DETERMINING NODE DENSITY TO GUARANTEE AVERAGE LATENCY IN DUTY-CYCLED WIRELESS SENSOR NETWORKS

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Abstract

Some applications of Internet of Things (IoTs) require that generated data are delivered to the sink within an end-to-end (E2E) delay bound. Moreover, to save energy consumption or to lengthen the network lifetime, a duty cycle scheme is applied in which sensor nodes periodically switch the radio on and off. In the duty-cycled networks, packet delay is greatly affected by node deployment, therefore we aim to determine node density in a wireless sensor network in order to guarantee the average E2E delay given network parameters using the probability theory. Simulation results show that the proposed node deployment method consumes less energy while requiring a smaller number of sensor nodes than those of other existing works.

Keywords: *Energy consumption; routing scheme; delay requirement; wireless sensor networks.*

1. Introduction

Thanks to the development of low-cost and multi-functional sensors, wireless sensor networks (WSNs) have been widely used in many areas, such as military, surveillance missions, industry, and agriculture, among others [1, 2]. In delay-sensitive WSNs, there is a demand that the E2E packet delay is lower than a given delay requirement. For example, detecting abnormal behavior (e.g., fire, gas leakage) should be reported to the operator within a threshold value. Therefore, the main purpose of this work lies on designing a wireless sensor network which guarantees the E2E packet delay while consumes a small amount of energy.

For reducing the energy consumption, a duty-cycling technique can be applied, in which nodes become active during a wake-up period, and sleep for the rest of a duty cycle interval [3]. Since the data rate in WSNs is quite low, using the duty-cycling technique is a good choice to preserve the energy of sensors. While using this technique, two important factors, i.e., the duty-cycle interval and node deployment, which have great impacts on the E2E delay, should be considered. More specifically, the packet latency is directly proportional to the duty-cycle interval and inversely proportional to node density of networks. Therefore, a node deployment strategy is introduced to meet

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the delay requirement for a given duty-cycle interval. Note that node deployment algorithms in the literature [4-8] generally focused on addressing the energy imbalance problem in the network, i.e., some nodes die early while other sensors still have plenty of energy. For example, in [5] they assumed that the maximum transmission range of nodes in a concentric layer is used as the layer width. For energy consumption balance, the authors computed the nodes' communication range in each layer given network parameters. Meanwhile, in [4] Wu et al. made an assumption that the whole area was classified into a number of concentric layers and all nodes shared the same transmission range. Then, it was proved that sub-balanced energy consumption can be obtained if the number of nodes from the outermost layer increases with the geometric rule. Despite of achieving energy balance, the existing algorithms did not consider the packet latency deadline, which is unsuitable for time-strict applications, e.g., fire detection.

To this end, we propose a node deployment algorithm, which aims to satisfy a given E2E deadline. Specifically, the one-hop packet delay is first estimated and then the E2E delay distribution can be derived by summing one-hop packet delay variables. Taking the advantages of the Taylor expansion and central limit theory, we analyze the mean of E2E delay as a function of network parameters such as the node density in each area and the duty cycle interval. Finally, using a brute-force search method, the node density is derived in order to satisfy the delay requirement.

The contribution of this work is summarized as follows. Firstly, we formulate the average E2E packet delay as a function of network parameters, which helps to estimate the expected packet delay with a given network topology before the network is deployed in the real situation. Secondly, the energy consumption and the required number of nodes are collected to check the performance of the proposed scheme and two other node deployment ones using Matlab. The simulation results indicate that the proposed method outperforms other ones, especially when the deployment area becomes larger.

In the remainder of this paper, the system model and assumption are first introduced in Section 2. Then, the estimation of E2E packet delay and numerical results are explained in details in Sections 3 and 4, respectively. Finally, conclusion of this work has been drawn in Section 5.

