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The Strip Clustering Scheme for data collection in large-scale Wireless Sensing Network of the road

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Abstract

For intelligent traffic and road structural health monitoring, Wireless Sensing Network has been applied widely in transportation, and large quantity of sensor nodes have been embedded in roadways. Now the service lives of sensors are limited mainly because of their battery power storage. So the life cycle of the whole network can be extended if the service life of each sensor in the network is prolonged. In this paper, the Strip Clustering Scheme (SCS) is proposed to replace the Conventional Scheme (CS). This method includes region division, cluster head node selection, link construction, data fusion and transmission. Adopting SCS can reduce a lot of redundant data and the total energy consumption of the network by data fusion. In addition, adopting SCS can also extend the monitoring area without increasing the communication range of the Access Point (AP), and facilitate further expansion of the network as a result. Based on the numerically simulated results, CS method can be used for the WSN within 75 m, and SCS method is more suitable when the monitoring range is larger than 75 m. To achieve the optimal network costs and the network life cycle by using SCS, the range of d (the longitudinal spacing of adjacent nodes), is suggested as 10–12.5 m and the energy of cluster head nodes is 60% higher than the energy of non-head nodes with fixed w (the transverse distance of adjacent nodes). And the extra energy of head nodes can be obtained by adding the number of battery within the head nodes or using renewable energy technologies.

Keywords: WSN; Road; Energy consumption; Conventional Scheme; Strip Clustering Scheme

Introduction

The application of Wireless Sensing Network (WSN) in transportation infrastructure has been a research hotspot for road health assessment and traffic monitoring [1–3]. Although there have been remarkable progress in the pavement performance evaluation using macro-scale simulation [4,5] and micro-scale simulation [6], to achieve intelligent traffic and road structural health monitoring, many sensors need to be embedded in the road to form a WSN. Different types of sensors and multi-sensors were used in WSN of road according to their objectives [7]. For traffic-monitoring purposes, the most popular sensors include: magnetic sensor [7–10], strain gauges [2,3], load cells [2,3], acceleration sensors [9–11], dual-loop detectors [12].

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For infrastructure monitoring purposes, various intrusive pavement sensors including acceleration sensors [13,14], magnetic sensor [13], temperature sensors [13,15], moisture sensor [15] and strain sensor [15], were used to collect the responses of pavements (e.g. stress, strain, temperature, vibration).

In some previous projects, the sensor nodes collected pavement responses and transmitted the data directly to the Access Point (AP) by wireless transmission module [10–13]. The AP sent data to the local server by certain communication technology such as GPRS/CDMA/IP. Then after processing the data, the local server sent the processed results to mobile terminals or traffic management center. In this way, the WSN manager can query information about traffic flow and structural health in real time, and the users can browse the relevant information on the website [7]. Since the AP is exposed to the air, it is easy to replace the batteries or use cable to supply power. But it is difficult to supply power to the sensor nodes, which are embedded and driven by internal batteries. The sensors will fail eventually because of the limited battery storage, and early failure of some nodes will reduce lifecycle of WSN [9,13]. The radio plays a critical role in the sensor node lifetime, as most of the energy is consumed in radio communication [8]. Therefore, the energy consumption of WSN can be optimized by adjusting its data collection scheme.

The Conventional Scheme (CS) for data collection is to make all the sensor nodes transmit data to the AP directly. The energy consumption of a node will be affected by the distance significantly. The sensor node, which is farther away from the AP, consumes more energy and is more likely to fail, which will reduces the efficiency of the WSN [8,16]. Energy is wasted because adjacent sensors send their signals to the AP in similar routes redundantly [2,3,13,17]. Channels might be congested and network speed might be decreased because all the nodes transmit their data at the same time to the AP following a TDMA schedule [1,7]. In addition, the packet dropping probability boosts when the number of nodes increases, and energy could also be wasted due to the re-transmission of packets lost in collisions [13,18].

In this paper, the Strip Clustering Scheme (SCS) is proposed to compare with the CS (Conventional Scheme) based on the formal radio model and characteristics of sensor nodes' deployment for the road. The procedures of SCS will be introduced, which includes region division, cluster head node selection, link construction, data fusion and transmission. SCS can reduce a lot of redundant data and the total energy consumption of the network by data fusion.

Related work

Deployment of sensor nodes in the road

Common deployments of sensor nodes include mesh topology (e.g., parking lot), string topology (e.g., overtaking assistance), star topology (e.g., speed detection), barrier topology (e.g., traffic load estimation) [1]. In a practical application, the deployment of sensor nodes depends on the monitoring object and algorithm.

In some previous research projects [7,8], two sensor nodes were embedded on the centerline of each lane to calculate the speed of vehicles, and the distance between sensors depended on the range of expected speeds to be measured. In the research conducted at Virginia Tech [2,3], three types of sensor nodes were embedded in transverse and longitudinal direction, and the sensor matrix was used to achieve traffic monitoring and pavement distress monitoring. In the research conducted at Sensys Networks, Inc [13,19], four arrays of vibration sensors were installed 15 ft apart along the traffic direction for weigh-in-motion and pavement performance monitoring. Note that though there have been many researches in the pavement area [20–22], very few are on the sensor layout.

