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Mobile sink discovery mechanism in wireless sensor networks with duty cycles

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Abstract

Wireless sensor network (WSN) is a multi-hop, self-organizing distributed network system composed of multiple micro-sensors through wireless communication. There are problems such as energy holes and transmission link interruption due to node failure for multi-hop mode of data transmission. Mobile sink (MS) supports data forwarding and collection to avoid multi-hop transmission, extending network life by saving network energy. In the work, we discussed transmission energy and delay problems of data collection by MS in WSN with duty cycle. Based on fixed MS moving speed and regular transmission performance, the network life cycle was maximized to propose an asynchronous path independent energy efficient algorithm irrelevant to the path. After that, the efficiency of the protocol was verified by experiments.

Keywords Wireless sensor networks · Mobile sink · Discovery protocol · Interaction time · Duty cycle

1 Introduction

The network is the most effective way for people to get massive information. Recently, with the rapid development of science and technology, network technology is rapidly improved. Higher requirements are put forward for the object of information, the speed of communication and the control of things. Internet of things (IOT) emerges to achieve easy identification, management and control by connecting networks to things and people. Acquiring, processing and transmitting object information will be a new research field. WSNS are integrated with sensing technology, communication technology and computational processing technology to provide basis for the acquisition and processing of the information.

As a multi-hop, self-organizing distributed network system, WSN consists of multiple inexpensive, low-power micro-sensors through wireless communication. In the network, the nodes send monitored, sensed and processed environmental information in network coverage area to sink or base station for further processing [1]. Typically, a WSN system consists of sensor, sink and task management nodes. The sensor nodes are distributed in the detection area by manual or aircraft layout. In the large-scale WSNs, the sensor nodes communicate in self-organization and multi-hop mode. For the network function, each sensor node acts as terminal and routing nodes. Firstly, sensor nodes conduct local data collection and information transmission. Secondly, the data forwarded by other nodes are stored, managed and forwarded by the sensor nodes. The sink nodes have stronger processing, energy storage and communication abilities than sensor nodes.

The sensor node is a tiny device powered by the battery with limited energy storage. Sensor nodes are often ineffective or obsolete due to power supply. Therefore, energy constraints seriously hinder the application of sensor networks. Power is far from meeting the needs of WSNs. It takes more energy for the nodes to transmit information than to execute calculation. Within 100-m communication range, electrical energy required by a sensor to transmit 1-bit information is enough to execute 3000 compute instructions. In addition, the sensor nodes are widely distributed. The environment of deployment area is so complicated that the people cannot reach. Therefore, it is not realistic to change the bat-

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tery. Energy efficiency is one of the key issues to be solved in sensor network applications [1,2]. Recently, researchers have proposed to use mobile sink (MS) to solve energy hole problems generated by multi-hop communication.

MS moves to the communication range of the sensor for data interaction, reducing the multi-hop transmission between nodes. In References [3–5], the sensor data are collected by the movement of people, animals or vehicles with communication equipments. There are also some applications by using robotic cars as MS [6,7], with high cost. MS collects sensor data by multiple ways. The first is to directly collect the data of all sensor nodes by MS, i.e., data transmission by one-hop communication [8,9]. The advantage is the maximization of energy savings, with great delay. Secondly, partial sensors are selected as data cache nodes. The sensors transfer data to cache nodes where MS accesses to complete the data collection [5,10].

Mobility is an important feature of heterogeneous sensor networks. Mobility is introduced in WSNs to solve two problems in static sensor networks: Energy hole and link interruption. Noses communicate with each other in multi-hop mode in static sensor networks, where some nodes produce and forward data [11]. Meanwhile, the data flow follows the many-to-one mode. The nodes closer to the Sink take on more communication loads. Therefore, these nodes are prone to prematurely exhaust their own energy, causing energy hole around the Sink. Then, the data collected by the network cannot be transmitted to the Sink nodes. Here, the lifetime of the network is over, leaving unused energy resources in the network. The mobile node assists in data forwarding and collection to avoid multi-hop transmission, saving network energy and extending network life. The mobile node repairs the interrupted link in the network [12]. The communication links may be interrupted due to energy exhaustion or intentional destruction of sensors in the network. The entire network is divided into multiple disconnected small networks. Node data cannot be transmitted to the Sink, forming unavailable network. Therefore, the static sensor network arranges multiple redundant nodes, which is costly. The nodes with mobility move to the region where the link is interrupted for interrupt repairment.

