A method of determining maximum transmission rate in wireless sensor network

Junying Yuan, Huiru Cao*, Choujun Zhan and Lin Wang

Department of Electronic Communication and Software Engineering, Nanfang College of Sun Yat-sen University, Guangzhou 510975, China
Email: cihisa@126.com
Email: caohuiru0624@163.com
Email: zchoujun2@gmail.com
Email: wlhgncc@163.com
*Corresponding author

Abstract: The lifetime of wireless sensor networks (WSNs) decreases with the increasing payload, such that extending the network lifetime has become a hot topic. This paper proposes a distance-based transmission rate selection algorithm, maximum emission rate (MER) determination, to select the pairwise maximum effective transmission rate in a given WSN environment. The proposed work is founded on two observations, one is the logarithmic relationship of internode communication distance to data transmission rate, the other is the linear relationship of receiving current to data transmission rate. The proposed work helps to reduce data transmission duration, and finally to increase the network lifetime. Simulation results show that the application of MER in existing network protocols extends 300% plus network lifetime while ensuring communication success rate.

Keywords: wireless sensor networks; WSN; network protocol; packet loss rate; PLR; node survival rate; network lifetime.


Biographical notes: Junying Yuan received her MSc in Computer Science and Technology from the Hebei University of China in 2007. She is currently a Lecturer in Nanfang College of Sun Yat-sen University. Her research interests include data mining, pattern recognition, cloud computing, and wireless sensor network.

Huiru Cao received her MSc in Automation from Guangdong University of Technology in 2010. She is currently a Lecturer in Nanfang College of Sun Yatsen University. Her research interests include wireless sensor network, cloud computing, and pattern recognition.

Choujun Zhan received his BSc in Automatic Control Engineering from Sun Yat-Sen University in 2007 and the PhD degree in Electronic Engineering from City University of Hong Kong in 2012. He is currently an Associated Professor in Nanfang College of Sun Yat-sen University. His research interests include systems biology, bioinformatics and complex network dynamics behaviour.
Lin Wang received her BSc in Physics from Huanggang Normal University in 2008. She is currently a Lecturer in Nanfang College of Sun Yat-sen University. Her current research interests are image optics, and photo-electric detection.

This paper is a revised and expanded version of a paper entitled ‘An emission rate adaptive algorithm of wireless sensor networks’ presented at the 2014 7th International Conference on Intelligent Computation Technology and Automation (ICICTA), Changsha, China, 25–26 October 2014.

1 Introduction

Wireless Sensor Networks (WSNs) usually deploys large amounts of sensors to collect environmental information. The amount of collected information shows an up-rising trend along with the expanding application of WSNs from agriculture to wireless body area networks (WBAN). Various issues and challenges are found during practical application, e.g., Sun et al. (2005) pointed out the trend of decreasing network lifetime, Zhou et al. (2013) indicated the problem in traffic routing, Liu et al. (2012a) and Suo et al. (2012) stated the problem of sensor node localisation. Li et al. (2013) and Han et al. (2013) stated that when converging the information from sensors in a large-scale WSN, the nodes distributed in cluster head and those nearby-base stations are faced with problems of communication congestion, hot-spot and funneling effect. As a result, energy consumption at those sensors increases and finally the network lifetime decreases.

Aiming at increasing the network lifetime, researchers have put forward a bunch of solutions from perspectives of network protocol, MAC protocol and transmission rate control. Sun et al. (2005) pointed out that the energy of WSN are spent on mostly data transmission. Elbhiri et al. (2011) presented a hierarchical clustering technique by distributing uniformly the energy in a dynamic probability way to elect the cluster head. Boubiche and Bilami (2011) advanced a creative network protocol HEEP by combining clusters-based and the chain-based approaches to improve the energy efficiency. Liu et al. (2012b) studied the impact of single-hop communication distance to the performance of WSNs. Dvir et al. (2011) proposed a highly agile approach called back-pressure routing for delay tolerant networks which makes routing and forwarding decisions on a per-packet basis. Sengupta et al. (2012) an online multi-objective optimisation algorithm to schedule wireless sensors so as to achieve maximum lifetime. Zhou et al. (2013) worked on the funnel effect and proposed a network protocol based on LEACH which improves control of cluster head by adding auxiliary cluster head sink selection. Zeng et al. (2013) presented a directional routing and scheduling scheme for green vehicle to optimise the energy efficiency with the considerations of congestion. Yin et al. (2014) optimised the energy consumption by proposing a minimum distance clustering algorithm. However, these network protocols focus on fixed per-bit energy consumption, but consider not the possibility of reducing it by increasing data transmission rate at the given communication distance.