This sensor layout was designed to minimize lane-to-lane interference and maximize the in-lane signal-to-noise ratio. In the research conducted by Wenteng Ma's group [10], 3 arrays of magnetic sensors were installed 4 ft apart in the middle of the lane to classify traffic, with three sensors installed 3 ft apart in each array.

According the previous relevant research, some assumptions are adopted in this research: the sensor nodes deployed with a spatial density and laid linearly along the road; the instrumentation section is L meters long and W meters wide; the longitudinal spacing between the sensor nodes is d meters and the transverse spacing is w meters, as shown in Fig. 1.

Radio model

Sensor node mainly consists of four parts: sensors, micro-processor, a radio (transceiver) and a battery power source. The radio plays a critical role in the sensor node lifetime, as the overall power consumption is mainly affected by the energy required by radio communication [8,13]. And the WSN lifetime directly depends on the sensors' power source.

In this paper, we use the formal radio model and this model took into account of energy consumption of data transmitter, data receiver and data fusion [16,23]. The

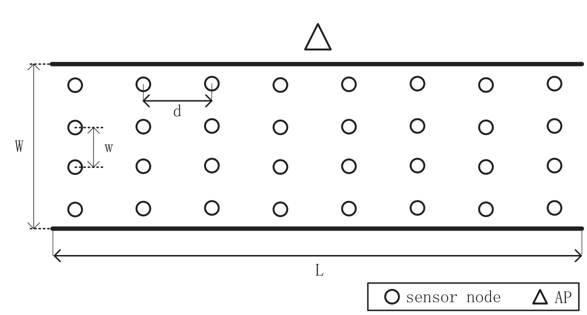


Fig. 1. Deployment of sensor nodes for the road.

energy consumption of data transmitter is shown in Eq. (1). It has two parts: energy consumption of transmission circuit and amplifier circuit.

$$E_{\mathrm{T}}(k,d) = fk(E_{T\_elec} + \varepsilon_{fs} \times d^2) \quad (1)$$

In the Eq. (1), k represents data transmission volume by the node in bytes. d represents data transmission distance in meter. f represents frequency of a node data collection in Hz. E_{T_elec} is the energy consumption of wireless transceiver circuit to transmit every unit of data. ε_{fs} is the energy consumption amplifier parameter in free space model.

The energy consumption of data receiver is shown in Eq. (2). E_{R-elec} is the energy consumption of wireless transceiver circuit to receive per unit data.

$$E_{\mathrm{R}} = fkE_{R\_elec} \quad (2)$$

The energy consumption of data fusion is shown in Eq. (3). E_{DA} is the energy consumption to aggregate every unit of data.

$$E_{\mathrm{A}} = kE_{DA} \quad (3)$$

The Strip Clustering Scheme for data collection

The Strip Clustering Scheme (SCS) is regional and hierarchical compared to conventional one. The sensor network embedded in the road will be divided into several strip-shaped regions with one cluster head node in each region. Data are transmitted from the non-head nodes to the head node one by one, and each sensor will aggregate all the data before transferring to the next one. Finally all the data will be gathered at the cluster head node in the region. After data fusion, the cluster head node will transmit the data to a higher level cluster head node or the AP. The steps of SCS are as follows:

Region division

The AP will be placed at one side of the instrumentation area. The instrumentation area will be divided into several stripe-shaped regions of the same size, along the traffic direction. The stripe closest to the AP is numbered as 1, the second is numbered as 2, and so on. The region division is shown in Fig. 2. Due to the symmetry, only the area on the right of the AP is analyzed in the following part of the paper.

The advantages of such region division are summarized as follows:

(a) Less energy will be wasted because of the shorter path. Then the signal–noise-ratio of the receiver will be increased as a result, which eventually increases the probability of successful reception [24]. Because of the shape of roads ($L \gg W$), the sensor node spacing (w) in the transverse direction is usually shorter than that in the longitudinal direction, data transmission in the transverse direction is more stable and controllable than the longitudinal one, especially for a long road.

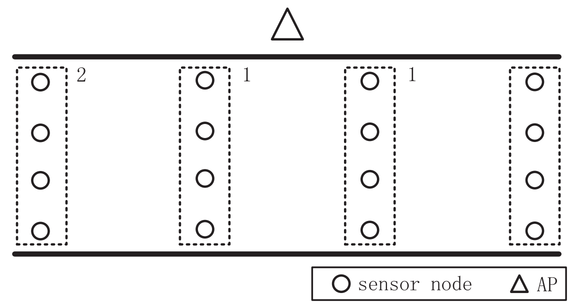


Fig. 2. Region division.

(b) Because the sensors in the same road cross section get affected by vehicles simultaneously, their signals are reliable and have a high correlation [2,3]. From this aspect, this region division is beneficial for analyzing and fusing data of road WSN.