In the existing research, mobile nodes consist of mobile sensor, Sink and relay. MS is a Sink node with mobility capability. Sink itself is used to receive sensor data in the network for processing. Therefore, MS is more suitable for event detection applications. Once being received by MS, the data are processed immediately [13–15].

Duty cycle is defined as follows. In order to save energy, the sensor closes communication module (i.e., data transceiver module) to enter the sleep state in the absence of data transmission. By setting the time, it wakes up to discover the channel. When there is data transmission, it enters the transmission state. The transformation process among sleep, discovery and transmission is also a duty cycle [16]. The longer sleep time leads to the more saved energy, which is called low duty-cycle [17].

In most applications, the sensor works in a low duty-cycle mode to save the energy. I.e., the sensor switches among sleep, discovery and data transfer states in the life cycle of node. The mobile node passes through the communication range of sensor with constant or variable speed. Under constant speed, the interaction time with the sensor is fixed. Besides, there is direct relationship between effective data transmission time and duty cycle. Under variable speed, the speed can be adjusted to ensure adequate data transmission time; however, it brings about great delay. In addition, the sensor conducts data transmission when Sink has moved to its own communication range in the duty-cycle mode. A simple discovery protocol is to use synchronous method [18]. The nodes interact strictly in accordance with the agreed time, but the synchronization process is difficult to achieve. In another asynchronous method, the sensor and MS work according to their own laws where MS is used to actively wake up the sensor nodes [19,20].

In the work, we discussed transmission energy and delay problems of data collection by MS in WSN with duty cycle. Based on fixed MS moving speed and regular transmission performance, the network life cycle was maximized to propose an asynchronous path independent energy efficient algorithm (PIEE) irrelevant to the path. After that, the efficiency of the protocol was verified by experiments.

2 Application scene model

The communication between MS and sensor is divided into MS discovery and data transmission stages. In the previous stage, the sensor needs to know whether the MS enters its own communication range. At later stage, the sensor transfers cache data to MS. Due to the limited energy of sensor, the activities at both stages must have efficient energy. As the main component of energy consumption, the communication module of sensor should have minimum working time [21]. The concept of rotation is introduced into sensor operating mode. When there is no data transmission, the sensor is in a sleep state where the communication module is closed to save energy. In the mobile-assisted data transmission mode, if the MS enters the communication range of sensor but the sensor does not find it in time, or if it is too late to transfer all cache data to the MS, then the sensor can only wait for the next arrival of the MS. This increases data transmission delay, causing unnecessary loss of energy. If the MS moves at a low speed in the mobile-assisted data collection, then the working mode of low duty-cycle completes data transmission task while saving the sensor energy. If the MS moves at a high speed, then the low duty-cycle is not the most economical way of saving energy. This conclusion is very important. It can provide basis for the working mode setting under duty-cycle system.

MS discovery process can be divided into synchronous and asynchronous modes. MS discovery of time synchronization is a simple process [22]. All the sensors know when the MS enters their own interactive areas, and keep the communication module in the ON state. When MS enters the interactive area, both can immediately perform data communication. However, the way of time synchronization requires advance prediction of MS mobile process and synchronous working according to the agreed mode. This is not conducive to actual application and difficult to achieve.

In contrast, the asynchronous discovery pattern allows the independent operation of MS and sensor without determining movement process of the MS in advance [19,23]. The sensor works according to its own duty-cycle. When receiving the beacon information, it enters the data communication stage. Asynchronous mode is easy to achieve and consistent with the actual application; however, it also has its own shortcomings. When the MS enters the sensor's interactive range, the communication module of sensor is possible to be in the OFF state. The sensor cannot find the MS in time. In the ON state, the sensor will find the arrival of MS. This mode results in the waste of communication time. In extreme cases, the MS may not be found, and the sensor data cannot be transmitted in time. In the work, Asynchronous MS discovery mode was used to analyze the state transition process of the sensor. Time requirement of data transmission was satisfied by controlling duty cycle of sensor or adjusting the moving speed of MS.

The sensor node operates in the duty-cycle mode. In life cycle of node, the sensor switches among sleep, discovery and data transfer states (See Fig. 1) [24–26]. In the sleep state, the node closes the communication module (wireless transceiver module) to save energy. After a period of time, the node wakes up to discover whether any node communicates with it. If not, continue to sleep; otherwise, turn to data transmission state for data transceiver. It is found that energy consumption of sensor is mainly concentrated in discovery and data transfer states. The energy consumption in sleep state is negligible.