In this paper, we propose a distance-based data transmission rate selecting algorithm MER to extend the network lifetime. MER determines the maximum transmission rate utilising the relationship of transmission rate to effective communication distance. When the network topology and the sensor distribution are given, MER can reduce the
communication duration significantly by increasing transmission rate at the constraint of communication distance. Experiments are carried out to obtain the accurate relationship of effective distance to transmission rate in a given environment, and then the proposed algorithm is applied to typical network protocols, such as LEACH advanced by Heinzelman et al. (2002), stable election protocol (SEP) presented by Smaragdakis et al. (2004) and distributed energy-efficient clustering (DEEC) proposed by Qing et al. (2006), to evaluate the effectiveness of the proposed algorithm.

The rest of the paper is organised as below. Section 2 details the energy consumption model of typical WSN sub-networks, and then simplifies the problem of optimisation of network energy consumption to selecting the maximum and effective data transmission rate. Section 3 introduces the setup and steps of the fundamental experiment which is used to verify the impact of transmission rate in a given environment. Section 4 first makes analysis on the fundamental experiment results and obtains the linear relationship of receiving current to transmission rate and the logarithmic relationship of communication distance to transmission rate, and then introduces the MER algorithm. Section 5 applies MER into existing network protocols to verify the effectiveness of MER. Section 6 gives the conclusions.

2 Mathematical models

In this section, we illustrates on the mathematical models related to energy consumption in this paper. First, we describe the energy consumption model of typical WSNs from perspective of data transmission duration, then present the relationship of communication distance to receiving signal strength, and then present a pairwise energy consumption mathematical model. Finally, we derive the relationship of network energy consumption to data transmission rate and receiving current.

2.1 Mathematical model of data communication duration

Consider a WSN sub-network composed of 1 parent node and m child nodes, where a child node transmits a data volume of $S_i$ during each round of data collection, the per-round network payload $S$ is the sum of $S_i$, that is

$$S = \sum_{i=1}^{m} S_i. \quad (1)$$

Let’s further assume that $S_i$ takes the same value $S_0$, then $S$ is simplified to

$$S = mS_0. \quad (2)$$

As indicated by researches Boubiche and Bilami (2011), Yao et al. (2013) and Smaragdakis et al. (2004), for each round of data collection, the data transmission duration $T_{all}$ is composed of the data transmission duration, the adjustment duration $T_z$ for communication parameter negotiation, and the communication interval $T_n$, so we write the per-round transmission duration mathematical model as

$$T_{all} = \frac{S}{V_{tr}} + T_z + T_n. \quad (3)$$
where $V_r$ is the data transmission rate, so

$$s \frac{s}{V_r}$$

is the data transmission duration. Putting equation (2) into equation (3), we get

$$T_{\text{all}} = m \frac{S}{V_r} + T_z + T_n,$$  \hspace{1cm} (4)

which describes the relationship of per-round transmission duration to data transmission rate $V_r$ in a WSN with 1 cluster head and $m$ child nodes. As per-round transmission duration $T_{\text{all}}$ is usually fixed, so if $V_r$ and the data size $S_0$ are determined, the adjusting time $T_z$ and communication interval $T_n$ are also determined. Equation (4) reveals that, for a working WSN, the per-round communication duration is related to data transmission rate, the number of sensor nodes and the payload.

### 2.2 Relationship of received signal strength to communication distance

For WSNs in open environments, Fang et al. (2007) and Lei et al. (2013) have proved that the relationship of received signal strength indicator (RSSI) $P_R$ to communication distance $d$ follows a logarithmic function, which is mathematically modelled as

$$P_R = A - 10n \log(d),$$  \hspace{1cm} (5)

where $A$ is a model parameter, and $n$ is the environment propagation factor. Equation (5) shows that RSSI decreases logarithmically along with the increment of communication distance $d$. In order to get the relationship of $d$ to $P_R$, we transpose equation (5) and get

$$d = 10 \frac{A - P_R}{10n}.$$  \hspace{1cm} (6)

As is well-known, RSSI at the receiver has to keep above a certain threshold so as to ensure the communication quality. We can see from equation (6) that the data transmission distance $d$ is constrained by the minimum RSSI received at wireless sensors.

