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An Energy-Efficient Sleep Strategy for Target Tracking Sensor Networks

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Abstract: Energy efficiency is very important for sensor networks since sensor nodes have limited energy supply from battery. So far, many researches have been focused on this issue, while less emphasis was placed on the optimal sleep time of each node. This paper proposed an adaptive energy conservation strategy for target tracking based on a grid network structure, where each node autonomously determines when and if to sleep. It allows sensor nodes far away from targets to sleep to save energy and guarantee the tracking accuracy. The proposed approach extend network lifetime by adopting an adaptive sleep scheduling scheme that combines the local power management (PM) and the adaptive coordinate PM strategies to schedule the activities of sensor nodes. And each node can choose an optimal sleep time so as to make system adaptive and energy-efficient. We show the performance of our approach in terms of energy drop, comparing it to a naive approach, dynamic PM with fixed sleep time and the coordinate PM strategies. From the experimental results, it is readily seen that the efficiency of the proposed approach. *Copyright © 2014 IFSA Publishing, S. L.*

Keywords: Energy efficiency, Target tracking, WSN, Sleep strategy, Power management.

1. Introduction

In wireless sensor network (WSN), sensor nodes are always deployed in unattended natural environment. It is infeasible to replenish energy via replacing their battery after deployment. Therefore, reducing energy consumption to prolong the life of the network is the most critical issue in WSN.

PM is a good way to conserve energy after sensor nodes deployed [1]. The main idea of PM is dynamically getting nodes sleep to reduce energy consumption. In order to devise a more efficient PM mechanism, the application constraints should be considered, mainly in WSN that strongly depend on an application. In target tracking sensor network, the users are only interested in the occurrence of a certain event. These interesting events don't happen frequently. There are two stages: the surveillance stage is to detect a target, while the tracking stage is to collectively track the moving path of a target.

Many pioneering research in the area of energy conservation for WSNs has focused on dynamic PM schemes, such as [3-5]. However, the existing works have follow limitations, 1) the sleep period of sensor nodes can not changes primely according to the position of the target. As a result, many nodes far away from the target consume more energy in active mode, however they do not detect any target. 2) In coordinate PM approach, when a node decides if it should go to sleep state, it will use the information from its neighbors. Due to dense nodes in WSN, the information from adjacent nodes is similar and

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related. If every node sends the detected information to its neighbors, lots of energy will be wasted.

Based on these concepts, we propose an energy-efficient sleep strategy (EESS) that considers the application constraints to exploit sleep states. We manage the power of sensor nodes based on a grid-based network structure, which divides the entire sensing field into virtual grids. In each grid, one node is selected as grid head (GH) and others are grid members (GMs) [12]. In detail, the contributions of this paper are three aspects:

- **Proposing a new adaptive PM approach:** our approach based on a grid network structure combined the advantageous of the synchronization and asynchronization sleep schedule. GH keeps active and reduces the data transmission delay, whereas GMs in different grids adopt adaptive sleep time to save energy.
- **Balancing the energy consumption:** the farther the distance from the grid to the network border is, the longer sleep time GMs have, so that the energy consumption between the border and interior nodes are balanced since the interior nodes always take more relay task.

2. Related Works

To achieve satisfactory network lifetime, several methodologies have already been studied. In [2, 3], the authors introduce some PM policies, in which nodes reduce the power consumption by selectively shutting down idle components. The authors in [4] use an adaptive learning tree scheme such that the quality of the shutdown control algorithm depends on the knowledge of the user behaviour. However, above-mentioned policies are intended for general sensor networks. There are few proposals considered the characteristics of tracking moving object application and use application constraints in a DPM scheme to optimize it.

