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# Deployment Algorithms of Wireless Sensor Networks for Near-surface Underground Oil and Gas Pipeline Monitoring

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**Abstract:** Oil and gas pipelines are the infrastructure of national economic development. Deployment problem of wireless underground sensor networks (WUSN) for oil and gas pipeline systems is a fundamental problem. This paper firstly analyzed the wireless channel characteristics and energy consumption model in near-surface underground soil, and then studied the spatial structure of oil and gas pipelines and introduced the three-layer system structure of WUSN for oil and gas pipelines monitoring. Secondly, the optimal deployment strategy in XY plane and XZ plane which were projected from three-dimensional oil and gas pipeline structure was analyzed. Thirdly, the technical framework of using kinetic energy of the fluid in pipelines to recharge sensor nodes and partition strategy for energy consumption balance based on the wireless communication technology of magnetic induction waveguide were proposed, which can effectively improve the energy performance and connectivity of the network, and provide theoretical guidance and practical basis for the monitoring of long oil and gas pipeline network, the city tap water pipe network and sewage pipe network. *Copyright © 2014 IFSA Publishing, S. L.*

**Keywords:** Oil and gas pipeline, Near-surface underground soil environment, Coverage, Connectivity, Energy consumption, Magnetic induction.

## 1. Introduction

Wireless underground sensor network (WUSN) is a main technical method to solve the problem of various kinds of information monitoring in near-surface underground soil environment [1], WUSN consists of a large number of resource-limited sensor nodes. Each node is typically equipped with different types of sensors, computational units, storage devices and communication modules, which are deployed with random or deterministic way in the monitoring area. These sensor nodes, as a whole, can automatically sense, process, and transmit all kind of monitored data, without any human intervention. At present, WSN already has many civil and military applications, such as health-care, environmental monitoring, industrial control, scientific exploration, battlefield surveillance and other civil and military fields, etc.

Oil and gas pipelines are vital infrastructure to national economy, which is the most economical way to transport crude oil, natural gas and chemical products due to its lower costs, higher capacity and better consistency than alternative transporting methods such as railroad and highway [2]. However, managing oil and gas pipelines is challenging, especially with the rapid growth in the length of the oil and gas pipelines. Successful oil and gas pipeline management must monitor leak, pressure, flow, corrosion, pollution in surrounding environment, and many other factors that can affect the safety of the oil and gas pipelines and thus transportation efficiency. WUSN can be used to ensure the efficiency and safety of oil and gas pipeline with low cost, sustainable and uninterrupted way, which can effectively improve the level of management and economic and social benefits [3].

The deployment ways of sensor nodes generally are divided into two categories, random deployment and deterministic deployment. Sensor node coverage and connectivity efficiency maximization is the basic requirement of sensor nodes deployment algorithm under the condition of network seamless coverage and network connectivity. In recent years, the research on sensor node deployment mainly focus on two-dimensional models, the existing three-dimensional models mainly face the open space, but the three-dimensional models for fixed structure (such as oil and gas pipeline system) haven't found. Therefore, the research of nodes deployment for oil and gas pipeline system has important theoretical significance and practical significance.

The research of nodes deployment in near-surface underground soil environment has been developed in literature [4-8]. The soil on the attenuation of electromagnetic (EM) wave is discussed in [4], which established the near-surface spatial channel models. Literature [5] proposed a MCC3D covering algorithm for wireless underground sensor network only based on covering performance. Literature [6] proposed a multiple targets associated coverage methods in the soil environment monitoring, which improved information exchange and transmission performance between the nodes. Literature [7] designed a data model and data structure for WSN deployment and proposed an automatic generation algorithm of network topology in mine roadway space. The algorithms in [5-7] only have 1-cover in network coverage performance, and did not consider the multiple coverage and characteristics of space-variant in underground soil environment, and their constraints on connectivity performance are only on the whole. In addition, the literature [8] explored a kind of three-dimensional deployment strategy of pipeline system, which discussed the pipeline structure and the relationship between the perception distance and communication distance of sensor nodes in detail, but does not take into account the problem that one hop communication distance between two adjacent sensor nodes is too short in underground environment.

The remainder of this paper is organized as follows. In Section II, environmental characteristics of near-surface underground soil is introduced. Then in Section III, oil and gas pipeline structure and the system structure is analyzed. In Section IV, three-dimensional sensor nodes deployment algorithm is developed. Finally, the paper is concluded in Section V.