2. System Model and Assumption

In this work, we assume that nodes are deployed in a circular area with the sink node at the center. Each node knows its position and should have at least one forwarder which is closer to the sink. Note that the minimum node density which guarantees network connectivity should be considered [9]. The area is divided into *k* circular layers [5, 10, 11] and nodes in layer *i* are supposed to forward data packets to only nodes in the very next layer (*i*-1). Even though the smallest number of hops may be less than *k*, we consider *k* hops in the worst case. The proposed algorithm, called E2E delay Bounded Node Deployment (EBND), determines the number of nodes in each circular layer $N_i\left(1 \le i \le k\right)$ in order to maximize network lifetime, then N_i nodes are deployed randomly with a uniform distribution throughout layer i. Note that each layer may have different node distributions in order to maximize network lifetime. Let R and c denote the transmission range and the width, respectively, of layer $j\left(1 \le j \le k\right)$, and l is defined as the radius of the entire area. The innermost layer is the circular area around the sink with radius R. In order to forward packets to nodes in the next layer, c should be less than R (i.e., $0 < c < R$). In other words, node A belongs to layer 1 if the distance between node A and the sink node, d_A, satisfies $0 \le d_A \le R$, meaning it can transmit packets directly to the sink. Node A belongs to layer $j\left(1 \le j \le k\right)$, if d_A satisfies:

$$R + c(j-1) < d_A < R + c(j-1) \tag{1}$$

where $0 \le d_A \le l$. The total number of layers *k* is calculated as follows:

$$k = \frac{l-R}{c} + 1 \tag{2}$$

Let R_j denote the radius of layer j, and R_j can be calculated as follows:

$$R_j = \left[\begin{array}{ll} R & \text{if } j = 1 \\ R + c\left(j-1\right) & \text{if } 2 \le j \le k \end{array}\right. \tag{3}$$

Define A_j as the area of layer j bounded by the radius of layers j and $\left(j-1\right)$. The size of A_j can be determined as follows:

$$A_j = \left[\begin{array}{ll} \pi R^2 & \text{if } j = 1 \\ \pi\left(R_j^2 - R_{j-1}^2\right) & \text{if } 2 \le j \le k \end{array}\right. \tag{4}$$

Let random variable S_j denote the forwarding area of nodes in layer j. As shown in Fig. 1, S_j of a sender in layer j is defined as the intersection area between 2 circles: the transmission range of the sender and the circular area with radius R_{j-1}. Since our previous publication included formulation of S_j, please refer to [12] for the detail equation of the forwarding area.

Sensors use a duty-cycling strategy, i.e., nodes turn on the radio during an active period and turn it off for the rest of duty cycle interval T. In this paper, a routing algorithm, called layer-based forwarding (LF) algorithm, which is extended from [12] is used. Unlike [12], LF uses neighboring nodes scheduling information (i.e., when neighboring nodes turn on and off radio). All sensor nodes randomly select the wake-up time during the duty cycle interval by using the same pseudo-random algorithm. Specifically, nodes exchange their seed values and IDs at the beginning of network formation. Using exchanged seed values, each node learns the schedules of its neighboring nodes.

