

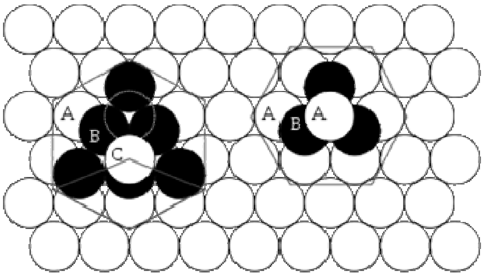


Figure 5: FCC and HCP

In HCP, every other layer is the same and alternatively consists of two layers shown in figures 6, saying A and B. The HCP based sphere packing shown in figure 7(a) 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 Close-packing-spheres (2010) 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 figure 7(b). 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 figure 7b, we can obtain an optimal sensing coverage of 74% while maintaining no overlapping.

4 RELIABILITY AND SCALABILITY OF AOFSN

There are several cases of link failures, e.g., link failure between/within the first two levels, link failure between/within the second and the third level. As we have discussed such kind of failures between/within the first two levels in our previous work Peng et al. (2010), we will focus on discussing the link failure and switch deployment in cases of the link failures within the third level.

Taking AOFSN using 2-D CestPSD for example, to improve the network reliability, we distributed the switches as shown in figure 8. We take a subnet consisting of twelve FBGs (Fi) as a sensing cell shown in figure 8 and a large-scale AOFSN is composed of a number of such kinds of cells. Each cell is consisted of twelve FBG sensor nodes, one remote node (RN) and four switches. Each cell can be further divided in to four subcells, e.g., FBGs F_0, F_1, F_2 and F_3 consist of $subcell_0$, and so on. The switch architecture of each RN is shown by figure 10, and the architecture of other switches (SWi) is shown by figure 11. In the normal case (when there is no link failure), RN is switched to the outputs of F_0 and F_6 through the couple C_2 in figure 10, and the switches are adjusted to the output of F_2, F_4, F_8 and $F_1$0 in SW_0, SW_1, SW_3 and SW_4 respectively. The light paths for scanning all the FBGs by light emitted from RN are as follows:

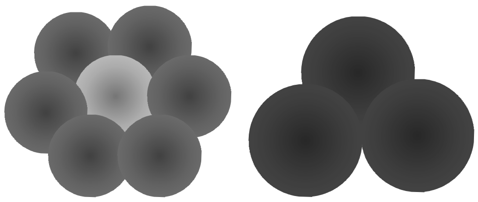

(a) (b)

Figure 6: a) layer A; b) layer B

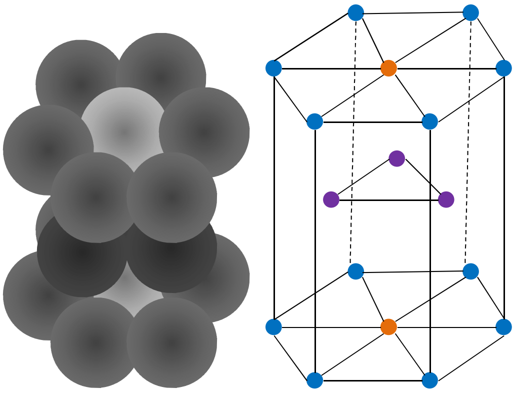

(a) (b)