## 2. Environmental Characteristics of Near-Surface Underground Soil

### 2.1. Wireless Channel Characteristics

At present, the communication technology of the wireless sensor network (WSN) is based on the electromagnetic wave. But, the communication link in near-surface underground soil has obvious space-variant features. Channel capacity is vulnerably affected by many factors such as the work frequency (denoted as F) of electromagnetic waves, soil water content (denoted as SWC) and space-variant features of channel [4]. Specifically, path loss (denoted as $L_p$) of near-surface underground soil environment can be expressed as,

$$L_p = 6.4 + 20\log(d_s) + 20\log(\beta) + 8.69\alpha d_s, \qquad (1)$$

where $d_s$ is the distance between the adjacent sensor nodes, the unit is meter; $\alpha$ is the attenuation coefficient, the unit is 1/m; and $\beta$ is the phase shift coefficient, the unit is radian/m. the experiment and simulation results show as follow.

The 300-500 MHz is feasible work frequency for wireless communication in near-surface underground soil environment using EM waves. The greater the working frequency, the greater the path loss; the greater soil volumetric water content, the greater the path loss; the path loss in near-surface underground soil environment is more than four to six times in the free space (such as in air). The simulation analysis results are shown in Fig. 1.

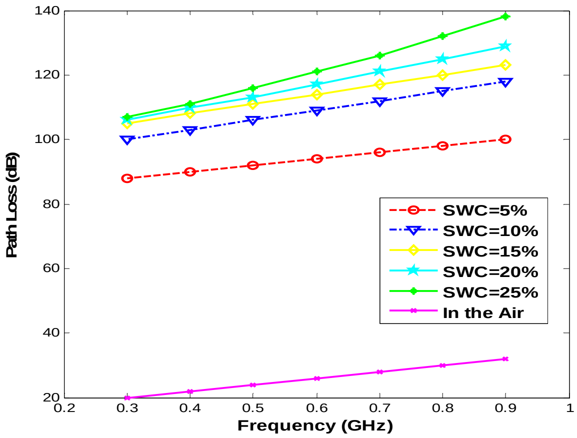


**Fig. 1.** Path loss versus operating frequency and soil water content (SWC).

The maximum effective transmission distance between the adjacent sensor nodes is no more than 4 meters with 433 MHz in near-surface underground soil environment. The greater the transmission distance, the greater the path loss. As shown in Fig. 2, it is shown that in the 300–500 MHz frequency band, the path loss can be limited to a degree (<=100 dB) supporting feasible communication in the near-surface underground soil environment, of which the maximum transmission distance ($R_c$) between the sensor nodes is not more than 4 m, and effective distance perception of sensor nodes (Rs) is about the same or even lower than $R_c$ [4]. But the effective communication distance of sensor nodes in air is more than 80 m, which is greater than the effective distance perception, namely the $R_c \gg R_s$. and when the $R_c \gg$ Rs, the node deployment algorithm can guarantee network connectivity if the algorithm can seamlessly cover monitoring area. Therefore, network connectivity is the first factors which need to consider in sensor node deployment.

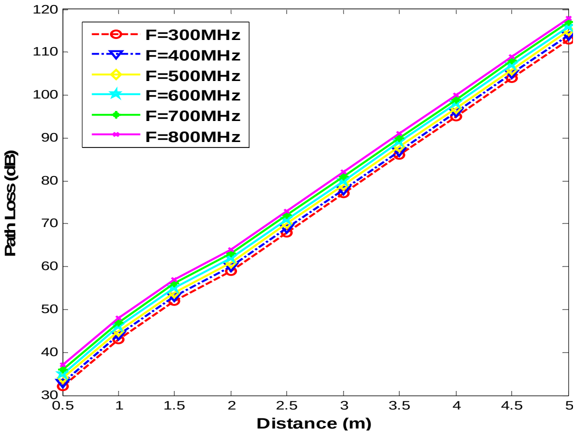


**Fig. 2.** Path loss versus operating frequency and internode distance.

## 2.2. Energy Consumption Model

Energy resources of sensor node are limited. Its energy consumption is related to the life cycle of the network. The classic sensor node energy consumption model is First Order Radio Frequency model which was putted forward by the Heinzelman as shown in Fig. 3 and the energy consumption formula is given in (2).

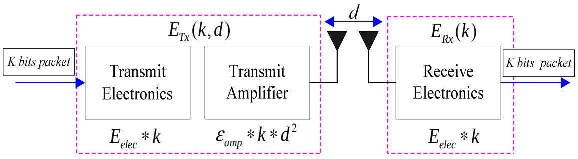


**Fig. 3.** Radio energy dissipation model.

$$\begin{cases} E_{Tx}(k,d)=kE_{elec}+k\varepsilon_{\text{amp}}d^{\gamma} \\ E_{Rx}(k,d)=kE_{elec} \end{cases} \qquad (2)$$

where k is the transmission data quantities, the unit is bits; d is the one hop transmission distance, the unit is meter; γ is the path loss factor, which is 2~4 in air medium. $E_{elec}$ is the circuit RF loss of transmitter and a receiver at work, $E_{elec}$ =50 nJ/bit, $\varepsilon_{amp}$ is the amplifier loss of transmitter, $\varepsilon_{amp}$ =0.0013 pJ/bit/m$^2$. A typical sensor node energy consumption distribution as shown in Fig. 4 [9].

