The Optimized Three-Dimensional Deployment for Pipeline Systems in Wireless Sensor Networks

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Abstract—**Pipeline systems are vital infrastructure to national economy, and are widely used for transporting liquid and gas matter, such as oil, natural gas, water and chemic materials. However, effective and efficient management of pipeline systems are challenging, due to its mere lengths and the diverse deployment environments. Wireless sensor network (WSN) consists of a large number of sensors, which can automatically and constantly collect and transmit monitored data, and thus can enable effective and timely management of pipeline systems. Successful WSNs rely on the deployment of sensor nodes. Most current research assumes that sensor nodes are deployed on a two-dimensional plane. However, in reality, sensor nodes deployed on pipeline surface exist in a three-dimensional space. In this paper, we present an optimized 3D deployment model of WSN particularly for pipeline systems. The model is based on analyzing various relationships between sensing ranges of sensor nodes and pipeline radii. We also provide an efficient deployment algorithm based on the model. Empirical simulation results show that the proposed model and the algorithm can provide both theoretical guidance and practical basis for the three-dimensional deployment of sensor nodes in pipeline systems.**

Index Terms—**three-dimensional deployment, pipeline system, hierarchical network architecture**

I. INTRODUCTION

Wireless sensor networks (WSNs) are networks that consist of a large number of resource-limited sensor nodes. Each node is typically equipped with sensors of different types, computational units, storage devices and communication modules. These components, as a whole, can automatically sense, process, and transmit all kind of monitored data, without any human intervention. Therefore, WSNs already have many civil and military applications, such as health-care[1], environmental monitoring [2], scientific exploration[3], battlefield surveillance[4] , etc.

Transmission pipelines are vital infrastructure to national economy. Such pipelines are widely used for

transporting large quantities of liquid and gas matter, such as crude oil, natural gas, water and chemic materials, due to its lower long-term costs, higher capacity and better consistency than alternative transporting methods such as railroad and highway. However, managing transmission pipelines is challenging, especially with the rapid growth in the length of the pipelines. Successful pipeline management must monitor leak, pressure, flow, corrosion, pollution in surrounding environment, and many other factors that can affect the safety of the pipelines and thus transportation efficiency. WSNs can be used to ensure the efficiency and safety of pipeline without costly expansion [5], which can effectively improve the level of management.

Successful application of WSNs relies on the deployment of sensor nodes. Recent research on sensor node deployment mainly focus on two-dimensional models—how to effectively and efficiently set up sensor nodes in a two-dimensional plane [6-9]. However, in reality, sensor nodes deployed on pipeline surface exists in a three-dimensional space. Although there exists some research on deployment models of sensor nodes in 3D space, few can be applied to the context of pipeline systems. In this paper, we study this problem—optimized sensor node deployment in a three-dimensional space—specifically for pipelines.

The rest of this paper is organized as follows. Next, we discuss related work. Then we describe the geometric structure of a pipeline and the typical three-tier-network architecture for WSNs. Section IV presents the new 3D sensor node deployment model for pipelines and its implementation algorithm, based on the analysis of the geometric relationships between sensor node's sensing ranges and the radius of a pipeline. Section V analyzes the empirical simulation results, from connectivity, coverage and energy consumption respectively. Section VI concludes the paper.

II. RELATED WORK

Maximizing sensing coverage efficiency is a fundamental and critical issue for successful WSN applications. In recent years, the coverage problem has been extensively studied in the context of two-dimensional planes [6-9]. However, in reality, sensor

