Vol.2012-DPS-151 No.26
Vol.2012-MBL-62 No.26
2012/5/22

無線センサネットワークにおけるデータ収集のための2ホップ方式

ヴーン アン ホン[1]　丹 康雄[1]　リム アズマン オスマン[1]

概要：無線センサネットワークでは，センサは通常，シンクをルートとするツリートポロジを形成し，センサからのデータは，マルチホップ通信によりシンクに送信される．その結果，シンクに近いセンサは，他のセンサからのデータ送信の中継に多く利用されるため，電池をより速く消耗する. 本稿では, 通常の信号出力時に 2 ホップ先に位置するノードに対して，一時的に信号出力を上げることで，1 ホップで送信する機能（2 ホップ送信）を付加し，通常送信と倍ホップ送信を織り交ぜることにより，ネットワーク全体のエネルギー消費のバランスをとる 2 ホップ方式を提案する．シミュレーション結果は, 提案方式がネットワーク全体の駆動時間を延ばすことを明らかにした.

2-hop Scheme for Data Collection in Wireless Sensor Networks

Vuong An Hong[1]　Tan Yasuo[1]　Lim Azman Osman[1]

Abstract: In wireless sensor networks (WSNs), sensors usually form a tree topology and the sensed data are transmitted to a sink using multihop communication. As a result, sensors close to the sink will overuse the energy for transmitting other sensed data and lead to the residual battery drained faster. In this paper, we propose a 2-hop scheme to balance the energy consumption throughout the network by assigning each sensor an optimal transmission probability, so that the energy consumption can be balanced. Simulation results reveal that our proposed scheme outperforms the hop-to-hop scheme and the direct scheme in term of network lifetime.

1. Introduction

Nowadays, wireless sensor networks (WSNs) are used in a wide range of applications such as in environmental applications (*e.g.*, habitat monitoring, fire detection), health applications (*e.g.*, monitoring patient's physiological data). In practical, sensors in such networks use small batteries and are expected to operate for a long time. However, replacing or recharging the batteries of the sensors is impractical after they have been deployed. Therefore, how to save energy of the sensors and how to prolong the network lifetime are the important considerations while designing or deploying a WSN.

There are many research works to maximize the network lifetime of a WSN. This leads to many algorithms to reduce energy consumption of sensors and prolong network lifetime. For example, Li et al. [1] proposed power-aware routing protocols to reduce energy consumption by selecting minimum-energy routing paths for transmitting packets. While contiguous link scheduling is one kind of sleep-management schemes, in which energy is conserved by periodically turn off radio circuit to avoid idle listening [2]. Usually sensors far away from the sink do not

1　北陸先端科学技術大学院大学 情報科学研究科
School of Information Science, Japan Advanced Institute of Science and Technology (JAIST), 1-1 Asahidai, Nomi, Ishikawa 923-1292, Japan

send their data directly to it, but instead through multihop wireless communications. Multihop communication causes the phenomena of unbalanced energy consumption, in which sensors close to the sink are overused due to transmitting not only their own sensed data but also packets from other sensors, and their batteries will run out of energy soon. By balancing energy consumption among sensors, the network lifetime can be increased; however, a few research works have been focused in this research domain.

The primary goal of our work is to maximize the network lifetime by reducing imbalance of energy consumption between sensors. Our contributions are that, firstly, we propose a scheme called "2-hop scheme" to address the problems of reducing energy unbalance and prolong the network lifetime by exploiting two kinds of transmissions: hop-to-hop and 2-hop transmissions. In details, a packet is forwarded to the next sensor using hop-to-hop transmission with a probability p, and is forwarded to the next-of-next sensor using 2-hop transmission with probability $1 - p$. Secondly, we investigate theoretically how to choose the optimal transmission probabilities p to maximize the network lifetime. Finally, we simulate the data collection of sensors in different random topology, which is the topology usually being formed in a WSN using a tree-based routing protocol, to see how our proposed scheme can increase the network lifetime compared to the conventional hop-to-hop scheme. Numerical and simulation results show that, 2-hop scheme can reduce the energy unbalance and prolong the network lifetime compared to hop-to-hop scheme.

We discuss the related work and system model in Section 2 and Section 3, respectively. We also address the problem statement in Section 4. Then, we numerically analyze how the 2-hop scheme can prolong the network lifetime on the networks of chain topology, binary tree topology, and random topology in Section 5, Section 6, and section 7, respectively. Finally, Section 8 conclude our research and future works.

2. Related Work

Zhang et al. [3] exploited the enery tradeoff between direct transmission and hop-to-hop transmission to balance energy consumption among sensors in the network. In [3], sensor i forwards a packet to sensor i - 1 with probability p_i and transmits a packet directly to the sink with probability 1 - p_i. By choosing the optimal value of p_i, the energy consumption of all sensors in the network could be balanced. However, if a sensor is too far from the sink, or its remaining energy is not high enough, it may not be able to perform direct transmission, which implies that direct scheme does not work in those cases. Our scheme does not use direct transmission, but instead 2-hop transmission, which does not consume too much energy as direct transmission. Therefore, it can be used in a large-scale network, where the distances between some sensors and the sink are high enough so that it becomes impractical for direct transmission.

