Dynamic Power Management and Adaptive Packet Size Selection for IoT in e-Healthcare

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ABSTRACT

Wireless communications in e-healthcare must work in a reliable, fast and energy-efficient fashion. In this paper, first, a power level decision (PLD) algorithm is proposed to select the optimal power level for each node, which enables the minimization of energy consumption in the successful transmission of a data packet based on the reliable data transmission scheme. Second, a power level and packet size decision (PPD) algorithm is presented for the optimal selection of data size. The proposed algorithm can either minimize the delay at a prescribed transmission power, or minimize the energy consumption of successful transmission of a data packet while guaranteeing a certain delay. Third, a global link decision (GLD) scheme is devised for improving the reliability of the whole network, decreasing the delay, and simultaneously obtaining the performance optimization by enhancing the transmission power using the remaining energy of nodes in the area far from the base station, and enlarging the size of data packet. Theoretical analysis and experimental results demonstrated the validity and effectiveness of the proposed algorithms in terms of energy efficiency, lifetime, reliability and delay. It is shown that the GLD scheme is capable of improving the energy efficiency and transmission reliability by 35.90% and 8.70%, respectively. Moreover, the delay is decreased by 7.74% while not reducing the network lifetime, which was hardly achieved in the existing research works.

1 INTRODUCTION

Internet of Things (IoT) technologies including smart healthcare wearable sensors [1], body area sensors [2, 3], smart sensors [4-7], and mobile sensors [8, 9], indicate the realization of smart e-Healthcare, which opens up a new dimension to provide e-Health interactions to the public for a better healthier life [10-11]. A smart hospital equipped with wireless sensors provides healthcare Internet of Things (IoT) service [12-17]. In this service, a sensing based surveillance system monitors and collects various data from the ward, intensive care unit, and diagnostic equipment, and then mines a large amount of collected data (i.e., e-Health big data) to obtain valuable information for healthcare environment. Smart e-Health is automatically controlled using the obtained information to achieve an efficient healthcare. Therefore, the smart hospital makes it possible to optimize the healthcare with less human resources, more efficient therapeutic effects, and more reliable and comprehensive surveillance coverage as well as safety guarantee [18-22]. On the other hand, a variety of sensing equipment detects and collects diverse signals data. These data, together with diagnostic data, form the big data which can be used for discovering new methods to provide remote diagnostics, superior understanding of disease, and evolution of innovative solutions for therapy [21-23].

Although wireless sensor based IoT technologies have significantly promoted the development of e-Health [1, 2, 3, 8, 10, 24], e-Health still has some issues to be coped with, which are not present in general wireless sensor networks (WSNs). The first issue is the high demand of reliability in wireless communications. The sensors deployed in the hospital usually require higher communication reliability than those in the general WSNs [1, 2]. In e-Health, the signals detected by sensors are mainly from patients and their vital signs, which are critically related with patients' safety. Therefore, reliable signal transmission plays an extremely important role in e-Health, and any loss or damage of key data may bring about great losses

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[25, 26]. Moreover, the transmission of the data detected by the sensors which are deployed in the hospital requires higher reliability in such an important application scenario. The second one is the maximization of network lifetime. The lifetime of sensors is always a key research problem, especially in the smart hospital sensors network. On one hand, the transmission power should be selected appropriately. In other words, the transmission power levels employed on each link should be optimized [27, 28]. On the other hand, sensor nodes should dissipate their energy in a balanced fashion so that premature death of any sensor due to over-utilization of its battery energy is avoided.

Numerous research works have investigated the lifetime maximization and reliable communication for e-Health. However, several issues still exist for further research. (1). Many research works hold the opinion that the transmission power of sensor nodes can be changed continuously. In practice, however, most sensor nodes can change their transmission power only in several limited levels. Also, the transmission power can affect the transmission reliability, and the transmission reliability is related with the number of data retransmission (i.e., the transmission delay). Thus, sensors' transmission power, transmission reliability and delay should be collectively optimized; (2). In spite of existence of many researches in the reliability of wireless communication, they consider the size of data packet to be fixed. In fact, the data packet size has a significant effect on the transmission reliability and delay. The transmission performance can be effectively improved by optimizing the size of the data packet; (3). Most researches adopt the same transmission power and data packet size for all sensors in the network. Thus, it is difficult to optimize the performance of the whole network. Practically, the sensors in different areas of the network undertake different transmission workload, leading to their different energy consumption. Hence, the same valued parameter setting cannot optimize the whole performance of the network. In this work, the limitations of existing research works are deeply studied, and the major novelties of this works are summarized as follows:

(1) A power level decision (PLD) algorithm is proposed to select the optimal power level for each node, which enables the minimization of energy consumption in the successful transmission of a data packet. This work first theoretically presents the optimization relationship among the transmission power, transmission reliability and delay. Based on the theoretical optimization result, the minimal transmission power for a node is then determined in forwarding a data packet in the PLD algorithm.

(2) A power level and packet size decision (PPD) algorithm is presented for the optimal selection of data size. The proposed algorithm can either minimize the delay on a basis of a prescribed transmission power, or minimize the energy consumption of successful transmission of a data packet while guaranteeing a certain delay.

(3). A global link decision (GLD) scheme is devised for improving the reliability of the whole network, decreasing the delay, and simultaneously maximizing the network lifetime. The GLD scheme is different from existing researches in that the GLD makes the optimal choice based on the entire network circumstances, rather than merely reduce the energy consumption of sensors. In the surveillance network of e-Health, the nodes close to the base station have much more transmission workload than those far from the base station, resulting in the over-utilization of the energy in the nodes near the base station, and energy surplus for the remote nodes away from the base station. In the proposed GLD scheme, therefore, the power level and data size are optimally selected for the nodes close to the base station. Meanwhile, the nodes far from the base station are equipped with increased transmission power and data size. In this way, the reliability of data transmission is largely improved, and the transmission delay is reduced significantly. Theoretical analysis and experimental results indicate that the GLD scheme can improve transmission reliability by 8.70% and decease the transmission delay by 7.74% while not reducing the network lifetime. This proposed scheme brings about important significance in greatly enhancing the network reliability and lowering the transmission delay without damaging other performances of the network.

The rest of this paper is organized as follows: In Section 2, the related works are reviewed. The system model and problem statement are described in Section 3. In Section 4, the PLD algorithm, PPD algorithm, GLD scheme are presented to select the optimal transmission power, data size such that the network lifetime and transmission reliability are maximized, and the transmission delay is minimized. The performance of the proposed algorithms is theoretically analyzed in Section 5. Section 6 presents experimental results and comparison. We conclude in Section 7.

2 BACKGROUND AND RELATED WORK

With the development of Internet of Things (IoT) technologies, IoT based e-Health has attracted increasing interests from both academia and industry [29, 30]. A growing number of surveillance machines and equipment have been applied in medical field for smart monitoring anywhere and at any time, including various temperature and humidity sensors and characteristic medical wireless sensor nodes. Thus, the modern hospitals are also called smart hospitals. Moreover, these applications have been evolving toward the family healthcare, e.g., Junnila et al. [31] introduced an in-home monitoring platform based on Zigbee networks, which was intended for e-health applications. There have been numerous research works which are aimed to improve the reliability of data transmission, decrease the transmission delay and enhance the energy efficiency for wireless sensor networks in e-Health.

Energy efficiency has always been a key issue in IoT research, especially for those sensor nodes with limited built-in battery power. In the past decades, a voluminous amount of research works has been presented for the energy efficiency of WSNs from MAC (media access control) layer, network layer to application layer. A dynamic adjustment of duty cycle in MAC layer for optimized network lifetime and delay was studied in [32]. In network layer, a clustering scheme for the WSN was proposed to improve the energy efficiency and reduce the delay. In [34], the network delay and reliability were optimized by adjusting the transmission power of sensor nodes.

Selection of optimal packet size was considered in [29], to improve energy efficiency in BANs. There exist complex relationships among packet size, energy efficiency, reliability and transmission delay. (1) There is an optimization relationship between packet size and energy efficiency. A packet contains a fixed-size header, and the ratio between the length of valid data in the data packet and the length of whole data packet is called the payload ratio. Obviously, if the packet size increases, the payload ratio will increase and more valid data will be transmitted. On the contrary, if the packet size decreases, the payload ratio will be reduced, leading to the waste of energy consumed on the transmission of invalid header. Therefore, there exists an optimization relationship between the data packet size and the energy consumption. (2). The packet size not only affects the energy consumption, but also has an impact on the reliability of data transmission [34]. When the transmission power is fixed (i.e., the bit error rate is fixed), the error rate of packet transmission will increase if packet size is enlarged, which can lower the transmission reliability of data packet. By contrast, if the packet size is decreased, transmission reliability of data packet will be raised. However, the increase of successful packet transmission rate for a single packet does not indicate the entire performance of packet transmission is enhanced. For a fixed-size data, a small size data packet transmission scheme needs a large number of transmissions. Although its successful transmission rate is relatively high for each transmission, the total successful transmission rate is not necessarily larger than that using a large size data packet. (3). The packet size can also affect the transmission delay. Likewise, at a fixed transmission power, the successful transmission rate will decrease if the packet size is increased. Since the number of data transmission for the same data is small when using large packet size scheme, its transmission delay is not necessarily longer than that using the small packet size.

The transmission reliability is related with a variety of factors in the network [35]. First, it is related to the transmission power of sensor nodes. The large transmission power corresponds to the large signal-to-noise ratio in the wireless channel and the strong signal that a receiver can receive, thus producing a low bit error rate for data transmission, and the high transmission reliability as well as high energy consumption. In order to enhance the transmission reliability of the network, researchers have proposed various methods, which can be summarized as follows: (1) Retransmission scheme: one of the most important methods for guaranteeing the transmission reliability of the network is the retransmission scheme, which can be extensively applied in the wired and wireless sensor networks. The idea behind the retransmission scheme is that a sender employs a certain scheme to determine whether a packet to be sent to the receiver is successfully received by the receiver or not. If the packet is successfully received, the sender will send next packet; otherwise the sender will resend current packet. In this scheme, the receiver usually sends ACK back to the sender in order to inform the sender it has successfully received the packet. If the sender does not receive an expected ACK in a fixed time, it will resend the packet. This process continues until either the receiver receives the packet successfully, or the number of practical retransmission exceeds the prescribed maximal number, leading to the start of the next packet transmission [34]. However, this scheme has a limitation: the packet transmission is ended either by the receipt of the ACK at the sender side, or by the packet drop due to the number of retransmission in excess of the prescribed maximal number. In fact, each packet transmission has to wait for one or more round trip time (RTT). Therefore, multiple retransmissions will result in large network delay in a data link with relatively high packet error rate [34]. (2) Network coding techniques [26] is an effective reliability-guaranteed scheme based on redundant coding. In network coding techniques, the source node encodes the packets with some redundant level. The destination node decodes the packets to retrieve the original packets. Due to the redundancy in the data transmitted by the source node, some data loss in the wireless channels with lossy nature will not affect the correct data receiving at the destination node. An advantage of *the network coding technique* is that the source node can send out the data at one time, and the destination node is capable of receiving the data with a relatively high reliability. Compared with the retransmission scheme, the network coding technique can reduce the transmission delay, whereas at the price of encoding and decoding at the node, as well as redundancy in the transmitted data, thus resulting in high computation workload and energy consumption. A novel method integrating the retransmission scheme and the network coding technique which was proposed in the previous work [26] achieves good performance in energy efficiency and transmission delay.