### 2.3 Mathematical model of per-round energy consumption

According to equation (3), and summarising from network protocols in Sun et al. (2005), Boubiche and Bilami (2011) and Smaragdakis et al. (2004), the energy consumption $E$ in one round of data transmission for a single sensor is composed of the data transmission energy consumption $E_{\text{tr}}$, the energy consumption $E_z$ during communication adjustment, and the inter-round internal energy consumption $E_n$. The mathematical composition of $E$ is

$$E = E_{\text{tr}} + E_z + E_n.$$  \hspace{1cm} (7)

Equation (7) represents the energy consumption of a single sensor in WSN, but for a pair of WSN sensors in communication, the energy consumption $E_{\text{tr}}$ at the receiver should
A method of determining maximum transmission rate in WSN

also be considered. In order to represent the pairwise energy consumption, equation (7) is enhanced to

\[
E_p = E_{tr} + E_z + E_n + E_{rv}.
\]  

(8)

The working current during communication adjustment is the same as the current during communication interval. So we combine the per-round communication duration in equation (4) into equation (8), and get the pairwise per-round energy consumption mathematical model

\[
E_p = \left[ \frac{S'}{V_w} \left( \frac{1}{I_{tr}} \right) \right] V,
\]  

(9)

where \(I_{tr}\) is the transmission current, as a constant; \(I_e\) is the inter-round working current, as a constant; \(I_{rv}\) is the working current at the receiving end; and \(V\) is the constant working voltage for both the transmitter and the receiver.

As proved in later Section 4.1 that the receiving current \(I_{rv}\) increases slightly in linear way with \(V_{tr}\), so a possible method to reduce energy consumption in WSN is to increase the data transmission rate. When the network hierarchy and the communication distance \(d\) between sensors are firmed, the problem of optimising network energy consumption can be simplified to minimising the pairwise energy consumption of a child node and its parent node. Hence, for a WSN sub-network with \(m\) child nodes and 1 cluster head, the per-round network energy consumption \(E\), is the sum of pairwise energy consumption \(E_p\).

So the network energy consumption

\[
E = mE_p = m(T_z + T_n)I_{tr}V + \sum_{i=1}^{m} \frac{S'}{V_w} (I_{tr} + I_{rv})V.
\]  

(10)

The first part \(m(T_z + T_n)I_{tr}V\) of equation (10) is a constant, so we can focus on the second part which is the energy consumption of the inter-sensor data communication, and it can be simplified to get the minimum pairwise data transmission energy consumption. However, as indicated by Sun et al. (2005) and Liu et al. (2012b), increasing transmission rate usually reduces communication distance and increases the receiving current. As a result, when determining the optimal transmission rate, we have to consider constraints from the relationship of energy consumption to transmission rate, the relationship of communication distance to transmission rate and the relationship of the receiving current to transmission rate. Those constraints are classified by a fundamental experiment detailed in the next section.

3 Fundamental experiments

As indicated by equation (10), when payload \(S_0\) is fixed, the inter-sensor energy consumption between a parent node and a child node is determined by the data transmission rate \(V_{tr}\) and the receiving current \(I_{rv}\). To solve the problem of minimising inter-node communication energy consumption as specified by equation (10), two relationships have to be clarified, the first is the relationship of the receiving current \(I_{rv}\) to transmission rate \(V_{tr}\), the second is the relationship of the data transmission rate \(V_{tr}\) to
inter-node distance $d$. Both of the two relationships are classified through the following fundamental experiment.

**Table 1** Influence factors in wireless communication for fundamental experiment

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmission rate (/kbps)</td>
<td>1.2, 2.4, 38.4, 250, 500</td>
</tr>
<tr>
<td>Decoding method</td>
<td>GFSK</td>
</tr>
<tr>
<td>Communication distance (/m)</td>
<td>0 s100</td>
</tr>
</tbody>
</table>

The fundamental experiment is designed to capture the maximum transmission rate $V_t$ and the related receiving current $I_r$ when PLR approaches 15% while changing communication distance from 100 to 0 metres. In the fundamental experiment, transmission rate $V_t$ is chosen as the influencing factor, the decoding method is configured as GFSK, and the communication distance varies from 0 to 100 metres, as shown in Table 1. The experiment is carried out at night using wireless module CC1101 in an open environment. The module is configured with 433 MHZ as carrier frequency, 0 dBm as the transmission power, and the antenna of transmitter and receiver fixed on the ground of about 1.4 m. The experiment steps are detailed as follows:

Step 1 Receiver is placed $d$ metres from transmitter, and $d$ is set to 100 m as initial value.