Figure 7: a) 3-D CestPSD based on HCP: ABABA; b) Sensor node deployment in AOFSN

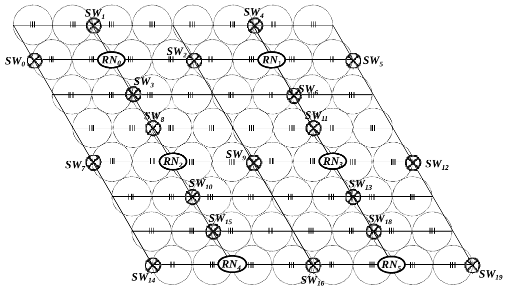


Figure 8: Switch deployment in AOFSN using 2-D CestPSD

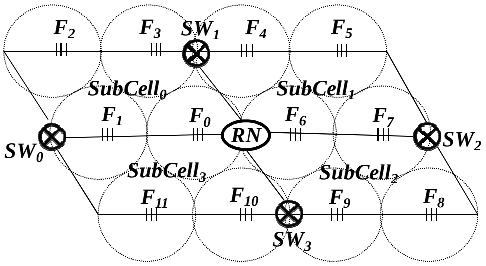


Figure 9: Switch deployment in a cell

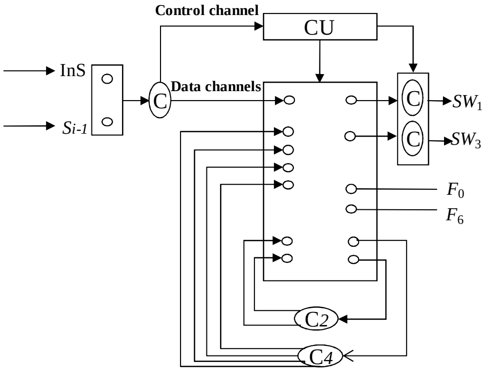
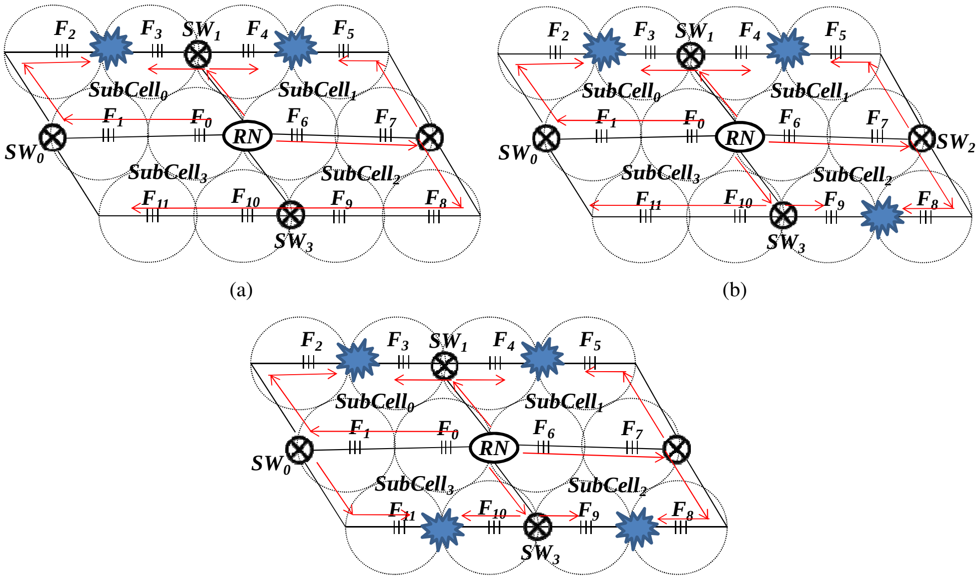


Figure 10: Architecture of RN

path1: $RN \rightarrow F_0 \rightarrow F_1 \rightarrow F_2 \rightarrow F_3 \rightarrow F_4 \rightarrow F_5$, and
path2: $RN \rightarrow F_6 \rightarrow F_7 \rightarrow F_8 \rightarrow F_9 \rightarrow F_10 \rightarrow F_11$.

All the FBGs within a cell can be scanned once through path 1 or path 2 in case of no link failure. By assigning switches like this in figures 9, each sensor cell can understand four simultaneous link failures assuming that no multiple link failures happen within one subcell. If one link failure happens, we can adjust the switches to change the scanning light to the output ports of F_3 in SW_1 and $F_5\&F_8$ in SW_2 as shown in figure 13. Similarly, the recovery adjusting of each switch in cases of two, three or four link failures is shown in figure 14. The results show that the 2-D CestPSD based sensor node deployment cannot only obtain sensing efficiency but also has high self-healing ability as well as high recoverability.