Cluster head node selection

The cluster head node in each region is selected in the order of smallest to largest in region number. In the first region, the node which is closest to AP is chosen as the cluster head node, as shown in Fig. 3(a). In the rest regions, the node which closest to the previous cluster head node is chosen as the cluster head node, as shown in Fig. 3(b).

The following are two advantages of using this way to select the head nodes:

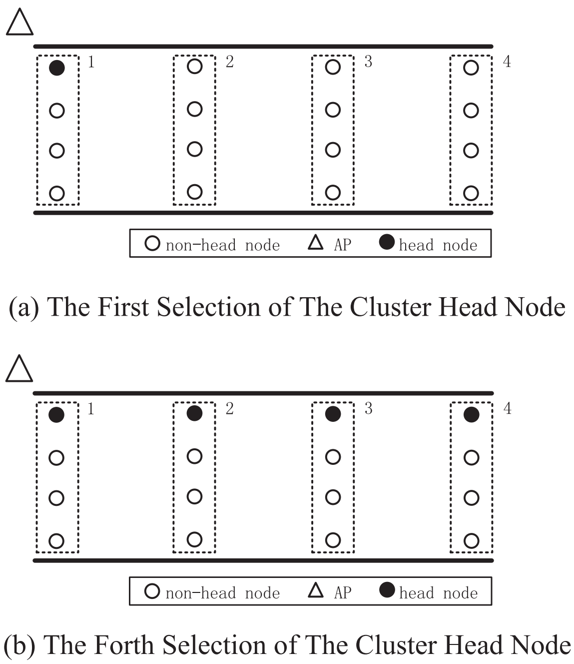
(a) The head nodes are at the roadside where the traffic load is lower, so failure rate is smaller. In addition it is convenient for energy supply (wind, solar, etc.) and maintenance.
(b) Since the distance between the head node to the gateway or the front head node is the shortest, least energy will be consumed in data transmission.

Link construction

In each region, the sensor node at the outer end of the region (farthest to the AP) searches for the closest node in the region, and then builds up a link with it. The PEGASIS communication protocol can be used in the link construction [23]. The non-head node, which is the farthest from the head node, links with adjacent node by greedy algorithm, until every node in the region is linked with the other, as shown in Fig. 4.

Data fusion and transmission

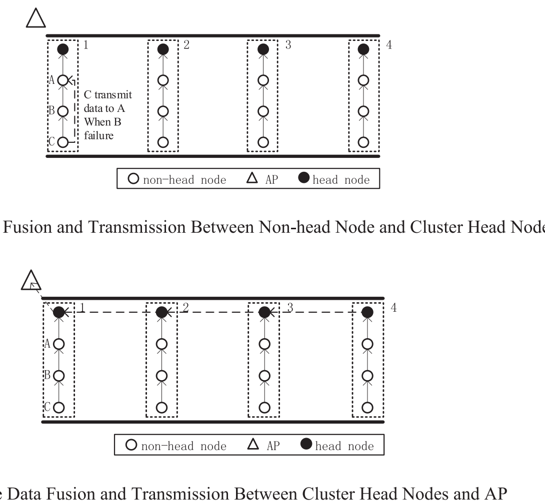
After determining the cluster head nodes, each non-head nodes will transmit and fuse data to the next node in the direction of the cluster head node until the cluster head



(a) The First Selection of The Cluster Head Node

(b) The Forth Selection of The Cluster Head Node

Fig. 3. Selection of the cluster head node.



(a) The Data Fusion and Transmission Between Non-head Node and Cluster Head Node

(b) The Data Fusion and Transmission Between Cluster Head Nodes and AP

Fig. 5. Data fusion and transmission.

node receives all the data, as shown Fig. 5(a). After data fusion, the cluster head node will transmit its data to the next head node in the direction of AP. Finally the data will be transmitted to the AP, as shown Fig. 5(b).

A node will transmit the data to the nearest surviving node (toward the cluster head direction) if its adjacent node fails. For example, as shown in Fig. 5(a), When the B node fails, C node will send data directly to the A node. Since the C node transmission distance is longer than before, the energy consumption of C node increases, which will affect the life of C node.

Compared to non-head nodes, head nodes have an extra duty: receiving and fusing the data of the last region. So the energy consumption of head nodes is higher than the energy consumption of non-head nodes, which will lead to energy holes in the network. In order to balance energy consumption, the head nodes' rotation strategy has been proposed, that is to set the largest residual energy of nodes in network as the head nodes [25]. However it is impractical in engineering applications, because the whole manufacturing cost will be increased obviously if all the nodes are designed as head nodes. In addition, more energy will be consumed in the head node rotation on link re-construction and rotation communications. The stability of the whole network could also be sacrificed, which might affect the monitoring efficiency [17,26].