For target tracking in WSN, information driven sensor collaboration mechanism is proposed in [5], which determines participants in "sensor collaboration" by dynamically optimizing the information utility of data for a given cost of communication and computation. In addition, to switch off the idle nodes, some prediction algorithms are developed for predicting the object movement in [6]. Some other researches like [7], the authors propose a tree-based approach for energy management to collaborate sensor nodes in detecting and tracking a mobile target. In [8], the authors extend the local timeout policy to a distributed network of nodes. And each node uses the results of the motion detection from neighbor nodes to more effectively make PM decisions. In [9], the authors divide sensor network into border nodes and interior nodes to dynamically change the each node's sleep schedule separately. However, every sensor node has a fixed sleep time in above strategies. And little effort has been made for the optimal sleep time of each node, which is an important factor for energy efficiency in tracking sensor network.

3. System Model

3.1. Network Model

We consider a static WSN which composed of one sink and some randomly distributed sensor nodes in a two-dimensional sensing field. The sink has an infinite power supply, and it gathers the sensed information from sensor nodes. We assume each node is aware of its location after deployment. In the definition of virtual grid, each pair of nodes in neighbour and diagonal grids can communicate directly with each other [12]. Assume the transmission range of sensor node is R_t. We size each grid is a $\alpha \times \alpha$ square. In order to meet the definition of virtual grid, in any two adjacent grids, the distance between two possible farthest nodes must not be larger than R_t. Therefore, we get:

$$(2\alpha)^2 + (2\alpha)^2 \le R_t^{\,2} \quad \text{or} \quad \alpha \le \frac{R_t}{2\sqrt{2}} \tag{1}$$

Initially, all the sensor nodes are in idle state and have the same initial energy. A node in each grid is selected as the GH randomly by broadcasting an announcement after waiting for a random time period. The node who first broadcasts its GH announcement in a grid will be the GH.

3.2. Energy Management Model

In target tracking application, if a target appears in the sensing area of a node, the node should be awake in advance to sense the target. For the other nodes, they remain in the sleep state s_k most of the time and switch to active state s_0 at specified time slots to check if there are sensing or relay tasks in the next time instant. If there are tasks, only one sensor node in same square keeps active to maintain the connectivity and forward data to the sink.

Fig. 1 shows the power-time curves for transition of the sleep states. Each sleep state s_k has power consumption P_k. The transition time to it from active state and back are denoted by $\tau_{d,k}$ and $\tau_{u,k}$, respectively [1]. We define the node sleep states as $i > j$, $P_j > P_i$, $\tau_{d,i} > \tau_{d,j}$ and $\tau_{u,i} > \tau_{u,j}$. In Fig.1, we assume an event is detected by N_i at some time. N_i finishes processing the event at time t_1 and predicts the next event occurs at time $t_2 = t_1 + t_i + \tau_{u,k}$. Thus a sleep time threshold $T_{th,k}$ can be utilized to avoid losing event,

$$T_{th,k} = \tau_{d,k} + \tau_{u,k} \tag{2}$$

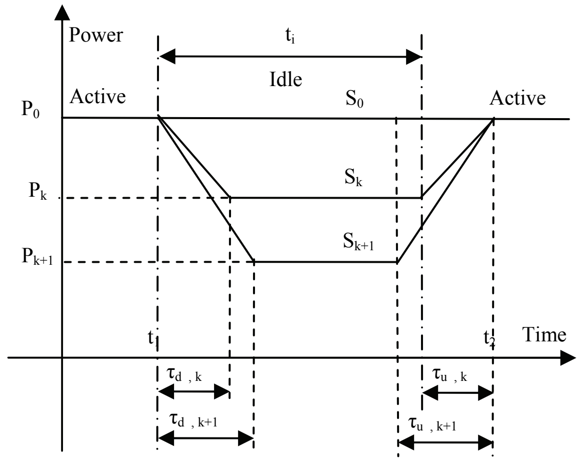

Fig. 1. Sleep states transition latency and power.