To sum up, there exist complex optimization relationships among the performance of energy efficiency, reliability, transmission delay, transmission power and the data packet size. However, all aforementioned works have not investigated the optimization relationships in a comprehensive way, which can affect the network performance. In this paper, a synthetic optimization strategy for optimized network performance is proposed.

3 SYSTEM MODEL AND PROBLEM STATEMENT

In this section, we present an overview of our system model, and introduce the problems to be solved.

3.1. System model

We consider a WSN consisting of a large amount of sensor nodes evenly deployed over a circular area centering at a base station for data collection from the environment such as hospital, industrial monitoring [1, 2, 6, 36]. Nodes forward their generated data to the base station either directly or via other sensor nodes acting as relays. Time is organized into rounds and each node generates D bytes of data at each round [25, 26].

Data transmission between any pair of nodes is completed through a two-way handshake mechanism. For a successful

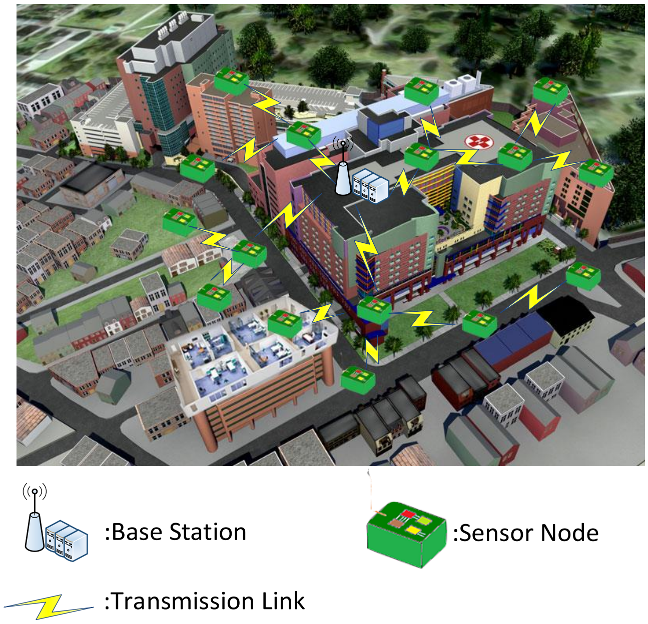

Fig. 1. The wireless sensor network application scene for hospital

handshake operation, both data and ACK packets are successfully received by the expected recipients. Transmission power levels for both data and ACK packets can be chosen from a finite set of discrete power levels. Data packet size can also be selected from a set of discrete values for bytes, whereas the ACK packets size are fixed to ensure message format for smooth communication [37]. Also, each packet has a fixed header, guaranteeing the data transmission process as well. If the handshake fails, the transmitter will restart the process until the times for retransmission of the same packet have reach a maximum value [35, 37].

In our framework, data flows over links in a centralized manner, and links on the route have equal intervals, e.g., r meters. The Shortest Path Routing Strategy is employed in routing [35]. TDMA time slots allocation is also assumed to be performed in a centralized manner to adapt to circular network topology [33]. Moreover, the network has sufficient bandwidth so that collision free communication can be guaranteed [36]. Hence, we assume that base station has the complete topology information, fast processing speed and sufficient energy resources to perform the necessary computation for data flow planning, so that the station can decide power level assignments for all the nodes in WSN [37].

In this work, the energy dissipation characteristics of Mica2 motes are utilized to construct our model. Mica2 motes, which consists of an Atmel Atmega 128L processor and Chipcon CC1000 radio, have been a heavily utilized workhorse of the experimental WSN research. The mote can adjust its power for transmission, and data transmission is more likely to succeed with higher power, while more energy consumption speed is also raised. The relationship between transmission power consumption and output antenna power for Mica2 Motes is adopted from Table 1 in [37]. Other parameters used in this paper are given in Table 1, with reference of [37], [40]-[43].

Furthermore, all nodes are roughly time synchronized. They have three stable modes: transmission mode, reception mode and sleep mode. In a slot, if any two nodes have a communication event, they only maintain the first two modes according to the intended arrangement. Otherwise, they go to sleep. In fact, there are many synchronization protocols designed specifically for WSNs with virtually no overhead and satisfactory synchronization performance [38].

3.2. Problem statement

Definition 1: Network lifetime (denoted as T_{life}, with the time of a round as a unit) is defined as the time intervals from the time when network is built to the time when the first one of dead nodes occurs due to running out of battery energy. As a result, T_{life} depends on the energy consumption speed of node. The energy dissipation of node consists of: (a) energy consumption in communication, for instance, E_x^t and E_x^r utilized for transmission and reception process, respectively, (b) the energy consumption E_{sleep} for sleep mode. Maximizing the lifetime is equivalent to minimizing the energy consumption speed of the first dead node, which can be depicted as the following formula, where $e_{battery}$ represents the initial energy of node:

$$\max T_{life} = \max \min_{x \in route}(e_{battery}/(E_x^t + E_x^r + E_{sleep})). \tag{1}$$

Definition 2: Network delay (denoted as L^s) refers to the interval between the time when data generate from network edge to the time when data arrives at sink, computed as the accumulation of delays on the link on route. L_x^{hop} represents the delay of data from a node with x meters to sink to next hop.

Consequently, the network delay minimization can be expressed as:

Table 1. Network Parameters

Symbol	Description	Value
R	Network radius	$500m$
r	Hop interval	$50m$
T_{rd}	Data collection round time	$60s$
$e_{battery}$	Battery Energy	$3000J$
γ_0	Reference path loss	$55dB$
l	Signal decay rate	2.36
σ	Gaussian random bound	$1.5dB$
W_n	Noise power	$-115dBm$
W_{th}	Reception sensitivity	$-102dBm$
N_{rtr}	Maximum retransmission times	3
N	Default data packet size	$1500\ bytes$
H	Packet header size	$50\ bytes$
A	ACK packet size	$20\ bytes$
W_r	Reception power	$35.4mW$
P_{sleep}	Sleep power	$3\mu W$
W_n	Noise power	$-115dBm$
W_{th}	Reception Sensitivity	$-102dBm$
v_{ch}	channel data rate	$19.2Kbps$

$$\min\ L^s = \min \sum_{(x-ir)\in route} L_{x-ir}^{hop}. \tag{2}$$

Definition 3: Transmission reliability (denoted as R_{edge}) refers to the probability of data arrival from network edge to sink, or the product of successful transmission probability on the links on route. A successful transmission from the node to next hop happens with a probability of Q_x. Hence, the maximization of transmission reliability is depicted as

$$\max\ R_{edge} = \max \prod_{(x-ir)\in route} Q_{x-ir}. \tag{3}$$

Definition 4: Energy utilization balance rate (denoted as τ) refers to the minimum ratio between the utilized energy of any node and the initial energy when the first dead node appears. We aim to maximum the energy utilization of the complete network topology. Therefore, the objective of maximizing the energy utilization balance rate is

$$\max\ \tau = \max\min \frac{E_x^{used}}{e_{battery}}, \tag{4}$$

where E_x^{used} is the used energy of a node with x meters to sink when network dies, and $e_{battery}$ denotes the initial energy given to every node.

Obviously, the goal of GLD scheme is to maximize the network lifetime T_{life}, minimize the network delay D^s, maximize transmission reliability P_{edge}, and maximize energy utilization balance rate, which can be summarized as follows:

$$\begin{cases} \max T_{life} = \max\min(e_{battery}/(E_x^t + E_x^r + E_{sleep})) \\ \min\ L^s = \min \sum_{(x-ir)\in route} L_{x-ir}^{hop} \\ \max\ R_{edge} = \max \prod_{(x-ir)\in route} Q_{x-ir} \\ \max\ \tau = \max\min \frac{E_x^{used}}{e_{battery}} \end{cases}. \tag{5}$$

4 DESIGN OF GLD SCHEME

In this section, to begin with, we present three observations to explain our research motivation. Then, based on energy minimization rule, we prove that there exists a pair of optimal power levels over a link in theory. We also propose an algorithm to find aforementioned optimal power levels. By exploring the impact of packet size over links on the network performance, two schemes involving power levels and packet size are obtained, with a tradeoff of energy cost and delay. Finally, we propose a GLD scheme, which incorporates energy consumption equilibrium strategy to fully utilize the residual energy in non-dead nodes. Thus, the data delay decline and reliability rise are obtained with a little extension of network lifetime.

4.1 Research Motivation of GLD Scheme

The research motivations of the GLD scheme is grounded on our comprehensive studies on WSNs, which is concluded as the following 3 observations.

Observation1. If multiple hop WSN model are used in hospital scene, transmission reliability is a key to network's quality. Transmission reliability can be reflected by the probability of a successful handshake, and the handshake failure mainly results from signal reduction and environment disturbance in the path. If the transmission power is raised, the degree to which signals are reduced can descend, so that the transmission reliability over links is enhanced. The specific functional relation is given in Eq. (6)-(10). Furthermore, to deal with emergency cases happening in wards and corridor with respect to human life, the network should have high transmitting speed during data collection, which can be reflected by transmission delay. When high power is provided over links, the average times of transmission for a packet can be reduced. Consequently, overall delay in the network are expected to decline significantly. However, power augment makes node consume energy in a faster speed, which is inevitable. Based on the description above, the optimization for power levels over links exists.

Fig. 2 shows the relation between the power level and transmission failure probability. Besides, each curve represents a specific value for packet size used in transmission, which is marked in Fig. 2. Obviously, transmission failure probabilities trend to decline with the raise of power level.

Fig. 3 illustrates the transmission delay with the fixed data size over link under various power level, and each curve denotes an individual packet size. As shown in Fig. 3, data delay on links has a violent decline when power level is in the range of 6 to 16 approximately. Hence, a very low power level surely cannot guarantee the overall performance optimization over link due to high delay. However, a very high power level is also needless due to limited delay reduction.

