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A green and reliable communication modeling for industrial internet of things

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ABSTRACT

Green and reliable communication has great significance for Industrial Internet of Things. Unfortunately, because of the loss nature, achieving reliable transmission is challenging. In this paper, a novel hybrid transmission protocol (HTP) is proposed to maximize lifetime while the reliability is still guaranteed. The proposed protocol adopts Send-Wait automatic Repeat-Request protocol in hotspot areas to reduce the energy consumption and network coding based redundant transmission approach with adaptive redundancy level in non-hotspot areas to guarantee the reliability. The proposed protocol could improve the lifetime and shorten the delay on the premise of ensuring the reliability. Comparing with Send-Wait automatic Repeat-Request protocol, it can improve lifetime by 15%–30% under the same reliability and improve the reliability by 12%–45% under the same lifetime. Comparing with network coding based redundant transmission approach, the lifetime has increased by more than one time under the same reliability.

1. Introduction

Industrial wireless sensor networks are of important component of Industrial Internet of Things that integrating the physical systems with sensing, computing, and actuation exhibit new capabilities with unprecedented dependability and efficiency [1–5]. It makes the smart factory real [6,7]. For the sensor nodes in these applications, sense the environmental data and transfer them to sink node is one of the important features. Due to the characteristics of the wireless networks, there are noise and error during data transmission, which leads to data lost [8–10]. The sensor networks depend on the sensory data to take action, if data reliability is not high, it may lead to decision-making mistakes [10–12]. Thus the packet delivery reliability becomes a prominent challenge in industrial WSNs [10–16]. Due to their inherent characteristics of resource-constrained, for data collection, Green (energy efficiency) communication is another vital issue since replacing or recharging the batteries of sensor nodes is extremely difficult [8–10,24]. Summarily, green (energy efficiency) communication, the delay and data reliability (the probability of data packets successfully received by receiver) are regarded as the major concerns

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in the design of industrial wireless sensor networks [10,17]. Many studies show that there is a trade-off among the delay, energy efficiency and reliability [10,13].

There have been some strategies to guarantee the reliability of data transmission, such as Send-Wait automatic Repeat-Request (SW-ARQ) protocol [10,13]. With SW-ARQ protocol, the sender transmits one packet each time and waits for an ACK or a timeout before its next transmission [10,13]. The advantages of this protocol are easy-to-use and energy-saving. But the disadvantage of it is the delay. Especially in the network with poor link quality, multiple retransmissions may lead to long delay. Another strategy which called network coding based redundant transmission (NCRT) approach [18] is to encode the data packets and transmit them with some redundancy levels. The delay of it is short, but the energy consumption is large, so the network lifetime of this method is short.

For industrial applications, they also require the protocol can improve the data transmission reliability, keep a longer network lifetime and reduce the delay. But to the best of our knowledge, there have not a method that can optimize the network performance simultaneously. The application of WSNs is more and more widely, especially in industrial production, a data transmission strategy that can achieve high-reliability, low-latency and long lifetime is urgently needed.

In this paper, combining the advantages of SW-ARQ protocol and NCRT approach, we proposed a new method which called hybrid transmission protocol (HTP) to maximize lifetime with reliability guarantees for wireless sensor networks. The main contributions of our study are as follows:

The HTP approach which we proposed adopts SW-ARQ protocol in hotspot areas (the areas near sink) and NCRT approach in non-hotspot areas (the areas far to sink), which can prolong lifetime as well as reduce end-to-end delay. In the areas near the sink, we adopt SW-ARQ protocol to save energy as much as possible. In the areas far to sink, we make full use of the rest energy to improve the network reliability and shorten the delay. On the whole, HTP approach can overcome the shortcomings of the other two methods. It can achieve low-latency, high-reliability and long lifetime in the network. It can also change the phenomenon of unbalanced energy consumption in WSNs. Through our extensive studies, comparing with the other two kinds of method, the performance of HTP is improved greatly.

The rest of this paper is organized as follows: In Section 2, the related works are reviewed. The system model is described in Section 3. In Section 4, a novel hybrid transmission protocol (HTP) is proposed. The HTP's performance analysis is provided in Section 5. Section 6 is experimental results and comparison. We conclude in Section 7.

2. Related work

Because the reliability, delay and network lifetime are all important performance for wireless sensor networks, so there has been a tremendous amount of research about them [1–7]. In this section, we review some current related research and divide them into two categories: one is improve the network reliability only by using data transmission method, the other one is cross-layer optimization.

(1) Cross-layer optimization is the method while optimizing at multiple levels. Such methods mainly optimize MAC layer and transport layer simultaneously. The principle of such methods is: there are strong correlations between data transmission reliability and sending power of the node. Generally speaking, if we improve the sending power of the node, the SNR also improves, so that the probability of successfully receiving packets for the receiver improved, and the data transmission reliability improved. This method requests the hardware of nodes can provide different transmit power, so it couldn't be used in some networks. Also, the energy consumption of this method is big and the lifetime is short. There are a lot of studies belong to this category, Ref. [19] proposed a method which adopts different transmit power to reduce the bit error rate (BER) and delay in adaptive MPSK-based wireless sensor networks. We can also see some related research in Ref. [20,21].