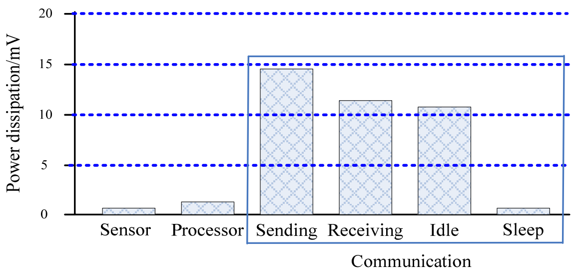


**Fig. 4.** Energy consumption of sensor nodes distribution.

As can be seen from the Fig. 4, communication module is the main energy consumption unit. According to the analysis of the section 2.1, compared to that in air, the energy consumption of sensor nodes that work in the underground soil environment will greatly increase. In addition, the energy consumption of sensor nodes are serious imbalance, which consist of linear WUSN for oil and gas pipelines monitoring. Therefore, the sensor node deployment algorithm should take into account the network energy consumption balance problem and reduce the data throughput and energy consumption of the network.

# 3. Oil and Gas Pipeline Structure and the System Structure

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

## 3.1. Oil and Gas Pipelines Spatial Structure

Oil and gas pipelines are made from steel or plastic tubes with an inner diameter typically ranging from 0.1 to 1.2 m, buried depth ranging from 0.9 to 2 m, fluid flow velocity of near-surface underground pipeline usually ranging from 1 to 6 m/s [2]; Fig. 5 shows the architecture of a standard pipeline with $R_p$ being the radius and L the length of the oil and gas pipeline. We project the 3D pipeline structure into two 2D planes-the XY plane and the XZ plane [8]. In oil and gas pipeline system, sensor nodes can only be deployed on the oil and gas 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.

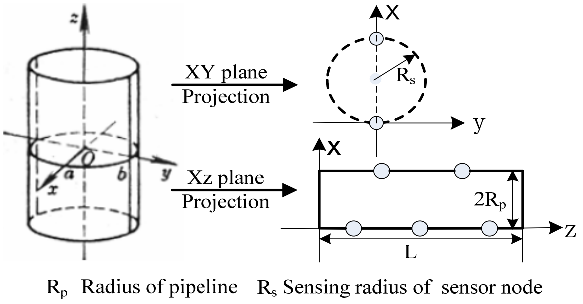


**Fig. 5.** Spatial structure of oil and gas pipeline system.

In the research of sensor nodes deployment algorithm, the optimal deployment of sensor nodes in the XZ plane is firstly determined, then the optimal deployment strategy of sensor nodes in the Z axis direction is determined.

### 3.2. System Architecture

Sensor nodes that deployed in the oil and gas pipeline system is mainly divided into two kinds: one kind is sensor nodes that deployed outside of pipe wall, mainly used to judge the pipeline leakage and detect soil parameters such as soil moisture, soil temperature and hydrocarbon contents. Another kind is sensor nodes that deployed inside of pipe wall, mainly including acoustic detection equipment, pressure sensor, flow sensor and temperature sensor, which used to detect pipeline state and fluid flow information. In order to ensure monitoring performance of oil and gas pipeline system, we use the three layer system structure is shown in Fig. 6 [9].

In the soil layer, sensor nodes (that is outside sensor node) are deployed along the underground oil and gas pipeline surface to realize the seamless full coverage and connectivity for pipeline system. The outside sensor nodes can provide high granularity soil state information near the pipeline system in real time, such as soil temperature, soil moisture content, soil hydrocarbon contents, environmental pollution and weather information. Each outside sensor node has restricted computing and storage capability and limited battery, which cannot be recharged. Therefore, it is important that the outside sensor nodes deployment must be energy-efficient so as to prolong system lifetime.