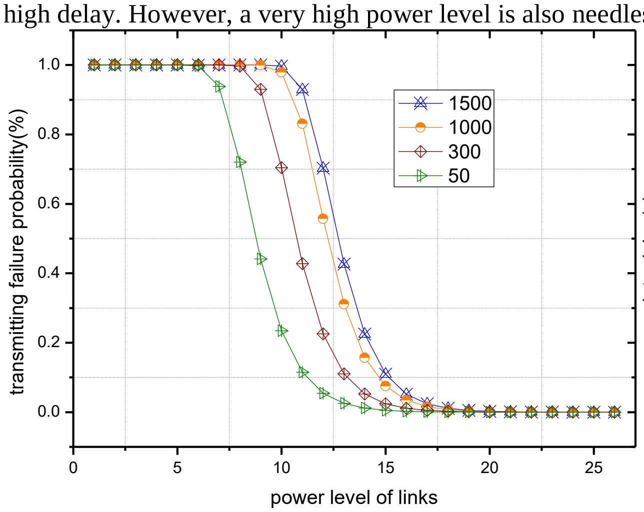

Fig. 2. Transmitting failure probability of nodes with various power levels

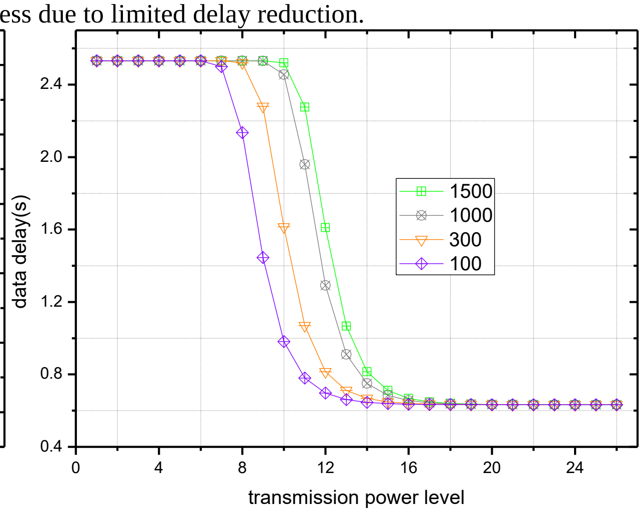

Fig. 3. Data delay over link with various power levels

Observation2. Obviously, to carry a tiny box is much easier than to carry a huge one for men, which is similar for transmitting a packet for sensor nodes. Hence, transmission reliability trends to ascend with packet size reduce. Yet, small packet scheme brings much extra data for triggering the communication in packet header and ACK, which leads to high data delay and colossal energy consumption. Based on aforementioned description, to collect details in hospital, the design of fixed-size packet can cause the unreliability in realistic transmission. Whereas, if packet size is flexible, the transmission reliability can be improved when the strategy of optimal power level decision is obtained. Consequently, it is necessary to study of network performance in various packet size circumstances.

Fig.4 shows the probability of transmission success and transmission failure with various packet size. The probability of transmission failure ascends with the growing packet size. In contrast, the probability of transmission success descends at the same time. This phenomenon validates our previous analysis about the influence of the change of packet size on transmission reliability.

The correlation between delay of fixed data size over a single link and transmission power level with different packet size is shown in Fig. 5. Apparently, when transmission for packet is provided with low power level, the highest delay is the one corresponding to the packet of 300 bytes. It can be illustrated by usual failure in transmission for above cases, and smaller packet has lower density of required information than the bigger packet. The same situation happens when transmission is provided with high power level. Whereas, it is not caused by usual failure, but usual success.

Observation3. Although a scheme for optimal performance over a single link is obtained, nodes with specific distance to sink have individual data size and individual energy consumption in a round of data collection in realistic WSN circumstance. In fact, nodes which are closest to sink collect all the data generated in the WSN, resulting in magnificent energy dissipation. Whereas, the nodes located in network edge just forward data generated by themselves. Therefore, if a scheme for optimal performance over single links is obtained, it should be applied to those nodes closest to sink. However, the residual energy still exists in nodes with farther distance. Thus, they can be further utilized to improve the performance of WSN. The pattern can be described as follows: once the residual energy of node is utilized, power levels over links can rise for fixed packet

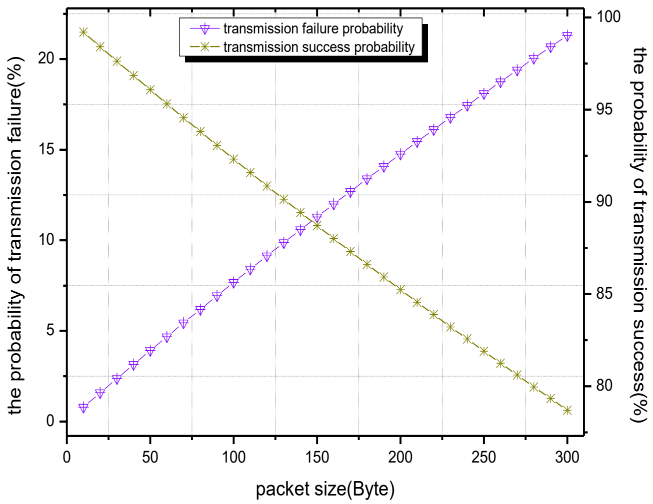

Fig. 4. Transmission success/failure probabilities of nodes with various packet size

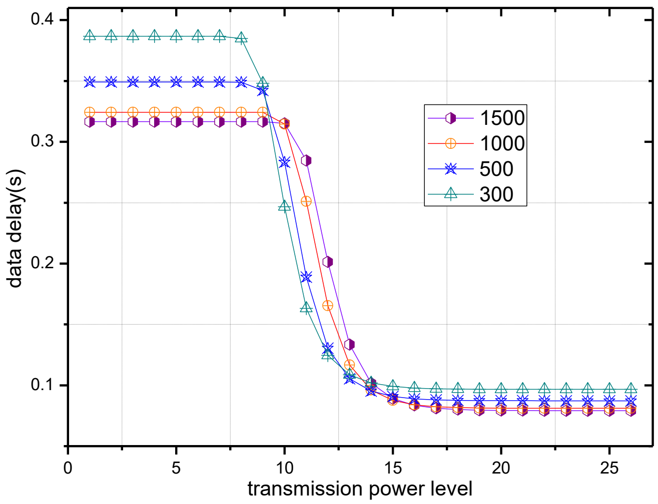

Fig. 5. Data delay over single link with various transmission power level

size, or packet size can rise for same power levels. According to observation 1 and observation 2, either of the two situations leads to better performance of WSN. Hence, a further optimization considering the distribution of data size in WSN can be obtained.

The distribution of data size in WSN with respect to different distance from node to sink is presented in Fig.6. As shown in Fig.6, data size ascends with descending distance, which is consistent with aforementioned analysis.

4.2 PLD Scheme for Choosing the Optimal Power Levels over Links

In this section, formulas for computing energy consumption are proposed to find the optimal power levels over links. Then an algorithm is proposed to decide the optimal power levels with minimization of energy consumption for successfully forwarded data per bit. In the end, some cases are given to validate feasibility of the algorithm.

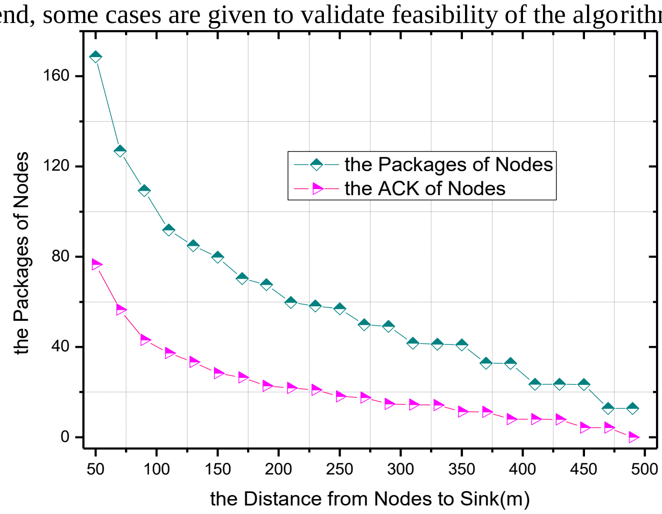

Fig.6. Packet quantity of nodes with various distance

In wireless communication, channel quality and physical layer parameter decide the reliability of links. We adopt the path loss model with a distance dependent attenuation and log-normal shadowing, providing a realistic assessment of communication characteristics of WSNs nodes in practice [41].

The loss in the path of a link(u,v), is given as follows [44]:

$$\gamma_{uv}[dB] = \gamma_0[dB] + 10l \cdot log_{10}\left(\frac{x_{uv}}{x_0}\right) + B_\sigma, \tag{6}$$

where u and v denote the transmitter and the receiver, respectively. x_{uv} is the distance from the transmitter u to the receiver v. γ_0 represents the path loss at the reference distance x_0, and l denotes the exponent indicating the path loss rate at which signal attenuates. B_σ is a Gaussian random variable with mean 0dB and standard deviation σdB when the shadowing effect is captured.

In order to perform data transmission, sensor node sends signal through antenna, but signal power is attenuated by path loss. The signal power over link(u,v) at transmission power level-k is expressed as $W_{uv,t}^{ant}(k)$, while the received signal power is represented by $W_{uv,r}^{ant}(k)$, which can be computed by

$$W_{uv,r}^{ant}(k)[dBm] = W_{uv,t}^{ant}(k)[dBm] - \gamma_{uv}[dB]. \tag{7}$$

Besides, the denotation for signal-to-noise ratio (SNR) is expressed as

$$\varphi_{uv}(k)[dB] = W_{uv,r}^{ant}(k)[dBm] - W_n, \tag{8}$$

where W_n represents noise power in environment.

Therefore, the probability of transmission success [41] of a φ-Byte packet at power level-k over link(u, v) is obtained as

$$Q_{k,n} = \left(1 - \frac{1}{2}\exp\left(\frac{-\varphi_{uv(k)}}{2}\frac{1}{0.64}\right)\right)^{8n}. \tag{9}$$

A successful handshake results from the successful reception of both the packet and ACK. Hence, the probability of valid communication over link(u, v) is

$$Q_{ij}^{N,A} = Q_{i,N} \times Q_{j,A}, \tag{10}$$

when the packet of N bytes is transmitted at power level-i and acknowledged with ACK of A bytes at power level-j, provided that $W_{uv,r}^{ant}(i)$ and $W_{vu,r}^{ant}(j)$exceed W_{th}, otherwise $Q_{ij}^{N,A} = 0$ where W_{th} indicates the reception sensitivity of the motes. $Q_{i,N}$ and $Q_{j,A}$ denote successful transmission probability for packet and ACK, respectively.

On the average, the transmission times for a generated packet is

$$t_{ij}^{N,A} = 1 + \sum_{n=1}^{N_{rtr}} \left[1 - Q_{ij}^{N,A}\right]^n, \tag{11}$$

where N_{rtr} denotes the upper bound of retransmission times.