Step 2 Transmitter launches 500 packets at transmission rate $V_t = 1.2$ kbps, each packet contains 30 bytes payload.

Step 3 Measure RSSI and PLR at the receiver during data communication.

Step 4 Record $V_t$, RSSI, $d$ and PLR.

Step 5 Increase $V_t$ and repeat Step 2 to Step 4 until PLR approaches 15%.

Step 6 Reduce $d$ by 5, and repeat Step 1 to Step 5 until $d = 0$ m.

PLR = 15% is commonly considered as the worst communication performance for effective data transmission, this value is also used in the rest experiments. After the experiment, we get a bunch of inter-sensor communication performance measurements, and each piece of measurement is composed of $V_t$, RSSI, $d$ and PLR. Then we employ Microsoft Excel to make data fitting analysis to get the relationship of maximum effective communication distance $d$ to the transmission rate $V_t$, and the relationship of receiving current $I_r$ to data transmission rate $V_t$. According to these two relationships, our max transmission rate selection algorithm (MER) is put forward.

4 Fundamental experiment analysis and the proposed work

In this section, we employ Microsoft Excel to make least square fitting analysis on the experiment data from the fundamental experiment. According to the numerical fitting analysis, the relationship of receiving current $I_r$ to transmission rate $V_t$ is proved to be of linear, the relationship of maximum effective communication distance $d$ to $V_t$ is proved to be logarithmic, and the relationship of RSSI to $V_t$ is in line with equation (6). Based on those relationships, we present the MER algorithm.
4.1 Relationship of receiving current to transmission rate

In the fundamental experiment, the receiving current is measured at the same distance with various transmission rates. The least square fitting analysis on the relationship of $I_{rv}$ to $V_{tr}$ produces a fitting curve as shown in Figure 1, which shows that in the process of inter-node communication, the receiving current $I_{rv}$ at the receiver is not fixed, but increases linearly with the increment of transmission rate $V_{tr}$. The least square fitting on the data also provides the mathematical function of the receiving current to the transmission rate,

$$I_{rv} = 0.0063V_{tr} + 16.568\left( R^2 = 0.9271 \right),$$

where the linear square fitting coefficient $R^2 = 0.9271$. The fitting result presents an obvious linear relationship between the receiving current $I_{rv}$ and transmission rate $V_{tr}$.

![Figure 1](image_url) The relationship of $I_{rv}$ to $V_{tr}$ (see online version for colours)

4.2 Relationship of maximum effective communication distance and RSSI to transmission rate

The maximum effective communication distance refers to the utmost data transmission distance $d_{max}$ when packet loss rate (PLR) approaches 15%. The further the communication distance is the higher PLR is. The least square fitting analysis on the relationship of $d_{max}$ to $V_{tr}$ produces a fitting curve as drawn in Figure 2, which illustrates that the increase of $V_{tr}$ decreases $d_{max}$. The least square fitting analysis of the relationship of $d_{max}$ to $V_{tr}$ is described mathematically by equation (12). With the fitting coefficient R2 as 0.9271, equation (12) indicates that increasing $V_{tr}$ logarithmically reduces $d_{max}$.

$$d_{max} = -5.6492 \ln\left(V_{tr}\right) + 53.77\left(R^2 = 0.9664 \right).$$

A further least square fitting analysis is made on the relationship of RSSI to $V_{tr}$, and result is in line with equation (6), as illustrated in Figure 2.
4.3 The presented work

From equation (12), we get the mathematical function of the maximum transmission rate to communication distance is

\[ V_{tr} = e^{-0.1790(d-53.55)}. \] (13)

Hence, if the pairwise communication distance is known, the maximum transmission rate \( V_{tr} \) for this sensor pair can be derived following equation (13). Now we put equation (11) into equation (10), and get the relationship of per-round energy consumption \( E \) to transmission rate \( V_{tr} \)

\[ E = A + \sum_{i=1}^{m} \frac{S'}{V_{tr}} (I_{tr} + 15.569) V_{tr}, \] (14)

\[ A = (T_s + T_a) I_s V_{tr} + 0.0063 n S'. \] (15)