It is assumed that the sensors are evenly distributed in a wide monitoring area. Based on duty-cycle mode, the sensor switches among three states including sleep, discovery and data transfer. Sink confirms whether to interact with the sensor by sending a beacon signal during the moving process. Data transmission is performed only if the ID number in the beacon matches the ID of sensor. The area, with the radius equivalent to sensor communication radius r, is called an interaction area. It is denoted that the maximum travel time of Sink is C_{max} in the interactive area. When the MS enters the interactive area, there is no communication between them in sleep state. Until the time d, the sensor converts to the discovery state and receive the beacon signal. The actual data transmission time $c = C_{\max} - d$.

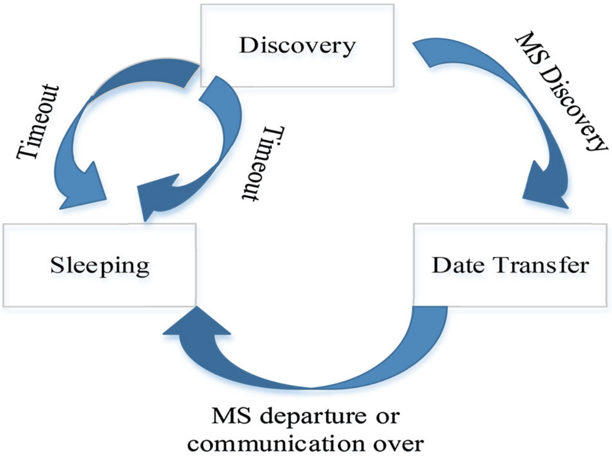

Fig. 1 Conversion of working conditions of the sensor under duty-cycle mode

In the work, the characteristics of application scenario were assumed as follows.

- A1: The communication range of sensor node is a circular area with radius of r.
- A2: MS has enough energy, storage resources and computing power.
- A3: We determine a moving path for MS, where the sensors are distributed around. The path can be arbitrary.
- A4: For easy calculation, let Sink adopt the linear movement mode [27]. The maximum moving distance is $2r$ within communication range of sensor.

3 PIEE efficiency optimization algorithm PIEE irrelevant to path

3.1 Discovery probability

It is assumed that the sleep time is t_{off}; the discovery time t_{on} in each duty cycle of the sensor. The wake-up rate of Node j conforms to the Poisson random process. When the MS enters the interactive area of Node j, information interaction generates between them. Sink sends beacon and ID information. The durations are denoted as t_B and t_C, respectively. After that, the Sink monitors the channel to wait for the sensor acknowledgment (ACK). The discovery time is denoted as t_A. Since t_{on} is small, we set $t_{on} = t_A + e_{\det ect}$ to ensure that the sensor can correctly receive the beacon information within the ACK time of the MS (t_A). Wherein, $e_{\det ect}$ is a very small value, which is negligible compared to t_A. Thus, $T_{on} \approx t_A$.

MS enters the interactive area of Sensor j at 0 o'clock. If Node j is at off state, then beacon signal misses. If j is not awakened in the former $(n-1)$-th beacon, the MS will send the n-th beacon in $[(t_C+t_B+t_A)(m-1), (t_C+t_B+t_A)(m-1)+t_C+t_B]$. Let Sensor j discovers the beacon signal during this period, and wakes up in $[(t_C+t_B+t_A)(m-1)-t_C-t_A, (t_C+t_B+t_A)m-t_C-t_A]$. According to Poisson distribution definition, the probability that $j$discovers the n-th signal is expressed as Eq. (1).

$$p_j = 1 - e^{-\lambda_j(t_c+t_B+t_A)} \tag{1}$$

We define p_j as the discovery probability of Node j. It is denoted that Q_j is the remaining total energy of j; μ_j the energy consumption for wakeup. Then the life cycle of j is $Q_j/\mu_j\lambda_j$. Set the energy consumption rate $e_j = \mu_j/Q_j$, then the life cycle of j can be defined as Eq. (2).

$$T_j(p_j) = \frac{1}{e_j\lambda_j} = \frac{t_C+t_B+t_A}{e_j \ln\frac{1}{1-p_j}} \tag{2}$$