Under certain circumstances, energy holes in wireless sensor networks are inevitable, and an effective solution to avoid the energy holes is energy supplement [27,28]. Backup batteries or renewable energy such as piezoelectric energy, solar energy and wind energy can be used for head nodes to avoid the network energy holes. In summary, the Strip Cluster Scheme has the following advantages:

(a) Redundant data transmission will be saved and the total energy consumption of the network will be reduced.
(b) By the partition-multi-hop way, data communication will not be limited by the AP communication range, and the monitoring range can be extended.
(c) Using different designs between head nodes and non-head nodes can reduce design and production costs of node and facilitate the energy supply and system maintenance.
(d) The energy holes can be avoided by increasing the number of battery within the head nodes or introducing renewable energy to power the head nodes, thus prolonging the life of the network.

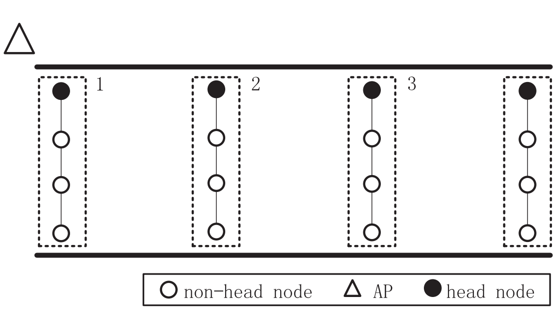


Fig. 4. Link construction.

Performance evaluation

Simulative model

To further compare the Conventional Scheme and the Strip Clustering Scheme, a model is built up to simulate a two-lane straight road, L meters in length and 8 m in width. The longitudinal spacing is d meters, and the transverse distance of adjacent nodes is w meter. The AP is located at the position (0, 0). Sensor nodes are numbered as Sij: i represents the column number and j represents the row number, as shown in Fig. 6.

Parameter setting

The simulation is based on the formal radio model. The efficiency of the WSN will be reduced if any sensor node in the network dies or fails. So the network lifecycle is defined as the time period from beginning to the first death in the network. The network lifecycle is expressed in rounds. According to the previous relevant studies, the other parameters used in the simulation are set as in Table 1 [16,23].

Results

(1) Case 1: fixed length of the monitoring network and changed density

MATLAB software was used to simulate the lifecycle of WSN for the 8 * 100 m road in the case of different value of d and w. By adopting CS or SCS, the relationships between the lifecycle and the density of WSN are shown in Fig. 7.

Fig. 7(a) shows that the network lifecycle is almost irrelevant to network density by adopting CS in that the nodes transfer data to AP directly. The farthest node from the AP will be the first to die no matter how the network density changes, while the node location is related to the length of road WSN. Fig. 7(b) shows that the network lifecycle is related to the network density by adopting SCS, and significantly affected by the d, while less affected by w. This is because of the road characteristics ($L \gg W$), i.e. the range of d is usually larger than the range of w, while energy consumption of node is closely related to the maximum distance between this node and its adjacent nodes. In addition, when the length of the WSN is 100 m, CS is better than SCS for the network lifecycle.

The network lifecycle is significantly affected by d and less affected by w when using the SCS, assuming seven sensor nodes installed 1 m apart in each array are embedded in 8 * 100 m road, i.e., the network transverse density is fixed, i.e., $w = 1$ m. And the number of columns ranges from 2 to

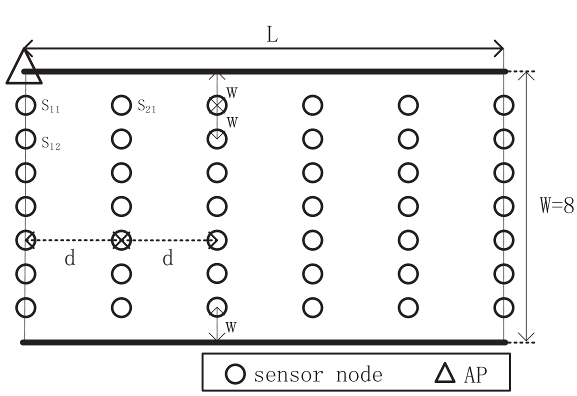


Fig. 6. Simulative model.

50 corresponding to different values of d, i.e., the network longitudinal density is changing. Fig. 8 illustrates how the network lifecycle changes with the number of columns.

As shown in Fig. 8, CS-1.0E0 represents initial energy of sensor nodes as E0; SCS-1.0E0 represents the initial energy of head nodes are of 1.0 times of the non-head nodes' initial energy (E0). SCS-1.2E0 represents the initial energy of head nodes which is 1.2 times of the non-head nodes' initial energy (E0). Similar explanations can be made to SCS-1.4E0, SCS-1.6E0 and SCS-1.8E0.

The lifecycle does not increase with the increase of network longitudinal density by adopting CS for monitoring the 100 m road. The network lifecycle changes significantly when the number of columns ranges 2–10 by adopting SCS, while the network lifecycle almost does not change in the column of 10–50. This is because the d values becomes smaller as the number of columns increases. If reducing the d value thereby increasing network density, the extension of the network lifecycle will be less impacted when the number of columns is above 11, and the network cost will be improved because of the high network density. If rising the d value and reducing the network density, the network lifecycle will be shorted sharply when the number of columns is under 9. So the optimal number of columns is considered as 9–11, i.e., the range of d is in 10–12.5 m when using SCS method to monitor a 100 m road.