3. System Model

We consider a WSN consisting of many sensors and one sink. Both the sensors and the sink are static after deployment. We assume that the sink always has sufficient power supply, while the sensors are powered by limited batteries and it is unfeasible to replace or recharge those batteries after deployment.

3.1 Data Gathering Model

Our analysis is for data gathering sensor networks where each sensor periodically transmits its sensed data to the sink. In most data gathering applications, usually the time between two adjacent data transmission cycles (duty cycles) is long, may be several minutes, hours or even days. Therefore, to avoid idle listening, sensors usually turn off their radio circuits when there is no data to transmit. In our model, we assume that a synchronized sleep/wake up scheme like T-MAC [4], S-MAC [5] or contiguous link scheduling [2] is exploited. The process in which all sensors wake up, generate the sensed data and transmit the data to the sink is defined as one *Data Gathering Cycle* (DGC). In one DGC, we assume that each sensor generates only one packet and sends that packet, together with all packets forwarded to it by other sensors, to the sink.

3.2 Energy Model

The first-order radio model proposed in [6] has been widely used to measure energy consumption in wireless communications. The energy consumption to transmit one m-bit packet is $\epsilon_t(d) = (\epsilon_{elec} + \epsilon_{amp} * d^\alpha) * m$, where ϵ_{elec} is the energy spent by electronic circuit to transmit or receive one data bit, ϵ_{amp} is the transmission amplifier and α $(i.e., \alpha \geq 2)$ is the propagation loss exponent. While receiving data, only the receiving circuit is invoked and the energy to receive one m-bit packet is $\epsilon_r = \epsilon_{elec} * m$.

In this study, because a synchronized sleep/wake up scheme is used to avoid idle listening, energy consumption for idle listening becomes much smaller compared to energy consumption for transmitting and receiving data, thereby we do not consider that kind of energy consumption. Moreover, comapared with data communication, other kinds of energy such as energy for data processing in sensors, etc. are much more smaller, and are not taken into account.

3.3 Communication Model

The communication model in our work is similar to [1], but instead of using direct transmission, we use 2-hop transmission. More specifically, sensor i forwards a packet to sensor $i-1$ using hop-to-hop transmission with probability p_i and transmits the packet to sensor $i-2$ using 2-hop transmission with probability $1-p_i$. p_i is called the transmission probability of sensor i and p_i is assigned for sensor i at initial. In our work, we assume that all the transmissions are reliable without any packet loss.

4. Problem Statement

We measure the network lifetime, denoted by L, as the total number of DGCs that can be done until one sensor runs out of battery. We assume that at initial (deployment time), all sensors' batteries have the same energy level, denoted by B, then

$$L = \frac{B}{\max\limits_{1 \le i \le N} \{E[\varepsilon_i]\}} \tag{1}$$

$E[\varepsilon_i]$ is the expected total energy consumption of sensor i in one DGC. Maximizing L is equivalent to minimize $\max\limits_{1\le i\le N}\{E[\varepsilon_i]\}$. It is obvious to see that, $E[\varepsilon_i]$ depends on p_i, if p_i is large, hop-to-hop transmission is more likely to be performed, and $E[\varepsilon_i]$ is smaller than when p_i is small (which means that 2-hop transmission is more likely to be performed, and the sensor consumes more energy). Therefore, the problem of maximizing the network lifetime can be transformed as choosing the optimal values of $p_i, 2 \le i \le N$ (p_1 is always 1) to minimize $\max\limits_{1\le i\le N}\{E[\varepsilon_i]\}$.

5. *2-hop Scheme* for Chain Networks

The chain topology network we consider in this section is a general chain network, where the sensors are deployed irregularly in an area. Each sensor select one of its near-sink neighbors for next hop packet relay. The sink is assumed to be at one end of the chain without loss of generality. The sensors are marked with 0 to n from the sink to the farthermost sensor (See **Fig. 1**).

Let $f_{1,i}$ and $f_{i,2}$ be the number of packets that sensor i forwards to sensor $i-1$ and sensor $i-2$ in one DGC, respectively. Let n_i be the total number of packets transmitted by sensor i in one DGC. Then,

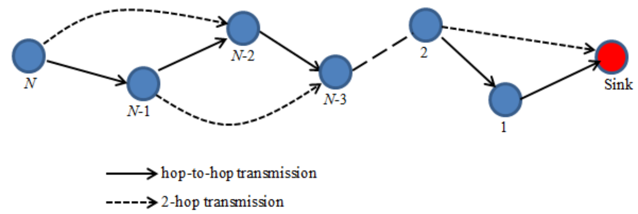

Fig. 1 A chain topology of N sensors

$$n_i = f_{1,i} + f_{2,i} \quad 1 \le i \le N \tag{2}$$

We can see that, sensor i receives the packet generated by sensor j ($i < j \le N$) if and only if that packet not being forwarded to sensor $i-1$, thus

$$n_i = N - i + 1 - f_{2,i+1}, \quad 1 \le i \le N \tag{3}$$

In (3), $N-i+1$ is the total number of packets generated by sensors $N, N-1, ..., i$ in one DGC.