The life cycle of network is defined as the time for the failure of the first node [28]. For the discovery probability $\vec{p} = (p_i, i \in N)$ of all the sensors in a given network, the life cycle of the network is expressed as Eq. (3).

$$T(\vec{\mathrm{p}}) = \min_{i\in\mathrm{N}} T_i(p_i) \tag{3}$$

3.2 Maximum of network life cycle

According to the above analysis, the maximization problem of network life cycle can be described as follows.

$$(P) \max_{\vec{p},v,r} T(\vec{p}) \tag{4}$$

$$Subject\, to\, C_i(p_i, v, r) \geq \xi_i, \forall_i \in \mathrm{N} \tag{5}$$

$$\vec{p} \in (0,1]^N \tag{6}$$

where $C_i(p, v, r)$ is the expected value of data transmission time when the discovery probability of Sensor i is p; ξ_i the minimum transmission time of the node in the system. It is an estimated value. The system ensures that each node transmits all data to the MS in Round 1. The goal of Problem (P) is to find the appropriate $\vec{p} \in (p_i, i \in N)$. Data transmission time of each sensor and MS can meet the minimum transmission time of the system while maximizing the network lifetime.

Theorem 1 *If the MS passes through interactive region of Sensor i at the speed of v, then the time of MS is $2r/v$ in interactive region. It is denoted that $t_I = t_C + t_B + t_A$. Then, data transfer time expectation between the two is expressed as Eq. (7).*

$$C_i(p_i, v, r) = \frac{2r}{v} - t_I \times \frac{1-(1-p_i)^{\frac{2r}{v*t_I}}}{p_i} \tag{7}$$

Proof Let the sensor be in the OFF state at the former $(h-1)$-th beacon time, then the probability of receiving the h-th beacon information is calculated by Eq. (8).

$$p_{i,h} = (1-p_i)^{h-1} \times p_i \tag{8}$$

Let $n = \frac{2r}{v\times t_r}$ be the total beacon number sent by the MS in the interaction area. Then,

$$\begin{aligned} C_i(p_i, v, r) &= \sum_{h=1}^{n} p_{i,h} \times \left(\frac{2r}{v} - h \times t_I\right) \\ &= \sum_{h=1}^{n} (1-p_i)^{h-1} \\ &\quad \times p_i \times \left(\frac{2r}{v} - h \times t_I\right) \\ &= p_i * \frac{2r}{v} * \sum_{h=1}^{n} (1-p_i)^{i-1} \\ &\quad - p_i * \frac{2r}{v*n} * \sum_{h=1}^{n} (1-p_i)^{i-1} * i \\ &= p_i * \frac{2r}{v} * \frac{1-(1-p_i)^n}{p_i} \\ &\quad - p_i * \frac{2r}{v*n} * \left(\frac{1-(1-p_i)^n}{p_i^2} - \frac{n*(1-p_i)^n}{p_i}\right) \\ &= \frac{2r}{v} - \frac{2r}{v*n} * \frac{1-(1-p_i)^n}{p_i} \end{aligned}$$

The n value is substituted in the above equation to prove the theorem.

It is denoted that Vector $\vec{T} = (T_1, T_2, \ldots, T_N)$ is the service life of all sensors. The problem (P) can be converted to the following equivalent problem.

$$(P1) \max \min_{i\in N} T_i \tag{9}$$

$$Subject\, to\, C_i(p_i, v, r) \geq \xi_i, \forall_i \in \mathrm{N} \tag{10}$$

$$p_i = 1 - e^{-\frac{t_I}{e^i T_i}} \forall_i \in N \tag{11}$$

Theorem 2 *If $\vec{T}^* = (T_1^*, T_2^*, \ldots, T_N^*)$ is the optimal solution of Problem $(P1)$. According to the definition of the network life cycle in Eq. (4), $\vec{T} = (T_i i = \min_k T_k^*, i \in N)$ satisfies Problem $(P1)$.*

Proof Equation (11) shows that p is the monotone function of T. It is denoted that the corresponding discovery probabilities of $\vec{T}^*$ and $\vec{T}$ are $\vec{p}^*$ and $\vec{p}$, respectively, If $\vec{T} \prec \vec{T}^*$, then $\vec{p}^* \prec \vec{p}$. (Symbol "$\prec$" means to compare the inequality one by one. If $\vec{T} \prec \vec{T}^*$, then $\vec{T} \leq \vec{T}^*$ for all $i (i \in N)$).