nodes embedded in the real physical world exist in three-dimensional space. Recently, there has been increasing research on 3D deployment models [10, 11, 12, 13, 14, 15, 16, 17]. Given a long-narrow region, Zhou[10] analyzes the basic requirements for optimal deployment of nodes in all directions, designs a 3D linear node deployment strategy adapted to fault coverage and proposes an energy-efficient network zoning strategy under fault-tolerant coverage. Liu [11] provides a new lattice-based technique for topology construction in 3D WSNs. Jiang and Liu [12] propose a energy-aware coverage algorithm that takes coverage ratio into account also for 3D WSNs. Zhang, Yu and Zhang [13] propose a distributed energy efficient 3D coverage control algorithm. Li, Feng and Hou [14] transfer their 2D algorithm SGA (Stand Guard Algorithm) to 3D, based on the characteristics of the 3D space. Li and Liu [15] propose a novel three-dimensional grid model algorithm MCC3D (Max Coverage Connectivity 3D). Ammari and Das [16] discuss the connectivity and k-coverage issues in 3D WSNs and propose the reuleaux tetrahedron model to characterize k-coverage of a 3D field and investigate the corresponding minimum sensor spatial density. Pompili, Melodia and Akyildiz [17] study the deployment strategies for two-dimensional and three-dimensional communication architectures for underwater acoustic sensor networks

Node deployment methods can be classified into two types: random deployment and deterministic deployment. Pipeline coverage—the problem we consider in this paper—belongs to the latter. None of the related research discussed above considers the structure characteristics of the pipelines, for example, their radius and lengths. However, these are the primary factors that can affect coverage efficiency. Consequently, in this research, we take the relationship between pipeline radius and sensor nodes' sensing ranges into account.

III. System Architecture and three-Dimensional Sensor node Deployment based on WSNs

In this section, we describe the pipeline architecture and the typical 3-tier deployment structure of WSNs. These form the basis of our 3D sensor node deployment model, which will be explained in details in the next section.

A. Architecture of a Pipeline

Pipelines are made from steel or plastic tubes with an inner diameter typically ranging from 0.1m to 5m [18]. Figure 1 (a) shows the architecture of a standard pipeline. We project the 3D pipeline structure into two 2D planes-the XY plane and the XZ plane, as shown in Figure 1 (b), with r being the radius and L the length of the pipeline. Wireless sensor nodes can only be deployed on the pipeline wall. This means that in the XY-projected topological graph, all sensor nodes exist on the edge of the circle, whereas in the XZ-projected graph they are located on the two longer edges of the rectangle, and inside the rectangle.
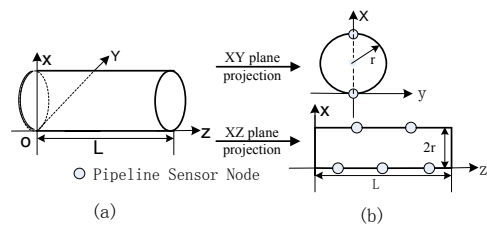

Figure 1.   The pipeline architecture

B. Three-tiers Network Architecture for Pipeline System Based on WSNs

A WSN-based pipeline monitoring network typically consists of three tiers: the pipeline sensor nodes (PSNs) at the bottom, the intermediate stations sink nodes (ISSNs) and the pipeline monitoring control center (PMCC) at the top, as shown in Figure 2 [19].
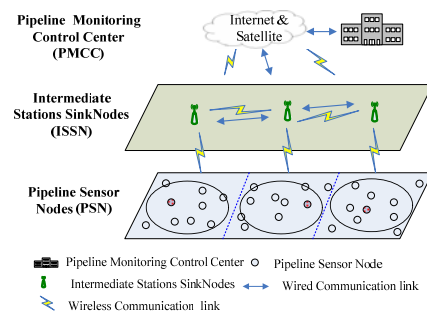

Figure 2.   The network architecture of pipeline system based on WSNs

PSNs, i.e. the sensor nodes, deployed on the pipeline surface, sense pipeline state information in real time, such as pressure, quantity of flow, pipeline leak, pipeline corrosion, wax precipitation, environmental pollution and weather information. Each PSN has restricted computing and storage capability and limited battery, which cannot be recharged. Therefore, it is important that the sensor nodes deployment must be energy-efficient so as to prolong system lifetime.