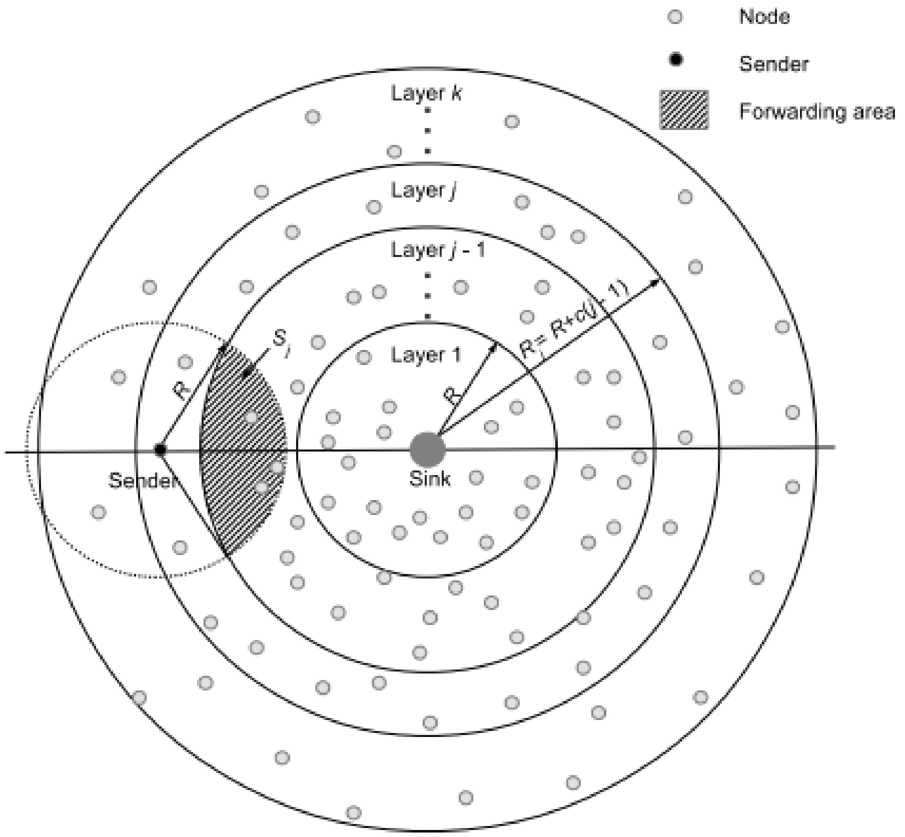

Fig. 1. Network model

Let potential forwarders of a node represent all neighboring nodes belonging to the forwarding area. When it has a data packet, the sender waits until a node from among all potential forwarders wakes up and forwards the packet to the node that wakes up earliest. Since a node is able to predict the schedules of its neighbors, the sender should be in sleep mode until the next hop becomes active. This strategy can help nodes reduce energy consumption by turning off the radio when unnecessary.

In this paper, the energy model is one referred by [13]. On the transmitter side, there are transmission electronics and a transmission amplifier, while the receiver side consists of reception electronics. Transmission power e_{tx} and reception power e_{rx} can be calculated as follows:

$$\begin{aligned} e_{tx} &= \left(\beta_1 + \beta_2 d^{\alpha}\right) L \\ e_{rx} &= \beta_3 L \end{aligned} \tag{5}$$

where α is the power coefficient, $\beta_1 L$ is transmission electronics energy consumption, $\beta_2 d^{\alpha L}$ is energy consumed by a transmission amplifier, and $\beta_3 L$ is reception electronics energy consumption. L and d denote the data rate of each node (bps) and the transmission range, respectively.

3. Estimation of End-to-end Packet Delay

In general, the delay of packets from nodes in the outermost layer is higher than the delay from inner layers. If nodes in layer *k* meet the delay constraint, nodes in the inner layers may also satisfy the delay requirement. Thus, in this paper, we use the average packet delay from nodes in the outermost layer as the delay requirement. Let μ and ξ denote the average end-to-end (E2E) delay of packets in layer k, and the given average delay requirement for the outermost layer (ADROL), respectively.

Average latency μ should be shorter than or equal to given ADROL ξ. Note that the mean of the sum of *k* random variables is equal to the sum of *k* random variables' means. Since μ is the average E2E delay of a packet in layer k, it can be expressed as follows: $\mu = \mu_2 + \ldots + \mu_{k-1} +\ \mu_k$ where μ_j is the one-hop packet delay of a node in layer j. Note that $\mu_1 = 0$, i.e., nodes in the first layer can transmit data packet to the sink immediately, because the sink is assumed to be active all the time. One-hop delay includes processing time and waiting time. In this manuscript, waiting time is from the time a node has a packet (its own packet or a packet received from a neighboring node) to the time a forwarder wakes up. However, processing time can be ignored, since it is much lower than the waiting time until the next hop wakes up. Thus, a one-hop delay can be estimated as the waiting time until the next hop becomes active. Let T denote the duty cycle interval of nodes in the network. Now, we will estimate the average one-hop delay as a function of network parameters, such as the number of nodes in each layer, the duty cycle interval, and the area radius. After that, the average delay of nodes in layer k can be approximated using one-hop delays.