It is proved that the transmission time expection $C_i(p_i, v, r)$ is a non-decreasing function of p. If the discovery frequency of Sensor i increases to p_i', then we obtain Eq. (12).

$$C_i(p_i, v, r) \leq C_i(p_i', v, r) \tag{12}$$

Therefore, $\vec{p}^*$ is the discovery probability when Problem $(P1)$ has optimal solution. Then, $\vec{p}$ also satisfies.

Using Theorem 2, Problem $(P1)$ is converted to the following form.

$$(P2) \max T \tag{13}$$

$$Subject\,to\, C_i(p_i, v, r) \geq \xi^*, \forall_i \in \mathrm{N} \tag{14}$$

$$p_i = 1 - e^{-\frac{t_I}{e^i T}} \forall_i \in N \tag{15}$$

where $\xi^* = \max \xi_i, i \in N$.

Equation (15) shows that the larger network life cycle T leads to the smaller discovery probability of the sensor. According to Eq. (12), the actual data transmission time of the sensor and MS becomes smaller. In the work, a binary chop is designed to find the optimal T value satisfying $\min_{i \in N} C_i(p_i, v, r) = \xi^*$.

Through the calculation of $m_{\max}$, the error between the optimal solution and output value T_{record} of T is less than $(T^{(1)}/2^m_{\max})$. If the error needs to be controlled in a small range ,ϵ then the complexity of the binary chop is $o(\log(1/\varepsilon) \cdot N)$.

4 Experimental evaluation

In this section, the performance of PIEE protocol is evaluated by theoretical analysis and simulation experiments. A multihop WSN with the size of n is randomly generated. In the network, each node works in the duty-cycle state. Firstly, we consider the effective data transmission time. The index is defined as the ratio of residual data transmission time and interaction time, namely the residual time ratio.

$$\eta = \mathrm{E}\left[\frac{C_i(p_i, v, r)}{c_{\max}}\right]$$

The above equation shows that the index is relevant to and the discovery probability, beacon length and movement speed. In the experiment, two moving speeds (1 and 8 m/s) are set to test the residual time ratios when MS is in low- and high-speed states. In Fig. 2, the sensor can quickly perceive the MS at the speed of 1 m/s. When the wake frequency is fixed, the index decreases with the increase of beacon length t_I. When the t_I value remains constant, the residual time ratio increases. Therefore, there is still much time for data transmission at low speed of MS even if the sensor has long duty cycle, thus enlarging the life cycle of the network. Figure 3 shows that the residual time ratio rapidly decreases with the increase of t_I or duty cycle when MS is at high speed.

In the experiment, the second index is the ratio of the frequency that the sensor finds MS to the total number of interactions, namely MS discovery rate. Three different protocols are applied, including DIRL [29–31], SORA [32] and PIEE. In Fig. 4, all the MS entering the interactive area can be found by the sensor at low speed. When the speed is high (8 m/s), MS discovery rate declines; PIEE discovery rate reaches more than 95%.

Algorithm 1: Binary chop to find the optimal T value

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Initial Setup: The sink sets $T^{(1)}$to a half of the maximum possible lifetime and sets $T_{record} \leftarrow 0$
for$m$=1 to $m_{max}$ do
    Every node$i$ computes $p_i^{(m)} = 1 - e^{-(t_I/(T^{(m)}e_i))}$.
    Node$i$ send their feedback of theirtransmission time $C_i$ to the sink.
    The sink sets $C_{min} \leftarrow min_i C_i$, and
    if$C_{min} < \xi^*$then
        $T^{(m+1)} \leftarrow T^{(m)} - (T^{(1)}/2^m)$.
    else
        $T^{(m+1)} \leftarrow T^{(m)} - (T^{(1)}/2^m)$and$T_{record} \leftarrow T^{(m)}$.
    end if
end for
return$T^* \leftarrow T_{record}$
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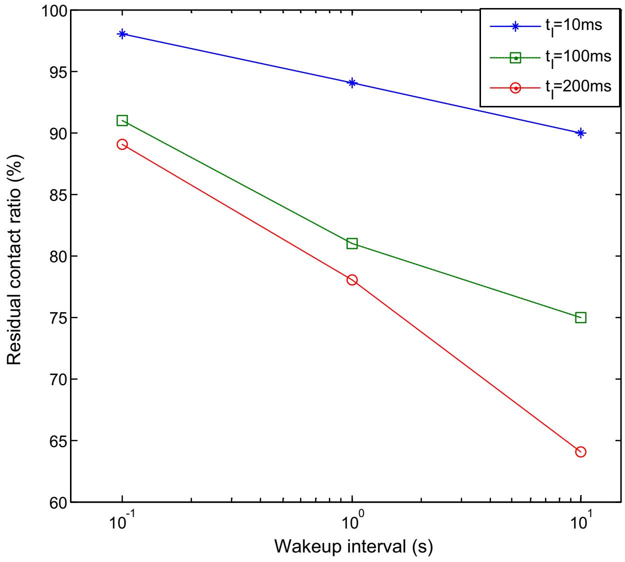

