

Optimization Scheme of Forming Linear WSN for Safety Monitoring in Railway Transportation

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Abstract: With the development of wireless sensing network, more and more applications have been deployed in the safety monitoring and in natural disasters prevention. The safety and disaster prevention systems have usually been laid out in linear network architecture, such as those of railway, motorway transportation and pipes. The background of the article is railway hazard goods transportation safety surveillance. The paper discusses about the network architecture of linear wireless sensor networks with multiple sink nodes, and proposes the grouping method of sink nodes and the formation scheme of networks. The scheme can re-establish a monitoring network when the train on the way is disconnected and re-grouped. The switching algorithm of group head nodes is put forward, so that the energy consumption of each node in the group is even. The optimal switching parameters for group head nodes are suggested by the simulation. Compared with the usual monitoring network, the method proposed enables the system life expectancy to prolong more than five times, and meets the monitoring requirements simultaneously.

Keywords: Wireless Sensor Network (WSN), linear network, strategy of forming the network, energy balance algorithms.

1 Introduction

The wireless sensor network has been more and more widely used in safety and disaster prevention area, because of its sensing capability in physical world, the adaptive capability and its flexibility in terms of deployment. In many sensor network applications, the energy consumption has become a limitation of long working hours of the system when performing the tasks like monitoring and data transmission, without outside electricity supply in the system. This is especially the case for the sink node working as gateway; the gateway not only needs to receive data from monitoring nodes but also needs to send data to the monitoring center through the internet [1]- [2]. These nodes have to consume a large amount of energy either in sending the data through the wireless mobile network or the satellite network. Because those nodes are essential for the whole network system, it has special significance to optimize the work of those nodes and to minimize their energy consumption [3].

It has been a major research topic to longer the lifetime of the wireless sensor networks and to lower the energy consumption whether from the aspect of sensing the physical world, the scheme of forming the network and data processing [4]. Because of the limitation imposed by the energy consumption, the computation resource and the storing capability and transmission capability are also limited. For the same reason, the gateways' storing and transmission capability are also limited. In today's researches of wireless sensor networks with multiple sink nodes, the

sensor network's coverage is usually a plane, which means the sensor nodes are located in a plane area [5]. Hence, most research interests are focused on the placement of sensor nodes, topology of the sensor networks and transmission strategies [6]- [7]. Hoping by placement of sink node in a reasonable way, the power consumption of the system will be lowered, the lifetime of the network will be increased. Those researches usually share an assumption that the sink node itself is a rich power node, hence the energy minimization and optimization of important sink node is less researched [8]. In many practical applications, sink node is usually the bottleneck of increasing the lifetime of the whole system. In some situation, when multiple sink nodes are presented in the system, the data exchange between sink nodes is also possible [9]- [10]. For instance, in the safety monitoring of railway goods transportation, the topology of sensor network is linear, the network in each section of the train send data to the sink node. The sink node of each section has the potential of exchange data. Other than that, same structure can also be seen in the monitoring system of fallen rocks on the sides of highway and railway slopes [11]- [12].

2 Raise of the question

The hazard goods safety monitoring system based on wireless sensor network is shown in figure 1. The sensor nodes located in each section monitor the status of hazard goods, and send the data to the sink node through the sensor network. The sink node acts as gateway, as a result, it is called gateway node. On one hand, the gateway node manages the sensor network in the car, and collects the monitoring data. On the other hand, it sends the merged data to the ground control center through the mobile network. To realize the monitoring of hazard goods in the entire transporting process, the system requires the gateway nodes to send data constantly to the ground control center through mobile network or satellite network, so that a large amount of energy in those nodes is consumed. The wireless sensor networks work in the harsh environment and usually a long time. And each node has only one battery as its power supply. Hence, how to reduce the energy consumption of gateway nodes and longer their lifetime are vital to realize whole time the hazard goods transporting monitoring. Fig. 1 shows the situation described above.

