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Method to deploy wireless relays in industrial wireless monitoring①

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Abstract

In light of demands for wireless monitoring and the characteristics of wireless channel, a complete deployment method containing channel survey, path loss estimation, and gradient grade of wireless relay nodes is proposed. It can be proved by experiments that under the premise of meeting the requirements of real-time and redundant-topology, the total number of relay nodes could be minimized by using the proposed method.

Key words: industrial wireless monitoring, relay node deployment, site survey, path loss factor, greedy randomized adaptive search procedure

0 Introduction

Deploying wireless relays is a process which we must solve when designing a wireless monitoring system for a chemical plant[1]. A good deployment can optimize sensor network topology, reduce the cost of construction and operation, meet the requirements of node calculation, communication and fault tolerant processing.

The advantages of a wireless monitoring network makes industrial wireless relay node deployment the focus of recent research. Deployment methods based on minimum spanning tree (MST) was proposed by Pettie and Ramachandran at the University of Texas-Austin[2]. A deployment method based on Delaunay triangle was proposed by Li and Hou at the Illinois State University[3]. Another deployment method based on connectivity matrix (CM) was proposed by Vairamuthu and Nesamony at the University of Queensland[4]. These algorithms can achieve full connectivity of the whole mesh using minimum number of relay nodes. However, these methods can not meet the requirements of real-time and reliability of industrial wireless monitoring due to neglecting capacity of wireless channels in an industrial environment and the effects of redundant nodes[5].

In this work, several methods of wireless relays deployment in an industrial environment are analyzed and a completely new method to deploy wireless relays for industrial wireless monitoring is proposed. In the proposed method, grid division of the entire region is done first to reduce the complexity of deployment. Then, path loss factors can be calculated by using site survey and conservative estimation. Based on path loss factors, wireless relays deployment can be processed hierarchically by using the Greedy Algorithm. In each step of deployment, a new Greedy restrictive adaptive search procedure is proposed to deploy a number of relay nodes by comparing the proposed proposal method with several other methods proposed in the literature and the results show that the proposed method can minimize the total number of relay nodes and meet the requirements of real-time and redundant topology in industrial wireless monitoring at the same time.

1 Wireless channel measurement in an industrial environment

The wireless channel measurement is mainly used to get the maximum path loss of each wireless link within the frequency band of 2.4GHz which is provided by a physical layer of IEEE 802.15.4[6]. For this purpose, a concept of grid loss factor is defined and the whole region is divided first by a number of grids. Then, path loss factors in different directions of each square are measured and the maximum value of path loss factor in each square is considered as the grid loss factor.

2 Conservative estimation of grid loss factor

Many experiments show that the wireless channel loss model in an industrial environment is a superposition model including: loss model in free space, shadow

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fading and frequency-selective fading[7-11]. The expression of this model is generally too complex to estimate its parameters. In order to solve this problem, a conservative method is proposed to estimate grid loss factor.

According to Central Limit Theorems, assuming a set of random variables $X_1, X_2, \cdots X_n, \cdots$, which is independent and identical distribution. And $E(X_k) = \mu$, $D(X_k) = \sigma^2 \neq 0, k = 1, 2, \cdots$ Then, random variable $Y = \sum_{k=1}^{n} X_k$ obeys the law of normal distribution $N(\mu, \sigma)$.

According to the above analysis, if the sum of a group of grid loss factors is considered as a sample, it obeys the law of normal distribution. Using the parameter estimation, the analytical expression of this normal distribution can be derived. Then, a grid loss factor can be calculated as upper bound estimation n_{max} according to a certain probability. Using this upper bound estimation n_{max}, the complex wireless fading channel model in an industrial environment can be transformed into wireless channel loss model in free space:

$$\Pr(d) = Pt \times d^{-n_{max}} \quad (1)$$

where Pt is the transmitting power of the wireless transmitting node, $\Pr(d)$ is the receiving power of the wireless receiving nodes and d is the distance between two nodes.

3 Wireless relay node deploying algorithm

3.1 Optimum gradient division

Wireless channel capacity can be determined by the following formula by Shannon:

$$C = B\log_2\left(1 + \frac{P}{n_0 \times B}\right) \quad (2)$$

where B stands for channel bandwidth, n_0 stands for the power spectral density of white noise and P stands for the receiving power of wireless receiving nodes. It is assumed that the transmission power is 3dbm, the communication distance is 100m, the bandwidth of each band is fixed for 5MHz and the gauss white noise power is −90dbm. According to Eqs(1) and (2), the relationship model of transmission time, transmission hops and path loss can be shown in Fig. 1.

Fig. 1 shows that, for two nodes of certain distance, there is an optimal number of hops that makes the shortest transmission time. The optimal number of hops can be identified as the node's gradient.