Fig. 2 Residual time ratio at low speed

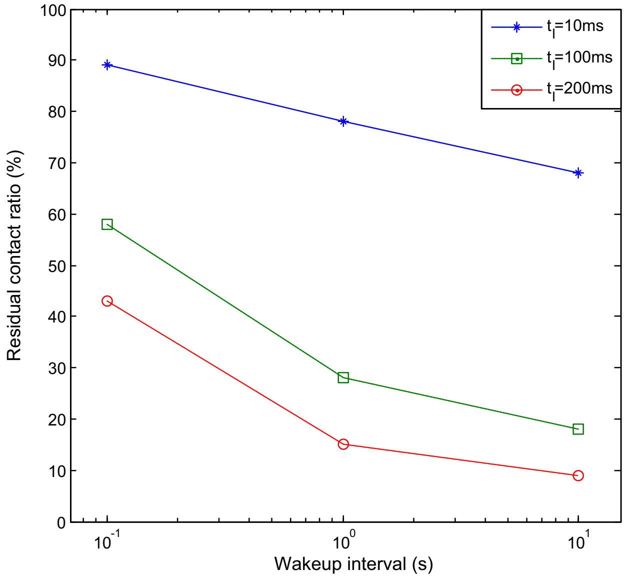

Fig. 3 Residual time ratio at high speed

The network life is tested in real mobile sensor environment. MS adopts the mobile robot with the sensor communication radius of 100 m. The speed of MS is denoted as 2 m/s; t_I as 10 ms; the maximum communication time as 100 s.

Figure 5 shows experimental results. The larger MS speed leads to the shorter network life, thus meeting residual time requirements ($\xi*$). Here, high wake-up frequency consumes the sensor energy. Correspondingly, the MS has low discovery rate. The sensor fails to transmit data, resulting in a waste of sensor energy.