In the middle tier, ISSNs are installed at initial injection station, compressor or pump station, partial delivery station, valve station and final delivery station [18]. The deployment is shown in Figure 3. Each ISSN has abundant computing and storage resource compared to PSNs. Furthermore, ISSNs can be recharged in time. The main functions of ISSNs include analyzing data from PSNs and uploading the data to pipeline monitoring control center (PMCC). ISSNs form a middle tier network via satellite or Internet communication.
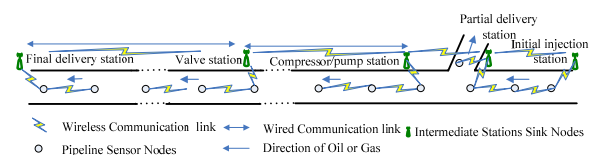

Figure 3.   The deployment of PSNs and ISSNs

In the top tier, PMCC connects all ISSNs by Internet or satellite communication. PMCC is responsible for

forming the overall analysis and issuing the information to managers.

IV. THE THREE-DIMENSIONAL DEPLOYMENT OF PIPELINE SENSOR NODES

As discussed before, successful application of WSNs rely on the effective deployment of sensor nodes: they must form a comprehensive and seamless coverage of the pipeline so that sensing information is complete and accurate. Meanwhile, because PSNs-sensor nodes for pipelines—are placed determinately and permanently, methods for finding their optimal positions on the pipeline surfaces are essential to PSN deployment.

Given r the radius of the pipeline and r_s the sensing range of a sensor node, there can be four possible relationships between r and r_s: $r_s \geq 2r$, $\sqrt{2}r \leq r_s < 2r$, $r \leq r_s < \sqrt{2}r$ and $r_s < r$. Different r_s means different sensing coverage of the sensor node. Therefore, we analyze the optimal deployment model for each of the four r_s ranges. We first determine the deployment model in the XY plane, and then expand it to the Z axis direction.

A. $r_s \geq 2r$

Figure 4 shows the sensing coverage of the sense node in blue dotted circle and the pipeline in black circle. Given a point A (x_s, y_s) on the sensing surface and a point B (x_p, y_p) on the pipeline surface, we can easily derive the following equations between the two points' coordinates and the radii r and r_s:

$$x_s = r_s \sin\theta \geq 2r\sin\theta, \; y_s = r_s\sin\theta \quad (1)$$

$$x_p = r\sin 2\theta = 2r\sin\theta\cos\theta, \; y_p = r + r\cos\theta \quad (2)$$
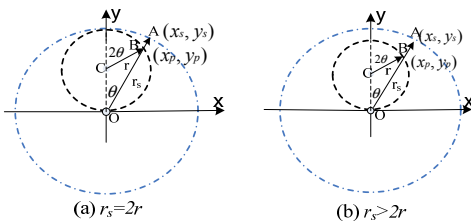
(a) $r_s=2r$ (b) $r_s>2r$

Figure 4.   Sensing coverage in the XY plane when $r_s \geq 2r$

Because $\cos\theta \leq 1, \theta \in [0, \pi/4], r > 0$, we get equation (3), which indicates that a single sense node can cover the pipeline completely.

$$x_p = 2r\sin\theta\cos\theta \leq 2r\sin\theta \leq x_s \quad (3)$$

Figure 5 illustrates the seamless coverage in the XZ plane while $r_s \geq 2r$. This can further be classified into two cases: $r_s=2r$ and $r_s>2r$. In either case, the distance between two closest sensor nodes on the same side of the pipeline S_n and S_{n-2} is