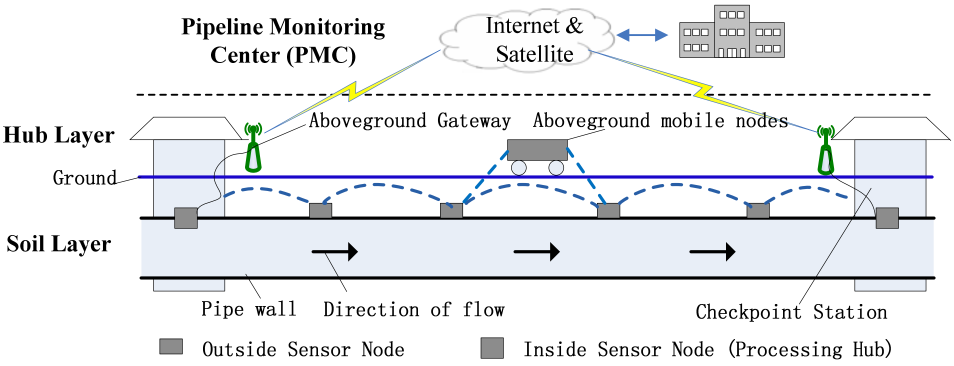


**Fig. 6.** System architecture.

In the hub layer, sensor nodes are installed at initial injection station, compressor or pump station, partial delivery station, checkpoint station, valve station and final delivery station [2], which include the inside sensor nodes and aboveground gateway. The inside sensor nodes are only deployed inside the pipeline at the middle site of pipeline system (such as compressor or pump station, partial delivery station, valve station, checkpoint and other places) to provide low granularity pipeline inside state information, such as pressure, quantity of flow and pipeline leak, which connect with the aboveground sensor nodes directly. Each sensor node in the hub layer has abundant computing and storage resource compared to outside sensor nodes. Furthermore, these nodes can be recharged in time. The main functions of hub layer include analyzing data from outside sensor nodes and uploading the data to pipeline monitoring center (PMC). In addition, the hub layer has configured the aboveground mobile node collection, which can be arranged to move along oil and gas pipelines to collect information from the outside nodes or direct detection the pipeline system information based on the management requirements of oil and gas pipelines.

PMC connects all sensor nodes in the hub layer by Internet or satellite communication. PMC is responsible for forming the overall analysis and issuing the information to managers. The operational procedure includes three steps [10]:

1) In the first step, the inside sensor nodes uninterruptedly measure the flow pressure, fluid temperature and rate of flow in the pipe and send the measurements to the remote PMC day and night. Through the analysis model of the pipeline network based on the measurements, the PMC can identify some suspicious areas where the oil and gas pipelines are possible to have risk.

2) In the second step, PMC activated the outside sensors in the suspicious areas to measure the required soil properties. The measurements are then

sent to the sensor nodes in the hub layer through a multi-hop fashion. In addition, PMC can arrange the aboveground mobile node to the suspicious area to collect further information.

3) In the thirdly step, the sensor nodes in the hub layer uploading oil and gas pipeline monitoring center accord the data collected in further to PMC. PMC make final decisions about the state of oil and gas pipelines.

## 4. Three-dimensional Sensor Nodes Deployment Algorithm

In this section, we analyzed the 3D deployment strategy of sensor nodes and used MATLAB to compare the performance in different conditions.

### 4.1. Analysis of Sensor Nodes 3D Deployment

The wireless underground sensor network for oil and gas pipeline monitoring is linear distribution structure. The topology of the network is determined by the position of sensor nodes in the Z axis direction and the position of the sensor nodes on the XY plane doesn't influence on the connectivity performance of the network. Thereby the coverage efficiency and the effective redundant relations between sensor nodes is the main consideration factor in determining the location of sensor nodes on the XY plane, and connectivity of network is the key factor in determining the location of sensor nodes on the XZ plane. Given $R_p$ the radius of the oil and gas pipeline and $R_s$ the effective sensing range of a sensor node, there can be four possible relationships between $R_p$ and $R_s$: $R_s>=2R_p$, $\sqrt{2}R_p=<R_s<2R_p$, $R_p=<R_s<\sqrt{2}R_p$ and $R_s<R_p$. According to the description of section 3.1, oil and gas pipeline complies with the first case that is $R_s>=2R_p$. The optimal 1-coverage and 1- connectivity is shown in Fig. 7.

In Fig. 7, L is the pipeline length, according to the pie chart; $d_s$ is the distance between adjacent nodes in the direction of Z axis and $N_s$ is the required number of sensor nodes for optimal 1-coverage and 1- connectivity of network. Then the $d_s$ and $N_s$ can be calculated as,

$$d_s = R_s + \sqrt{R_s^2 - 4R_p^2} \tag{3}$$

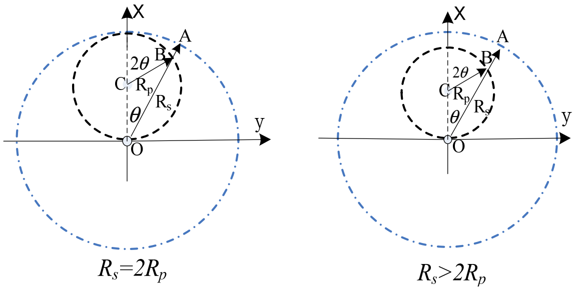
$$N_s = L/(R_s + \sqrt{R_s^2 - 4R_p^2}) + 1 \tag{4}$$