We consider a node in layer j that has m_j potential forwarder(s). Let random variable $D_{i'}$ denote the wake-up time of the i'^{th} node among the m_j potential forwarder(s) $1 \le i' \le m_j$. Since sensor nodes randomly and independently choose a wake-up time, $D_{i'}$ are independent and identical random variables. The distribution function of $D_{i'}$ is $F_{D_{i'}}\left(d_{i'}\right) = P\left(D_{i'} \le d_{i'}\right) = \frac{d_i\,'}{T}$ if $0 \le d_{i'} \le T$. Let random variable Y_j denote the one-hop delay of a packet at layer j, then Y_j will be defined as follows: $Y_j = \min\left(D_1, D_2, \ldots, D_{m_j}\right)$. Let $P\left(Y_j < y_j | m_j\right)$ define the probability that a one-hop latency is shorter than y_j given m_j, i.e., it is the probability that at least one $D_{i'} < y_j$ exists if the node has m_j potential forwarder(s). Then, the cumulative distribution function $F(y_j \mid m_j)$ of y_j given m_j can be expressed as follows:

$$\begin{aligned} F\left(y_j | m_j\right) &= 1 - \text{probability that all } D_i > y_j \\ &= 1 - \prod_{i=1}^{m_j}\left(1 - \mathrm{F}_{D_i\left(\mathrm{y_j}\right)}\right) \\ &= 1 - \left(1 - \frac{y_j}{T}\right)^{m_j} \end{aligned} \tag{6}$$

Now, distribution function $F\left(y_j\right)$ can be obtained using Bayes' theorem, that is:

$$\begin{aligned} F\left(y_j\right) &= \sum_{m_j=0}^{N-1} P_j\left(m_j\right) F\left(y_j | m_j\right) \\ &= \sum_{m_j=0}^{N-1} P_j\left(m_j\right)\left[1 - \left(1 - \frac{y_j}{T}\right)^{m_j}\right] \end{aligned} \tag{7}$$

where $P_j\left(m_j\right)$ is the probability that a node in layer j has m_j potential forwarders in the forwarding area. After that, probability density function $f\left(y_j\right)$ can be obtained by computing a derivative of distribution function $F\left(y_j\right)$:

$$\begin{aligned} f\left(y_j\right) &= \frac{dF\left(y_j\right)}{dy_j} \\ &= \sum_{m_j=0}^{N-1} P_j\left(m_j\right)\frac{m_j}{T}\left[1-\left(1-\frac{y_j}{T}\right)^{m_j}\right] \end{aligned} \tag{8}$$

Then, the average one-hop

$$\begin{aligned} \mu_j &= \int_0^T y_j f\left(y_j\right) dy_j \\ &= \sum_{m=0}^{N-1} P_j\left(m_j\right)\frac{T}{m+1} = E\left[\frac{T}{m_j+1}\right] \end{aligned} \tag{9}$$

where m_j is the number of potential forwarders of a node in layer j.

After applying a Taylor expansion for function $\frac{1}{X}$ around $E\left[X\right]$, we can obtain the expectation of the inverse function by only considering three first elements of the Taylor expansion as follows:

$$\begin{aligned} E\left[\frac{T}{m+1}\right] &\approx E\left[\frac{1}{E\left[X\right]}-\frac{1}{E\left[X\right]^2}\left(X-E\left[X\right]\right)+\frac{1}{E\left[X\right]^3}\left(X-E\left[X\right]\right)^2\right] \\ &= \frac{1}{E\left[X\right]}+\frac{1}{E\left[X\right]^3}\operatorname{Var}\left(X\right) \end{aligned} \tag{10}$$

The ratio between the first and second terms is $\frac{E\left[X\right]^2}{\operatorname{Var}\left(X\right)}$. Note that in our work since X is a non-negative variable with the minimum value 1, $E\left[X\right]^2$ is much greater than $\operatorname{Var}\left(X\right)$. As a result, the second term $\frac{1}{E\left[X\right]^3}\operatorname{Var}\left(X\right)$ is much smaller than the first term $\frac{1}{E\left[X\right]}$. For example, using our simulation setup, the first term is approximately 13.38 times higher than the second one. Therefore, by ignoring the second term, Equation. (9) can be written as follows: $\mu_j = E\left[\frac{T}{m_j+1}\right] \approx \frac{T}{E[m_j+1]} = \frac{T}{E\left[m_j\right]+1}$