$$|S_n S_{n-2}| = 2(r_s + \sqrt{r_s^2 - 4r^2}) \quad (4)$$

When r_s is greater than $2r$, $|S_n S_{n-2}|$ is greater than $2r_s$, which means the sensor node placed between S_n and S_{n-2} but on the opposite side can provide partial coverage, as shown in Figure 5(b).
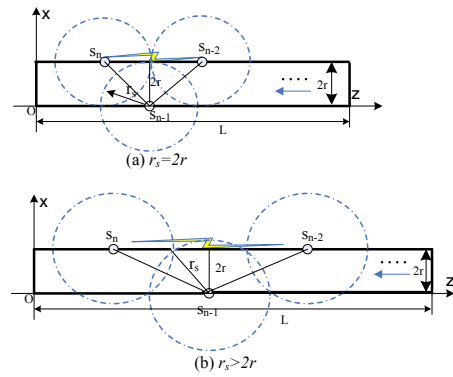
(a) $r_s=2r$

(b) $r_s>2r$

Figure 5.   Sensing coverage in the XZ plane when $r_s \geq 2r$

B. $\sqrt{2}r \leq r_s < 2r$

When $\sqrt{2}r \leq r_s < 2r$, as shown in Figure 6, a single node cannot provide full coverage, but two nodes can do when placed properly. Let A, B denote the intersection points between the sensing ranges of two sense nodes deployed on the opposite side of the pipeline with the same Z position, i.e. one on O and one on D in figure 6. It is clear that as long as $|BC| \geq r$, that is, when $r_s \geq \sqrt{2}r$, two sensor nodes placed opposite each other can provide seamless coverage of the pipeline.

(a) $r_s = \sqrt{2}r$ (b) $2r > r_s > \sqrt{2}r$
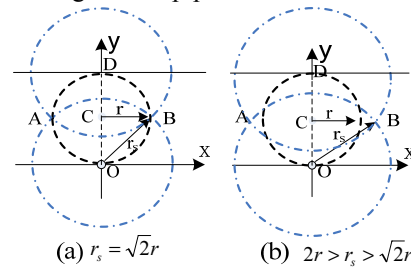
Figure 6.   Sensing coverage in the XY plane when $\sqrt{2}r \leq r_s < 2r$

In the XZ plane, coverage model is shown in Figure 7. For clarity for analysis, two PSNs are located on the surface of the pipeline with a symmetrical way. It is clear that the distance of between two nearest PSNs on the same side of the pipeline can be expressed as follow according to the figure 7.

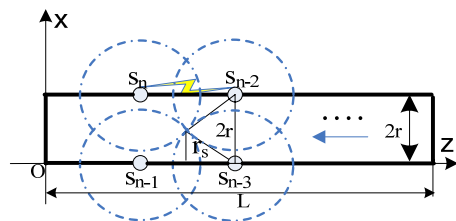$$|S_n S_{n-2}| = |S_{n-1} S_{n-3}| = 2\sqrt{r_s^2 - r^2} \quad (5)$$

Figure 7.   Sensing coverage in the XZ plane when $\sqrt{2}r \leq r_s < 2r$

C. $r \leq r_s < \sqrt{2}r$

When $r \leq r_s < \sqrt{2}r$, two PSNs cannot cover the entire pipeline, but three PSNs could cover it completely if

placed properly. Figure 8 shows the seamless coverage in the XY plane when $r \leqslant r_s < \sqrt{2}r$.
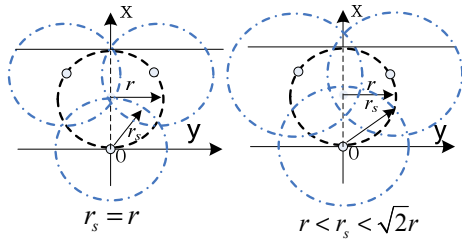

Figure 8. Sensing coverage in the XY plane when $r \leqslant r_s < \sqrt{2}r$

In particular, Figure 9 demonstrates the seamless coverage in the XZ plane. It is clear that the distance between two nearest PSNs on the same side of the pipeline can be expressed as follow:

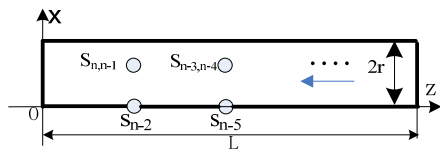$$|S_{n-2}S_{n-5}| = 2\sqrt{r_s^2 - 9/16 * r^2} \qquad (6)$$

Figure 9. Sensing coverage in the XZ plane when $r \leqslant r_s < \sqrt{2}r$

D. $r_s < r$

In this case, the PSNs set cannot completely cover the pipeline surface in the XY plane, no matter how many PSNs are placed, as shown in figure 10.
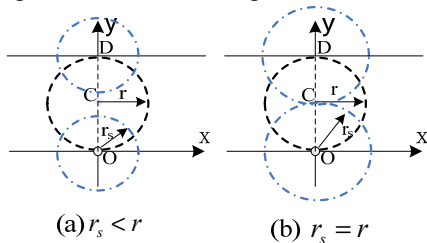

(a) $r_s < r$ (b) $r_s = r$

Figure 10. Sensing coverage in the XY plane when $r_s < r$

E. *Optimized 3D Deployment Algorithm*

Let L denotes the length of a pipeline, on which sensor nodes are to be deployed and N_s the total number of PSNs. Then the relation between L and N_s is

$$N_s = \lceil 2L / |S_nS_{n-2}| \rceil + 1, \qquad (7)$$

according to Figures 4 and 8.

Based on previous analysis of the relationships between sensing range and the pipeline radius, the optimized algorithm for 3D deployment can be described in pseudo-code as below.

Input: pipeline parameters(r,L), effective sense radius (r_s) and communication radius (r_c)
Output: the required number of sensor node (N_s), coordinate matrix P[N_s][3]. P[i][0] denotes the X axis of node S_i(i=0,N_s-1), P[i][1] the Y axis and P[i][2] the Z axis.

Main()
{ int L, r, r_s, r_c, N_s;
If ($r_s \geqslant 2r$)
{ Num1();   //output the number of sensor node (N_s) for pipeline monitoring system
    Pos1(N_s); }   //output the coordinate matrix P[N_s][3]
else ($2r > r_s \geqslant \sqrt{2}r$)
{ Num2();
    Pos2(N_s); }
else ($\sqrt{2}r > r_s \geqslant r$)
{ Num3();
    Pos3(N_s); }
else printf("These sensor nodes that locate on the surface of pipeline can't completely cover pipeline system while $r_s < r$") // as shown in figure 10.

Num1(), Num2(), Num3() are functions for computing the numbers of sensor nodes required in different situations. They are described respectively below.

Function Num1() // output the number of sensor node (N_s), as shown in figure 4-5
{int $d_s = |S_nS_{n-2}| = 2(r_s + \sqrt{r_s^2 - 4r^2})$;
       $N_s = \lceil L/(r_s + \sqrt{r_s^2 - 4r^2}) \rceil + 1$; }

Function Num2() // output the number of sensor node (N_s) , as shown in figure 6-7
{int $d_s = |S_nS_{n-2}| = 2\sqrt{r_s^2 - r^2}$;
       $N_s = \lceil L/\sqrt{r_s^2 - r^2} \rceil + 1$; }

Function Num3() // output the number of sensor node (N_s) , as shown in figure 8-9
{int $d_s = |S_{n-2}S_{n-5}| = 2\sqrt{r_s^2 - 9/16 * r^2}$;
       $N_s = \lceil L/\sqrt{r_s^2 - 9/16 * r^2} \rceil + 1$; }

Likewise, Pos1(), Pos2(), Pos3() are functions for computing the coordinates of the sensor nodes in different situations, and are described below.