Let $E[\lambda]$ be the expectation value of a random variable λ.

Lemma 1 $p_i = \frac{E[f_{1,i}]}{E[f_{1,i}]+E[f_{2,i}]}, \quad 1 \le i \le N$

Proof. See Appendix.

In practical, most current sensor motes cannot transmit a packet with power as small as possible and usually there is a minimum transmission power. Therefore, it is reasonable to make an assumption that all the sensors in the network are identical, they use the same power P_1 for hop-to-hop transmission and the same power P_2 for 2-hop transmission. Let d_1 and d_2 be the maximum distance that a packet can be transmitted with power P_1 and P_2, respectively.

$$\begin{aligned} E[\varepsilon_i] &= E[f_{1,i}]\epsilon_t(d_1) + E[f_{2,i}]\epsilon_t(d_2) \\ &\quad + (E[f_{1,i}] + E[f_{2,i}] - 1)\epsilon_r \end{aligned} \tag{4}$$

5.1 Optimal Transmission Probabilities to Maximize Network Lifetime

A set of transmission probabilities $(p_N, p_{N-1}, ..., p_2)$ is called an optimal solution if with $(p_N, p_{N-1}, ..., p_2)$, $\max\limits_{1\le i\le N}\{E[\varepsilon_i]\}$ is minimized.

Theorem 1 For a set of transmission probabilities $(p_N, p_{N-1}, ..., p_2)$; if $E[\varepsilon_N] = E[\varepsilon_{N-1}] = ... = E[\varepsilon_1]$, then $(p_N, p_{N-1}, ..., p_2)$ is an optimal solution.

Proof. See Appendix

Now, we will find $(p_N, p_{N-1}, ..., p_2)$ to balance energy consumption of all sensors in the network. The energy consumption of the N sensors are balanced if and only if

$E[\varepsilon_i] = E[\varepsilon_{i-1}], 2 \le i \le N$. $E[\varepsilon_i] = E[\varepsilon_{i-1}] \Leftrightarrow$

$$\begin{aligned} &- E[f_{1,i-1}] - E[f_{2,i-1}]\frac{\epsilon_t(d_2)+\epsilon_r}{\epsilon_t(d_1)+\epsilon_r} + E[f_{1,i}] \\ &+ E[f_{2,i}]\frac{\epsilon_t(d_2)+\epsilon_r}{\epsilon_t(d_1)+\epsilon_r} = 0 \end{aligned} \quad (5)$$

For the ease of writing, let us denote $E[f_{1,1}]$ by x_1; $E[f_{1,i}]$ by x_{2i-2} and $E[f_{2,i}]$ by $x_{2i-1}, 2 \le i \le N$. We also denote $\frac{\epsilon_t(d_2)+\epsilon_r}{\epsilon_t(d_1)+\epsilon_r}$ by C. Now, with the new notations:

$$E[\varepsilon_i] = E[\varepsilon_{i-1}] \Leftrightarrow$$

$$-x_{2i-4} - Cx_{2i-3} + x_{2i-2} + Cx_{2i-1} = 0 \quad (6)$$

And then, $E[\varepsilon_i] = E[\varepsilon_{i-1}], 2 \le i \le N \Leftrightarrow$

$$\begin{cases} -x_{2N-4} - Cx_{2N-3} + x_{2N-2} + Cx_{2N-1} = 0 \\ -x_{2N-6} - Cx_{2N-5} + x_{2N-4} + Cx_{2N-3} = 0 \\ ... \\ -x_1 + x_2 + Cx_3 = 0 \end{cases} \quad (7)$$

We regard $x_{2N-1}, x_{2N-2}, ..., x_1$ as the variables of the system of simultaneous linear equations (9). There are a total of $2N-1$ variables but (9) has only $N-1$ equations. Therefore; to solve (9), we need N more equations.

As we can see from *Fig. 1*: $f_{1,i} + f_{2,i} = f_{1,i+1} + f_{2,i+2} + 1 \Rightarrow E[f_{1,i}] + E[f_{2,i}] = E[f_{1,i+1}] + E[f_{2,i+2}] + 1$, or $x_{2i-2} + x_{2i-1} = x_{2i} + x_{2i+3} + 1 \Leftrightarrow x_{2i-2} + x_{2i-1} - x_{2i} - x_{2i+3} = 1, 1 \le i \le N$. We assume that $x_{2N} = E[f_{1,N+1}] = x_{2N+3} = E[f_{2,N+2}] = 0$. We can add N more equations to (9) to get a system of simultaneous linear equations of $2N-1$ variables and $2N-1$ equations:

$$\begin{cases} -x_{2N-4} - Cx_{2N-3} + x_{2N-2} + Cx_{2N-1} = 0 \\ -x_{2N-6} - Cx_{2N-5} + x_{2N-4} + Cx_{2N-3} = 0 \\ ... \\ -x_1 + x_2 + Cx_3 = 0 \\ x_{2N-2} + x_{2N-1} = 1 \\ x_{2N-4} + x_{2N-3} - x_{2N-2} = 1 \\ ... \\ x_1 - x_2 - x_5 = 1 \end{cases} \quad (8)$$

If (10) has a solution and all the values of $x_i, 1 \le i \le 2N-1$, are non-negative numbers, then we can calculate p_i based on *Lemma 1*: $p_i = \frac{x_{2i-2}}{x_{2i-2}+x_{2i-1}}$.