Compared to SCS-1.0E0, CS-1.0E0 is more suitable for a 100 m long road. If 20% of the energy is added to head nodes, which use the SCS-1.2E0, the network lifecycle will be extended about 20%. If 40% of the energy is added to head nodes, the network lifecycle will be extended about 40%. If 60% and 80% of the energy is added to head nodes, the network lifecycle will be extended about 52%. It is visible that with the increasing energy of head nodes, the network lifecycle using SCS will be extended, but after 60% of the energy is added to head nodes, network lifecycle will not be extended with the increase of energy to the head nodes. This is because there is still energy in head nodes before the energy of non-head nodes runs out.

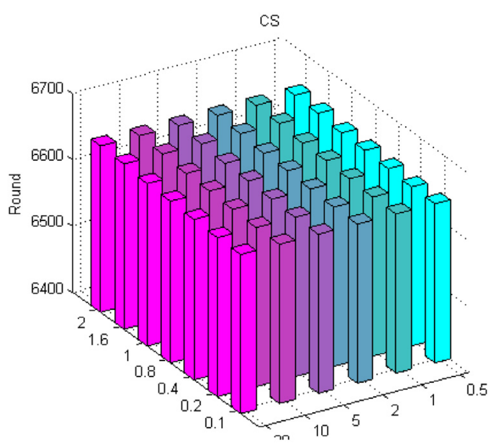
In practical engineering applications, to achieve the optimal network costs and the network life cycle by using SCS, the range of d should be 10–12.5 m and the energy of head nodes should be 60% higher than the energy of non-head nodes with fixed w.

(2) Case 2: fixed density of the monitoring network and changed length

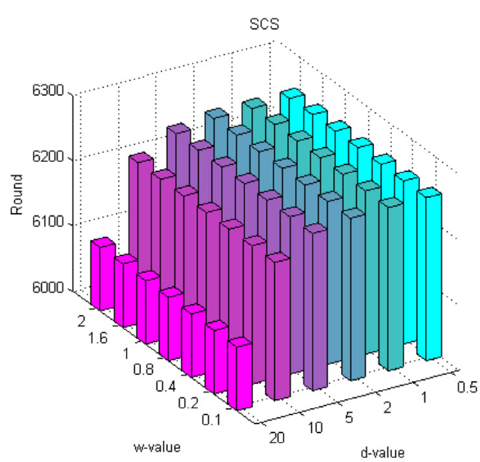
Based on the above analysis, the CS is not affected by network density, while SCS is affected significantly by the value of d, and d is preferably in the range 10–12.5 m, so $w = 1$ m and $d = 10$ m are used in this case study. With the same instrumentation density, 20 simulations were conducted with the length of the road ranged from 0 to 200 meter (10 m between adjacent columns). Based on the simulated network lifecycles (refer to Fig. 9), if there is one column, i.e., $d = 0$, the lifecycle of WSN only be

Table 1
Parameter setting.

Explanations	Parameter	Value
Energy consumption of transmitting every bit data	ET-elec	50 nJ/bit
Energy consumption of receiving every bit data	ER-elec	50 nJ/bit
Amplifier parameter in free space model	ε_{fs}	10 pJ/bit/m^2
Energy consumption of aggregating every bit data	E_{DA}	5 nJ/bit
Data acquisition frequency	f	1 Hz
Initial energy of non-head nodes	E_0	1 J
Initial energy of head nodes	E_{h0}	$N * E_0$ ($N = 1,1.2,1.4,1.6,1.8,2.0$)
The amount of data generated from every sensor node in a round	k	1000 b



(a) Adopting CS



(b) Adopting SCS

Fig. 7. The relationships between the lifecycle and the density of WSN by adopting CS & SCS. ($L = 100$ m, $w = [2,1.6,1,0.8,0.4,0.2,0.1]$, $d = [20,10,5,2,1,0.5]$).

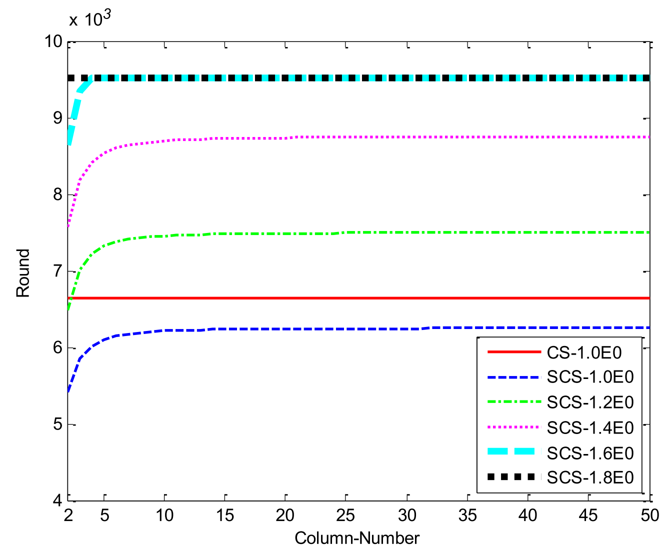


Fig. 8. The network lifecycle changes with the number of columns. ($L = 100$ m, row-number = 7, column-number = [2:50]).