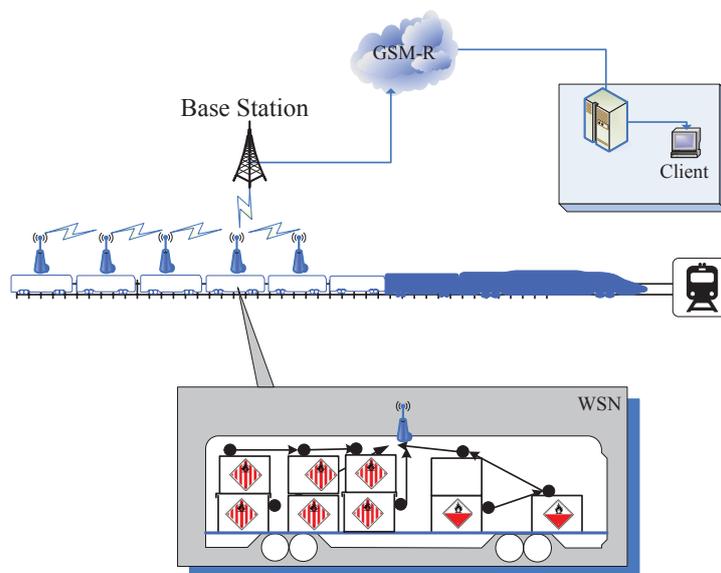


Figure 1: Hazard goods safety-monitoring system in railway transportation

In the situation showed in Fig. 1, if the gateway nodes send the data to the ground through mobile network or satellite network, it can guarantee that the information of each section of the train will be send to the ground timely. But it can easily cause the gateway nodes stop working by exhausting the power. Take GPRS (general packet radio service) as a way of sending the information, for instance, before gateway nodes send the data, they need to perform a series of test of parameters. It includes: signal strength of BCCH (Broadcast Control CHannel) or PDCH (Packet Data CHannel) received by the node, the variance of signal strength of downlink PDCH received signal, downlink PDCH signal strength, downlink PDCH signal interference and so on. On one hand, when sending the data, it takes a large amount of energy when establishing the connection and sending the data. On the other hand, it also takes a large amount of energy to measure the incoming and outgoing of message. Because the monitoring data is usually a small amount, comparing with pure data transmission, establishing connection and measuring process take a large proportion in the energy consumption. As a result, if multiple sink node can be grouped together and form a high network, only one node takes a task of sending data in a certain period of time. This will reduce multiply sink node GPRS measuring signal's sending and receiving; hence the total amount of energy consumption will be reduced. Besides this, because of the disconnection and regrouping of the train, the original network structure will be altered. As a result, it requires reforming the monitoring network with minimum energy consumption and satisfies the monitoring requirement.

This article focuses on the above situation, suggests the scheme of forming the linear wireless sensor network with sink node of each section of the train and the energy balance algorithm, so that those sink nodes energy can be shared to achieve lower energy consumption and longer the system lifetime. At the mean time, the scheme suggested can support the disconnection and regrouping of the train in the trip and reforming the monitoring network according to the regrouping of the train.

3 Reforming the network strategy

The normal trains car has length between 10 meter and 20 meter. The basic idea of forming the network can be seen as follows: connecting sink node in each car with the sink node in neighbor car/cars, so as to form new networks, and the monitoring data are sent to one of the sink nodes. Through that sink node, the data will be sending to the ground by mobile network. By applying reasonable method to balance the energy consumption, the lifetime of the network can be extended. For linear structure wireless sensor networks, it is very common that the multi-hop method is used to realize the monitoring data gathering. However, normal hazard transportation train contains more then ten cars, or even the cars of whole train. Due to the electrical and magnetic interference, if multi-hop method is applied to the whole train, the interference can easily affect the transmission, and causing high hop count and too much data stored on one node, in term causing the data package lost or over time. As a result, grouping cars so that hop count can be reduced, hence better transmission efficiency. Now we assume:

- 1) Each car has a sink node which is uniquely numbered, the node number is a value;
- 2) Each car has a sink node with same initial energy;
- 3) All sink node has the same distance with its neighboring sink node.

We take N_s as the sink node number; N_g as sink node number in each group, hence the group number: $N = N_s/N_g$, where N_g can be decided using the following method:

We assume the channel error as e_c , average data length as $D_L(\text{bit})$, sending data from arbitrary node to sink node has a successful rate no smaller than r_d , we can easily derive that the maximum hop count h_{MAX} :

$$h_{MAX} = \frac{\lg r_d}{\lg(1 - D_L e_c)} \quad (1)$$

Under the worst case, sink node as the border node of the group, and the node on the other side of the group takes $N_g - 1$ hop to reach sink node. Hence node number in each group N_g should be:

$$N_g \leq h_{MAX} + 1 \quad (2)$$

Grouping algorithm:

Idea of grouping algorithm: first decide two border nodes. Then take the both border nodes as starts respectively. Group every N_g node from the starts towards the middle nodes. The process is shown in Fig 2.