Let \( \text{Min} \{E\} \) denote optimising the per-round energy consumption, if inter-node distance \( d \) is known, the problem of solving \( \text{Min} \{E\} \) can be simplified as finding the minimum pairwise per-round data transmission energy consumption

\[
\arg \min_{V_{tr}} \{ E_i \} = \arg \min_{V_{tr}} \left( I_{tr} + 15.659 \right) V_{tr},
\] (16)

where \( E_i \) is energy consumption of a child node \( i \) and its parent node. As \( S_0, I_s \) and \( V \) are constants, it is clearly that the higher \( V_{tr} \) is, the less \( E_i \) is. According to equation (13), \( V_{tr} \) is constrained by the communication distance \( d \). Hence, solving the problem of \( \text{Min} \{E\} \) is transformed into finding the maximum transmission rate \( V_{tr} \) given communication distance \( d \), then equation (16) is reformulated as

\[
\arg \min_{V_{tr}} \{ E_i \} = \frac{S'}{\arg \max_{V_{tr}(d)} \left( I_{tr} + 16.568 \right) V_{tr}}.
\] (17)
where arg max \( V_{tr}(d) \) can be derived from equation (13).

Based on the above analysis, we can conclude that, in the process of inter-node data transmission, data transmission rate \( V_{tr} \) should be set to the highest effective value under the constraint of PLR 15%. Now we propose our maximum emission rate (MER) selection algorithm, and listed the detailed steps as below:

Step 1 WSN uses minimal transmission rate 1.2 kbps during network initialisation. The receiver, usually the cluster head, utilises equation (6) to determine communication distance \( d \), and then it notifies the transmitter, usually the child nodes, of the information \( d \).

Step 2 The transmitter selects the optimal transmission rate \( V_{tr} \) based on \( d \) following equation (13).

Step 3 The transmitter notifies the cluster head of the optimum transmission rate at default communication rate 1.2 kbps. Then both sides modify their configuration for data transmission.

Step 4 During later communication, if PLR > 15%, the transmitter and the receiver can reduce communication rate \( V_{tr} \) to ensure the quality of communication.

Step 5 Transmitter and receiver communicates at the adjusted transmission rate.

We can see from the above steps that MER adds only a bit of inter-node negotiation cost, but it is negligible comparing to the amount of reduced communication duration.

5 Experiment and result analysis

Given the inter-node distance \( d \) in the same environment as that in fundamental experiment, the maximum \( V_{tr} \) is derived according to equation (13), however, the calculation is a little complex and environment dependent, we can simplify it so as to make calculation of the WSN energy consumption easier. This is achievable by using the reference energy consumption \( ETX(V_{ref}) \) when using default transmission rate \( V_{ref} \).

Throughout the rest experiments, to ensure the communication performance during data transmission, we take the same assumption as the one in fundamental experiment that PLR < 15%.

From equation (10), we know that the variation part of pairwise energy consumption includes the transmission energy consumption at the transmitter and the receiving energy consumption at the receiver. We could calculate both of them on a per-bit basis. Given the maximum effective communication distance, the per-bit transmission energy consumption

\[
ETX(V_{tr}) = ETX(V_{ref}) \cdot \frac{V_{ref}}{V_{tr}},
\]

where \( V_{ref} \) is the default transmission rate 1.2 kbps, \( V_{tr} \) is the transmission rate, \( ETX(V_{ref}) \) and \( ETX(V_{tr}) \) are the per-bit transmission energy consumption when transmission rates are \( V_{ref} \) and \( V_{tr} \) respectively.

Similarly, we simplify the calculation of per-bit receiving energy consumption at the receiver by combining equation (10) and equation (17),
\[ \text{ERX}(V_r) = \text{ERX}(V_{ref}) \frac{V_{ref}}{V_r} + \frac{I_w(V_r)}{I_{rv}(V_{ref})} \]

\[ \frac{I_w(V_r)}{I_{rv}(V_{ref})} = \frac{0.0063V_r + 16.568}{0.0063V_{ref} + 16.568^3} \]

where \( \text{ERX}(V_{ref}) \) is per-bit receiving energy consumption at transmission rate \( V_{ref} \) at the receiver; \( I_w(V_r) \) is receiving current at transmission rate \( V_r \); \( I_{rv}(V_{ref}) \) is receiving current at transmission rate \( V_{ref} \).