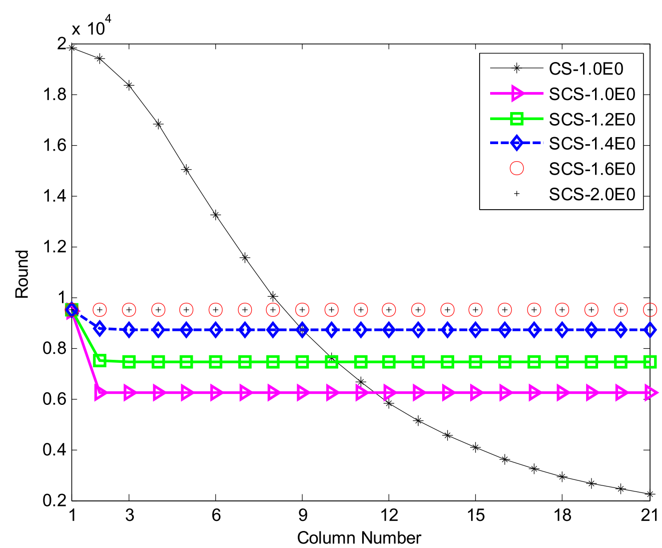


Fig. 9. Network lifecycle comparison of CS & SCS when the monitoring range is 0–200 m.

affected by w. If there are two columns, the lifecycle will be more affected by d as $d > w$. With the road length increases, the lifecycle of SCS will keep constant, but one of the CS will decrease continuously as the road length increases.

Based on the results shown in Fig. 9, it's better to adopt CS when the length of the instrumentation area is shorter than 105 m, while it is more beneficial to adopt the SCS when the monitoring length is more than 105 m. The comparison of the results between CS-1.0E0 and SCS-1.2E0, SCS-1.4E0, SCS-1.6E0, SCS-2.0E0 is shown in Table 2.

Table 2 shows that, SCS-1.6E0 compared with the CS-1.0E0 has the maximum advantage of the range, i.e., [75,+∞).

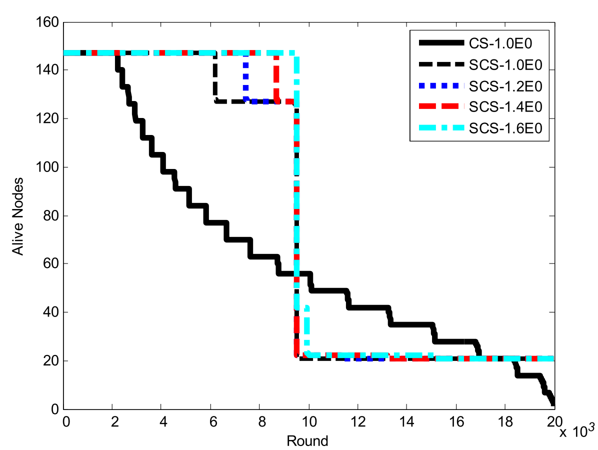
(3) Case 3: fixed density of the monitoring network and changed length

Assuming the length of the instrumentation area is $L = 200$ m, $w = 1$ m, $d = 10$ m. The network lifecycles by using different data collection schemes are shown in Fig. 10.

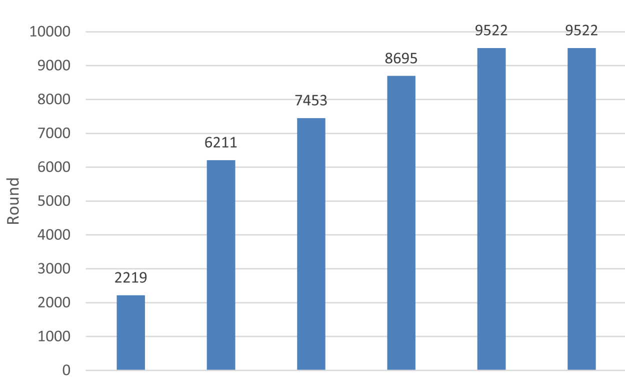
Fig. 10(a) shows that, SCS makes the whole network balanced energy consumption, the nodes run out of energy almost at the same time. While the sensor nodes which are farther away from AP fail earlier by adopting CS, which reduces the efficiency of the WSN.

Table 2
The applied length of monitoring network in road by adopting CS and SCS.