Based on the aforementioned formulas, detailed energy consumption over links can be obtained. During a handshake process, the transmitter stays in transmission mode until the data has been sent completely, and stays in the receive mode in the rest time of slot. Consequently, the consumption of transmitter in a handshake for forwarding a packet of N bytes at power level- i and receiving an ACK of A bytes at power level-j is denoted as

$$E_{ij}^{t,one}(N, A) = W_i \times T_{MP}^n + W_r \times (T_{slot} - T_{mp}^n), \tag{12}$$

where W_i denotes transmission power at which energy is consumed when node stays in transmission mode, and W_r represents the reception power when node stays in reception mode.

According to the energy consumption of a transmitter in a handshaking process, and the aforementioned average retransmission times given in Eq. (11), which incorporates the influence of packet loss and ACK loss, the transmitter's entire dissipation for forwarding a packet can be depicted as

$$E_{ij}^{t}(N, A) = EPP + t_{ij}^{N,A} \times E_{ij}^{t,one}(N, A), \tag{13}$$

where EPP is packet processing energy dissipated only once for a packet over the link and computed by the product of power consumption of Mica2 platform in an active mode and the entire utilization time of CPU for the packet of specific size [39] (e.g., if $N = 256\, Bytes$, then $EPP = 120\mu J$ [37]). $t_{ij}^{N,A}$ denotes the average retransmission times when power levels for packet and ACK are i and j, respectively.

Similarly, on receiver side, the dissipation for successfully receiving the packet and feeding back an ACK is computed by

$$E_{ij}^{rs,one}(N, A) = W_j \times T_{ma}^n + W_r \times (T_{slot} - T_{ma}^n), \tag{14}$$

As long as the packet is received, no matter whether the ACK is transmitted successfully or not, the cost will not change on the receiver's side.

However, if communication failure happened due to packet loss, the consumption on receiver's side should be modified as

$$E_{ij}^{rf,one}(N, A) = W_r \times T_{slot}. \tag{15}$$

Therefore, the aforementioned two situations happening on the receiver's side in a handshake and EPP are combined into a formula of the entire dissipation on receiver's side for receiving a packet:

$$E_{ij}^{r}(N, A) = EPP + t_{ij}^{N,A}\left((Q_{i,N} \times E_{ij}^{rs,one}(N, A) \quad + \left(1 - Q_{i,N}\right) \times E_{ij}^{rf,one}(N, A)\right). \tag{16}$$

Thus far, energy consumption of transmission on both sides has been obtained. In WSN, the main goal of decision for optimal power levels, is to minimize energy consumption and maximize transmission reliability, which can be reflected by successfully forwarded data size. Therefore, minimization of energy consumption for successfully forwarded data per bit is regarded as a criterion to decide the optimal power levels.

Based on above formulas and description, the optimal power levels over a single link can be established according to minimization of energy consumption for successfully forwarded data per bit.

Theorem 1: In a link transmission process, if packet size and ACK size are fixed to N bytes and A bytes, respectively, and a set G_l of values with m elements are given to represent transmission power over links, then the optimal power levels pair$\{l_P^{opt}, l_A^{opt}\}$ used by transmitter and receiver can be obtained to minimize the sum of energy consumption on both sides for successfully received data per bit, as long as the threshold Q_T for the probability of successful transmission is given.

Proof: Assume the packet size and ACK size are given, if the power levels pair$\{i, j\}$ for transmitting them are decided, the probability of transmission success and the average retransmission times can be computed by Eq. (6)-(9). Then, for each pair$\{i, j\}$, if the constraint $Q_{ij}^{N,A} > Q_T$ is satisfied, pick out $\{i, j\}$ into a result set R. For each pair$\{i, j\}$ in R, its transmitter's consumption $E_{i,j}^{t}(N, A)$ and receiver's consumption $E_{i,j}^{r}(N, A)$, as well as their sum can be worked out if Eq. (10)-(14) are used. Dividing each sum with successfully forwarded data size per packet, which can be expressed as a function of successful transmission probability, the result is obtained as cost degree $S_{i,j}$ which reflects the energy cost for successfully forwarded data per bit due to fixed packet size. Meanwhile, the optimal power levels enable the least cost for successfully forwarded data per bit, which means to extract the minimum value among all of $S_{i,j}$. Consequently, its corresponding power levels pair is the optimal power levels pair $\{l_P^{opt}, l_A^{opt}\}$.

■

Algorithm 1. Suppose the packet of N bytes, ACK of A bytes, as well as a set of value for power level with m elements are given. The threshold of successful transmission probability is Q_T. Algorithm 1 is proposed to decide the optimal power levels pair for energy consumption minimization of successfully forwarded data per bit.

Algorithm 1. The Power Level Decision (PLD) Algorithm for Links

if (m > 1)
  for i = 1 to m// update the power level for packet
    for j = 1 to m // update the power level for ACK
      compute transmission success probabilities $Q_{i,N}$ and $Q_{j,A}$
      transmission failure possibility is
$$Q_{ij}^{f}(N,A) = 1 - Q_{i,N} \times Q_{j,A};$$
      $k_{i,j} = 1;$
      for k = 1 to N_{rtr}
$$t_{ij} = t_{ij} + Q_{ij}^{f}(N,A)^{k};$$
      End for
      If $Q_{ij}^{N,A} > Q_T$
        pick out the pair (i,j) into result set R
      End if
      compute the energy consumption of transmitter and receiver $E_{ij}^{t}(N,A)$ and $E_{ij}^{r}(N,A)$
      compute successfully forwarded data as
$$N_v = N \times [1 - Q_{ij}^{f}(N,A)^{(1+N_{rtr})}];$$
      compute the cost degree as
$$S_{ij} = \frac{E_{ij}^{t}(N,A) + E_{ij}^{r}(N,A)}{N_v};$$
    End for
  End for
  select the optimal power levels pair as
$$\{l_P^{opt}, l_A^{opt}\} = argmin(S_{ij}); \quad //(i,j) \in R$$
Else
  l_P^{opt} is equal to l_A^{opt} and the sole level;
End if

To illustrate algorithm 1, an example is given as follows: some cases of the PLD implementation are shown in Table 2. As Table 2 shows, when the threshold of successful transmission probability is 90%, a pair is given to optimal power levels. Taking case 3 for example, the obtained pair is {15, 18}. In other words, the optimal power levels for packet and ACK are 15 and18, respectively.

Table 2
Cases of PLD Implementations

case	1	2	3	4	5	6
Packet(Byte)	1500	1200	1500	1000	600	400
ACK(Byte)	20	20	40	30	50	40
l_P^{opt}	15	15	15	15	15	15
l_A^{opt}	15	15	18	18	18	18
S_{ij} $(10^{-6} J/bit)$	4.09	5.00	4.09	5.91	9.56	14.12

4.3 PPD Scheme for Optimal Packet Size Over Links

In subsection 4.3, the energy consumption and transmission delay on both sides for constant generated data size with various packet size are explored in the beginning. Then, a method is introduced to decide optimal packet size and power levels over single link. An example follows to illustrate the aforementioned method. In the end, based on the method, two algorithms are proposed to decide optimal packet size and power levels with energy consumption restriction and transmission delay restriction, respectively.

In subsection 4.2, the PLD scheme is proposed for the optimal power levels decision of links with constant packet size. Furthermore, considering the effect of valid data size in a packet on the total data size including data size of valid data, header and ACK, further improvement can be achieved if the packet size is adjusted to a suitable value and the optimal power levels obtained by the PLD scheme are adopted.

In link transmission, data size partly decides energy consumption and transmission delay, minimization of which belongs to main goals of network optimization. However, it cannot be guaranteed that they are minimized at the same time with data size variation. Besides, minimizing both of them is also needless in most applications, because some applications are only very strict with energy consumption, and some other applications are only very strict with transmission delay. As a result, a trade-off should be taken into the consideration.

To tackle this problem, the specific effect of data size on energy consumption and transmission delay should be figured out.

Data size over links mainly comes from packet. The context of packet consists of two parts: the generated data from environment and header data for communication, which can be denoted as

$$N = D + H, \tag{17}$$

where N, D, H denotes the size of forwarded data, generated data and header data in a packet, respectively.

Obviously, data size of header and ACK are proportional to packet number. For generated data of constant size, small packets bring many headers and ACKs. As a result, forwarded data size and transmission delay increase. On the other hand, however, small packets decline the hardness to transmit them, which results in that the low transmission power levels are required for enough probability of transmission success. According to the description above, a suitable packet size can be found to trade off energy dissipation and transmission delay.

For D_e bytes of data generated from environment, when packet size is N bytes, forwarded data size D_w is computed by the product of packets number and supposed data size in a handshake, which is the sum of packet size and ACK size. Thus, D_w can be denoted as

$$D_w = \frac{D_e}{D} \times (N + A). \tag{18}$$

Then, the entire energy consumption $E_{ij}^{t,D_e}(N, A)$ for transmitting D_e bytes of generated data with power levels pair(i, j) is obtained as

$$E_{ij}^{t,D_e}(N, A) = \frac{D_w}{N+A} \times E_{ij}^{t}(N, A) . \tag{19}$$

Similarly, the entire energy consumption$E_{ij}^{r,D_e}(N, A)$ of receiving D_e bytes of generated data with power levels pair(i, j) is computed by

$$E_{ij}^{r,D_e}(N, \mathrm{A}) = \frac{D_w}{N+A} \times E_{ij}^{r}(N, A) . \tag{20}$$

The entire energy consumption on both sides is depicted as

$$E_{ij}^{w,D_e}(N, A) = E_{ij}^{t,D_e}(N, A) + E_{ij}^{r,D_e}(N, A). \tag{21}$$

Hence, we plug Eq. (18)-(20), and eventually transform Eq. (21) to

$$E_{ij}^{w,D_e}(N, A) = \frac{D_e}{(N-H)} \times \left[E_{ij}^{t}(N, A) + E_{ij}^{r}(N, A) \right]. \tag{22}$$

Transmission delay over single link depends on the speed for transmitting in physical channel and forwarded data size over the link, as well as average retransmission times. Therefore, the delay is computed as

$$L^{hop} = \frac{D_w}{v_{ch}} \times t_{ij}. \tag{23}$$

In former parts, the relation between forwarded data size and packet size have been obtained, and effect of forwarded data on energy consumption and transmission delay are worked out. Thus, energy consumption and transmission delay can be traded off in the following method.

Firstly, give a threshold of successful transmission probability. For each usable packet size N_i, the optimal power levels $\{l_{N_i}^{opt}, l_A^{opt}\}$ can be obtained by the PLD scheme, and then we combine them with the packet size as a triple $\{N_i, l_{N_i}^{opt}, l_A^{opt}\}$.

Secondly, based on aforementioned formulas, for each triple, the sum of energy consumption on both sides and transmission delay can be computed.