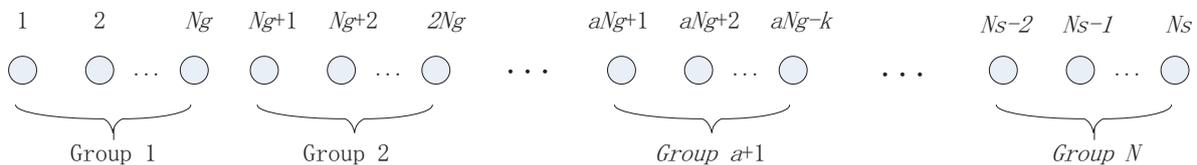


Figure 2: Nodes grouping

The detailed steps are as follows:

(1) Confirmation of the border node

- 1) After each node switched on and activated, a detection package is send with minimum power. At the meantime, the node listens to the neighboring node for response. If there are no responses, then increase the sending power by one level and send the detection package again. If response is received, goes to next step. If there is still no response even with maximum sending power, then end the process. It shows that two ends of the node have no monitored car, the node works alone.
- 2) Send the response package at once, when receive the detection package.
- 3) If two response packages are received, then the node is not a border node, and the node goes into idle.
- 4) If the node only receives one response package, it shows that this node is a border node.

(2) Algorithm of forming the network:

The grouping of the nodes starts from the border node. After the border nodes have confirmed their positions, it goes into forming network phase of the algorithm. In this phase, each node sends the message with small power so that it only covers the neighboring nodes (the power is determined by previous step). The detailed steps are as follows:

- 1) The border node send invitation package to neighboring node. The invitation package includes: group number (using the node number), member number (initialize to be 1) and so on;

- 2) When the node receives the invitation package, it firstly decides if itself has been given group number. If so goes to step 4. Otherwise, increase the member number by 1, and set the group number to be received group number, and check if the member number is N_g . If the member is less than N_g then send invitation package with member number increase by 1. If the member number is bigger or equal to N_g then send the regroup package to the new neighboring node, and send confirmation package to its own group nodes.
- 3) When the regrouping package is received, the node checks itself if the group number is given yet. If the group number is given then no response is needed. The forming network is ended. Otherwise, the node creates a new invitation package. Within the invitation package, the nodes number serves as the new group number, the member number is 1. And then send invitation package to neighboring nodes.
- 4) When the node whose group number has been decided receives the invitation package, if the group number in the invitation package is the same with the nodes group number, then no response is needed. Otherwise, compare the sum of member number of the group and the member number of the invitation package, if the sum is less than N_g , then compare the group number. If the group number is smaller, then send invitation packages to node of the same group. Otherwise, replace the group number with new group number and send altered invitation package. If the sum of member number of the group and the member number in the invitation package is equal or larger than N_g , then responds with reject package, and send confirmation package to nodes of own group.
- 5) When invitation sender receives reject package, send confirmation package to own group and end the forming network.

Performing grouping based on the algorithm may create at most 2 groups with member number less than N_g . Each group works independently and that won't affect the whole system.

After the grouping process, each group needs to choose its own group head which transmits monitored signal to the surveillance center through mobile network. In the grouping process, the information of remaining energy of each node is exchanged. Hence, the node with maximum remaining energy can be picked as head. When more than one node has the maximum energy, the node closest to the middle will be picked as head.

The sink node of each car will send data to the group head through several hops while fulfilling the monitoring requirement. Group head will merge all the monitoring data and then send it to the ground surveillance center through mobile network. During the transportation, the train might go through multiple splitting and regrouping. If the car in same group is separated, and the head node has not received information from certain node sometimes, it assume those node has leave the group and the rest of the nodes will reform the network. On the other hand, if some node cannot send information to the group head, those nodes will reform the network according to the above method. In this process, due to the uniqueness of the node number, those group numbers will not be duplicated. The separated group will form two new group and two new group head.