3.2 Greedy hierarchical deployment

The whole node of the wireless monitoring network

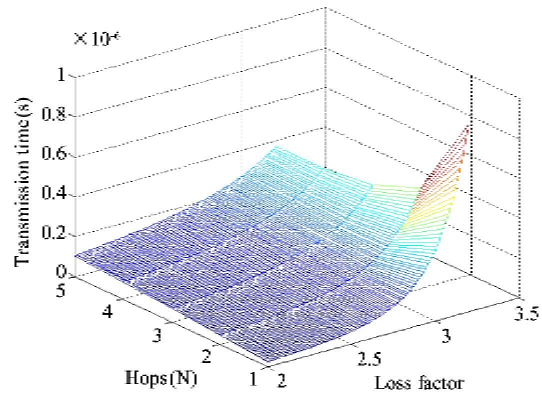

Fig. 1 the relationship model of transmission time, transmission hops and path loss

is divided into three categories: (1) $D\_node = [D_1, D_2, \cdots, D_n]$ stands for the data source of node; (2) $R\_node = [R_1, R_2, \cdots, R_n]$ stands for wireless relay node; (3) $S\_node = [S]$ stands for sink node. The problem of wireless relays can be described as: For any node in the network, it requires K wireless relays and the number of the whole network relays has to be minimized. Supposing $P^m_{(x,y)}$ stands for each grid intersection of the whole deployment area, where in (x, y) stands for coordinates and m stands for gradient. If a wireless relay is deployed at a grid intersection (x, y), then $P^m_{(x,y)} = 1$; if not, $P^m_{(x,y)} = 0$. Supposing the number of candidates of wireless relay of each D_n and R_n is $N^m_{(x,y)}$, then the deployment problem can be transformed to this 0 − 1 programming problem:

$$\min Z = \sum_{x=10}^{200}\sum_{y=10}^{200} P^m_{(x,y)} \quad (3)$$

$$\text{s. t.} \begin{cases} N^m_{(x,y)} \geq K, \; m \geq 2 \\ P^m_{(x,y)} = 0 \;\text{ or }\; 1 \end{cases} \quad (4)$$

Assuming the collection of D_n and R_n nodes after deploying is Φ and the maximal gradient of Φ is n. The process of Greedy hierarchical deployment is: First, Φ is divided into different gradient subsets $\Phi = [\Phi_1, \Phi_2, \cdots, \Phi_n]$ and each node of Φ is classified into different subsets according to its gradient. All R_node of which gradient is less than n is selected as candidates. With some heuristic algorithm, a set of next hop relays for all nodes in Φ_n could be deployed and the number of the set could be made minimal. Then, all next hop relays can be classified into different subsets of Φ according to its gradient. Based on the above process, next hop relays for each Φ_n are deployed, until $n = 1$. The flow chart of the proposed Greedy algorithm is shown in Fig. 2.

In addition to the proposed Greedy algorithm, a Greedy restrictive adaptive search procedure (GrASP) is proposed in light of the next hop relays.

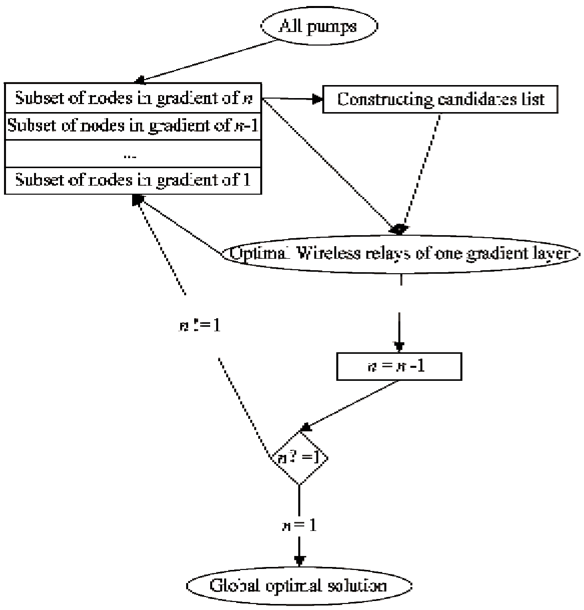

Fig. 2 The flow chart of the proposed greedy algorithm

The algorithm consists of three sub parts:

1) Judgement of connectivity

Supposing d_{total} stands for the distance, n_{total} stands for the path attenuation factor between two nodes, then, Wireless channel capacity C can be obtained by

$$C = B\log_2(1 + \frac{Pt \times d_{total}^{-n_{total}}}{n_0 \times B}) \qquad (5)$$

If rated transmission rate of wireless communication module is R and $C \geqslant R$, both nodes are judged to be connected.

2) Connectivity matrix

Connectivity matrix stands for the connected relation between Φ_n and *R _ node*. Supposing each node in Φ_n is indicated by *Pump _ k* and each node in *R _ node* is indicated by Relay _ k, then the whole connectivity matrix can be shown in Table 1.