Function Pos1(N_s) // output the coordinate matrix P[N_s][3], as shown in figure 4-5
{int i,P[N_s][3];
For(i=1;i<=Ns;i++)
{if (i%2==0) P[i-1][0]= 2r; else P[i-1][0]=0; // the coordinate of x axis
P[i-1][1]=0 ;   // the coordinate of y axis
P[i-1][2]= (i-1)* d_s /2 ; }   // the coordinate of z axis

Function Pos2(N_s) // output the coordinate matrix P[N_s]
[3], as shown in figure 6-7
{int i,P[N_s][3];
For(i=1;i<=Ns;i++)
{if (i%2==0) P[i-1][0]= 2r; else P[i-1][0]=0;
P[i-1][1]=0; P[i-1][2]= (i-1)* d_s; }

Function Pos3(N_s) // output the coordinate matrix P[N_s]
[3], as shown in figure 8-9
{int i,P[N_s][3];
For(i=1;i<=Ns;i++)
{if (i%2==0) { P[i-1][0]= 3/2r; p[i-1][1]=3r/(2 $\sqrt{5}$); p[i-1][2]=(i-1)*ds;}
else if (i%3==0) {p[i-1][0]=0; p[i-1][1]= 0; p[i-1][2]=(i-1)*ds;}
else {P[i-1][0]=3/2r; p[i-1][1]=-3r/(2 $\sqrt{5}$); p[i-1][2]=(i-1)*ds; }
}

V. SENSOR NODES DEPLOYMENT PERFORMANCE ANALYSIS

This section presents empirical simulated performance analysis of our sensor nodes deployment algorithm. We evaluate from three aspects: connectivity performance, coverage performance and energy consumption performance. We also adopt the line PSNs deployment strategy to avoid unbalanced energy consumption in PSNs, which can effectively prolong the life span of network.

A. Connectivity Performance

Connectivity is an important performance indicator of wireless sensor network. The connectivity model is categorized into two types: Boolean model and probabilistic model. The latter is often regarded as can better reflect the actual communication quality between nodes. Using the probabilistic model, the communication quality between sensor node i and j $C(s_i,s_j)$ is

$$C(s_i,s_j) = \begin{cases} 1 & 0 \leq d(s_i,s_j) \leq R_{c1} \\ \dfrac{E_{ir}}{E_i} e^{-\lambda(d(s_i,s_j)-R_{c1})} & R_{c1} < d(s_i,s_j) \leq R_{c2} \\ 0 & R_{c2} < d(s_i,s_j) \end{cases} \quad (8)$$

In equation (8), denotes the communication quality from node s_i to s_j. R_{c1} defines the communication range and R_{c2} the maximum communication range of the node. E_i and E_{ir} denote the initial and the remainder energy of sensor node s_i respectively. The parameter λ is the degree of attenuation of signal intensity based on communication distance, and is determined by the physical properties of the sensor node. The typical value of λ is 1 [20].

The communication quality of sensor node s_i, according to equation (8) is $C_i = 1/(m-1)\sum_{j=i}^{m} C(s_i,s_j)$, with

m being the number of communicable neighbor sensor

nodes of node s_i. Therefore, the network's connection performance can be described by equation (9).

$$C = \frac{1}{N_s} \sum_{i=1}^{N_s} C_i \quad (9)$$

Generally, $r_c \geqslant 2r_s$ (r_c: the communication radius of PSN) is both necessary and sufficient to ensure a complete three-dimensional coverage of a pipeline, and this implies full connectivity in the network [21]. In practice, this requirement is achievable for most pipeline system.

B. Coverage Performance

Network coverage efficiency (referred to as τ) is defined as the ratio of the actual coverage volume against the maximum effective volume of a sensor node, see equation (10) [10].

$$\tau = V_s(r_s)/V_m(r_s) \quad (10)$$

r_s denotes the sensing radius of PSNs, V_s indicates the actual coverage volume of PSNs, and V_m denotes the max coverage volume of these PSNs.