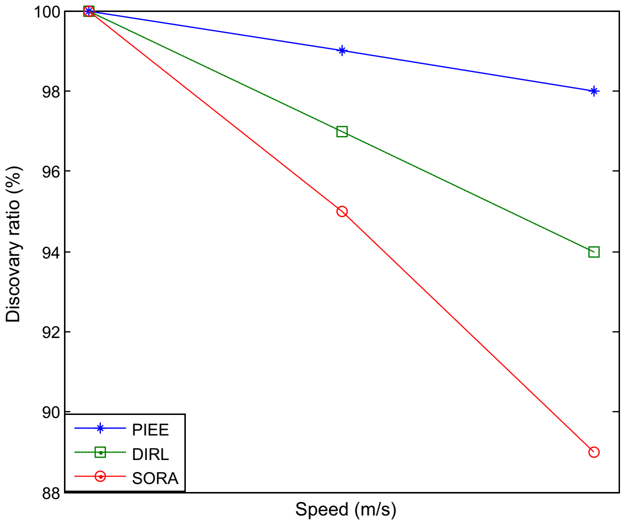

Fig. 4 MS discovery ratios at different speed

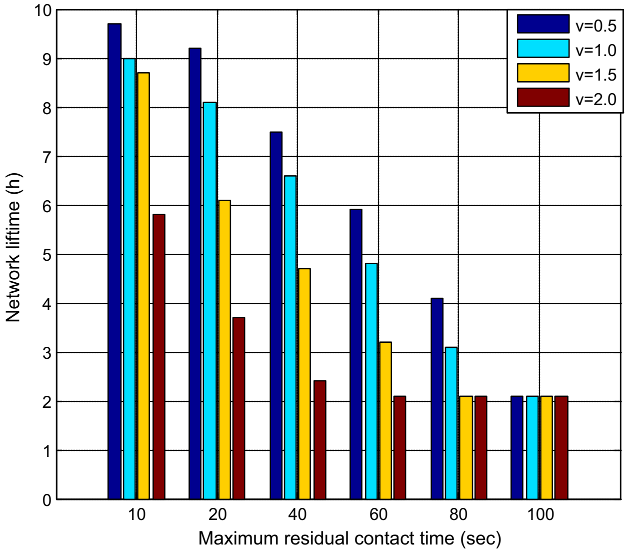

Fig. 5 Relationship between network lifetime and maximum residual transmission time

5 Conclusions

In the work, the data were collected by MS to propose a MS discovery and data collection protocol relevant to time. The protocol was applied in the duty-cycle sensor network. Based on adequate data transmission, we used the lower duty cycle to maximize the life of network. PIEE was an asynchronous protocol which was easily achieved. It was irrelevant to the time when MS reaches the sensor. The theoretical results are in good agreement with the experimental results.