If (10) does not have any solution; or some of the variables are negative numbers, then we can conclude that the energy consumption of all sensors cannot be balanced. In that case, we assign an initial value to p_N and find $(p_{N-1}, p_{N-2}, ..., p_2)$ making $E[\varepsilon_{N-1}] = E[\varepsilon_{N-2}] = ... = E[\varepsilon_1]$ by solving a system of simultaneous linear equations similar to (10).

If for all initial values of p_N, we cannot find any $(p_{N-1}, p_{N-2}, ..., p_2)$ making $E[\varepsilon_{N-1}] = E[\varepsilon_{N-2}] = ... = E[\varepsilon_1]$, then we assign initial values to p_N and p_{N-1} and find $(p_{N-2}, p_{N-3}, ..., p_2)$ making $E[\varepsilon_{N-2}] = E[\varepsilon_{N-3}] = ... = E[\varepsilon_1]$. This process continues until we find $(p_{k-1}, p_{k-2}, ..., p_2)$ making $E[\varepsilon_{k-1}] = E[\varepsilon_{k-2}] = ... = E[\varepsilon_1]$ after assingning initial values to $p_N, p_{N-1}, ..., p_k, 2 \le k \le N$.

The reason why we always try to balance energy consumption of sensors $1, 2, ..., k-1$ after assigning initial values to $p_N, p_{N-1}, ..., p_k$ is based on *Theorem 2*.

Theorem 2 After assigning initial values to $p_N, p_{N-1}, ..., p_k (2 \le k \le N)$, for a set of transmission probabilities $(p_{k-1}, p_{k-2}, ..., p_2)$, if $E[\varepsilon_{k-1}] = E[\varepsilon_{k-2}] = ... = E[\varepsilon_1]$ then $(p_{k-1}, p_{k-2}, ..., p_2)$ is the best probabilities we can choose. That is, for other $(p'_{k-1}, p'_{k-2}, ..., p'_2)$ that does not make $E[\varepsilon'_{k-1}] = E[\varepsilon'_{k-2}] = ... = E[\varepsilon'_1]$, then $\max_{1 \le i \le N}\{E[\varepsilon'_i]\} > \max_{1 \le i \le N}\{E[\varepsilon_i]\}$.

Proof. See Appendix

5.2 Numerical Analysis and Results

In this section, we will find an optimal solution for a chain topology of network consisting of $N = 10$ sensors. The maximum hop-to-hop transmission range is $d_1 = 20m$, the maximum 2-hop transmission range is $d_2 = 2d_1 = 40m$. The propagation loss exponent $\alpha = 3.5$. $\epsilon_{elec} = 50nJ/bit, \epsilon_{amp} = 100pJ/bit/m^{\alpha}$. The size of each packet is set at $m = 1024$ bits. We also set the initial energy level in each sensor $B = 30J$.

Solving (10) with $N = 10$, we see that all the variables are positive numbers, then we can calculate the probabilities for sensors 10, 9, 8, ..., 2 (See **Fig. 2**).

We also compare the expected energy consumption of each sensor in *2-hop scheme* with the expected energy consumption of each sensor in *Direct scheme*[1] and the energy consumption of each sensor in *Hop-to-hop* scheme (See **Fig. 3**).

Finally, we compare the expected network lifetime (measured by the number of DGCs can be done until one sensor runs out of battery, calculated by (1)) in *2-hop scheme*, *Direct scheme* and *Hop-to-hop scheme* (See **Table 1**).

Table 1 Expected network lifetime (the number of DGCs that can be done until one sensor runs out of battery)