After discussing the reliability of AOFSN using 2-D CestPSD, we now have a look at the network reliability of network using 3-D CestPSD. From figure 7, we can generalize the sensor node deployment as shown in figure 15, and the architecture shown in figure 16 can be seen as a 3-D CestPSD cell (similar to that of figure 9). Each 3-D CestPSD cell consists of seventeen FBG sensor nodes, one RN and five switches. The architecture of RN and switches in figure 15(a) is shown in figure



(a)

(b)

(c)

Figure 14: (a) two link failure; (b) three link failure; (c) four link failure

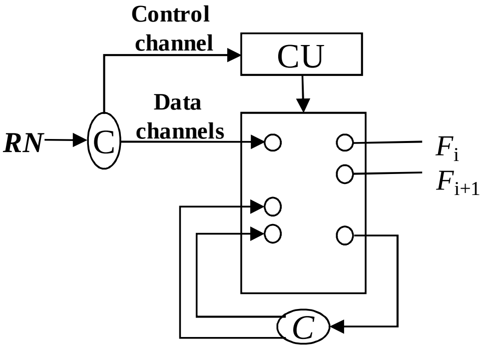


Figure 11: Architecture of each switch

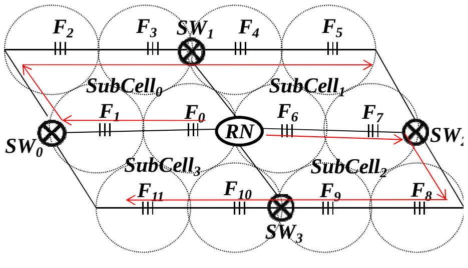


Figure 12: Two Scanning path in normal case

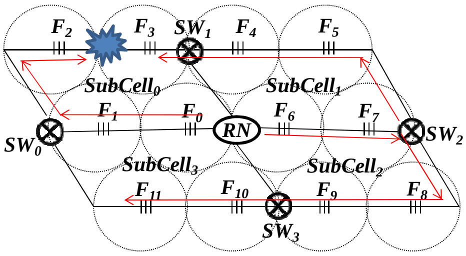


Figure 13: One link failure: SW_1 to F_3 and SW_2 to F_5 & F_8

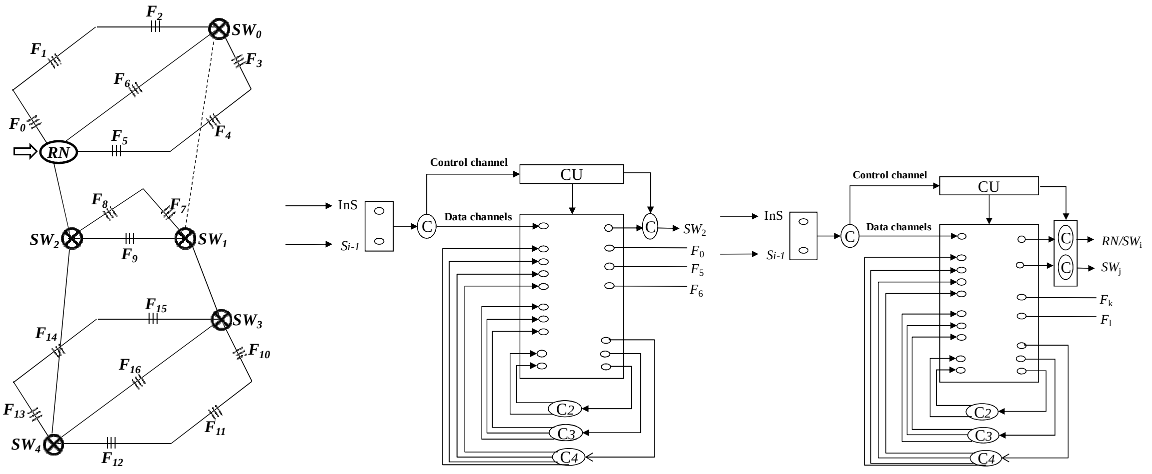
15(b) and figure 15(c). The scanning path when there is no link failures is shown in figure 16(a) and the recovery process when five simultaneous link failure happen (worst case) is shown in figure 16(b). The result also shows that AOFSN using the considered switch deployment and architecture in three dimensions has high self-healing ability and high reliability.