If (t_2- t_1)> $T_{th,k}$, N_i can go to sleep state s_k at time t_1 and wake up at t_2 . Otherwise, when (t_2- t_1) ≤ $T_{th,k}$, N_i should not. So the saving energy from a state transition can be calculated as follow,

$$E_{save,k} = P_0\left(t_i+\tau_{u,k}\right)-\frac{P_0+P_k}{2}\left(\tau_{d,k}+\tau_{u,k}\right)-P_k\left(t_i-\tau_{d,k}\right) = \frac{P_0-P_k}{2}\left(2t_i-\tau_{d,k}+\tau_{u,k}\right) \quad (3)$$

The energy saving makes sense when $E_{save,\,k}$> E_c, where E_c is the additional energy consumption for the sleep states transition. So the threshold,

$$T_{th,k} = \frac{1}{2}(\tau_{d,k} - \tau_{u,k}) + \frac{E_c}{P_0 - P_k} \quad (1)$$

4. Adaptive Sleep Policy

4.1. Sleep Policy in Surveillance Stage

To save energy, the sensor nodes should stay in the sleep mode as much as possible. During surveillance time, though there is no target in the sensing area, all the sensor nodes should remain at a certain level of vigilance to get ready for detecting. When a target enters into the sensing area, it has to pass through the border of the area. Due to this reason, to avoid missing a target and have less energy consumption, only a necessary the sensor nodes in fringe grids (FG) keep alert and the nodes in interior grids (IG) can have more sleep time as shown in Fig. 2. Therefore, this way not only conserves more energy but also grantees the target detecting. Moreover, it can balance the energy consumption between the fringe nodes and the interior nodes since the nodes in IG always take more relay task.

The GMs in each grid have the same sleep/awake period. The sleep time of the GMs is adaptively adjusted by their GH according to the distance from the grid to the network border. At the initial stage, each GH calculates the sleep time for its GMs and informs them. In each period, GH decide if the sleep time of its GMs needs to be changed based on the information received or detected (e.g. the GH received the detected information from one of its GMs). If needed, the GH will send a new sleep time value to its GMs. Otherwise, the GMs keep the sleep period as the same value as before. To meet the requirement of the application and not miss the target, the maximum sleep time of the GMs in FG can be calculated as follow,

$$\max t_{sleep}^{FG} = \left(\frac{R_{sense}^{FG}}{v_{\max}} - \tau_{d,sp} - \tau_{u,sp}\right)/\eta, \quad (5)$$

where R_{sense}^{FG} is the side length of sensing area of the nodes in FG. And η is the success ratio of detecting required by application. When $\max t_{sleep}^{FG}$ meets the requirement mentioned in equations (2) and (4), the sleep time of the GMs in FG t_{sleep}^{FG} can be set as $\max t_{sleep}^{FG}$, otherwise it is 0.

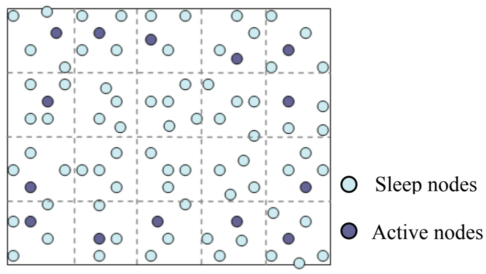

Fig. 2. Sleep intervals algorithm in the surveillance stage.

As the distance between the grids and the network border increases, the GMs can have more sleep time to save energy and GMs in the different grids can have different sleep time schedules. In the interior grids, the GHs calculate the maximum sleep time for its GMs using follow equation,

$$\max t_{sleep}^{IG} = \left(\frac{L\alpha}{v_{\max}} - \tau_{d,sp} - \tau_{u,sp}\right)/\eta, \quad (6)$$

where L is the number of grids from the current grid to the nearest network border.