4 Energy balance scheme

After grouping using the above algorithm, the head node needs to handle the transmitting information to the ground surveillance center through the mobile network and it has large energy consumption. Hence, a scheme is necessary so that the group head will be performed in turns

by certain rules. So the energy consumption of each node is balanced, and the lifetime of the system is maximized.

Scheme of group head rotation:

After the group head is firstly settled, the group head record the remained energy of itself, which is called the initial energy, denoted by P_γ . After each transmission of data, the head checks its remaining energy. When the energy drops to $\alpha\%$ ($0 \leq \alpha \leq 100$) of P_γ , the head sends repacking message to the group nodes through broadcast. The repacking message includes node number, the remaining energy. The group nodes send its own remaining energy information to other nodes, record the group nodes' remaining energy information and compare the information with themselves. Finally, pick the node with largest remaining energy as new group head. When equal energy is seen, the system picks the node with smallest node number. The new group head generate process is shown in Fig. 3.

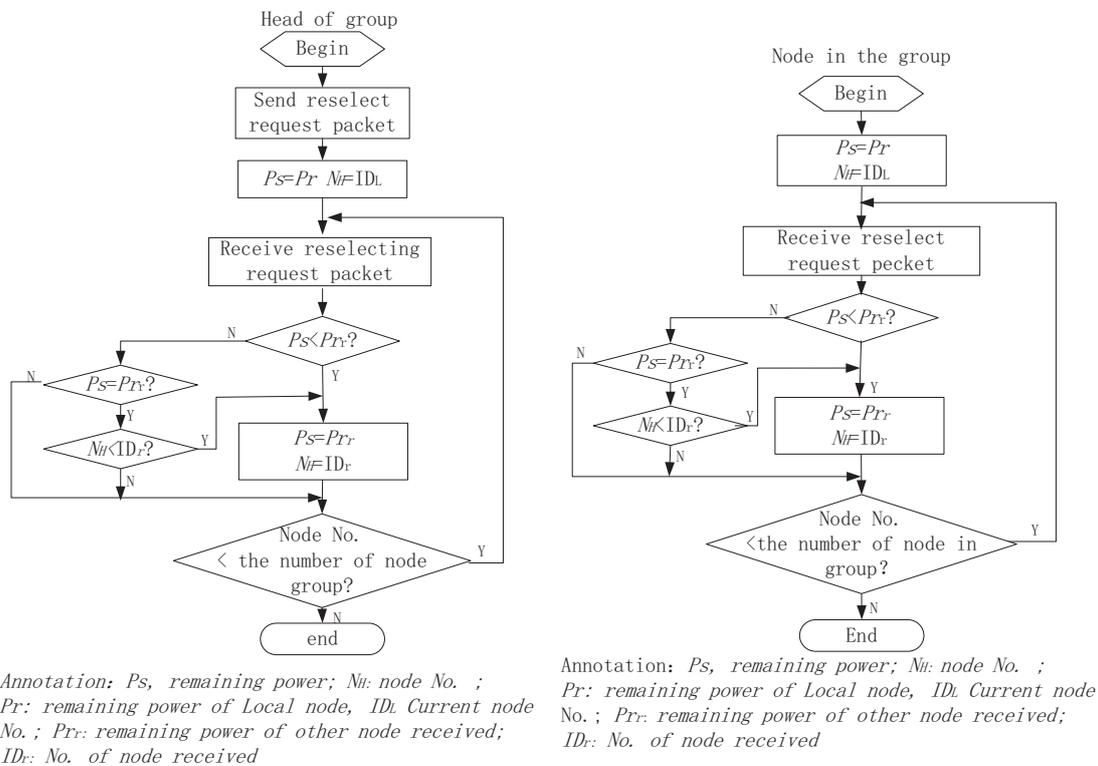


Figure 3: The new group head generation procedures

After the process shown above finished, all the node number stored in the node N_H are same, this number is the node number for the new group. This node is automatically the new group head; the new group will work around the head node. The node will record its remaining energy and when the energy drops to $\alpha\%$ of the remaining energy, the next rotation process is triggered. The whole network works as shown above and the energy of each node is balanced.