5 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.

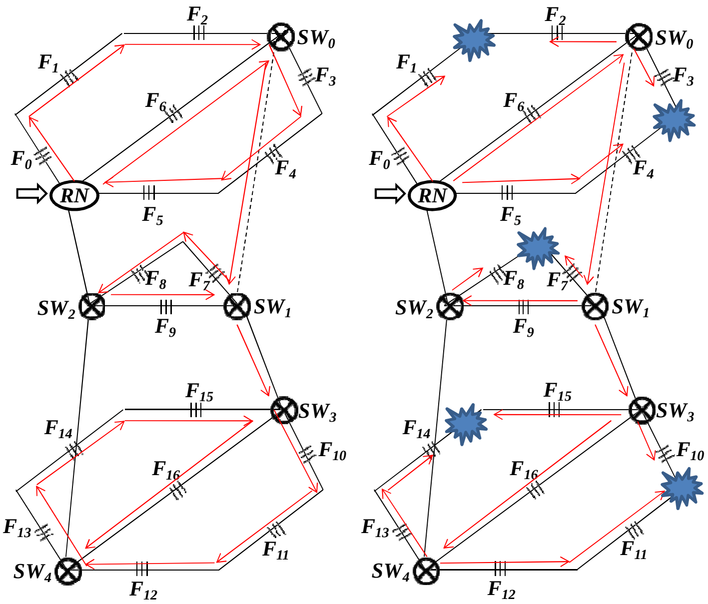
5.1 Definition of Metrics

- *Coverage(C):* The sensing area of AOFSN.
- *Coverage Ratio(CR):*Given a coverage area, the area ratio how AOFSN can cover using a node deployment scheme.
- *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).
- *Overlapping Ratio (OR):*The ratio of the sensing area that is covered by more than one sensor nodes.
- *Node Density (ND):*Given the coverage requirement, the number of sensor nodes that are needed to satisfy the requirement.



(a) (b) (c)

Figure 15: (a) 3-D CestPSD cell; (b) architecture of RN and SW_0, SW_3 & SW_4; (c)architecture of SW_1 & SW_2



(a) (b)

Figure 16: (a) Norma case with no link failure; (b) Five simultaneous failures (worst case).

5.2 Results 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 64r2. The coverage area, the coverage ratio, the blinding ratio, the overlapping ratio and the node density for SSC-based node deployment scheme are calculated as follows in formulas (1), (2), (3), (4) and (5).

$$C_{SSC} = 5\times(2r)^2 + 8\pi r^2 + 4\times(\frac{4r^2-\pi r^2}{2}) = (28+6\pi)r^2 = 46.82r^2 \quad (1)$$

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

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

$$BR_{SSC} = 1 - 73.2\% \approx 26.8\% \quad (4)$$

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

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

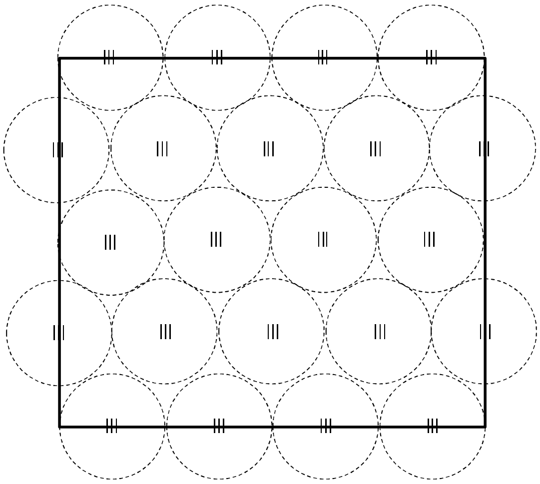


Figure 17: 2-D CestPSD to satisfy the required coverage;

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

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

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

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

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

For the given coverage area requirement of 64r2, the node deployment of 2-D CestPSD should be constructed as shown in figure 17, where the periphery square means the requirement of 64r2. Therefore, the coverage area, the coverage ratio, the blinding ratio, the overlapping ratio and the node density for 2-D CestPSD are calculated as follows in formulas (11), (12), (13), (14) and (15).