Thirdly, in order to trade off the energy consumption and delay, one of them can be set with an upper bound as a constraint. Then, the minimization of the other one can be reached.

To make aforementioned method more clear, an example with upper bound of energy consumption is given below.

Fig. 7(a)-(c) show the relation between energy consumption of node and packet size with different threshold Q_T of successful transmission probability, in which the values for B_σ are 1dB, 1.5 dB, 2dB, respectively. The energy consumption is the total consumption on both sides for transmitting 5000 bytes of generated data, which can be computed by Eq. (22) and power levels for each packet size are obtained by applying the PLD scheme. Meanwhile, Fig. 7(d) shows the relation between energy consumption and Q_T with different packet size when $B_\sigma = 1.5$ dB.

As shown in Fig. 7(a)-(c), energy consumption descends with packet size growth. In Fig. 7(d), energy consumption ascends with the increase of Q_T.

Similarly, Fig. 8(a)-(c) show relation between transmission delay and packet size with different value for Q_T ,and values for B_σ are 1dB, 1.5 dB, 2dB, respectively. The delay is total transmission delay for transmitting 5000 bytes generated data, which is computed by Eq. (23) and power levels for each packet size are also obtained by applying the PLD scheme. Meanwhile, Fig. 8(d) shows the relation between transmission delay and Q_T with different packet size.

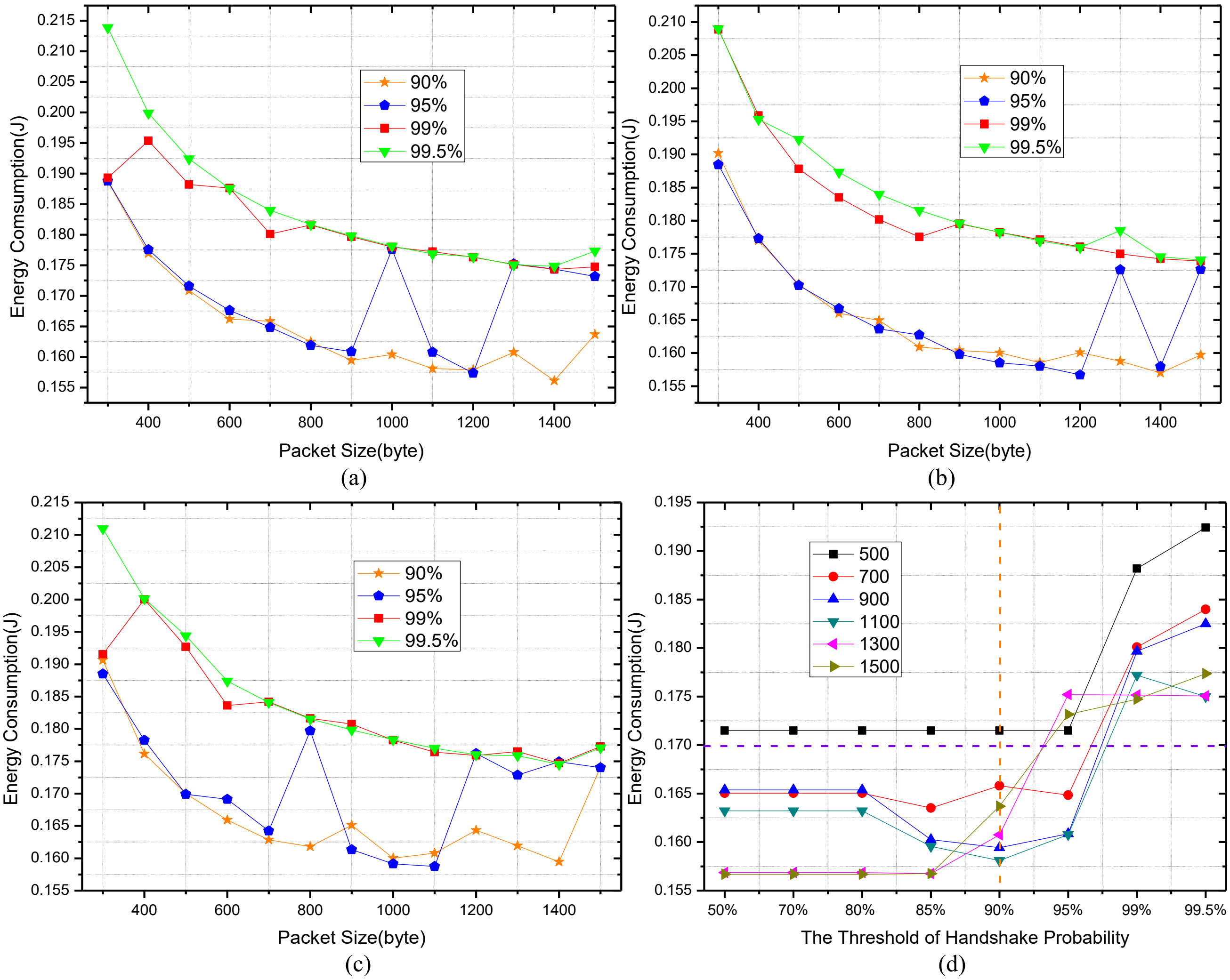

Fig. 7. Energy consumption with packet size variation
(a) $B_\sigma = 1dB$. (b) $B_\sigma = 1.5dB$. (c) $B_\sigma = 2dB$. (d) $B_\sigma = 1.5dB$.

Fig. 8(a)-(c) show that the transmission delay descends with packet size growth. In Fig. 8(d), transmission delay descends with the increase of Q_T.

The method to decide the optimal packet size and power levels is explained in the following example:

①Choose a given value for Q_T in Fig. 7(d) and Fig. 8(d).

②Assume an upper bound E_T of energy consumption or an upper bound L_T^{n-n} of transmission delay.

③If E_T is assumed, pick out cases whose energy consumption is less than E_T and threshold of successful transmission probability equals to Q_T in Fig. 7(d). Then, for cases picked out, find the one with minimum transmission delay in Fig. 8(d). Therefore, the given packet size and power levels in this case can be chosen as decision for optimal packet size and power levels.

④Otherwise, if L_T^{hop} is assumed, pick out cases whose transmission delay is lower than L_T^{hop} and threshold of successful transmission probability equals to Q_T in Fig. 8(d). Then, for cases picked out, find the one with minimum energy consumption in Fig. 7(d). Therefore, the given packet size and power levels in this case can be selected as the decision for optimal packet size and power levels.

For further illustration, assume that upper bound E_T of energy consumption is $0.17J$, and the chosen value for Q_T is 90%, which indicates step 1 and step 2 of the method have been completed.

In step 3, pick out cases whose energy consumption is less than $0.17J$ and threshold of successful transmission probability equals to 90% in Fig. 7(d). As shown in Fig. 7(d), the cases with 90% for Q_T and packet size in set {700bytes, 900bytes, 1100bytes, 1300bytes, 1500bytes} are picked out.

Then, according to Fig. 8(d), find the case with minimum value of transmission delay from cases picked out above. In this example, the case with 90% for Q_T and 1100 bytes for packet size is found.

Finally, obtain optimal power levels pair {15, 15} by applying the PLD scheme in this case, and combine packet size with the pair into a triple {1100bytes, 15, 15}. The triple is exactly the optimal packet size and power levels.

Besides, if upper bound E_T is replaced by upper bound L_T^{hop} of transmission delay, the decision for optimal packet size

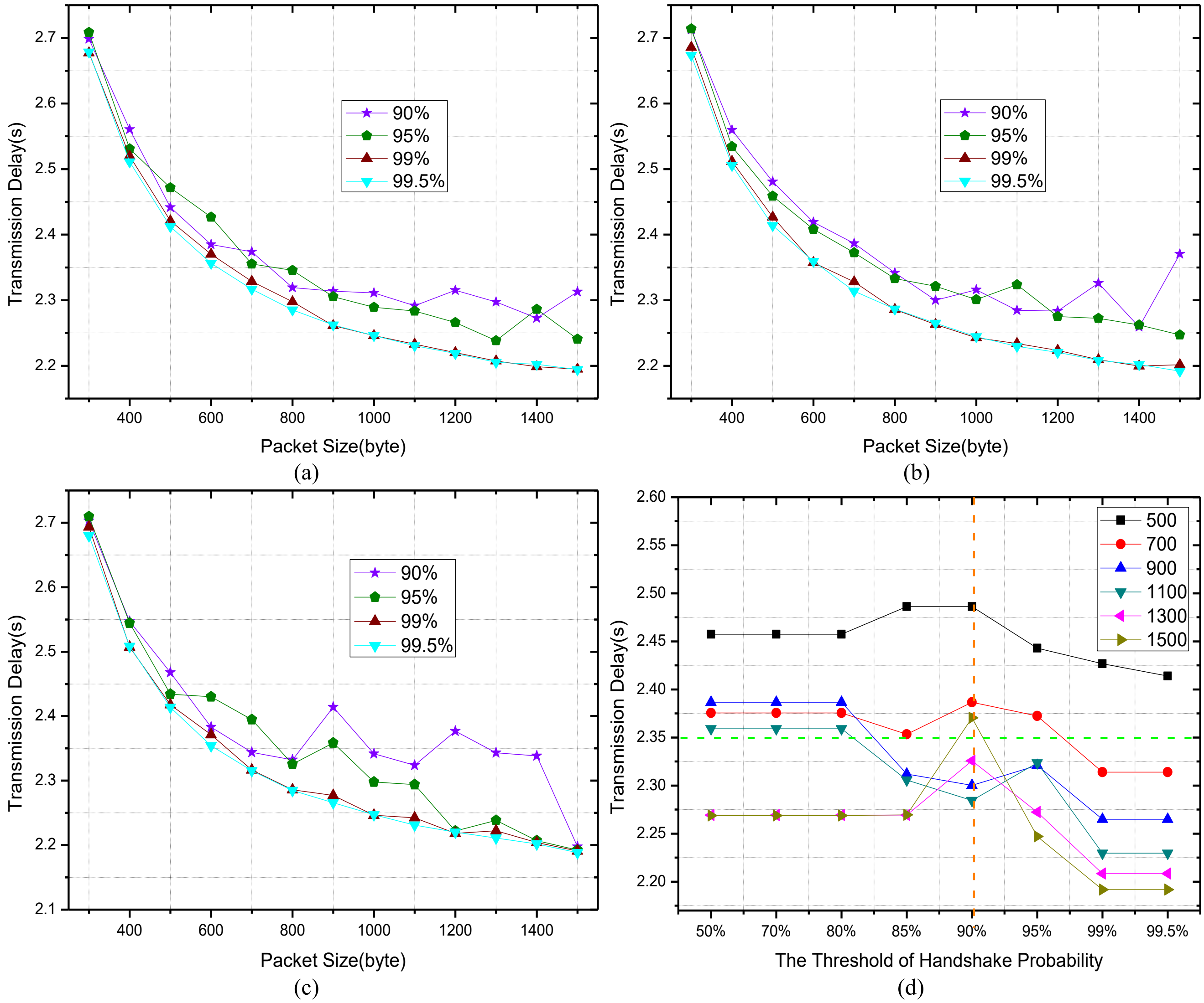

Fig. 8. Transmission delay with packet size variation
(a) $B_\sigma = 1dB$. (b) $B_\sigma = 1.5dB$. (c) $B_\sigma = 2dB$. (d) $B_\sigma = 1.5dB$.

and power levels can similarly be made according to the former description of the method.