In addition, the active parts of GMs and their GH must be partially overlapping to allow GMs and their GH to communicate with each other. Thus, a reasonable sleep time of the CMs in the IG can be obtained,

$$t_{sleep}^{IG}\,' = \left\lfloor \frac{\max t_{sleep}^{IG}}{T_{GH}} \right\rfloor T_{GH} - \tau_{u,sp}, \quad (7)$$

where T_{GH} is the periods of GHs. The sleep/awake periods of GHs are set the same as that of the GMs in FG so that the GMs in FG can send their sensing data to their GHs or receive the PM information from their GHs to adjust their sleep time accordingly. Just all the GHs adopt the local PM policy and they keep synchronization. GHs keep a timer recording how long no event has been detected and goes to sleep after this timer times out. After a fixed sleep time, they return to active. If they detect a target, they keep active at the next time instant. When $t_{sleep}^{IG}{}' \geq T_{th^1}$ and $t_{sleep}^{IG}{}' > T_{th^2}$ holds, the sleep time of the GMs in IG t_{sleep}^{IG} can be set as $t_{sleep}^{IG}{}'$, otherwise t_{sleep}^{IG} =0.

When one fringe node detects a target, it can report the information of the moving target to its GH without delay. Then, the GH can inform its neighbour GHs to re-arrange the sleep time for their GMs. In this way, the interior nodes have an adaptive sleep time without missing targets in the surveillance stage.

4.2. Sleep Policy in Tracking Process

When a target appears, the node who detects the target first will broadcast a message "*found_target*" to the whole network. Then each sensor node received the message turns to active state to get ready for detection. If they detected a target, they will transmit their data toward the sink by multi-hop routing. Otherwise, one active node will be elected on duty in a grid and others get to sleep. At the same time, the node on duty (*NoD*) sets a timer to record how long no event has been detected by itself. Once the target is detected, the timer will be reset. Then the node wakes up the others in same square (*SS)* to track the target and sends a message to the *NoD* in neighbour square (*NS)* so that they can prepare to track the target at the next moment. If a *NoD* N_i did not find any event during a fixed time, the node sends a message "*collect_information*" to *NoD* in *NS*. If the *NoD* in *NS* detected the target, they reply a message "*detection_information*" which includes their ID and the estimations about the speed and distance of the target. Or else, they do not send anything. After receiving the replies, N_i can calculate the sleep time t_{sleep} by equation (8),

$$t_{sleep} = \begin{cases} \left(\dfrac{d_{i1} + d_{i2} + \cdots + d_{ik}}{k} - r\right) / v_{max} & m_{received} = 0 \\ \left(d_{ij} - d_{jt} - r\right) / v_{max} & m_{received} = 1 \\ \sum\limits_{j=m}^{j=1} \left(\alpha \dfrac{d_{ij}}{v_{max}} - \beta \dfrac{d_{jt}}{v_{max}}\right) - \dfrac{r}{v_{max}} & m_{received} = m, m > 1 \end{cases}, \quad (8)$$

where k is the number of *NoD* in *NS* of node N_i. The distance between N_i and *NoD* in *NS* denoted as d_{ij} (*j=1, 2…k*). $m_{received}$ is the quantity of the replies received by N_i. d_{jt} is the distance between the *NoD* in *NS* and the target. α is the weight of distance between N_i and *NoD* in *NS*, $\alpha = d_{ij} / (d_{i1} + \cdots + d_{im})$. β is the weight of distance between the nodes detected target and the target, $\beta = d_{jt} / (d_{1t} + \cdots + d_{mt})$.

When N_i calculated the sleep time t_{sleep}, it compares the t_{sleep} value with the sleep time threshold $T_{th,k}$ above-mentioned equations (2) and (4). If $t_{sleep} \leq T_{th,k}$ holds, N_i will keep the current sleep mode. If $t_{sleep} > T_{th,k}$, N_i informs other nodes in *SS* about the updated sleep time and puts itself into the low-power mode s_k for a length of time t_{sleep}. Once the sleep time expires, N_i returns to the active mode again and the process repeats as Fig. 3.