5 Performance measurement of the algorithm

Assume the minimum successful rate of send data from arbitrary node to sink node r_d as 0.9. The average data package length D_L is 200 bits, the channel error rate is 10^{-4} , by formulation(1)

we can get:

$$h_{MAX} = \frac{\lg r_d}{\lg(1 - D_{Le_c})} = \frac{\lg 0.9}{\lg(1 - 200 \times 0.0001)} \approx 5 \quad (3)$$

By formulation(2) we can get:

$$N_g \leq h_{MAX} + 1 = 5 + 1 = 6 \quad (4)$$

Hence, under worst case, the data transmission success rate r_S :

$$r_S = (1 - D_{Le_c})^h = (1 - 200 \times 0.0001)^5 \approx 0.904 > 0.9 \quad (5)$$

We can know that have 6 nodes in one group can satisfy the reliability requirement.

We assume the sum of time used between nodes' transmission t_S as 0.1s, the maximum system data transmission delay:

$$t_{MAX} = t_S \times h_{MAX} = 0.1 \times 5 = 0.5s \quad (6)$$

5.1 GPRS consumption analysis

To save energy, the GPRS module will work in an intermittent way, which means cut off the electricity right after the transmission. The voltage will be applied when the next transmission is ready. The time interval will be determined according to real monitoring requirement, usually ranges from several minutes to several tens of minutes, we pick 10 minutes in this case. According to real test, GPRS receiving and sending power \bar{P}_{send} has its peak value around of 80mw. Taking the channel interference into account, the speed can be picked at 56kbps. We assume GPRS module takes about $t_{Link} = 20s$ to connect with system (including the GPRS ground system), the node monitoring data package has a average length of 200 bytes. The transmission time is:

$$t_{send} = \frac{1600}{56000} = 0.028s \quad (7)$$

After transmission, the node controls GPRS module to cutoff the electricity.

In this situation, each sink node takes more than $t_{Total} = t_{Link} + t_{send} = 20.028s$ to transmit data. The energy consumption of sending the data is:

$$A_{SUN} = \bar{P}_{send} \times t_{Total} = 0.08 \times 20.028 \approx 1.60448J \quad (8)$$

There is not data exchange between sink nodes; hence the energy consumption of data transmission is 0. We can know from this that the total energy consumption of one transmission of 6 sink nodes is:

$$A_{Total} = A_{SUN} \times 6 = 1.60448 \times 6 = 9.62688J \quad (9)$$

Using the method given in this paper, 6 nodes' information is sent by one node which acts as a gateway. This node takes same amount of time to send the data and establish connection, the data sending time is:

$$t_{SUN} = t_{send} \times 6 = 28 \times 6 = 168ms \quad (10)$$

Now,

$$t_{Total} = t_{Link} + t_{SUN} = 20 + 0.168 = 20.168s \quad (11)$$

5.2 Computation of energy consumption of data transmission between nodes

The data transmission between sink nodes uses zigbee protocols. Under the presumption of maintaining the channel transmission quality, system should send data with minimum power. Ordinary sensor node has a very small sending power and a high sending rate. Take CC2430 for instance; when it performs sending and receiving data, the typical working current is 27mA, the supply voltage is 3.3V, the sending rate can achieve 250kbps. If the average data is 200 bytes long, even under the worst case: it takes 15 hops for 6 nodes to send data to sink node. Hence, the total energy consumption is:

$$A_{ST} = 0.0891 \times 15 \times 1600 \div 250000 = 0.00855J \quad (12)$$

Hence,

$$A_{Total} = \bar{P}_{send} \times t_{Total} + A_{ST} = 0.08 \times 20.168 + 0.00855 \approx 1.623J \quad (13)$$

As we can see, every time those 6 nodes send their data, the energy consumption using the method of this paper is just 17% of the original method. The effect of saving the energy is significant. When the node is not sending data, the node is in sleep mode with minimum power consumption. That minimum energy consumption has little effect in analyzing the power consumption. Hence the above analysis ignores the consumption of sleeping node.

5.3 Energy balance simulation

Assume a set of 6 sink nodes uses 3.3V, 30mA battery as power supply. Each node has same initial remaining energy:

$$A = 3.3 \times 3600 \times 0.03 \approx 356J \quad (14)$$

From above computation: It takes about 1.6J of energy to send data to the ground surveillance center every time; each sending or receiving data between each node takes about 0.0086J. When there is no grouping, the system working cycle are shown in Fig. 4.