Comparison	The applied length of CS (m)	The applied length of SCS (m)
CS-1.0E0 & SCS-1.0E0	[0,105]	[105,+∞)
CS-1.0E0 & SCS-1.2E0	[0,90]	[90,+∞)
CS-1.0E0 & SCS-1.4E0	[0,80]	[80,+∞)
CS-1.0E0 & SCS-1.6E0	[0,75]	[75,+∞)
CS-1.0E0 & SCS-2.0E0	[0,75]	[75,+∞)



(a) The Relationship Between Alive Nodes and Round



(b) The Network Lifecycles by Using Different Data Collection Schemes

Fig. 10. Network lifecycle comparison of CS & SCS. ($L = 200$ m, $w = 1$ m, $d = 10$ m).

Fig. 10(b) shows that, SCS-1.6E0 is optimal for a 200 m long road, the network lifecycle of SCS-1.6E0 is 9522 rounds, 329.1% more than that of CS, which is 2219 rounds, and 53.3% more than that of SCS-1.0E0, which is 6211 rounds. So it's better to adopt SCS-1.6E0 when the monitoring length is 200 m. And with the increasing energy of head nodes, the network lifecycle using SCS will be extended but does not increase proportionally. When 60% of the energy is added to head nodes, network lifecycle will not be extended with the increase of energy to the head nodes.

In summary, CS method is more suitable for the WSN within 75 m. However, it is more beneficial to adopt the SCS when the monitoring length is more than 75 m. To achieve the optimal network costs and the network lifecycle by using SCS, the range of d should be 10–12.5 m and the initial energy of head nodes should be 60% higher than the energy of non-head nodes with fixed w.

WSN is an enabling technology to ITS which needs to place a large number of road sensor nodes. The length of monitoring road is usually more than 75 m. In addition, the environment around the instrumentation section keeps changing, and it is inconvenient or difficult to set the AP or receiver at some special places. As a result, the distance between the AP and the middle of the WSN could be very long. In this case, it will be very beneficial to adopt SCS in the monitoring system instead of CS.

Conclusions

In this paper, the Strip Cluster Scheme is proposed and compared with the Conventional Scheme. The procedures of SCS are introduced in details, including region division, cluster head node selection, link construction, data fusion and transmission. SCS can reduce a lot of redundant data and the total energy consumption of the network. Explicit layout of head nodes and non-head nodes can reduce design and production costs of nodes and facilitate the energy supply and system maintenance. The energy holes can be avoided by increasing the number of battery within the head nodes or introducing renewable energy to power the head nodes, thus prolonging life of the network. In addition, adopting SCS can extend the monitoring area without increasing the communication range of the Access Point (AP), and facilitate further expansion of the network as a result. Based on the numerically simulated results, CS method is more suitable for the WSN within 75 m, however, it is more beneficial to adopt the SCS when the monitoring length is more than 75 m. To achieve the optimal network costs and the network life cycle by using SCS, the range of d should be 10–12.5 m and the initial energy of head nodes should be 60% higher than the energy of non-head nodes with fixed w.

Large-scale road WSN will be formed in the future with the WSN technology becoming more mature and being applied ubiquitously to Intelligent Transport System, such as freeway traffic count stations, ramp metering, signal control, and parking guidance. This WSN consists of inexpensive wireless sensor nodes capable of sensing, processing and distributing information acquired from the environment through the collaborative effort of nodes. It will be very beneficial to adopt SCS in the monitoring system instead of CS for the large-scale road wireless sensors network.

There is only one head note transmits at each step of SCS, the response time of SCS is improved for large-scale deployments and this will be studied in future. In addition, some technologies including the communication protocols, data fusion also need to be developed for SCS.