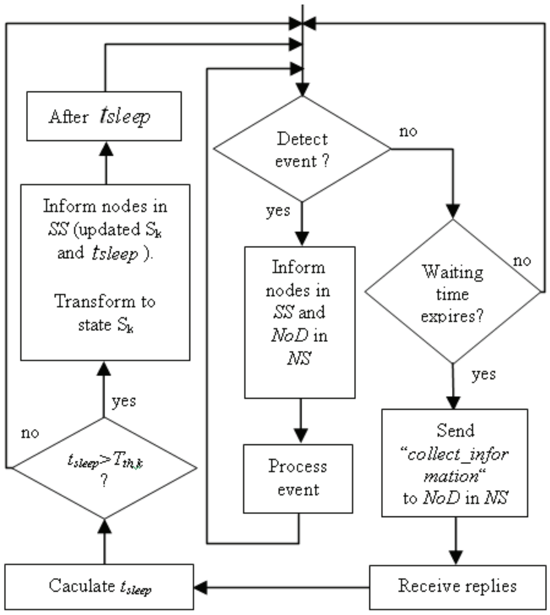

Fig. 3. Sleep state transition algorithm and process.

In this way, sensor nodes will get the target movement information from the *NoD* in *NS* and accurately estimate the sleep state and time interval considering the impacts of different distances between nodes and the target.

5. Simulations and Analysis

5.1. Experiment Environment

We set up simulation by OMNet++4.0, which is an object-oriented discrete event network simulation platform. We assume that there are 512 sensor nodes distributed randomly over an area of 1000 m by 1000 m. And the sensing range of each sensor node is r=50 m. We also assume each node has an initial energy of 100 J (Joules).

The transmission cost between the sensor nodes is calculated as $\psi_{Tx} = \lambda_1 u + \lambda_2 d_{ij}^2 u$ [11], where u denotes the data rate, λ_1 denotes the electronics energy expended and $\lambda_2 > 0$ is a constant related to the radio energy. In our simulation, we set parameters

λ_1 = 50 nJ/b, λ_2 = 100 pJ/($b \cdot m^2$). The bandwidth of wireless channel is 2.4 Kbps, and the data packet size is 512 bytes.

5.2. Simulation Results

To compare the performance of EESS with other schedules, we implemented the other three policies, namely 1) No PM approach (nodes are always on), 2) local PM approach (all the nodes sleep periodically if they did not detect any event in 0.5 s and the fixed sleep time is set as 1.5 s), 3) adaptive coordinate PM approach (all the nodes collect detection information from their neighbors periodically, the detection time is 0.5 s). Firstly, we simulated the sensor network in the surveillance stage.

Fig. 4 shows the average energy consumption changed with simulation time of the approaches in the surveillance stage. It can be seen that EESS approach can save about 45 % and 35 % more energy compared to local PM and coordinated PM approach in the surveillance stage. EESS can obtain the best energy efficiency because only network border nodes and GHs keep alert, whereas lots of interior nodes have a long-term sleep. In local PM, all nodes have fixed sleep schedule, the energy consumption depends on the active and sleep intervals set by user. If nodes have longer sleep time, more energy is saved but it brings longer transmission delay and more target missing. Coordinated PM consumes less energy than that in local PM because each node knows there is no target in its and its neighbors sensing range by communicating with its neighbors. No PM approach network consumes the most energy because nodes are always active.

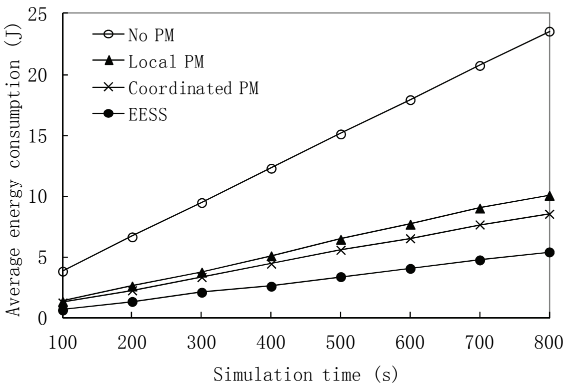

Fig. 4. Average energy consumption in surveillance stage.