Given a pipeline system with length L, if N_s PSNs are deployed on its surface, then τ is calculated as follows:

$$\tau = \frac{\pi r^2 L}{4N_s \pi r_s^3/3} = \frac{3r^2 L}{4N_s r_s^3} \quad (11)$$

As shown in equation (11), the ratio between r and r_s directly affects the coverage efficiency τ . Figure 11 further plots this relationship. As Figure 11 shows, when $r = r_s$, the network coverage efficient τ is about 75%; when $r = 0.71 r_s$, τ is about 26%; and when $r = 0.5 r_s$, τ is about 10%. Therefore, in order to maximize τ , we should choose nodes with a sensing range r_s close to r.
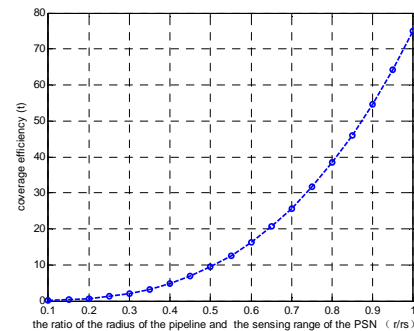

Figure 11. Impact of the ratio of r/r_s on τ

Similarly to measuring communication quality, sensor nodes perception can also be modeled with either a Boolean or a probabilistic model. The probabilistic model can better reflect the actual perception quality [20].

$$p(s_i,a_k) = \begin{cases} 1 & d(s_i - a_k) \leq R_{s1} \\ \dfrac{E_{ir}}{E_i} e^{-\alpha d(s_i - a_k) - R_{c1}} & R_{s1} < d(s_i - a_k) \leq R_{s2} \\ 0 & R_{s2} < d(s_i - a_k) \end{cases} \quad (12)$$

In equation (12), p(s_i,a_k) denotes the perception quality from node s_i to a_k. E_i and E_{ir} denote the initial and the remainder energy of sensor node s_i. R_{s1}

determines the range of perception and R_{s2} the maximum perception range. α is a parameter affected by the physical characteristics of sensor nodes. $d(s_i - a_k)$ denotes the euclidean distance between the target node and sensor node, which is calculated as:

$$d(s_i - a_k) = \sqrt{(x_i - x_k)^2 + (y_i - y_k)^2 + (z_i - z_k)^2} \qquad (13)$$

In practical application environment, one wireless sensor node can cover multiple target points in the monitoring area [21]. If a target point j is covered by m sensor nodes at the same time, the coverage of j is defined as:

$$P(j) = 1 - \prod_{i=1}^{m} (1 - p_{ij}) \qquad (14)$$

C. Energy Consumption Performance

Figure 12 shows a typical sensor node energy consumption distribution. It is clear that wireless communication module is the main energy consumption unit. The radio energy dissipation model is defined as:

$$E_{Tx} = \begin{cases} k.E_{elec} + k.\varepsilon_{fs}.d^2 & for \quad 0 \le d < d_0 \\ k.E_{elec} + k.\varepsilon_{mp}.d^4 & for \quad d \ge d_0 \end{cases} \qquad (15)$$

The amount of energy consumed for transmission E_{Tx}, of k-bit message over a distance d is given by equation (15). The energy expended in receiving a *k*-bit message is given by equation (16).

$$E_{Rx} = k.E_{elec} \qquad (16)$$

Where E_{elec} is the amount of energy consumed in electronic circuits, ε_{fs} is the energy consumed in an amplifier when transmitting at a distance shorter than d_0, and ε_{mp} is the energy consumed in an amplifier when transmitting at a distance greater than d_0.
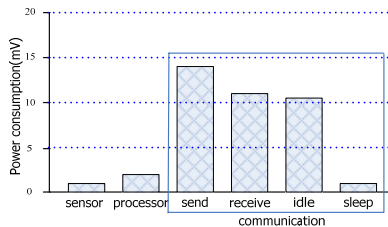