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

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

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

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

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

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 64r2, 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.

6 Conclusion

In this paper, we considered a hierarchical all-optical fiber sensor network (AFOSN), and proposed two node deployment schemes based on the concept of close/closest-packing, which was called CPSD and CestPSD for both two-dimension and three-dimension. AOFSN using CestPSD scheme performed to have the highest sensing efficiency, with the highest coverage ratio, no overlapping, lower node density/cost under the assumption of no link failure. Then the reliability of AOFSN using CestPSD in both 2-D and 3-D spaces was considered. The switch deployment schemes and switch architectures were proposed to guarantee the reliability of such kind of AOFSN in case of multiple simultaneous failures. The proposed deployment scheme and switch architecture were shown to be efficient in terms of high recoverability when multiple link failures happen.

REFERENCES

Peng, L.M., Yang, W.H., Li, X.W., Kim, Y.C. (2008) ‘The Construction of a FBG-Based Hierarchical AOFSN with High Reliability and Scalability’, *Proc. SPIE 2008*, Hangzhou China, 71362J1-71362J12.

Peng, L.M., Yang, W.H., Li, X.W., Kim, Y.C. (2010) ‘Investigation on Reliability and Scalability of an FBG-Based Hierarchical AOFSN’, *Journal of Sensors*, Vol. 10, No. 4, pp. 2901-2918.

Peng, P.C., Tseng, H.Y., Chi, S. (2003) ‘A Novel Fiber-Laser-Based Sensor Network with Self-Healing Function’, *IEEE Photonic. Technol. Lett.*, Vol. 15, pp.275-277.

Eduardo, L.I., Paul, U., Manuel, L.A.(2007) ‘Protection Architectures for WDM Optical Fiber Bus Sensor Arrays’, *J. Eng. Comput. Arch.*, Vol. 1, pp. 1-18.

Gillooly, A.M., Zhang, L., Bennion, I. (2004) ‘High Survivability Fiber Sensor Network for Smart Structures’, *Proc. SPIE 2004*, pp.99-106.

Table 1: Network performance comparison

	Coverage Ratio	Blinding Ratio	Overlapping Ratio	Node Density
SSC	73.9%	26.8%	34.7%	$0.427/r^2$
CPSD	78.5%	21.5%	0	$0.318/r^2$
CestPSD	88.3%	11.7%	0	$0.389/r^2$

Huang, C.F., Tseng, Y.C. (2003) ‘The coverage problem in wireless sensor network’, *Proc. of the 2nd ACM international conference on Wireless Sensor Networks and Applications*, pp. 115-121, San Diego, USA.

Liu, Y.Z. , Liang, W.F. (2005) ‘Approximate Coverage in Wireless Sensor Network’, *Proc. of LCN’05*, PP. 68-75.

Zhang, M.Z., Chan, M.C., An, A.L. (2007) ‘Coverage Protocol for Wireless Sensor Networks Using Distance Estimates’, *IEEE SECON*, June 18, 2007.

Xing, X.F. , Wang, G.J., Wu, J., Li, J. (2009) ‘Square Region-based Coverage and Connectivity Probability Model in Wireless Sensor Networks’, *Proc. of the 5th CollaborateCom*, Nov. 2009.

Stewart, L. (2003) ‘The 24-dimensional greengrocer’, *Nature*, August, pp. 895-896.

(2010) ‘http://en.wikipedia.org/wiki/Close-packing_of_spheres’, *wikipedia*, .