The network lifetime of the four approaches in surveillance and tracking stages is compared in Fig. 5 and Fig. 7, respectively. In the figure, we compare the network lifetime for the different percentage of nodes dying. As shown, EESS can significantly prolong the network lifetime in all cases. For example, if the lifetime is defined as the time when 20 % of nodes die, EESS achieves lifetime extensions by 60 % and 35 % compared to local PM and coordinated PM in surveillance stage, and 15 % and 25 % in tracking stage respectively. Similar lifetime extensions are achieved for the other cases.

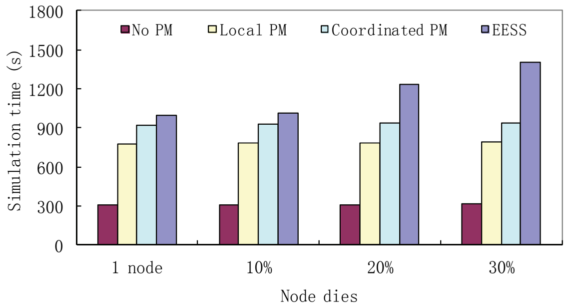

Fig. 5. Lifetime in surveillance stage.

Next, we assume the target enters the field at a random location and moves continuously with the maximum speed of 10 m/s. Fig. 6 shows the average energy comparison of the approaches. We can see that the energy consumption of no PM and local PM approaches in tracking stage has a little increase compared with that in surveillance stage because these approaches adopt the same PM strategies in both surveillance and tracking stage and the increase part is just caused by the sensed data transmission, whereas EESS has relative higher increase in tracking stage because the interior nodes have shorter sleep time compared with that in surveillance stage. Coordinated PM approach consumes more energy than EESS due to more communication cost among neighbor nodes. Each node periodically broadcast its detected information in coordinated PM while only GH broadcast the detected information when a target is detected in EESS. It can be seen that EESS saves about 26 % and 33 % more energy compared to local PM and coordinate PM approach in tracking stage.

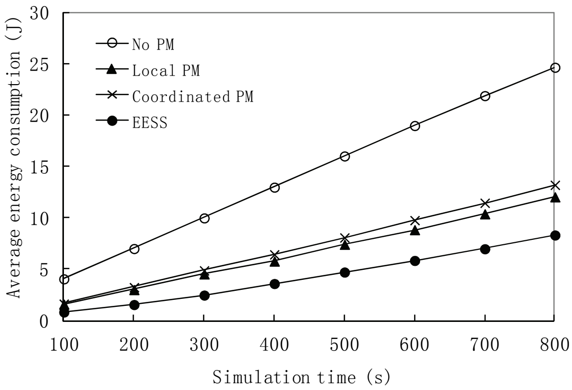

Fig. 6. Average energy consumption in tracking stage.

We further investigated the performance of our approach as the number of nodes increases while keeping the other parameters constant. The number of nodes is varied from 256 to 1536 nodes. Fig. 8 and Fig. 9 show the average energy consumption in the surveillance and tracking stages, respectively. EESS consumes significantly less energy compared to the other approaches because only GH is always awake in each grid and the GMs are awake periodically and have a short-term active and long-term sleep interval. The average energy consumption decreases with the increasing nodes because more sensor nodes can go to long-term sleep both in the surveillance and tracking stage when node density increases, which leads to further energy saving.

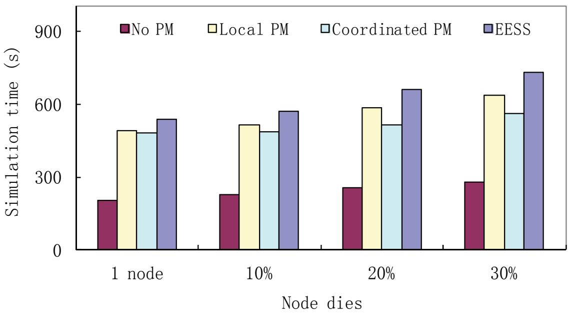

Fig. 7. Lifetime in tracking stage.