If we need to consider the multiple coverage of sensor nodes [11] (the degree of coverage is marked as $K_f$), the $d_s$ can be developed as,

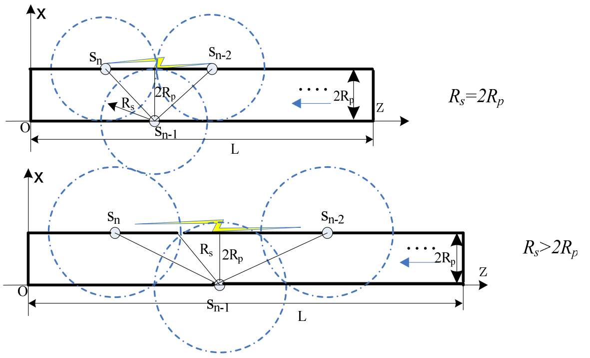
$$d_s = \begin{cases} R_s + \sqrt{R_s^2 - 4R_p^2} & k_f = 1 \\ \sqrt{R_s^2 - 4R_p^2}/(k-1) & k_f > 1 \end{cases} \tag{5}$$

Accordingly, multiple connectivity between sensor nodes (the degree of connectivity is marked as $K_c$), the $N_s$ can be expressed as,

$$N_s = \begin{cases} L/d_s & k_c = 1 \\ L/d_s(k-1) & k_c > 1 \end{cases} \tag{6}$$



a) Optimal deployment of sensor nodes in the XY plane.



b) Optimal deployment of sensor nodes in the XZ plane.

**Fig. 7.** Optimal deployment of sensor nodes.

### 4.2. Network Performance Analysis

### 4.2.1. Network Connectivity Analysis

According to the description of section 2.1 and 3.1, we use the $R_c$=4 meters and $R_p$= 0.5 meters to analyze the network connectivity performance. The expression of 1 m=<$d_s$<=2.125 m can be got under the condition of 1-coverage and 1-connectivity of network based on (3). If the Rs is less than 1.0 m, the pipeline cannot be covered completely. If the Rs is greater than 2.125 m, the network full connectivity cannot be achieved under the condition of 1-coverage, the $d_s$= 4 m will not be able to meet the connectivity of the network. In Fig. 7, the default values are set as follows: the pipeline length (L) is 100 km, soil water content (SWC) is 5 % and buried depth for sensor nodes (H) is 0.5 m. The required number of sensor nodes increased with operating frequency of sensor node increasing and the required number of sensor nodes in soil medium is far greater than the required number of sensor nodes in the air medium.

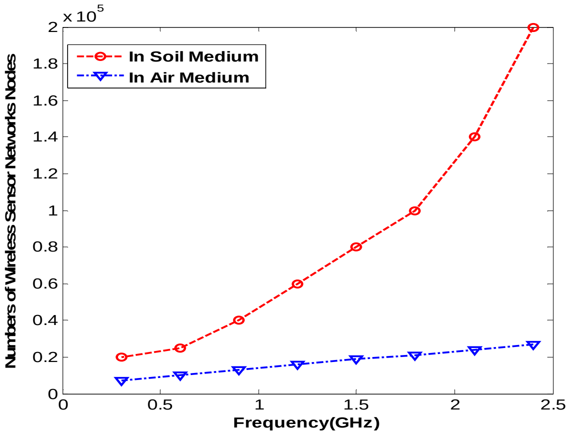


**Fig. 8.** Numbers of sensor nodes versus operating frequency in soil and air (L=100 Km, SWC=5 %, H=0.5 m).

In Fig. 9, the parameters values are set as follows: operating frequency (F) is 433 MHz, the pipeline length (L) is 100 km, soil water content (SWC) range from 0 % to 35 % and buried depth for sensor nodes (H) is 0.5 m. The required number of sensor nodes increased with soil water content increasing.