In the light of above description, our method of deciding the optimal packet size and optimal power levels are extremely hard to be expressed as a mathematical method or implemented only through formula computation. Hence, two algorithms are proposed, with upper bound of energy consumption and upper bound of transmission delay, respectively.

Suppose the probability threshold of a successful transmission is Q_T. The overall energy consumption on both sides in a transmission has an upper bound E_T. Also, the generated data size is D_e, and the size of header and ACK are H and A, respectively. Besides, a set of values G_P are given to packet size. Other assumptions about power level are the same as those in the PLD scheme.

Based on above assumptions, The Power Level and Packet Size Decision Algorithm for Single Link with energy upper bound E_T (PPD-E) can be obtained as Algorithm 2.

To illustrate Algorithm 2, an example is given as follows: the cases with the PPD-E scheme application are presented in

Table 3
Cases of PPD-E Scheme Application

Case	**1**	**2**	**3**	**4**	**5**	**6**
$Q_T(\%)$	70	80	90	95	99	99.5
$E_T(J)$	0.17	0.17	0.17	0.17	0.18	0.18
$N_{best}(byte)$	1500	1500	1100	900	1500	1500
$l_{N_{best}}^{opt}$	15	15	15	15	18	18
l_A^{opt}	15	15	15	18	15	18
$L^{hop}(s)$	2.27	2.27	2.29	2.32	2.19	2.19
$E_{ij}^{w,D_e}(J)$	0.156	0.156	0.158	0.161	0.175	0.177

Algorithm 2. The Power Level and Packet Size Decision Algorithm for Single Link with energy upper bound E_T(PPD-E)

1: **For** i = 1 : sizeof(G_P)
2: obtain optimal power levels pair $\{l_{N_i}^{opt}, l_A^{opt}\}$ by implementing the PLD scheme with N_i and Q_T
3: combine N_i and$\{l_{N_i}^{opt}, l_A^{opt}\}$ as a triple $\{N_i, l_{N_i}^{opt}, l_A^{opt}\}$
4: **End for**
5: **For** i = 1 : sizeof(G_P)
6: compute the energy costs $E_{l_{N_i}^{opt} l_A^{opt}}^{w,D_e}(N_i, A)$ for triple $\{N_i, l_{N_i}^{opt}, l_A^{opt}\}$
7: **If** $E_{l_{N_i}^{opt} l_A^{opt}}^{w,D_e}(N_i, A) < E_T$
8: pick $\{N_i, l_{N_i}^{opt}, l_A^{opt}\}$ into residual set G_S
9: **End if**
10: **End for**
11: **For** i = 1 : sizeof(G_S)
12: compute transmission delay D_i^{hop} for all triples in G_S.
13: **End for**
14: pick out the optimal triple $\{N_{best}, l_{N_{best}}^{opt}, l_A^{opt}\}$ from G_S whose transmission delay $L_{best}^{hop} = Min(L_i^{hop})$, where $N_i \in G_P$.

Table 3 As Table 3 shows, by applying the PPD-E scheme, a triple can be obtained for optimal packet size and power levels in each case.

The PPD-E scheme provides a resolution to optimal packet size and power levels over link when the threshold Q_T and upper bound E_T of energy consumption are given. In many applications, however, transmission delay threshold is required when network obstruction occurs frequently, yet energy consumption threshold is not required at the time. As a result, another resolution is necessary when Q_T and upper bound of transmission delay L_T^{hop} are given.

Except for upper bound of energy consumption E_T, all the other assumptions are similar to those in the PPD-E scheme. The Power Level and Packet Size Decision Algorithm for Single Link with upper bound of transmission delay L_T^{hop} (PPD-D) is obtained as above.

In the same way as the PPD-E scheme, cases of the PPD-D scheme implementation are shown in Table 4.

Table 4
Cases of PPD-D Scheme Implementation

$Case$	1	2	3	4	5	6
$Q_T(\%)$	70	80	90	95	99	99.5
$L_T^{hop}(s)$	2.4	2.4	2.4	2.35	2.3	2.25
$N_{best}(byte)$	1500	1500	1100	1100	1500	1100
$l_{N_{best}}^{opt}$	15	15	15	16	18	19
l_A^{opt}	15	15	15	14	15	14
$L^{hop}(s)$	2.27	2.27	2.29	2.32	2.19	2.23
$E_{ij}^{w,D_e}(J)$	0.156	0.156	0.158	0.161	0.175	0.175

4.4 GLD Scheme for Optimal Global Link Decision

In subsection 4.3, the PPD-E and PPD-D schemes have been proposed to obtain the optimal packet size and power levels over single link.

However, in realistic network of hospital system, due to accumulation of forwarded data over multiple links transmission, forwarded data size of nodes varies with the change of distance to sink. The farthest nodes to sink are only responsible for data generated by themselves. In contrast, close nodes are responsible for their own generated data as well as data received from farther area, as shown in Fig. 7. As a result, energy consumption is distributed in an unbalanced manner,

Based on aforementioned description, to resolve this issue for further network optimization, the global link decision (GLD) scheme is proposed below.

In the beginning of the GLD scheme, since the closest nodes take the maximum data size in network, decision of optimal packet size and power levels over the link between the closest node and sink should be made. According to specific requirement of network, the PPD-E scheme or PPD-D scheme is supposed to be applied over the closest link to make the decision.

To level off the distribution of energy consumption, other links can be adjusted to a suitable state, in which energy consumption over a link is less than and closest to it over the closest link.

Algorithm 3. The Power Level and Packet Size Decision Algorithm for Single Link with delay upper bound L_T^{hop}(PPD-D)

1: **For** i = 1 : sizeof(G_P)
2: obtain optimal power levels pair $\{l_{N_i}^{opt}, l_A^{opt}\}$ by implementing the PLD scheme with N_i and Q_T
3: combine N_i and$\{l_{N_i}^{opt}, l_A^{opt}\}$ as a triple $\{N_i, l_{N_i}^{opt}, l_A^{opt}\}$
4: **End for**
5: **For** i = 1 : sizeof(G_P)
6: compute transmission delay $T_{delay,i}^{n-n}(N_i, A)$ for triple $\{N_i, l_{N_i}^{opt}, l_A^{opt}\}$
7: **If** $D_i^{n-n}(N_i, A) < L_T^{hop}$
8: pick $\{N_i, l_{N_i}^{opt}, l_A^{opt}\}$ into residual set G_S
9: **End if**
10: **End for**
11: **For** i = 1 : sizeof(G_S)
12: compute energy consumption $E_{l_{N_i}^{opt} l_A^{opt}}^{w,D_e}(N_i, A)$ for all triples in G_S.
13: **End for**
14: pick out the optimal triple $\{N_{best}, l_{N_{best}}^{opt}, l_A^{opt}\}$ fromG_S ,whose entire energy cost is computed as
$E_{l_{N_{best}}^{opt} l_A^{opt}}^{w,D_e}(N_{best}, A) = Min(E_{l_{N_i}^{opt} l_A^{opt}}^{w,D_e}(N_i, A))$, where $N_i \in G_P$.

Although the entire energy cost includes the cost for sleep, energy cost for sleep is nearly the same for all nodes, since the occupied time for data transmission is much less than the rest time in which nodes sleep. Thus, the sleep time will not change with data size variation, and power for sleep is lower than powers for data transmission by thousands of times. As a result, even though the energy consumption in transmission is only considered in the decision scheme, it will not influence the decision because the same energy cost of nodes for sleep have no effect on the distribution of energy consumption in network.

Therefore, the decision for packet and power levels of other links can be depicted in the following formula:

$$\{N_x, l_{N_x}, l_A\} = \text{argmin}\{E_{close}^{rd} - E_x^{rd}(N_c, i, j)\}, \tag{24}$$

and the constraint for energy consumption is described as

$$E_{close}^{rd} \geq E_x^{rd}(N_c, i, j), \tag{25}$$

where $N_c \in G_P$, the set of values given to packet size, and $i, j \in G_l$, the set of values given to power for transmission. E_{close}^{rd} and $E_x^{rd}(N_c, i, j)$ respectively are energy consumption of the closest node to sink and consumption of a node with x meters to sink in a round, which can be computed as follows:

$$E_{close}^{rd} = E_{l_{N_{best}}^{opt} l_A^{opt}}^{w,D_w}(N_{best}, A) \times \frac{D_{close}}{D_e}, \tag{26}$$

$$E_x^{rd}(N_c, i, j) = E_{l_i l_j}^{w,D_w}(N_c, A) \times \frac{D_x}{D_e}. \tag{27}$$

where D_x is forwarded data size of node in a round, which equals the sum of generated data D from the node itself, and the data survived through former link, so is D_{close}.

Consequently, data size D_x depends on data size D generated by a node and successfully forwarded data rate P_{x+r} which is the rate of received data size to forwarded data size over former link. In addition, every node on receivers' side is responsible for more than one node on the transmitters' side, owing to square difference between the two areas. The elaborate reasoning process to figure out the relation between D_x and D has been given in [45].

The formula for computing D_x is given below (D_{close} can be computed in the same way as D_x if the distance from the closest node to sink is obtained):

$$D_x = \begin{cases} D + \frac{x+r}{x} \times P_{x+r} D_{x+r} & x + r \leq R \\ D & x \leq R \text{ and } x + r > R, \\ 0 & x > R \end{cases} \tag{28}$$

where the successfully forwarded data rate P_{x+r} represents forwarded data except those transmitted unsuccessfully for N_{rtr} times. Therefore, P_{x+r} can be expressed by

$$P_x = 1 - \left(1 - Q_{i_x j_x}^{N_x, A}\right)^{N_{rtr}}. \tag{29}$$

Iterate Formula(28), and we obtain a more explicit expression:

$$D_x = \begin{cases} D[1 + \sum_{i=1}^{z} (\frac{x + ir}{x} \prod_{j=1}^{i} P_{x+jr})\,] & x + r \leq R \\ D & x \leq R \text{ and } x + r > R \\ 0 & x > R \end{cases}, \tag{30}$$

where z is the maximum integer satisfying the range constraint $x + zr \leq R$.