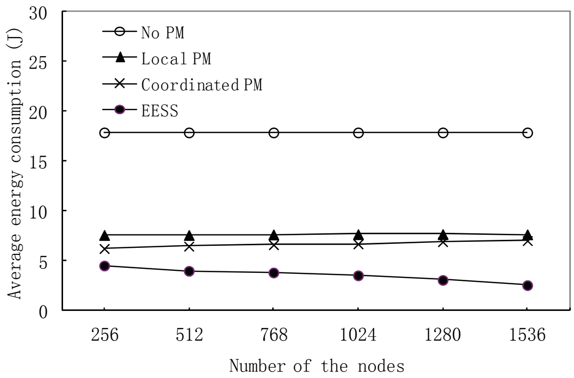

Fig. 8. Average energy consumption vs. the nodes number in surveillance stage.

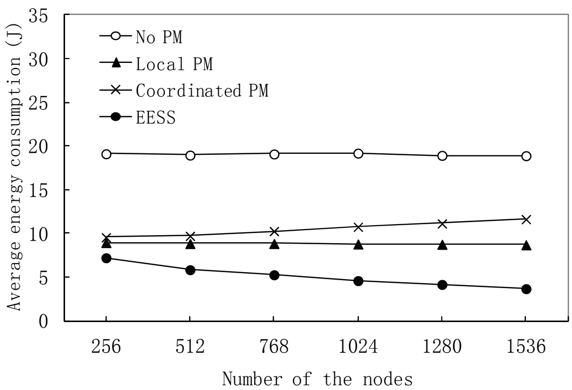

Fig. 9. Average energy consumption vs. the nodes number in tracking stage.

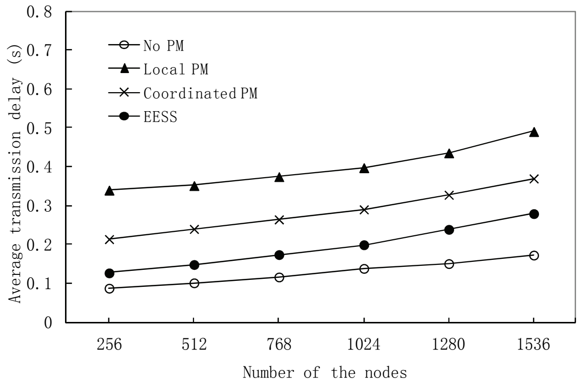

Fig. 10. Average transmission delay vs. the nodes number in tracking stage.

Fig. 10 shows that average transmission delay changed with the number of the sensor nodes in the different PM approach. If the other parameters are fixed, the average delay increases when node density increases. More nodes will be awake and detect the target at a higher density, which may create more data packets and hence increase the delivery delay. The delay of local PM is the largest among these approaches because the nodes with local PM has fixed sleep schedule and the node decide if it go to sleep by itself so that the nodes have to wait for its relay nodes awake to send data when it has sensed data. EESS performs better than local and coordinated PM approaches because the GHs always keep active for the sensed data transmission.

6. Conclusions

This paper proposed an energy-efficient sleep strategy (EESS) for tracking target in WSN. It can reduce energy consumption and extend the network lifetime without degrading the tracking performance. EESS outperforms the other PM approaches by allowing more nodes to sleep in the surveillance state and tracks the target by dynamically changing the schedule in the tracking state. GHs utilized the information sensed both locally and by neighboring GHs to optimal the sleep time of their GMs. Moreover, our approach also reduces the data transmission delay. Simulation results proved that EESS performs better than three state-of-the-art approaches in terms of energy consumption and data transmission delay.

Acknowledgements

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