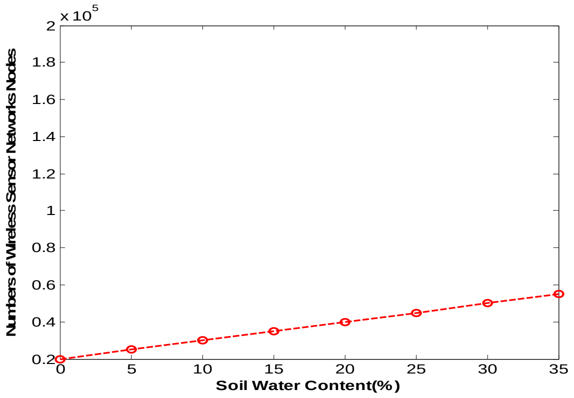


**Fig. 9.** Numbers of nodes versus volumetric water content (L=100 Km, F=433 MHz, H=0.5 m).

### 4.2.2. Network Energy Consumption Analysis

According to the energy consumption model (2), transmission data quantities (k), path attenuation factor (γ) and transmission distance (d) are the key factors that influencing the energy consumption of sensor nodes. The circuit RF loss of transmitter and receiver ($E_{elec}$) and amplifier loss of transmitter ($\varepsilon_{amp}$) is relatively stable. Specifically, parameter k is related to the specific mission requirements and it can be reduced by data fusion technologies and data collecting strategies; parameter d can be optimized with the sensor nodes partition strategies; while parameter γ is easily affected by buried depth of sensor node, operating frequency, soil water content and other factors.

In Fig. 10, the parameters values are set as follows: soil water content is 5 %, soil composition includes 50 % sand, 15 % clay and 35 % salt. Path attenuation factor is shown as a function burial depth for various operating frequency. It can be observed that an optimum burial depth exists such that the path attenuation factor is minimized for a particular operating frequency, and the higher the operating frequency, the smaller the optimal burial depth of sensor nodes.

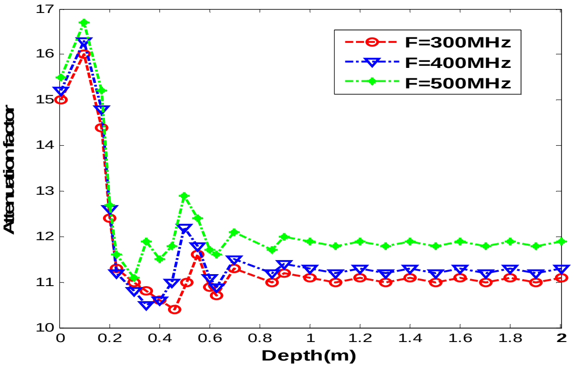


**Fig. 10.** Attenuation factor versus burial depth for different operating frequencies.

### 4.3. Improvement Strategies

At present, wireless communication frequency band of sensor nodes includes 2.4 GHz, 867 MHz and 433 MHz [4]. According to the analysis of section 2.1, 433 MHz is feasible operating frequency in near-surface underground soil environment, but its longest transmission distance is not more than 4 m which can't completely adapt to the actual needs of the long distance oil and gas pipeline monitoring. This is because the oil and gas pipelines laid several hundred kilometers to more than 1,000 kilometers, which need a huge number of sensor nodes to achieve coverage and connectivity performance of network. It is obvious that the sensor network deployment cost and management cost will greatly increase and seriously degrade stability and reliability of network. Therefore, in order to guarantee the performance of network and reduce costs, the single hop transmission distance ($R_c$) of sensor nodes need to be further extended. Our improvement strategies are described below.

#### 4.3.1. Using the Kinetic Energy of Oil and Gas Flow in Pipelines to Recharge Sensor Nodes

Improving the transmission power of sensor node ($P_t$) can effectively extend the transmission distance ($R_c$). But the underground sensor nodes are powered by battery and its energy is extreme limited. Compared to that in air, the energy consumption is much more. Furthermore, the underground environment also not suitable for installing solar energy charging devices compared to the aboveground environment.

According to the specific application environment of underground oil and gas pipeline (as shown in figure 6), we designed a new type of sensor nodes, which is particularly suitable for underground oil and gas pipeline monitoring, and the sensor node uses the kinetic energy of oil and gas flow in pipelines to recharge. The structure diagram of the sensor node shown in Fig. 11.

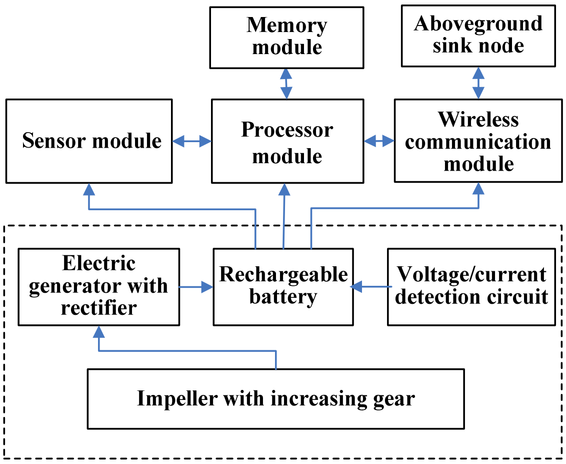


**Fig. 11.** Structure diagram of sensor node that use the kinetic energy of the fluid in pipelines to charge.

In Fig. 11, the impeller was firstly drove by kinetic energy of oil and gas flow in the oil and gas pipelines, and then the impeller drove the electric generator to charge the rechargeable batteries. In this way, the energy supply of sensor nodes can be guaranteed, which will effectively prolong the network life cycle. At the same time, this technique also lay a good foundation for improving the transmission power of sensor nodes, extending the single hop transmission distance of the sensor nodes and promoting the connectivity of network.