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References

1. Akyildiz, I F., Su, W., Sankarasubramaniam, Y., Cayirci, E.: A survey on sensor networks. IEEE Commun. Mag. **40**(8), 102–114 (2002)
2. Ren, F.Y., Huang, H.N., Lin, C.: Wireless sensor networks. J. Softw. **14**(7), 1282–1291 (2003)
3. Li, M., He, Y., Liu, Y., Zhao, J., Tang, S., Li, X., Dai, G.: Canopy closure estimates with greenorbs: sustainable sensing in the forest[C]. In: Proceedings of the 7th ACM Conference on Embedded Networked Sensor Systems (Sensys), pp. 99–112 (2009)
4. Luo, J., Zhang, Q., Wang, D.: Delay tolerant event collection for underground coal mine using mobile sinks. In: Proceedings of the IEEE International Workshop on Quality of Service (IWQoS), pp. 1–9 (2009)
5. Xing, G., Wang, T., Xie, Z., Jia, W.: Rendezvous planning in wireless sensor networks with mobile elements. IEEE Trans. Mob. Comput. **7**(12), 1430–1443 (2008)
6. Gao, S., Zhang, H.K.: Optimal path selection for mobile sink in delay-guaranteed sensor networks. Acta Electron. Sin. **39**(4), 742–747 (2011)
7. Dantu, K., Rahimi, M., Shah, H., Babel, S., Dhariwal, A., Sukhatme, GS.: Robomote: enabling mobility in sensor networks. In: Proceedings of the ACM/IEEE International Conference on Information Processing in Sensor Networks (IPSN), pp. 404–409 (2005)
8. Gao, S., Zhang, H., Das, S.K.: Efficient data collection in wireless sensor networks with path-constrained mobile sinks. Mob. Comput. **4**, 592–608 (2011)
9. Erman, A.T., Dilo, A., Havinga, P.: A fault-tolerant data dissemination based on honeycomb architecture for mobile multi-sink wireless sensor networks. In: International Conference on Intelligent Sensors, pp. 97–102 (2017)
10. Hawbani, A., Wang, X., Kuhlani, H., Karmoshi, S., Ghoul, R.: Sink-oriented tree based data dissemination protocol for mobile sinks wireless sensor networks. Wirel. Netw. **2**, 1–12 (2017)
11. Xia, R., Tian, Y.-C., Li, Y., Sung, Y.: Wireless sensor/actuator network design for mobile control applications. Sensors **7**(7), 2157–2173 (2007)
12. Wang, Y., Wu, H.Y., Dang, H., Lin, F.: Analytic, simulation, and empirical evaluation of delay/fault-tolerant mobile sensor networks. IEEE Trans. Wirel. Commun. **1**(11), 3287–3296 (2007)
13. Luo, J., Zhang, Q., Wang, D.: Delay tolerant event collection for underground coal mine using mobile sinks. In: Proceedings of the IEEE International Workshop on Quality of Service (IWQoS), pp. 1–9 (2009)
14. Chebrolu, K., Raman, B., Mishra, N., Valiveti, PK., Kumar, R.: BriMon: A sensor network system for railway bridge monitoring. In: Proceedings of the ACM International Conference on Mobile Systems, Applications, and Services (Mobisys), pp. 2–14 (2008)
15. Ammari, H., Das, S.: Data dissemination to mobile sinks in wireless sensor networks: an information theoretic approach. In: Proceedings of the 2th IEEE International Conference on Mobile Ad Hoc and Sensor Systems (MASS), pp. 305–314 (2005)
16. Ye, W., Heidemann, J., Estrin, D.: Medium access control with coordinated adaptive sleeping for wireless sensor networks. IEEE/ACM Trans. Netw. **12**(3), 493–506 (2004)
17. Ye, W., Silva, F., Heidemann, J.: Ultra-low duty cycle MAC with scheduled channel polling. In: Proceedings of the 4th International Conference on Embedded Networked Sensor Systems (Sensys), pp. 321–334 (2006)
18. Chakrabarti, A., Sabharwal, A., and Aazhang, B.: Using predictable observer mobility for power efficient design of sensor networks. In: Proceedings of the ACM/IEEE International Conference on Information Processing in Sensor Networks (IPSN), pp. 129–145 (2003)
19. Polastre, J., Hill, J., and Culler, D.: Versatile low power media access for sensor networks. In: Proceedings of the 2nd ACM Conference on Embedded Networked Sensor Systems (SenSys), pp. 95–107 (2004)
20. Yang, X., Vaidya, N.: A wakeup scheme for sensor networks: Achieving balance between energy saving and end-to-end delay. In: Proceedings of the IEEE Real-Time and Embedded Technology and Applications Symposium (RTAS), pp. 19–26 (2004)
21. Anastasi, G., Conti, M., Francesco, M.D., Passarella, A.: Energy conservation in wireless sensor networks: a survey. Ad Hoc Netw. **7**(3), 537–568 (2009)
22. Chakrabarti, A., Sabharwal, A., and Aazhang, B.: Using predictable observer mobility for power efficient design of sensor networks. In: Proceedings of the ACM/IEEE International Conference on Information Processing in Sensor Networks (IPSN), pp. 129–145 (2003)
23. Yang, X., Vaidya, N.: A wakeup scheme for sensor networks: Achieving balance between energy saving and end-to-end delay. In: Proceedings of the IEEE Real-Time and Embedded Technology and Applications Symposium (RTAS), pp. 19–26 (2004)
24. Anastasi, G., Conti, M., Francesco, M.D.: Reliable and energy-efficient data collection in sparse sensor networks with mobile elements. Perform. Eval. **66**(12), 791–810 (2009)
25. Anastasi, G., Borgia, E., Conti, M., Gregori, E.: A hybrid adaptive protocol for reliable data delivery in WSNs with multiple mobile sinks. Comput. J. **54**(2), 213–228 (2011)
26. Anastasi, Q., Conti, M., and Francesco, M.D.: An analytical study of reliable and energy efficient data collection in sparse sensor networks with mobile elements. In: Proceedings of the European Conference on Wireless Sensor Networks (EWSN), pp. 199–215 (2009)
27. Sugihara, R., Gupta, R.K.: Optimal speed control of mobile node for data collection in sensor networks. IEEE Trans. Mob. Comput. **9**(1), 127–139 (2010)
28. Francesco, D.M., Das, S.K., Anastasi, G.: Data collection in wireless sensor networks with mobile elements: a survey. ACM Trans. Sens. Netw. **8**(1), 1805–1821 (2011)
29. Schurgers, C., Tsiatsis, V., Ganeriwal, S., Srivastava, M.B.: Optimizing sensor networks in the energy-latency-density design space. IEEE Trans. Mob. Comput. **1**(1), 70–80 (2002)
30. Liu, R., Pan, T., Li, Z.: Multi-model recursive identification for nonlinear systems with non-uniformly sampling. Clust. Comput. **20**, 25 (2017). https://doi.org/10.1007/s10586-016-0688-0
31. Ranran, Liu, Enxing, Zheng, Shan, Chang, Shaoyi, Bei, Lanchun, Zhang: Hierarchical stochastic gradient identification for non-uniformly sampling Hammerstein systems with colored noise. Comput. Syst. Sci. Eng. **31**(6), 425–430 (2016)
32. Mainland, G., Parkes, D., Welsh, M.: Decentralized, adaptive resource allocation for sensor networks. In: Proceedings of IEEE NSDI, pp. 315–328 (2005)

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