Hop-to-hop	*Direct*	*2-hop*
797	813	806

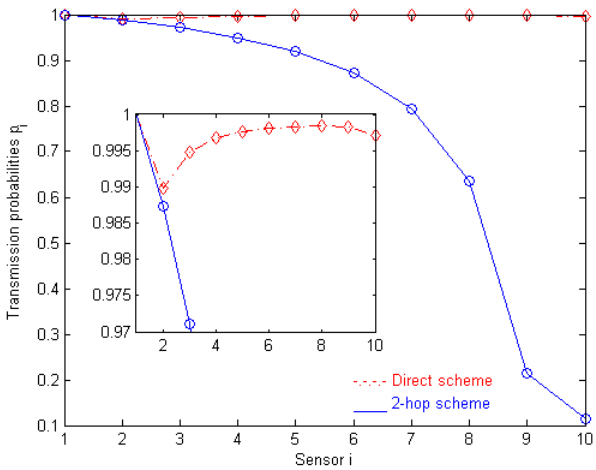

Fig. 2 Transmission probabilities for N sensors

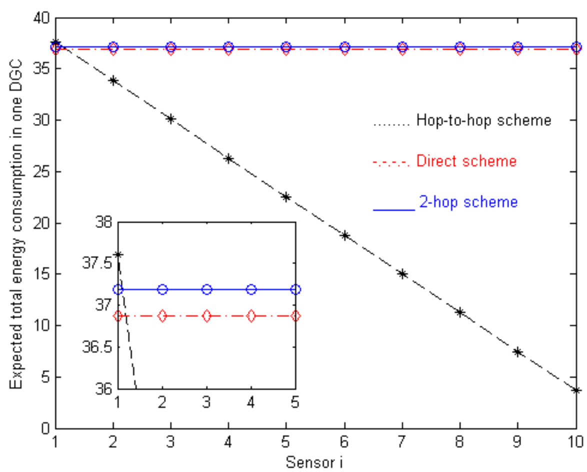

Fig. 3 Expected total energy consumption for N sensors in *Hop-to-hop scheme*, *Direct scheme* and *2-hop scheme*

In **Fig. 3**, we can see that, with *Direct scheme*, the expected energy consumption of each sensor in one DGC is smallest compared to that with *Hop-to-hop scheme* and *2-hop scheme*, as a result, the expected network lifetime with *Direct scheme* is also larger than that with the other two schemes. However, the calculation is based on the assumption that all the sensors in the network can perform direct transmission to the sink. There are 10 sensors in the network, and we assume that the transmission range between sensor i to the sink is $d_i = id_1 = 20i$ meters. For sensor 10, $d_{10} = 200m$ and the energy consumed to transmit one packet to the sink is $(\epsilon_{elec} + \epsilon_{amp}d_{10}^{\alpha})m \approx 11.6J$, which is around one-third of the initial energy supply of each sensor is $30J$, in practical, such energy-consumed transmission is likely unable to perform. This implies that in practical, *Direct scheme* may not work. On the other hand, the energy needed to send one packet in 2-hop

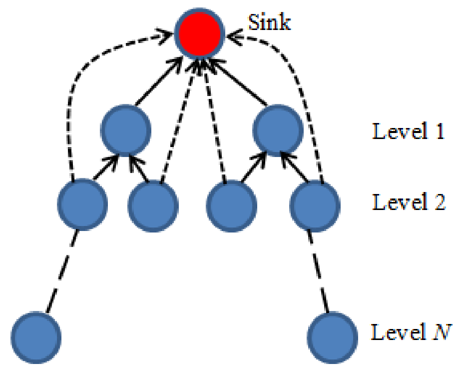

Fig. 4 Binary tree network with N levels

transmission is just $(\epsilon_{elec} + \epsilon_{amp}d_{10}^{\alpha})m \approx 41.5mJ$, which is much more smaller than energy for direct transmission.

In **Table 1**, the expected network lifetime with *2-hop scheme* is increased about 1.1% compared to that with *Hop-to-hop scheme*. This means that *2-hop scheme* does help prolong the lifetime of the network. 1.1% is not so large, but in the next section, we will see that *2-hop scheme* can help increase network lifetime of a binary tree topology network at a better percentage.

6. *2-hop Scheme* for Binary Tree Networks

Let us consider a binary tree network as shown in **Fig. 4**, where all sensors form a tree topology of N levels. A sensor in level i has exactly two children in level $i+1 1 \leq i \leq N$. We denote by $S_{i,j}$ the j^{th} sensor in level i (if $j = 1$, then the sensor is the leftmost one of level) $i, 1 \leq i \leq N, 1 \leq j \leq 2^i$. We also denote by $n_{i,j}$ the number of packets transmitted in one DGC by sensor $S_{i,j}$; denote by $f_{1,i,j}$ and $f_{2,i,j}$ the number of packets sent in hop-to-hop and 2-hop transmission, respectively, by sensor $S_{i,j}$.

Let $p_{i,j}$ be the transmission probability of $S_{i,j}$. Because all sensors in a same level are completely identical to each other in terms of the number of children and the initial energy level; therefore, it is reasonable to assume that all the sensors in level i forward a packet to its parent sensor with the same probability p_i and forward a packet to its parent-of-parent sensor with the same probability $1 - p_i$. So, $p_{i,1} = p_{i,2} = ... = p_{i,2^i} = p_i$.

Lemma 2 In a binary tree network, $p_i = p_{i,j} = \frac{E[f_{1,i,j}]}{E[f_{1,i,i}]+E[f_{2,i,j}]}, 1 \leq i \leq N, 1 \leq j \leq 2^i$.

Proof. See Appendix

Theorem 3 In a binary tree network, $E[f_{1,i,j}] = E[f_{1,i,k}]$ and $E[f_{2,i,j}] = E[f_{2,i,k}], 1 \leq i \leq N, 1 \leq j,k \leq 2^i$. This means that, the expected number of packets sent in hop-to-hop and 2-hop transmission of all sensors in the

Table 2 Expected network lifetime (the number of DGCs that can be done until one sensor runs out of battery)

Hop-to-hop	*2-hop*
126	142

same level are the same.

Proof. See Appendix

From *Theorem 3*, for simplicity, let us denote by $E[f_{1,i}]$ and $E[f_{2,i}]$ the expected number of packets sent in hop-to-hop and 2-hop transmission of any sensor in level i.