### 4.3.2. Partition Strategy for Energy Consumption Balance Based on the Wireless Communication Technology of Magnetic Induction Waveguide

The WUSN for oil and gas pipeline monitoring is typical linear topology. In this linear network topology, the vast majority of sensor nodes cannot directly communicate with the gathering node (such as the inside sensor nodes and aboveground mobile nodes in the hub layer), which leads the energy consumption of sensor nodes near the gathering nodes to be consumed quickly and then soon to "death". The "death" of sensor nodes is fatal for the whole network because the data of other sensor nodes can't be sent to the gathering nodes by means of the relay way. Therefore, in the uniform node deployment cases, partition strategy is very necessary to introduce to ensure network coverage and improve network lifetime.

According to the analysis of section 2.1, the longest transmission distance of sensor node is not more than 4 m and the dynamic change of channel conditions in soil is severe, which isn't adopt to the partition strategy for long distance oil and gas pipeline monitoring. The magnetic induction (MI) and MI waveguide techniques were developed to solve the problems in EM wave-based techniques and provide more favorable advantages for WSN in soil: the communication range is greatly enlarged to 100 m and the MI channel conditions remain constant in soil since the attenuation rate of magnetic fields does not change in non-magnetic media [12], which fully meet the needs of the partition strategy. MI waveguide communication channel model as shown in Fig. 12.

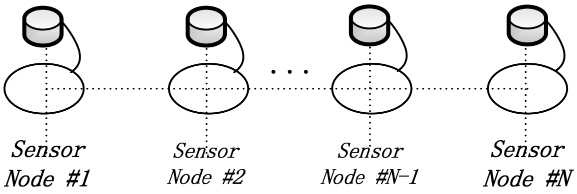


**Fig. 12.** MI waveguide communication channel model.

In Fig. 12, each sensor node was equipped with a magnetic induction coil, which does not consume extra energy and unit cost is negletable. And the coil is easy to deploy on the surface of pipeline and does not need regular maintenance because coil does not deviate from the ideal positions due to the pipeline structure.

Partition strategy shown in Fig. 13, which is ensuring that energy consumption of network is balanced. The monitoring area (that is oil and gas pipeline) is divided into M subareas marked as $A_1$, $A_2$,..., $A_M$, respectively. The length of each subarea on the Z axis is $L_1$, $L_2$,...$L_M$. The average communication distance (marked as $d_i$) of adjacent partitions of $A_i$ and $A_{i+1}$ is $d_i=(L_i+L_{i+1})/2$ on the direction of Z axis

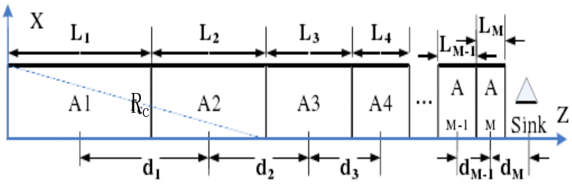


**Fig. 13.** Partition strategy for energy consumption balance.

Supposing that events to be tested in the monitoring area will occur with the probability of uniform distribution within unit time, and the amount of data collection of each sensor node is k. the energy dissipations (marked as $E_i$) of the sensor node i (marked as $S_i$) include the energy consumption of receiving the data from the $S_{i-1}$, the energy consumption of forwarding the data from the $S_{i-1}$ and the energy consumption of sending the data of the $S_i$ within unit time, the computational formula can be developed as (7) based on (2).

$$E_i = \left( E_{elec} \times N \times k \times \frac{\sum_{j=1}^{i-1} L_j}{L} \right) + \left( E_{elec} \times N \times k \times \frac{\sum_{j=1}^{i} L_j}{L} + \varepsilon_{amp} \times N \times k \times \frac{\sum_{j=1}^{i} L_j}{L} (d_i^{\gamma}) \right) \quad (7)$$

In (7), N is the total number of outside sensor nodes deployed in pipeline system. Furthermore, we can have $E_i = E_{i+1}$ because the energy consumption of each subarea ($A_i$) need to be balanced to prolong the network lifetime. Then the (7) can be expressed as,

$$L_{i+2} = 2 \times \left( \frac{\sum_{j=1}^{i} L_j \times (\frac{L_i + L_{i+1}}{2})^{\gamma} - \frac{E_{elec} \times (L_i + L_{i+1})}{\varepsilon_{amp}}}{\sum_{j=1}^{i+1} L_j} \right)^{\frac{1}{\gamma}} - L_{i+1} \quad (8)$$

In the (8), the value of L1 should be as large as possible to ensure that time delay of network is as little as possible, and $L_i > L_{i+1}$. In order to ensure that subarea within the scope of the effective communication of sensor node, there is $L_1 + L_2 <= R_c$. and then we can get the length of each subarea ($L_i$).