The approximate error is $\frac{1}{14.38} = 6.9\%$, which is acceptable due to the assumption that we are considering the worst case of k forwarding hops. Define $\rho_j = \frac{N_j}{A_j}$ as the node density in circular layer j where A_j is the area of layer j and N_j is the total number of node in area A_j. The average number of potential forwarders of a node in layer j can be expressed $E\left[m_j\right] = \rho_{j-1} E\left[S_{j-1}\right] = \frac{N_{j-1}}{A_{j-1}} E\left[S_{j-1}\right]$ where forwarding area S_j is defined in Section 2. Let random variable x denote the distance between the sender (group j) and the boundary of group $j-1$; so that x has a uniform distribution in the range $\left[0, c\right]$ where c is the width of a layer. Note that S_j is a function of x, then the average of forwarding area is calculated as below:

$$E\left[S_j\right] = \frac{1}{c}\int_0^c S_j\left(x\right) \mathrm{dx} \tag{11}$$

Thus, average one-hop delay μ_j can be rewritten in relation to the number of nodes, N_j, in layer j as follows:

$$\mu_j \approx \frac{T}{E[m_j + 1]} = \frac{T}{\frac{N_{j-1}}{A_{j-1}} E\left[S_{j-1}\right] + 1} \tag{12}$$

Define $\alpha_j = \frac{E\left[S_j\right]}{A_j}$, and the delay constraint can be rewritten as follows:

$$\frac{T}{\frac{N_{k-1}}{A_{k-1}} E\left[S_{k-1}\right] + 1} + \frac{T}{\frac{N_{k-2}}{A_{k-2}} E\left[S_{k-2}\right] + 1} + \ldots + \frac{T}{\frac{N_1}{A_1} E\left[S_1\right] + 1} \le \xi \tag{13}$$

The optimization problem determines the number of nodes in each layer (i.e., $N_1, N_2, \ldots, N_{k-1}$) to meet the delay constraint in Eq. (13) given the total number of nodes $N = \sum_{j=1}^{k} N_j$. If $f\left(N_j\right) = \frac{T}{\frac{N_{k-1}}{A_{k-1}} E\left[S_{k-1}\right] + 1} + \frac{T}{\frac{N_{k-2}}{A_{k-2}} E\left[S_{k-2}\right] + 1} + \ldots + \frac{T}{\frac{N_1}{A_1} E\left[S_1\right] + 1}$, then the optimization problem can be written as below:

minimize $f\left(N_j\right)$

subject to $f\left(N_j\right) \le \xi$

$$\sum_{j=1}^{k} N_j = N$$

In order to determine the number of nodes in each layer, we consider a brute-force algorithm which tries all possible cases of N_j. Then, the proposed algorithm outputs the case with the smallest average E2E packet delay.

4. Numerical Results

In this section, we compare EBND with other schemes that also aim at maximizing network lifetime or balancing energy consumption. For example, Olariu's scheme [5] adjusts the transmission range, and Wu's scheme [4] proposed a deterministic non-uniform node deployment strategy. According to numerical results, both schemes require a large number of nodes, which is costly.

The communication energy parameters $\beta_1, \beta_2, \beta_3$ are referred to as follows [13]: $\beta_1 = 50\times10^{-9}\dfrac{J}{bit}, \beta_2 = 10\times10^{-12}\dfrac{\frac{J}{bit}}{m^2}, \beta_3 = 50\times10^{-9}\dfrac{J}{bit}$. Let N and a denote the total number of nodes in the network, and the number of packets generated by each node during the simulation period, respectively; t_p and t_{sim} are defined as packet transmission time, and simulation time, respectively; α is defined as duty cycling rate; and p_{tx}, p_{rx} and p_{sleep} are power consumption for transmission of one data packet, reception of one data packet, and sleep mode, respectively. Let n_{tx} and n_{rx} denote the total number of packet transmissions and receptions, respectively, when each node generates only one packet. Then, n_{tx} and n_{rx} can be calculated based on the number of nodes, N_i, in layer i as follows: $n_{tx} = \sum_{i=1}^{k} iN_i$ and $n_{rx} = \sum_{i=1}^{k} (i-1)N_i$

The total energy consumption in the network can be estimated as follows:

$$E = at_p\left(n_{tx}p_{tx} + n_{rx}p_{rx}\right) + (1-\alpha)t_{sim}Np_{sleep} + \left(\alpha t_{sim}N - at_p\left(n_{tx}+n_{rx}\right)\right)P_{idle}$$

where $at_p\left(n_{tx}p_{tx} + n_{rx}p_{rx}\right)$ is transmission and reception energy, $(1-\alpha)t_{sim}Np_{sleep}$ is energy consumption in sleep mode, and $\left(\alpha t_{sim}N - at_p\left(n_{tx}+n_{rx}\right)\right)P_{idle}$ is energy consumption in idle mode.