6.1 Optimal Transmission Probabilities to Maximize Network Lifetime

Similar to the previous section, maximizing the network lifetime means choosing optimal transmission probabilities to minimize $E[\varepsilon_{i,j}]$, where $\varepsilon_{i,j}$ is the energy consumption of $S_{i,j}$ in one DGC. Similar to the previous section, we can prove that, if there is a set of probabilities to balance energy consumption of all sensors in the network, then with that set of probabilities, the network lifetime could be maximized. In order to find probabilities to balance energy consumption, we solve a system of simultaneous linear equation similar to (10), but the relationship between $E[f_{1,i}], E[f_{2,i}]$ and $E[f_{1,i+1}], E[f_{2,i+2}]$ is now: $E[f_{1,i}] + E[f_{2,i}] = 2E[f_{1,i+1}] + 4E[f_{2,i+2}] + 1$. We can verify this equation by looking at **Fig. 4**.

6.2 Numerical Analysis and Results

We consider a binary tree network with $N = 6$ levels. We set $\alpha = 3.5, \epsilon_{elec} = 50nJ/bit, \epsilon_{amp} = 100pJ/bit/m^{\alpha}$, packet size is 1024 bits and initial battery is $B = 30J$.

With binary tree network, solving the system of simultaneous linear equations gives negative values for some variables, which means that we cannot balance the enrg consumption of all sensors in the network. We then assign $p_6 = p_5 = 0.9$ for all sensors in level 5 and level 6 and, using *Theorem 2*, try to find p_4, p_3, p_2 to balance the energy consumption of sensors from level 1 to level 4. We get $p_4 = 0.2331, p_3 = 0.01$ and $p_2 = 0.8321$. The expected energy consumption of all sensors from level 1 to level 6 with *Hop-to-hop scheme* and *2-hop scheme* is shown in **Fig. 5**.

The expected network lifetime with *Hop-to-hop scheme* and *2-hop scheme* is shown in *Table 2*. We can see that *2-hop scheme* can prolong the network lifetime by about 12.7%, which is better than in chain network.

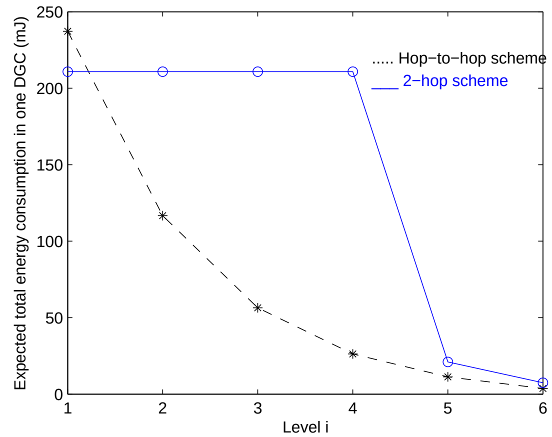

Fig. 5 Expected total energy consumption for sensors in N levels with *Direct scheme* and *2-hop scheme*

Table 3 Simulation parameters and settings

Number of sensor nodes	100
Number of sink nodes	1
Network coverage	200 meters x 200 meters
Transmission range	20 meters
Network protocol	Tree-based routing protocol [7]
RANN packet size	20 bytes
RANN broadcast interval	15 seconds
Traffic type	Constant bit rate
Data gathering cycle	10 seconds
Data payload size	104 bytes
MAC header size	24 bytes
Hardware specification	IEEE 802.15.4
MAC protocol	Beacon-enabled access method
Transmission rate	250 kbps
Number of channels	1
Energy model	First-order radio model
Propagation loss exponent, α	3.5
ϵ_{elec}	$50nJ/bit$
ϵ_{amp}	$100pJ/bit/m^{\alpha}$
Initial battery capacity	$30J$
Processing time	1ms

7. *2-hop Scheme* for Random Networks

In our simulations, we investigate the performance of the *2-hop scheme* in a random topology of WSNs. The simulation parameters and settings for the simulator are shown in **Table 3**.

7.1 Simulation Setup and Environment

We assume that the physical and MAC conditions of the IEEE802.15.4 are used in the simulations. Our simulations are written in the C language based on time-driven program. We also assume that all the sensors are iden-

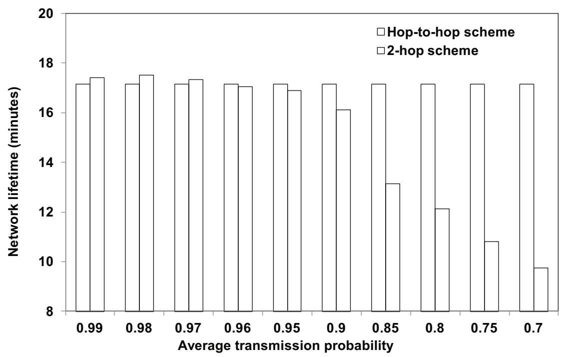

Fig. 6 The performance results of *2-hop scheme* and *hop-to-hop scheme* for network lifetime versus average transmission probability.

tical, uniformly, and independently distributed in a two-dimensional square are and no sensor moves throughout the simulation. The sink node is located at the center of the simulation area. Since all the sensors are identical, they have the same transmitting and receiving power. We also use the first-order radio model in our simulation by assuming the propagation loss exponent is 3.5.