After partition, the lifetime of every subarea is the same, so the lifetime of the partition $A_1$ is network lifetime. Assume that the initial energy of each sensor node is e and the total energy of entire network is e×N. Since the sensor node is uniform deployment, therefore, the total energy of subarea $A_1$ is in the $E_{A1} = e \times N \times L_1 / L$, the network life span can be calculated as,

$$T = \frac{E_{A1}}{E_i} = \frac{e}{k \times \left( E_{elec} + \varepsilon_{amp} \times ((L_1 + L_2)/2)^{\gamma} \right)} \quad (9)$$

## 5. Conclusions

In this work, we carefully analyzed the wireless channel characteristics of near-surface underground soil environment, spatial structure of oil and gas pipelines and three layer architecture of WUSN, and presented a three-dimensional sensing deployment model. In order to further improve the sensor nodes one hop communication distance, enhance the energy consumption of the network performance, we put forward the energy strategy of using the kinetic energy of oil and gas flow in pipelines to recharge sensor nodes and partition strategy for energy consumption balance based on magnetic induction waveguide technology. The analysis results show that these strategies can effectively increase connectivity and energy performance of network. In future, we plan to further investigate the cognitive radio technology and link quality detection algorithm [13] to enhance adaptive performance of network.

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## References

[1]. I. F. Akyildiz and E. P. Stuntebeek, Wireless underground sensor networks: research challenges, *Ad Hoc Networks*, Vol. 4, 2006, pp. 669-686.

[2]. Y. Wikipedia, Pipeline transport, (http://en.wikipedia.org/wiki/Oil_pipeline#For_oil_or_natural_gas, 2014, 2).

[3]. H. P. Yu and M. Guo, An efficient oil and gas pipeline monitoring systems based on wireless sensor networks, in *Proceedings of the Information Security and Intelligent Control*, Taiwan, China, 11-13 August 2012, pp. 188-193.

[4]. M. C. Vuran and I. F. Akyildiz, Channel model and analysis for wireless underground sensor networks in soil medium, *Physical Communication*, Vol. 3, 2010, pp. 245-254.

[5]. L. Li and Y. A. Liu, Sensor deployment algorithm for wireless underground sensor network, *Journal of Jilin University (Information Science Edition)*, Vol. 25, Issue 6, 2007, pp. 15-20.

[6]. Q. Z. Zhang, Research on some theory and technology of sensor networks using in soil environment monitoring, *Zhejiang University (Hangzhou)*, 2009.

[7]. K. Wang, Research on key technologies of mine wireless sensor networks node deployment, *China University of Mining and Technology (Xuzhou),* 2011.

[8]. H. P. Yu and M. Guo, The research of three-dimensional node deployment of wireless sensor network for pipeline systems, *CAAI Transactions on Intelligent Systems*, Vol. 8, Issue 4, 2013, pp. 333-338.

[9]. H. P. Yu, C. X. Wu and M. Guo, Energy efficiency analysis for mobile wireless sensor network, *Computer Engineering*, Vol. 35, Issue 14, 2009, pp. 127-129.

[10]. Z. Sun, P. Wang, M. C. Vuran, M. A. Al-Rodhaan, A. M. Al-Dhelaan and I. F. Akyildiz, MISE-PIPE: Magnetic induction-based wireless sensor networks for underground pipeline monitoring, *Ad Hoc Networks*, Vol. 9, 2011, pp. 218-227.

[11]. M. Liu, J. N. Cao, Y. Zheng, L. J. Chen and L. Xie, Analysis for multi-coverage problem in wireless sensor networks, *Journal of Software*, Vol. 18, Issue 1, 2007, pp. 127-136.

[12]. Z. Sun and I. F. Akyildiz, Magnetic induction communications for wireless underground sensor networks, *IEEE Transactions on Antenna and Propagation*, Vol. 58, Issue 7, 2010, pp. 2426-2435.

[13]. L. Li, Study of some key techniques in wireless underground sensor networks, *University of Posts and Telecommunications (Beijing)*, 2008.

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