Thus far, the forwarded data size of node is obtained. Hence, according to Eq. (24), the decision for packet size and power

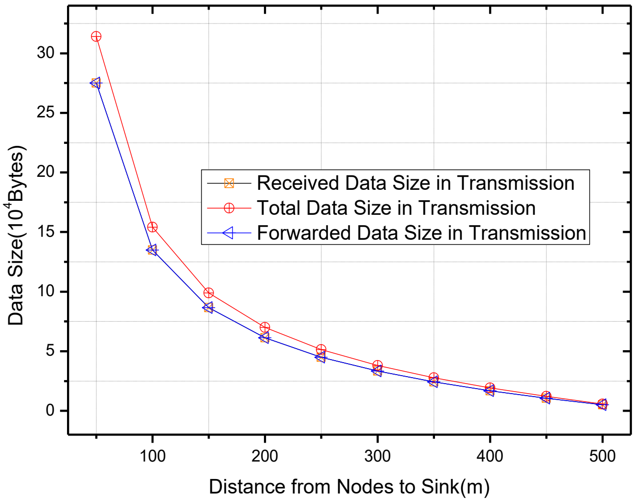

Fig. 9. Data size of node with different distance by applying PPD-D scheme

levels over links can be made in the GLD scheme.

In Fig. 9, the forwarded data size, received data size and total data size obtained by applying the PPD-D scheme with different distance are shown. Total data size includes data size of packet and ACK in transmission. As a result, it is a little higher than the received data size.

In Fig. 10, relations between energy consumption rates of nodes and different distances are given when WSN dies in the GLD, PPD-D and the ideal case. As shown in Fig. 10, the GLD raises energy consumption rate in farther nodes, compared to PPD-D.

Fig. 11 shows transmission delay of 5000 bytes of generated data over multiple links from the farthest node to another node with different distance in the PPD-D, GLD and ideal case. The delay of the GLD is less than that of the PPD-D. It indicates that, by applying the GLD scheme to balance energy consumption in network, delay is reduced over links.

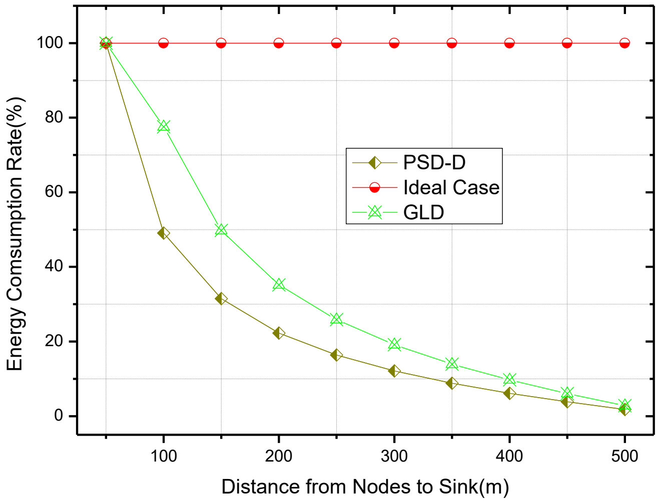

Fig. 10. Energy consumption rate of nodes

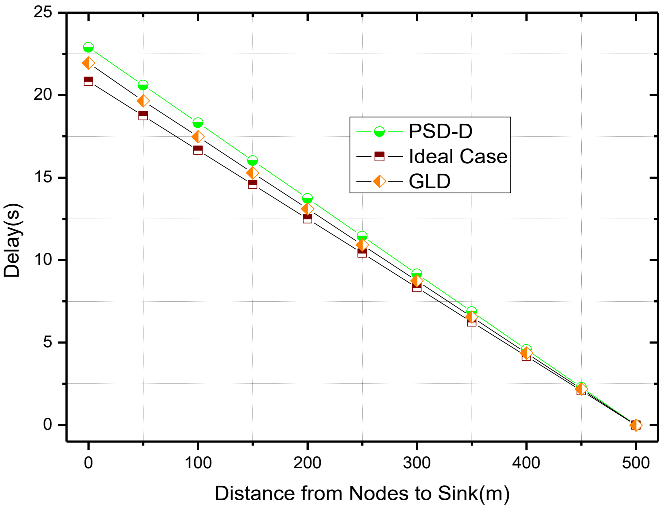

Fig. 11. Transmission delay over multiple links

5. Performance Analysis of GLD Scheme

The theoretical performance of network in the GLD scheme is analyzed in this section.

5.1. Transmission Delay of GLD Scheme

In the GLD scheme, transmission delay mainly results from the time occupied by data transmission. Therefore, delay over links depends on the entire forwarded data including ACK on route.

Based on aforementioned description and analysis with respect to transmission delay of specific data size over a link and the distribution of data size in WSN, the delay of transmitting D bytes of generated data from a node with x meters to sink to next hop can be expressed as

$$L_x^{D,hop} = \frac{D}{N_x - H} \times \frac{N_x + A}{v_{ch}} \times t_{i_x j_x}, \tag{31}$$

where v_{ch} is channel data rate, and $t_{i_x j_x}$ denotes the average times for forwarding a packet of N_x bytes on the link.

Transmission delay over multiple links from the farthest node to another node with x meters to sink, is the accumulation of the delay over each link on route, which is computed as

$$L_x^{D,rd} = \sum_{i=0}^{z-1} L_{R-ir}^{D,hop}, \tag{32}$$

where z is the maximum integer satisfying $R - ir \geq x$.

5.2. Energy Consumption Balance in A Round of GLD Scheme

In subsection 4.3, formulas for computing energy consumption on both sides in a transmission are given. Whereas, in a round of data collection, sensor nodes do not transmit data most of the time. In fact, they always sleep when data is still on the way or having gone. Hence, energy consumption in transmission and consumption in sleep are combined as the overall consumption:

$$\begin{aligned} E_{w,x}^{rd} = & \frac{D_x}{(N_x - H)} \times E_{i_x j_x}^t (N_x, A) \\ & + \frac{D_{x+r}}{(N_{x+r} - H)} \times E_{i_{x+r} j_{x+r}}^r (N_{x+r}, A) \\ & + \left(T_{rd} - \frac{D_{w,x} t_{i_x j_x} + D_{w,x+r} t_{i_{x+r} j_{x+r}}}{v_{ch}} \right) \times P_{sleep}, \end{aligned} \tag{33}$$

where $D_{w,x}$ is forwarded data size in the node with x meters to sink, which can be obtained from Eq. (17)-(18) by replacing N with N_x . P_{sleep} denotes the power of node used in the sleep mode.

Hence, the balance degree of energy consumption in WSN can be depicted as the average rate of the consumption of each node to the maximum consumption in a round, which is described as

$$\eta = \frac{\sum \frac{E_{w,x}^{rd}}{num}}{\max E_{w,x}^{rd}}, \tag{34}$$

where num represents the number of nodes in WSN.

5.3. Transmission reliability of GLD Scheme

The criterion of data collection quality is the transmission reliability over links, including the reliability over a single link and over multiple links. Obviously, transmission reliability depends on the probability of successful transmission. Therefore, transmission reliability over a single link is precisely the probability of successful transmission over the link, which is denoted as

$$R_{x,x-r} = Q_{i_x j_x}^{N_x, A}, \tag{35}$$

Transmission reliability over multipole links from a farthest node to another node with x meters to sink is accumulation of reliability over the links on route, which can be computed as

$$R_{edge,x} = \prod_{i=0}^{z-1} Q_{i_{R-ir} j_{R-ir}}^{N_{R-ir}, A}, \tag{36}$$

where z is the maximum integer satisfying $x + zr < R$.

5.4. Network Lifetime of GLD Scheme

To evaluate the performance of WSN, the lifetime is a key attribute, which is defined as the interval between the time when network is built to the time when the first dead node occurs. According to aforementioned network model in section 3, the lifetime takes the time of a round as a unit. In the GLD scheme, each node is assigned with equal initial battery energy $e_{battery}$.

Based on our former description in the GLD scheme, the first node which uses up energy must be the node closest to sink. Hence, lifetime can be obtained from the following formula:

$$T_{life} = \frac{e_{battery}}{E_{close}^{rd}}, \tag{37}$$

where E_{close}^{rd} is energy consumption of the closest node to sink in a round, which is obtained by Eq. (26).

The GLD scheme provides a way to decide the power levels and packet size over links. As a result, these formulas in section 5 can also be utilized to analyze performance of the Local Power Level Decision (LPLD) scheme [37], as long as the values assigned to power levels and packet size are obtained from the LPLD scheme.

In the LPLD scheme, packet size is fixed, and power levels for each link are only decided by energy dissipation minimization rule. The decision strategy can be expressed as

$$\{i^{opt}, j^{opt}\} = \underset{i \in S_L, j \in S_L}{argmin} (E_{ij}^t (N, A) + E_{ij}^r (N, A)) \tag{38}$$

where N is default packet size.

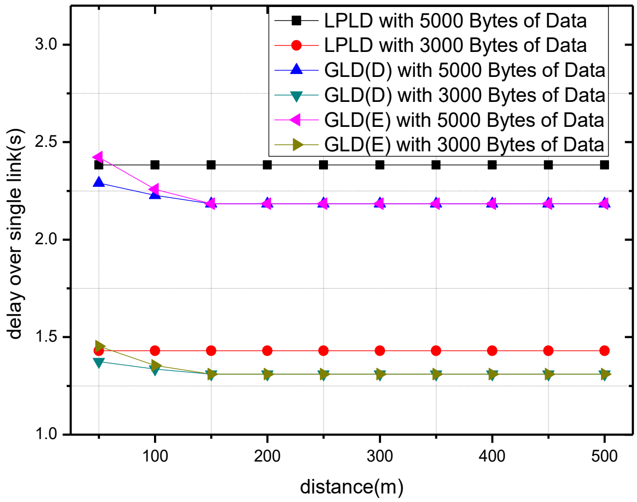

Fig. 12. Delay over a single link with different distance to sink

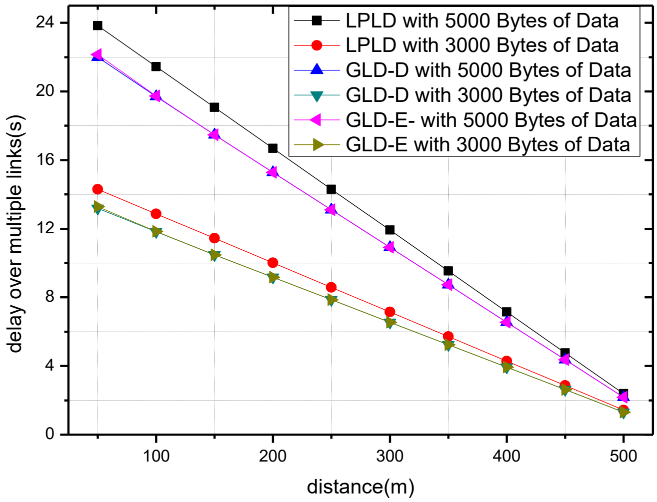

Fig. 13. Delay over multiple links from the farthest node to another node with different distance to sink

6. EXPERIMENTAL RESULTS AND ANALYSIS

In this section, a simulation experiment is conducted to evaluate the Global Link Decision (GLD) scheme. In the beginning, parameters of network and node are introduced. Then, we conduct the experiment according to parameters above. Besides, experiment results are compared with the Local Power Level Decision (LPLD).