We apply the tree-based routing (TBR) protocol as proposed in [7]. The RANN packet size is 20 bytes and we set the RANN broadcast interval is 15 seconds. We model our traffic based on constant bit rate (CBR). The CBR traffic consists of 104-byte payload size, which sends at the data packet is sent at every 10 seconds. For comparison purposes, ten simulation scenarios with different random topology are averaged.

7.2 Simulation Results

As we can seen in **Fig. 6**, the performance of *2-hop scheme* decreases as the average transmission probability decreases. Simulation results reveal that the proposed *2-hop scheme* attains a higher network lifetime compared to the hop-to-hop scheme when the average transmission probability is nearer to 1. This is because the sensors at the level two can transmit the data packet directly to the sink rather to the sensors at the level one. As a result, the sensors at the level one can save their batteries to forward other data packets, in which this leads to the longer network lifetime. Although the improvement of *2-hop scheme* does not contribute much in this simulation, the reason is that the average transmission probability given to each sensor is not optimum.

8. Concluding Remarks

In this paper, we have addressed the problem of imbalancing energy consumption for data gathering in a WSN. We have proposed and studied a new scheme called *2-hop scheme*. In this *2-hop scheme*, the combination of hop-to-hop transmission and 2-hop transmission is exploited. We also formulated that maximizing the network lifetime means choosing an optimal transmission probability for a sensor in the network to minimize the maximum of expected energy consumption in one DGC. Furthermore, we proven that a set of optimal transmission probabilities can be derived to balance the total energy consumption of all sensors throughout the chain and binary tree networks. In a random tree network, we use a computer simulation to simulate the *2-hop scheme* and hop-to-hop scheme. Numerical results reveal that our proposed scheme can prolong the network lifetime compared to that with the conventional *Hop-to-hop scheme*. In comparison to *Direct scheme*, although the expected network lifetime with *Direct scheme* is larger than that with our scheme, One advantage of our scheme over *Direct scheme* is, while *Direct scheme* may not work if the sink is too far away from the sink, our scheme still performs well in that case. A future work also will focus on examining the performance of the *2-hop scheme* when we assume the optimum transmission probability of each sensor.

Appendix

Proof of Lemma 1. Let $P(j,i)$ $(1 \leq i < j \leq N)$ be the probability that sensor i receives a packet from sensor j. Then $1 - P(j,i)$ is the probability that sensor i does not receive a packet from sensor j, this occurs if and only if that packet is forwarded to sensor $i+1$ and then forwarded to sensor $i-1$. Thus,

$$1 - P(j,i) = P(j,i+1)(1-p_{i+1}), \quad 1 \leq i \leq N \quad \text{(A.1)}$$

$n_{i-1} - 1$ is also the number of packets received by sensor $i-1$, thus

$$\begin{aligned} E[n_{i-1}] - 1 &= \sum_{k=i}^{N} P(k,i-1) \\ &= P(i,i-1) + \sum_{k=i+1}^{N} P(k,i-1) \qquad \text{(A.2)} \\ &= p_i + N - i - (1-p_i)(E[n_i]-1) \\ &= N - i + 1 - E[n_i] + p_i E[n_i] \end{aligned}$$

$\Rightarrow$ $p_i E[n_i] = E[n_i] + E[n_{i-1}] - (N - i + 2)$. From (3), $E[n_{i-1}] - (N-i+2) = -E[f_{2,i}]$, then $p_i E[n_i] = E[n_i] - E[f_{2,i}] = E[f_{1,i}] \Rightarrow p_i = \frac{E[f_{1,i}]}{E[n_i]} = \frac{E[f_{1,i}]}{E[f_{1,i}]+E[f_{2,i}]}$. *Lemma 1* has been proved.

Proof of Lemma 2. The proof of *Lemma 2* is similar to that of *Lemma 1* and we omit it here.

Proof of Theorem 1. If $(p_N, p_{N-1}, ..., p_2)$ is not an optimal solution, then there is another set of transmission probabilities $(p'_N, p'_{N-1}, ..., p'_2)$ where $\max_{1\le i\le N}\{E[\varepsilon'_i]\} < \max_{1\le i\le N}\{E[\varepsilon_i]\}$. Then, $E[\varepsilon'_i] < E[\varepsilon_i], 1 \le i \le N$.

For sensor $N, n_N = n'_N = 1$. By (6), $E[\varepsilon_N] = \epsilon_t(d_2) - p_N(\epsilon_t(d_2) - \epsilon_t(d_1))$ and $E[\varepsilon'_N] = \epsilon_t(d_2) - p'_N(\epsilon_t(d_2) - \epsilon_t(d_1))$. $E[\varepsilon'_N] < E[\varepsilon_N] \Leftrightarrow p'_N > p_N$. Therefore $E[f'_{2,N}] = 1 - p'_N < E[f_{2,N}] = 1 - p_N$.