In this section, Matlab was used to validate the proposed algorithm and compare it with other strategies. First, we present a network performance comparison of EBND and Olariu's scheme. Then, a comparison with Wu's scheme is made.

4.1. Comparison of EBND and Olariu's Scheme

In Olariu's scheme [5], the transmission range of a node in layer i is the same as the width of layer i. In order to achieve balanced energy consumption, the authors derive the transmission range of nodes in each layer according to given network parameters. However, the obtained transmission radius of nodes in inner layers is much smaller than the maximum transmission radius, which reduces network connectivity. To avoid the connectivity issue, Olariu's scheme requires a large number of nodes.

The number of nodes needed for network connectivity and total energy consumption are selected as performance metrics. The area radius is set to 225 m, and the maximum transmission range is 55 m. The number of layers is varied from 3 to 9. Then, Olariu's scheme obtains the transmission ranges of nodes from the innermost layer to the outermost, which are {8.19, 15.95, 20.95, 25.15, 29.22, 34.69, 40.50, 49.98} meters.

Note that while selecting c value ($0 < c < R$), there is a tradeoff between the hop count and the number of forwarding nodes. More specifically, a small c value leads to an increase in the hop count, which results in higher communication overhead. In contrast, a high c value can reduce the hop count; however, the forwarding area S_j becomes smaller, which means fewer forwarding nodes can be found. Therefore, we initially set $c = 0.5R$ to balance between the hop count and the number of forwarding nodes. The effects of c selection on network performance (e.g., packet latency, energy consumption) should be considered intensively in the future work.

The difference between EBND and Olariu's is that instead of using a uniformly random node deployment in the whole area, EBND determines number of nodes N_i in each layer, then deploys N_i nodes in layer i randomly with a uniform distribution. Moreover, in EBND, the maximum transmission range is used for all nodes, whereas the transmission range of nodes increases from the innermost layer to the outermost in Olariu's scheme.