6.1. Experimental parameters settings

MATLAB R2015a was employed for experimental verification. With consideration of generality, the parameters for WSN in the experiment circumstance are: network radius $R = 500$m, hop interval $r = 50m$, generated data D in a round is 5000bytes, default packet size $N = 1500$bytes, default maximum retransmission times $N_{rtr} = 3$, default threshold of successful transmission probability $Q_T = 90\%$, the threshold of transmission delay $L_T^{hop} = 2.35s$ for the PPD-D scheme, and the threshold of energy consumption $E_T = 0.17J$ for the PPD-E scheme.

6.2. Transmission Delay of Hospital Network

Figure 12 and Figure 13 show the comparisons on delay over a single link and over multiple links between the GLD scheme and the LPLD scheme, respectively. In Fig. 13, multiple links represent the links from the farthest node to another node with various distances to sink. The GLD(D) indicates this kind of the GLD scheme application is based on the PPD-D scheme, and the GLD(E) is based on the PPD-E scheme.

As shown in Figure 12, the delay of the GLD is lower than that of the LPLD over a single link. When generated data are 5000 bytes in a round, delays of the GLD(D) and GLD(E) are both lower than the delay of the LPLD by 8.37%. A similar situation occurs when generated data is 3000 bytes.

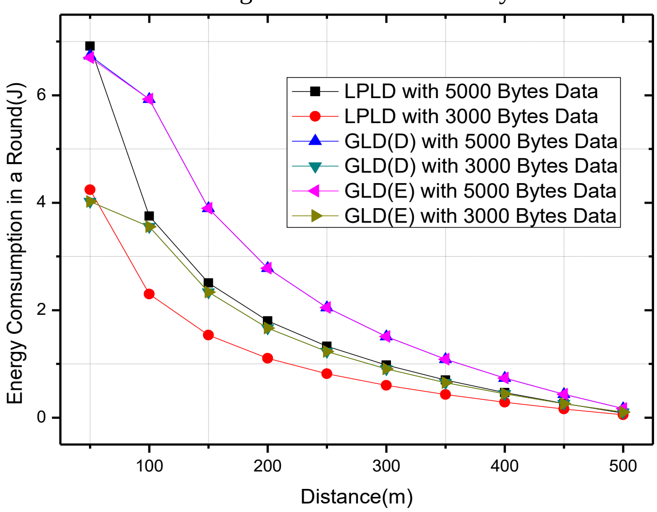

Fig. 14. Energy consumption of nodes in a round

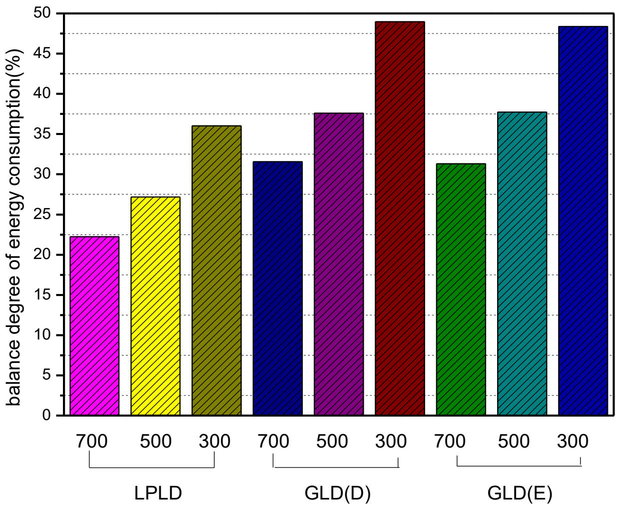

Fig. 15. Balance degree of energy consumption in different schemes

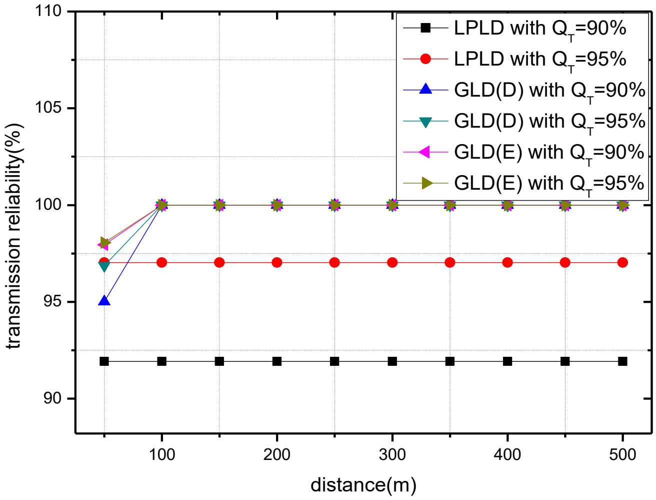

Fig. 16. Transmission reliability over a single link

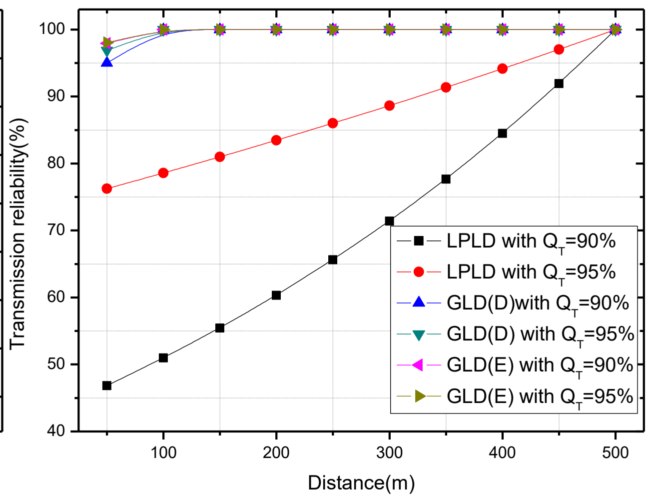

Fig. 17. Transmission reliability over multiple links

In Figure 13, the gap of delay between the GLD scheme and the LPLD scheme grows with hops increase on route. Comparing delay of GLD and LPLD over multiple links from the farthest node to the closest node to sink between the two schemes when $D = 5000bytes$, the delays of the GLD(D) and GLD(E) are lower than those of the LPLD by 7.74% and 7.06%, respectively.

6.3. Energy Consumption Balance of Hospital Network

Figure 14 shows the distribution of energy consumption with distance variation in a round. Not only the highest point occurs in the LPLD scheme, but also curves of the GLD scheme are more horizontal, indicating that the equilibrium of energy consumption in network is reinforced in the GLD.

Figure 15 uses a bar graph to further compare balance degree of energy consumption in the GLD and LPLD. Obviously, balance degrees of the GLD are much higher than those of the LPLD. Detailed percent respectively are 35.9% and 34.3%, when $R = 300m$, 38.3% and 38.9% when $R = 500m$, or 41.9% and 40.8% when $R = 700m$ for the GLD(D) and GLD(E).

6.4. Transmission reliability of Hospital Network

Transmission reliabilities of the GLD and LPLD are given in Figure 16 and Figure 17. Figure 16 shows the transmission reliability over single link with various distance from transmitter to sink. As it shows, transmission reliabilities of the GLD over a single link, is almost 100% except the transmission reliability of the closest node, although the threshold of successful transmission probability is 90% or 95%. Conversely, an unsuccessful transmission happens with a probability of 8.08% on each link when $Q_T = 90\%$, or with a probability of 2.97% when $Q_T = 95\%$ in the LPLD, which are lower than that of the GLD by 8.70% and 3.06, respectively.

In Figure 17, transmission reliability over multiple links from the farthest node to another node with various distances are shown. When $Q_T = 90\%$, transmission reliability from the farthest node to the closest node of the LPLD scheme is only 46.85%. Nonetheless, the reliability of the GLD(D) and the GLD(E) can reach 95% and 97.9%, respectively. Even if Q_T is raised to 95%, transmission reliability throughout the route of the LPLD scheme is still only 76.23%. In contrast, the reliabilities of the GLD(D) and the GLD(E) can reach 96.87% and 98.06%, respectively.

6.5. Lifetime of Hospital Network

Figure 18 shows the simulative network lifetime of the GLD and the LPLD. It can be observed that the lifetime of the

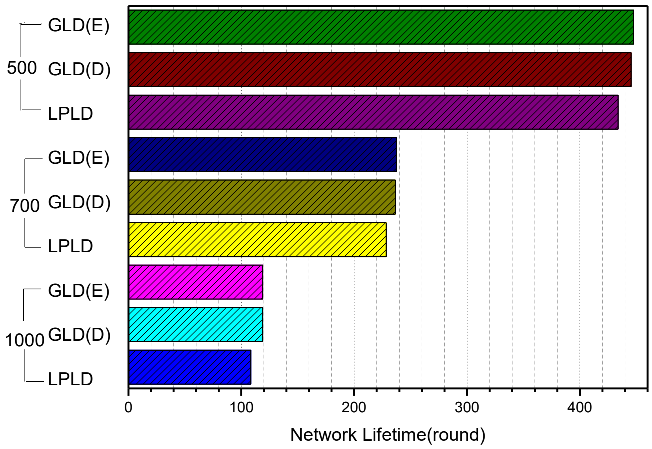

Fig. 18. Lifetime of network with different default packet size

GLD(D) and GLD(E) scheme respectively are higher than those of LPLD by 2.64% and 3.2% when $R = 500m$. When $R = 700m$, the exceeding degrees are 3.56% and 4.05%, respectively. Moreover, when $R = 1000m$, the exceeding rates are 9.69% and 9.72%, respectively.

CONCLUSION

In this paper, we propose a novel global link decision (GLD) scheme to prolong network lifetime, enhance transmission reliability and reduce transmission delay, based on power level and packet size control on links. Being different from former studies about link control, we decide the optimal packet size and power levels over single link by minimization of successfully forwarded data per bit, which reflects both energy consumption and transmission reliability. Besides, the decision is only used for the closest link, and its transmitter's death decides network lifetime. Furthermore, we fully utilize redundant energy in nodes when network will die. Hence, other links can be assigned larger packet size and higher power levels than the closest link. As a result, higher transmission reliability and lower transmission delay than usual schemes are obtained, which only regard power level control over links and ignore the effect of data size variation over links on network performance. In the end, a simulation experiment shows that the GLD scheme achieves better performance, compared with the Local Power Level Decision (LPLD) scheme.

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