By (3), $E[n_{N-1}] = 2 - E[f_{2,N}]$ and $E[n'_{N-1}] = 2 - E[f'_{2,N}]$. Because $E[f'_{2,N}] < E[f_{2,N}]$, then $E[n'_{N-1}] > E[n_{N-1}]$. By (2) and (6), $E[\varepsilon_{N-1}] = E[n_{N-1}](\epsilon_t(d_1) + \epsilon_r) + E[f_{2,N-1}](\epsilon_t(d_2) - \epsilon_t(d_1)) - \epsilon_r$ and $E[\varepsilon'_{N-1}] = E[n'_{N-1}](\epsilon_t(d_1) + \epsilon_r) + E[f'_{2,N-1}](\epsilon_t(d_2) - \epsilon_t(d_1)) - \epsilon_r$. Thus, $E[\varepsilon'_{N-1}] < E[\varepsilon_{N-1}] \Leftrightarrow (E[f'_{2,N-1}] - E[f_{2,N-1}])(\epsilon_t(d_2) - \epsilon_t(d_1)) < (E[n_{N-1}] - E[n'_{N-1}])(\epsilon_t(d_1) + \epsilon_r)$. Because $E[n'_{N-1}] > E[n_{N-1}]$, then $(E[f'_{2,N-1}] - E[f_{2,N-1}])(\epsilon_t(d_2) - \epsilon_t(d_1)) < 0 \Rightarrow E[f'_{2,N-1}] < E[f_{2,N-1}]$.

Continuing this reasoning, $E[f'_{2,N-1}] < E[f_{2,N-1}] \Rightarrow E[n'_{N-2}] > E[n_{N-2}] \Rightarrow ... \Rightarrow E[n'_1] > E[n_1] \Rightarrow E[\varepsilon'_1] > E[\varepsilon_1]$. This contradicts with $E[\varepsilon'_1] < E[\varepsilon_1]$. Therefore, $(p_N, p_{N-1}, ..., p_2)$ must be an optimal solution. *Theorem 1* has been proved.

Proof of Theorem 2. The proof of *Theorem 2* is similar to that of *Theorem 1* and we omit it here.

Proof of Theorem 3. For all sensors in level N, in one DGC, they all generate and send one packet. Then, from *Lemma 2*, $E[f_{1,N-1,j}] = p_N$ and $E[f_{2,N,j}] = 1 - p_N, 1 \le j \le 2^N$. Thus, *Theorem 3* is true for all sensors in level N. Let $E[f_{1,N}] = E[f_{1,N,j}]$ and $E[f_{2,N}] = E[f_{2,N,j}], 1 \le j \le 2^N$.

For a sensor $S_{N-1,j}$ in level $N-1$. Let $S_{N,k}$ and $S_{N,k+1}$ be the two children of $S_{N-1,j}$. From *Fig. 4*, we can see that $n_{N-1,j} = f_{1,N,k} + f_{1,N,k+1} + 1 \Rightarrow E[n_{N-1,j}] = E[f_{1,N,k}] + E[f_{1,N,k+1}] + 1 = 2E[f_{1,N}] + 1 \Rightarrow E[f_{1,N-1,j}] = p_{N-1}(2E[f_{1,N}] + 1)$ and $E[f_{2,N-1,j}] = (1 - p_{N-1})(2E[f_{1,N}] + 1)$. It is easy to see that $E[f_{1,N-1,j}]$ and $E[f_{2,N-1,j}]$ do not depend on j. Therefore, *Theorem 3* is true for all sensors in level $N-1$.

Continuing this reasoning, *Theorem 3* is true for all levels in the network.

References

[1] Q. Li, J. Aslam, and D. Rus, "Online power-aware routing in wireless ad-hoc networks," Proc. of the Int. Conf. on Mobile Computing and Networking (MobiCom), pp.97–107, 2001.
[2] J. Ma, W. Lou, Y. Wu, X.Y. Li, and G. Chen, "Energy efficient TDMA sleep scheduling in wireless sensor networks," Proc. of the 28th IEEE Conf. on Computer Commun. (INFOCOM), pp.630–638, 2009.
[3] H. Zhang, H. Shen, and Y. Tan, "Optimal energy balanced data gathering in wireless sensor networks," Proc. of IEEE Int. Parallel and Distributed Processing Symposium (IPDPS), pp.1–10, 2007.
[4] T.V. Dam, and K. Langendoen, "An adaptive energy-efficient MAC protocol for wireless sensor networks," Proc. of the ACM Conf. on Embedded Networked Sensor Systems, pp.171–180, 2003.
[5] W. Ye, J. Heidemann, and D. Estrin, "Medium access control with coordinated, adaptive sleeping for wireless sensor networks," ACM/IEEE Transactions on Networking, vol.12, no.3, pp.493–506, 2004.
[6] W.R. Heinzelman, A. Chandrakasan, and H. Balakrishnan, "Energy efficient communication protocol for wireless microsensor networks," Proc. of the Annual Hawaii Int. Conf. on System Sciences, vol.2, pp.4–7, 2000.
[7] A.O. Lim, X. Wang, Y. Kado, and B. Zhang, "A hybrid centralized routing protocol for 802.11s WMNs", Journal Mobile Netw. and Appl. (MONET), vol.13, no.1-2, pp.117–131, 2008.