Figure 4: System lifetime when one node is working

Under grouping situation, each node has different energy consumption when sending and receiving due to the difference of location of head node. The sending and receiving count of each node under different situations is given below in Table 1.

Node heads switching strategy is set as: when the remaining energy is 70%, 50%, 30% and 20% of the initial energy. When any nodes remaining energy is less then energy needed for one

Table 1: Count of each node under different situations

Node1	Node2	Node3	Node4	Node5	Node6
*5	9	7	5	3	1
1	*5	7	5	3	1
1	3	*5	5	3	1
1	3	5	*5	3	1
1	3	5	7	*5	1
1	3	5	7	9	*5

Note: * means the node is head node

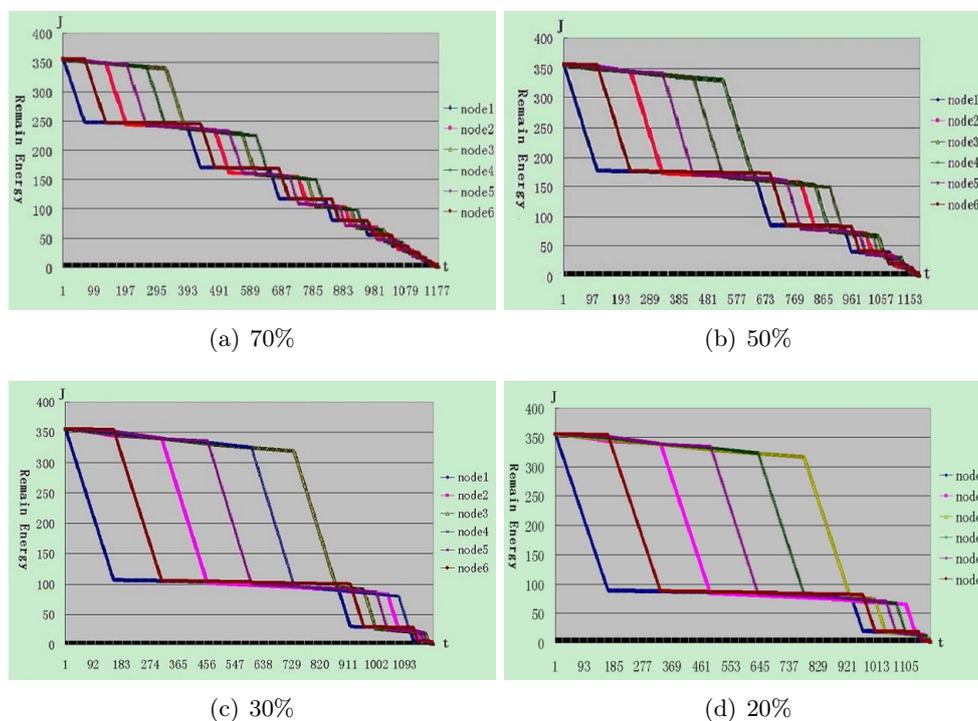


Figure 5: System lifetime after grouping.

Table 2: The Simulation Result

Forming network	Switching strategy	Simulation steps	Remaining total energy J
Grouping (one group contains 6 nodes)	70%	1179	1.6
	50%	1182	2.74
	30%	1182	6.35
	20%	1182	7.38
Single Node	None	222	0.768

transmission, or the energy of every node is less than 1.6J, the system can no longer send the monitoring data, this ends the simulation. The simulation result is shown below both in Fig. 5 and in Table 2.

As it is shown in the simulation, the system lifetime after grouping is far better than the lifetime of single node mode (5.3 times over). After grouping, the steps are minimum when switching strategy is 70%. When the switching strategy is 50%, 30%, 20%, the step count is 1182, but the remaining energy is different, maximum at 20%, minimum at 50%. The reason is that the head node switching requires certain energy and in the whole working time, less switching time is healthy for the lifetime of the system.

6 Conclusion

Linear sensor network as a wide application, it especially has significant meaning to transportation safety monitoring. Due to the special node allocation, how to forming the network to maximize system lifetime is still a great challenge. This paper discussed about the question of sink node working together in a linear sensor network, and proposed a method to determine the sink node number in a group and network forming scheme. The experimental results and analysis can support the proposed method perfectly. The author hopes this can contribute to the optimization of this kind of sensor network.

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