Figure 12. Distribution of energy consumption of sensor nodes

Every sensor node has the same initial energy (refer as E_i) and the same connection performance according to equation (9) at the start of the network to work. However, as time went on, the remainder energy of sensor node (refer as E_{ri}) will be far different because the unbalance energy consumption. Thus the perception of the sensor nodes radius (r_s) and the communication radius (r_c) will be affected, and so do node's coverage and connectivity. As the network running time grows, the residual energy of sensor nodes reduces. When running time reaches a threshold (or the energy of the sensor node is less than a threshold), network coverage performance and connectivity will drop dramatically, as shown in Figure 13.
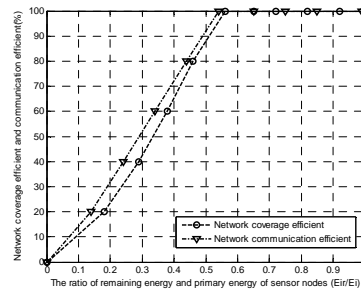

Figure 13. Impact of the remaining energy of sensor nodes on network coverage efficiency and network communication efficiency.

In order to accurately evaluate network connection performance, we design the Ns×7 network connection performance matrix which is described by equation (17). The matrix C[i][0] denotes the identifier of node s_i (i=0,Ns-1). C[i][1,2,3] denotes the X,Y,Z coordinates of s_i (i=0,Ns-1). C[i][4] denotes s_is connection, C[i][5] the remainder energy and C[i][6] the network route path.

$$C = \begin{bmatrix} \overset{\text{identifier}}{\underset{\text{of node}}{}} & \overset{\text{X,Y,Z coordinate of}}{\underset{\text{node}}{}} & & & \overset{\text{connection}}{\underset{\text{of node}}{}} & \overset{\text{energy of}}{\underset{\text{node}}{}} & \overset{\text{route path}}{\underset{\text{of node}}{}} \\ 1 & X_1 & Y_1 & Z_1 & C_1 & E_1 & R_1 \\ 2 & X_2 & Y_2 & Z_2 & C_2 & E_2 & R_2 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ N_s & X_{N_s} & Y_{N_s} & Z_{N_s} & C_{N_s} & E_{N_s} & R_{N_s} \end{bmatrix} \qquad (17)$$

D. Energy Prior Line Deployment Strategy

In order to avoid unbalanced energy consumption of WSN, we use the energy prior line deployment strategy of PSNs to prolong the life span of network. The deployment strategy is shown in figure 14.
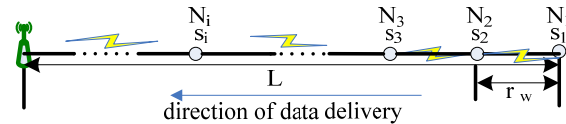

Figure 14. Line PSNs deployment strategy

In figure 14, N_i denotes the number of PSNs in the i-th position of multi-hop data transmission route to ISSN. In order to keep the same ratios (refer as β) of energy consumption in each position to the total amount of energy in the position, we need to deploy more PSNs in the positions closer to ISSN, and less PSNs that are far from ISSN. β can be determined by equation (18), where E_{i-all} denotes the total energy consumption of PSNs in the i-th position. We can effectively prolong the life span of network by scheduling PSNs to switch between active state and sleeping state, so that each position has only one active PSN to sense and relay data packets to ISSN in the same time.

$$\beta = \frac{N_1}{E_{1-all}} = \frac{N_2}{E_{2-all}} = \cdots = \frac{N_i}{E_{i-all}} = \cdots = \frac{N_n}{E_{n-all}} \qquad (18)$$

VI. CONCLUSION

In this work, we carefully analyze the three-dimensional sensing deployment model based on the different relationships between sensing range of a sensor

node and the radius of a pipeline. We also present a complete algorithm description for the deployment model. We evaluated the presented 3D deployment model from the connectivity, coverage and energy consumption aspects. Empirical results showed that our algorithm is effective and efficient.

Although energy is an important issue in WSNs for pipeline systems, we only briefly discussed it in this work. In future, we plan to further investigate the energy and delay issues based on our three-dimensional sensing coverage model for pipeline systems

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