### 5.1 Simulation results with fixed scene scale

We apply MER algorithm to the widely used network protocols, such as LEACH, SEP and DEEC, to verify the effectiveness of MER. The improved network protocols can be named as LEACH-MER, SEP-MER and DEEC-MER respectively. Assuming a WSN network deploys 100 nodes in an \( M \) by \( M \) square with the base station placed in the centre; experiments are executed in MATLAB with commonly used parameters as listed in Table 2. Three network quality indicators, the network lifetime in rounds of data transmission, the node survival rate and the network energy consumption rate, are used as performance measurements. Assuming the same environment factors as in the fundamental experiment, each simulation is run 10 times for each protocol with the same network topology and configuration. The average of performance measurements from the ten runs are used as the final performance measurements, and the experimental results are captured in Figure 3 and Figure 4 respectively to compare the quality measures of network lifetime and the network energy consumption.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>( E_{elec} )</td>
<td>50 nJ/bit</td>
<td>Per bit energy consumption when ( V_r = 1.2 ) kbps</td>
</tr>
<tr>
<td>( efs )</td>
<td>10 pJ/bit/m²</td>
<td></td>
</tr>
<tr>
<td>( emp )</td>
<td>0.0013 pJ/bit/m⁴</td>
<td>Determined by ( efs ) and ( emp )</td>
</tr>
<tr>
<td>( d_0 )</td>
<td>87.7 m</td>
<td></td>
</tr>
<tr>
<td>( E_0 )</td>
<td>0.5 J</td>
<td>Default battery energy capacity</td>
</tr>
<tr>
<td>EDA</td>
<td>5 nJ/bit</td>
<td></td>
</tr>
<tr>
<td>( n )</td>
<td>100</td>
<td>Number of sensors in WSN</td>
</tr>
<tr>
<td>( p_{opt} )</td>
<td>0.1</td>
<td>Probability of being cluster head</td>
</tr>
<tr>
<td>( a )</td>
<td>1</td>
<td>Alpha</td>
</tr>
<tr>
<td>payload</td>
<td>4,000 bits</td>
<td>Payload in each round of data transmission</td>
</tr>
</tbody>
</table>

Figure 3 provides the figure of node survival rates to rounds of data transmission for LEACH, LEACH-MER, SEP, SEP-MER, DEEC and DEEC-MER. For the WSNs running with LEACH, SEP or DEEC, sensors starts running out energy after about 1,200 rounds of data transmission, and only 10% of the nodes are found alive after about 1,500 rounds of data transmission. While, for the WSNs running with LEACH-MER, SEP-MER, or DEEC-MER, sensors starts running out energy after about 3,900 rounds of data transmission, and over 20% of sensors are still alive even after 15,000 rounds of data transmission.
A method of determining maximum transmission rate in WSN

determination of maximum transmission rate in WSN. As much more nodes are found alive after the same rounds of data transmission, the improved protocols outperform much than the existing protocols in the sense of the node survival rate and the network lifetime. The improvement is obvious as the later three networks live at least three times longer than the former three networks at the same node survival rate.

Figure 3  Comparison of network lifetime (rounds) (see online version for colours)

Figure 4  Comparison of network energy consumption (rounds) (see online version for colours)

Figure 4 presents the curve of data transmission rounds to the network energy consumption rate for LEACH, SEP, DEEC, LEACH-MER, SEP-MER and DEEC-MER. For the WSNs running with LEACH, SEP or DEEC, 90% of the network energy is used after 1,500 rounds of data transmission. While, for the WSNs running with LEACH-MER, SEP-MER, or DEEC-MER, only 10% of the network energy is used after the same rounds of data transmission, and 90% of sensors are consumed after 12,000 rounds of data transmission. It is clear that the improved protocols outperform
much than the existing protocols in the sense of energy consumption. The reason is the MER enhanced protocols require less per-bit energy consumption such that they transmit more rounds of data at the same energy consumption. The improvement is obvious as the later three networks consume much less energy after the same cycles of data transmission comparing to the former three networks.