Table 1 Connectivity matrix

	Relay _ 1	Relay _ 2	…	Relay _ k
Pump _ 1	0	1	…	1
Pump _ 2	1	0	…	0
…	…	…	…	…
Pump _ k	1	0	…	0

If two nodes can be connected, the corresponding position in the connectivity matrix is set 1, otherwise zero.

3) Optimization process

The whole optimization process includes two sub-processes named "initial feasible solution construction" and "restrictive local searching".

In the subprocess of initial feasible solution construction, there are mainly two improvements:

A) a Full Connectivity List (FCL) is constructed before we construct a restricted Candidate List (RCL). Supposing the need of redundancy is K and the number of wireless relays in FCL is N. If $N \geqslant K$, then the construction of an initial feasible solution can be skipped.

B) Along with more and more candidate relay nodes added into initial feasible solution, when the number of Relay _ k nodes which corresponds to some Pump _ k reaches to K, the row of Pump _ k in connectivity matrix needs to be eliminated and each greedy value needs to be recalculated, as shown in Fig. 3. In this way, Grasp algorithm has adaptive characteristics and can be adaptive to the changing of the problem scale.

Fig. 3 Modification of connectivity matrix

In the sub-process of restrictive local searching, if one node of Φ_n has a sufficient number of next hop relays, it will not participate in updating the Greedy function, there does not exist any redundant relay node in the initial feasible solution constructed by GrASP. However, any node which is going to be added into the initial feasible solution has greater relationship with the nodes which have been added into it, the feasibility of the initial feasible solution could be destroyed by arbitrary exchange. Thus the connectivity of the nodes in the range of local searching needs to be the same as the node in the initial feasible solution. The flow chart of GrASP is shown in Fig. 4:

4 Instance of deployment

To verify the advantage of this method, deployment process of wireless relays in the wireless monitoring system of pump groups in CNPC Liaoyang petrochemical 1400000 tons of reforming unit is selected as an example. Each wireless node in this wireless monitoring system needs at least 3 next hop relays to forward its data. The position relations of pumps and wireless relays are shown in Fig. 5.

4.1 Number of relay nodes

For this problem, number of relay nodes calculated by minimum spanning tree (MST), delaunay triangle (DT) and connectivity matrix (CM) are shown in

Table 2.

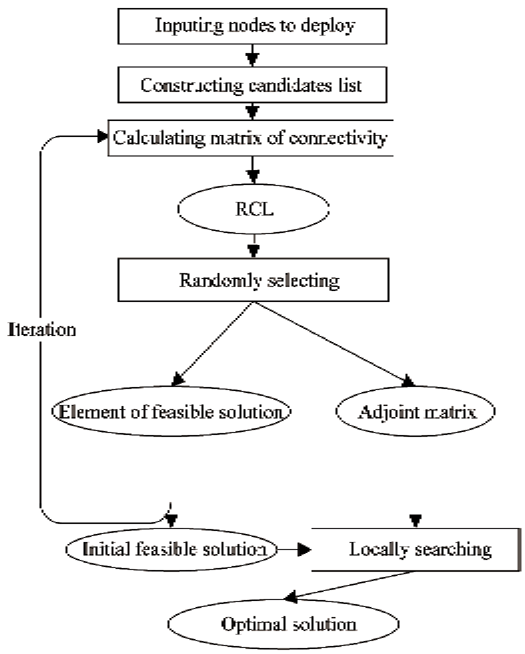

Fig. 4 The flow chart of GrASP

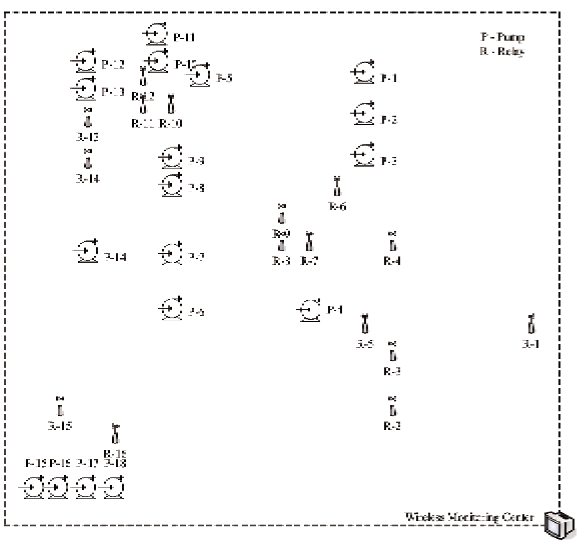

Fig. 5 The position relations of pumps and wireless relays

Table 2 Comparison of relay nodes number

Methods	number of relay nodes (N)
Minimum spanning tree (MST)	21
Delaunay triangle (DT)	22
Connectivity matrix (CM)	23
The proposed method	16

From the table we can see that, comparing with other methods, the proposed method can reduce the number of relay nodes to 30% ~ 40%, so that the proposed method is economical.