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References

[1] F. Losilla, A. Garcia-Sanchez, F. Garcia-Sanchez, J. Garcia-Haro, Z. J. Haas, A comprehensive approach to WSN-based ITS applications: a survey, Sensors 11 (12) (2011) 10220–10265.
[2] W. Xue, D. Wang, L. Wang, Monitoring the speed, configurations, and weight of vehicles using an in situ wireless sensing network, IEEE Trans. Intell. Transport. Syst. 16 (4) (2015) 1667–1675.
[3] W. Xue, L. Wang, D. Wang, A prototype integrated monitoring system for pavement and traffic based on an embedded sensing network, IEEE Trans. Intell. Transport. Syst. 16 (3) (2015) 1380–1390.
[4] Y. Hou, L. Wang, P. Yue, T. Pauli, W. Sun, Modeling mode i cracking failure in asphalt binder by using nonconserved phase-field model, J. Mater. Civil Eng. 26 (4) (2014) 684–691.
[5] Y. Hou, P. Yue, L. Wang, W. Sun, Fracture failure in crack interaction of asphalt binder by using a phase field approach, Mater. Struct. 48 (9) (2015) 2997–3008.
[6] Y. Hou, L. Wang, T. Pauli, W. Sun, Investigation of the asphalt self-healing mechanism using a phase-field model, J. Mater. Civil Eng. 27 (3) (2015) 04014118.
[7] A. Haoui, R. Kavaler, P. Varaiya, Wireless magnetic sensors for traffic surveillance, Transport. Res. Part C Emerg. Technol. 16 (3) (2008) 294–306.
[8] M. Bottero, B. Dalla Chiara, F.P. Deflorio, Wireless sensor networks for traffic monitoring in a logistic centre, Transport. Res. Part C Emerg. Technol. 26 (2013) 99–124.
[9] R. Bajwa, R. Rajagopal, P. Varaiya, R. Kavaler. In-pavement wireless sensor network for vehicle classification, in: Proc., 10th International Conf. on Information Processing in Sensor Networks (IPSN2010), IEEE, Chicago, Illinois, USA, 2011, pp. 85–96.
[10] W. Ma, D. Xing, A. McKee, R. Bajwa, C. Flores, B. Fuller, P. Varaiya, A wireless accelerometer-based automatic vehicle classification prototype system, IEEE Trans. Intell. Transport. Syst. 15 (1) (2014) 104–111.
[11] E. Levenberg, Estimating vehicle speed with embedded inertial sensors, Transport. Res. Part C Emerg. Technol. 46 (2014) 300–308.
[12] L. Wu, B. Coifman, Improved vehicle classification from dual-loop detectors in congested traffic, Transport. Res. Part C Emerg. Technol. 46 (2014) 222–234.
[13] R. Bajwa, R. Rajagopal, E. Coleri, P. Varaiya, C. Flores. In-pavement wireless Weigh-In-Motion, in: Proc., 12th international Conf. of information processing in sensor networks, ACM, 2013, pp. 103-114.
[14] E. Levenberg, Inferring pavement properties using an embedded accelerometer, Int. J. Transport. Sci. Technol. 1 (3) (2012) 229–246.
[15] W. Xue, L. Wang, D. Wang, C. Druta, Pavement health monitoring system based on an embedded sensing network, J. Mater. Civ. Eng. (2014), http://dxdoi.org/10.1061/(ASCE)MT.1943-5533.0000976, 04014072.
[16] W.B. Heinzelman, A.P. Chandrakasan, H. Balakrishnan, An application-specific protocol architecture for wireless microsensor networks, IEEE Trans. Wireless Commun. 1 (4) (2002) 660–670.
[17] A. Mostefaoui, A. Boukerche, M.A. Merzoug, M. Melkemi, A scalable approach for serial data fusion in Wireless Sensor Networks, Comput. Networks 79 (2015) 103–119.
[18] M.A. Kafi, D. Djenouri, J. Ben-Othman, N. Badache, Congestion control protocols in wireless sensor networks: a survey, IEEE Commun. Surv. Tutor. 16 (3) (2014) 1369–1390.
[19] R. Rajagopal, R. Bajwa, E. Coleri, C. Flores, V. Pravin, Sensor network for pavement performance monitoring, J. Comput. Civ. Eng. (2013), http://dxdoi.org/10.1061/9780784413029.013, 97-104.
[20] Y. Hou, F. Sun, W. Sun, M. Guo, C. Xing, J. Wu, Quasi-brittle fracture modeling of pre-flawed bitumen using a diffuse interface model, Adv. Mater. Sci. Eng. 2016 (2016) 7. Article ID 8751646.
[21] Y. Hou, Y. Huang, F. Sun, M. Guo, Fractal analysis on asphalt mixture using a two-dimensional imaging technique, Adv. Mater. Sci. Eng. 2016 (2016) 7. Article ID 8931295, (SCI-index).
[22] Y. Hou, W. Sun, P. Das, X. Song, L. Wang, Z. Ge, Y. Huang, Coupled Navier-Stokes phase-field model to evaluate the microscopic phase separation in asphalt binder under thermal loading, J. Mater. Civil Eng. 28 (10) (2016) 04016100.
[23] S. Jung, Y. Han, T. Chung. The concentric clustering scheme for efficient energy consumption in the PEGASIS, in: Proc., 9th International Conference on Advanced Communication Technology, IEEE, Gangwon-Do, 2007, pp. 260–265.
[24] D.U. Campos-Delgado, J.M. Luna-Rivera, Distributed power allocation algorithm in wireless networks under SNR constraints, AEU Int. J. Electron. Commun. 67 (12) (2013) 1015–1024.
[25] O. Younis, M. Krunz, S. Ramasubramanian, Node clustering in wireless sensor networks: recent developments and deployment challenges, Network 20 (3) (2006) 20–25.
[26] Z. Feng, W. Kai, C.H. Bin, Data aggregation node election algorithm based on average residual energy for wireless sensor networks, Appl. Res. Comput. 29 (8) (2012) 3096–3102 (in China).
[27] J. Li, P. Mohapatra. An analytical model for the energy hole problem in many-to-one sensor networks, in: Proc. the IEEE Vehicular Technology Conference, 62(4), 2005, pp. 2721.
[28] S. Olariu, I. Stojmenovic. Design guidelines for maximizing lifetime and avoiding energy holes in sensor networks with uniform distribution and uniform reporting, in: Proc. the IEEE INFOCOM. New York, USA, 2006, pp. 1–12.