5.2 Simulation results with various scene scales

For MER enhanced network protocols, the smaller the inter-node distance is, the higher the data transmission rate is and the longer the network lifetime is. To study the impact of scene scale $M$ to MER, with the same number of sensor nodes deployed in various scene scales, we use LEACH-MER, SEP-MER, DEEC-MER, LECH, SEP and DEEC as network protocols respectively to check the rounds of data transmission at the same node survival rate and energy consumption. Table 3 and Table 4 list the experiment results by calculating ratios of data transmission rounds at given percentage of nodes alive and energy consumption respectively.

**Table 3**  Relationship of nodes alive to scene scale and time (rounds)

<table>
<thead>
<tr>
<th>$M$(m)</th>
<th>Ratio of sensors alive</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>90%</td>
</tr>
<tr>
<td>LEACH-MER/LEACH</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>80</td>
</tr>
<tr>
<td></td>
<td>100</td>
</tr>
<tr>
<td>SEP-MER/SEP</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>80</td>
</tr>
<tr>
<td></td>
<td>100</td>
</tr>
<tr>
<td>DEEC-MER/DEEC</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>80</td>
</tr>
<tr>
<td></td>
<td>100</td>
</tr>
</tbody>
</table>

**Table 4**  Relationship of energy consumption to scene scale and time (rounds)

<table>
<thead>
<tr>
<th>$M$(m)</th>
<th>Ratio of energy consumption</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>90%</td>
</tr>
<tr>
<td>LEACH-MER/LEACH</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>80</td>
</tr>
<tr>
<td></td>
<td>100</td>
</tr>
<tr>
<td>SEP-MER/SEP</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>80</td>
</tr>
<tr>
<td></td>
<td>100</td>
</tr>
<tr>
<td>DEEC-MER/DEEC</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>80</td>
</tr>
<tr>
<td></td>
<td>100</td>
</tr>
</tbody>
</table>
In Table 3, when $M$ is 60 m, 80 m and 100 m and the sensor survival rate is 90%, 70%, 50% and 30% respectively, we compare the ratio of data transmission rounds at given node survival rate for MER improved algorithm against that of original. From the experimental result, we can see that with the same scene scale $M$ and at the same sensor survival rate, the network lifetime of the MER improved networks outperform several times than the original networks. Meanwhile, the smaller the scene scale $M$ is, the better the performance is. The reason is that, for MER improved networks, smaller scene scale $M$ results smaller inter-node distances, and smaller inter-node distance enables higher the transmission rates. As a result, the per-round energy consumption is reduced and the network lifetime extends. The conclusion is when scene scale $M$ is set smaller, the network lifetime stays the same for LEACH, SEP and DEEC, but it increases for MER enhancement algorithms LEACH-MER, SEP-MER and DEEC-MER.

In Table 4, when $M$ is 60 m, 80 m and 100 m and the network power consumption is 10%, 30%, 50% and 70% respectively, we compare the ratio of number of data transmission rounds at given energy consumption rate for MER improved algorithm against that of original. From the experimental result, we can see that with the same scene scale and at the same network energy consumption rate, MER enhanced network protocols improves the network lifetime. In addition, the smaller the scene scale $M$ is, the better the performance is. The reason is that smaller $M$ results in shorter inter-node distance, shorter inter-node distance results in higher data transmission rate, and finally, the transmission duration is reduced and more rounds of data transmission are possible at the same energy consumption. The result in Table 4 coincides with the conclusion in Table 3 in the sense that the application of MER algorithm in existing network protocols can reduce the network power consumption and extend the life of the network.

6 Conclusions

In the application of large-scale WSNs, it is usually required to transmit a large data volume. As a result, the communication duration increases greatly such that network energy consumption grows accordingly. In order to shorten the communication duration so as to reduce the network power consumption and extend the network lifetime, this article presents a transmission rate selection algorithm MER according to the relationships of transmission rate to the effective communication distance. It is experimentally proven that the application of the MER into the existing network protocols can substantially extend the network lifetime while ensuring PLR.

Due to the limited experimental environment, the verification experiments are executed as simulation only. The next step is to dig into the specific influences of the MER algorithm to real sensor networks. In addition, as the parameters of the proposed MER algorithm depends on specific environment factors, one further study before making the solution practical is how to collect them automatically during the network setup and adjust them accordingly during data transmission.
Acknowledgements

The work is supported by the Foundation for Distinguished Young Talents in Higher Education of Guangdong, China (Grant Nos. 2013LYM0123). Any options, findings, and conclusions or recommendations expressed in this paper are those of the authors.

References


A method of determining maximum transmission rate in WSN