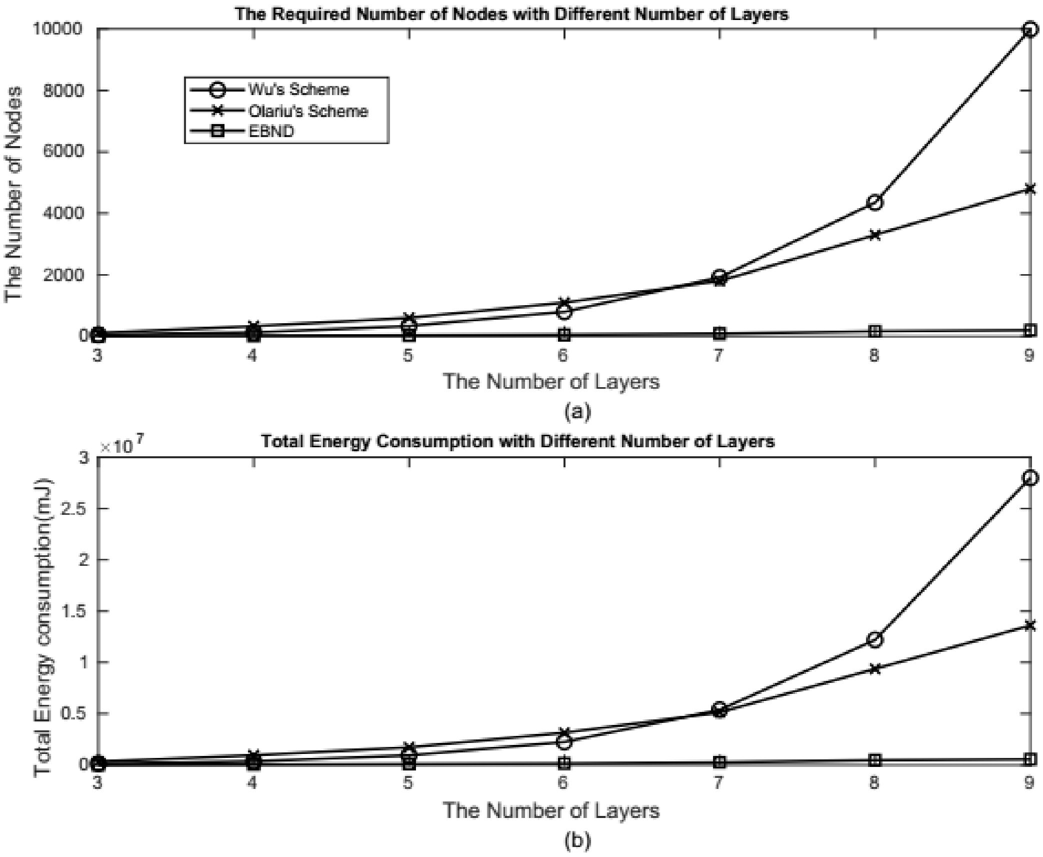

Fig. 2. Comparison with Olariu's and Wu’s schemes:
(a) The total number of nodes; (b) Total energy consumption.

As shown in Fig. 2a, to satisfy the desired network connectivity, the Olariu's scheme requires a much larger number of nodes than EBND. This is attributed to the fact that the obtained transmission range set in Olariu's scheme is much lower than the maximum transmission range. For example, nodes in the innermost layer can only transmit a signal up to 8.19 m, while the maximum radio range is 55 m, i.e., the connectivity range is reduced $\left(\frac{8.19}{55}\right)^{2} = 44.89$ times compared to nodes that use the maximum transmission range. Total energy consumption of Olariu's scheme, as shown in Fig. 1(b), is also much higher than that of EBND. Thus, Olariu's scheme is not practical in a large network.

4.2. Comparison of EBND and Wu's Scheme

Wu et al. [4] proposed a non-uniform node distribution strategy in order to achieve sub-balanced energy consumption between nodes. The area is divided into a number of concentric layers and nodes have the same transmission range. They proved that sub-balanced energy consumption can be achieved if the number of nodes from the outermost layer increases with the geometric rule.

As shown in Fig. 2, with a small number of layers, the required number of nodes in Fig. 2a and total energy consumption in Fig. 2b for EBND are slightly higher than in Wu's scheme. This result is attributed to the fact that Wu's scheme uses a deterministic deployment strategy and the number of nodes in layers increases from the outermost layer to the innermost with a common ratio. Thus, when the number of layers increases, the total number of nodes and total energy consumption increase exponentially.

5. Conclusions

This paper introduced a node deployment algorithm for delay-constrained applications in duty-cycled WSNs. We determined number of nodes in each layer using a brute-force search method given the total number of nodes. We conducted a simulation using Matlab and experimental results show that EBND required fewer sensor nodes and less energy consumption than other two node deployment strategies considered.

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TÍNH TOÁN MẬT ĐỘ NÚT MẠNG ĐỂ ĐÁP ỨNG ĐỘ TRỄ TRUNG BÌNH TRONG MẠNG CẢM BIẾN KHÔNG DÂY LÀM VIỆC THEO CHU KÌ

Tóm tắt: *Các ứng dụng trong Internet kết nối vạn vật (IoT) yêu cầu dữ liệu thu thập phải được truyền tới người quản trị trong một khoảng thời gian trễ giới hạn. Để tiết kiệm năng lượng hay kéo dài thời gian làm việc của mạng, kỹ thuật duty cycle được sử dụng, ở đó các cảm biến bật và tắt mạch thu phát theo chu kì. Trong mạng làm việc theo chu kì, độ trễ gói tin bị ảnh hưởng lớn bởi việc phân bổ nút mạng, do đó chúng tôi xác định mật độ nút mạng trong một mạng cảm biến không dây nhằm bảo đảm độ trễ đầu cuối trung bình với các tham số cho trước sử dụng lý thuyết xác suất thống kê. Kết quả mô phỏng cho thấy phương pháp phân bổ nút mạng đề xuất tiêu hao ít năng lượng hơn trong khi yêu cầu số lượng nút cảm biến ít hơn các phương pháp hiện có.*

Từ khóa: Tiêu hao năng lượng; kỹ thuật định tuyến; yêu cầu về độ trễ; mạng cảm biến không dây.

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