4.2 Deploying time analysis

Heuristic algorithms have extensive applications in solving large-scale complex optimization problems[12-15]. Classical heuristics are often based on intuition and experience, such as genetic algorithm and ant colony algorithm.

GrASP is compared with Ant colony algorithm, Genetic algorithm and GRASP in this paper. Simulation environment is shown in Table 3. Considering the deployment process of the node in 6 gradient as an example, the convergence process are shown in Fig. 6.

Table 3 Conditions of simulation system

CPU	Intel Pentium 2.6
EMS memory	2G
Computer model	IBM X60
Operating system	Windows XP
Simulation software	MATLAB 2010b

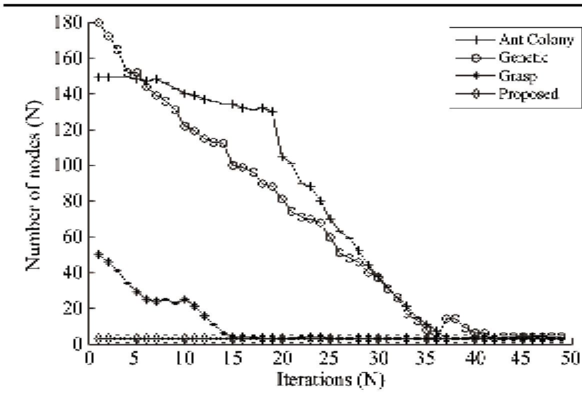

Fig. 6 the convergence process of deployment process of the node in 6 gradient

From Fig. 5, it can be found that, the iteration times of GrASP is significantly less than other methods. This is mainly because of significant improvements in the two sub-processes of initial feasible solution construction and restrictive local searching. Ant colony algorithm and Genetic algorithm construct the initial feasible solution in a complete random way which makes the range of Local search much larger. In contrast, the initial feasible solution constructed by Greedy algorithm makes the initial feasible solution close to optimal solution so that the times of iteration are greatly reduced. In the sub-process of local searching, the randomness of local searching can be greatly reduced by FCL. From Fig. 5, it can be found that, because the number of wireless relays in FCL is 3, the initial feasible solution is the optimal solution, without local searching.

4.3 Channel capacity of wireless link after deployment

As is known to all, as long as the wireless channel capacity is less than transmission rate, serious Packet loss is caused. Considering this situation, packet loss rate is used to compare wireless channel capacity with transmission rate. Considering the limitations of wireless measurement conditions, changes of lost packets within 24h are generally selected as approximate reference.

In order to verify the advantage of the proposed method in the security of transmission rate, the following experiment is designed: deploying wireless relays by using MST, Del, CM and the proposed method, and the average packet loss rates are compared. The results are shown in Fig. 7.

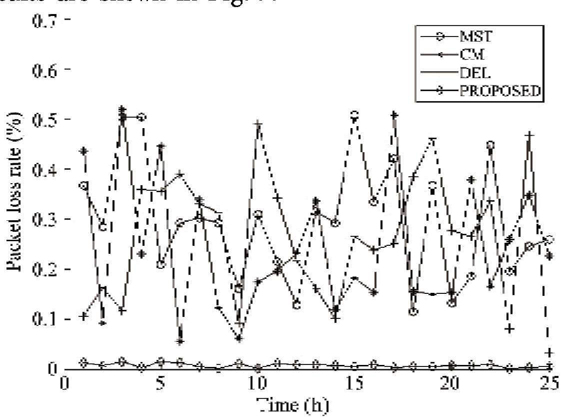

Fig. 7 the average packet loss rates of different deploying methods

It can be found from Fig. 7, that throughout the 24h testing process, strong fluctuations of packet loss rate are presented with the time-variant characteristics of wireless channel in an industrial environment. Real-time is not considered in other three methods, thus, average packet loss rates of these methods are similar. The average packet loss rate in the proposed method is under 2% throughout the 24h testing process, that accounts for the truth that the transmission rate can be met by the proposed deployment method.

5 Conclusion

A method of wireless relays deployment is proposed in this paper which includes the following steps: (1) Path loss factor of each grid can be reasonably estimated counting on the industrial wireless environment. (2) By taking path loss factor into the model of the wireless channel, the connectivity between any two points can be evaluated. (3) Using GrASP, wireless relays are deployed step by step. There are mainly two advantages of this proposed method: (1) The requirements of real-time and reliability are met effectively. (2) Site survey and calculation of deployment are both fairly simple. To sum up, the proposed methods are quite fit for the construction of an industrial wireless monitoring system.

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