(2) The reliability and delay guaranteed mechanism in data transport layer. Because the cross-layer optimization method has higher requirement for the networks, and it also requires to optimization in the transport layer. Therefore, many studies still research at the transport layer. Such studies can be divided into following categories:

(a) Retransmissions-based reliability and delay guaranteed mechanism. In this method, for each sender node, it sends the packets to the destination node one time, then waiting the receiver returns an ACK to ensure the packets are received. If the sender receives an ACK within the expected time, it continues to send next packet. Otherwise, the packets would be sent by the sender the second time. Repeated the above process again and again, until the sender receives an ACK or the retransmission times exceed the predetermined maximize retransmission times. The advantages of it are that, it is simple and has low requirement for the system, it can be adopted in all kinds of networks, and the network lifetime of it is high. But the disadvantage of it is the long delivery delay, especially in a low link quality network. While the retransmission mechanism has several transformations: (1) Go-Back-N (GBN) protocol (2) Selective repeat (SR) [9,11–13]. All the retransmission protocols can operate in hop-by-hop (HBH) or end-to-end (E2E) mode [11,13].

(b) Multi-path transmission. It belongs to redundant transmission. In Ref. [22], it divides redundant transmission methods into following categories: (1) Multi-path data transmission mode. It means the same data packets can reach sink through multiple routing and as long as one route reaching is ok. (2) Multi-copy data transmission mode. This method is similar to the above retransmission mechanism. It sends the same packets in the same link several times. But it doesn't need to wait the return of ACK. For these methods, the advantages of it are the reliability can be guaranteed

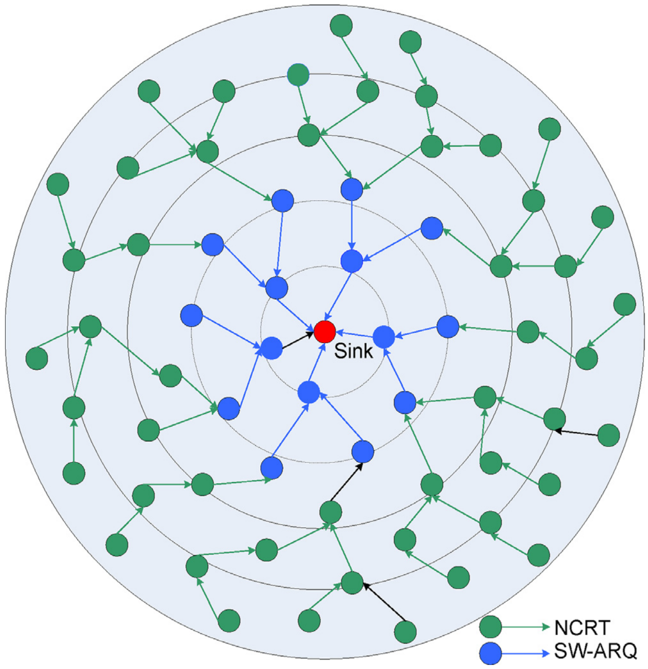

Fig. 1. The planar network model under HTP protocol.

and the delay is short. But the disadvantage is the high energy consumption. So they affect the network lifetime seriously.

(c) Network coding technique [18]. On the basis of redundancy encoding, Network coding technique is a reliability assurance mechanism [18]. The source node encodes the packets with some redundancy levels and the destination node decodes them to retrieve the original packets. So even there are some data lost during the transmission, it would not affect the destination node receives the right data packets. The advantages of it are that, the amount of data to transfer is less than the condition that employs redundant transmission mechanism. Although the amount of data to transfer is more than the condition that employs the retransmission mechanism, the delay of it is shorter. Therefore, network coding technique is a better method.

From the above studies we can find out that the data transmission reliability is related to the delay. Generally speaking, if we use the cross-layer optimization, the reliability can be increased through improving the transmit power of nodes, then the number of retransmission times is reduced and the delay is shortened. But its lifetime is short. For the methods in the transport layer, if the energy consumption is small, the delay would be very big, such as the retransmission mechanism; if the delay is short, the energy consumption would be big, such as multi-path transmission. So, in this paper, we proposed a comprehensive approach which can optimize the reliability, delay and energy consumption simultaneously.

3. The system model and problem statement

3.1. The network model

The network model is same as that in Ref. [11,13,18], which can be described as: (1) the sensor nodes are uniform randomly distributed in a circular area and sink is located at the center; (2) The nodes' transmitting radius is r. In each round, we assume the probability of each node generating packets is λ [23]. The sensory data is sent to sink by greedy geographic routing [17]. (3) For any node, the probability of successfully transfer data between two nodes is denoted by p. For SW-ARQ, the probability of ACK reach the sender node is denoted by q. The same with [11,13], we assume that reception failures are spatial dependent but time independent [11,13]. The planar network model under HTP protocol is as Fig. 1 shows.

3.2. Energy consumption model and related definitions

In this paper, we adapt the typical energy consumption model which can also be seen in Ref. [19,22]. The energy consumption in transmission data can be calculated through formula (1), and the calculation of the energy consumption for

Table 1
Parameters in the network.

Parameter	Value	Meaning
Threshold distance (d_0) (m)	87	/
E_{elec} (nJ/bit)	50	the energy consumption in the transmission circuit
ε_{fs} (pJ/bit/m^2)	10	the energy required to amplify in the models
ε_{amp} (pJ/bit/m^4)	0.0013	the energy required to amplify in the models
l	/	the number of data bits
d	/	The transmission distance

Table 2
The notations.

Parameters	The meanings
$D_{e\,2\,e}$	End to end delay (from the packet generation to it arrives sink) for data collection routing
d_i	The delay of the packets arrival at the i^{th} hop of multi-hop routing to sink
ℓ	The network lifetime
E_{ini}	The initial energy of each node
e_i	The energy consumption of node i
ζ	The energy efficiency
δ_{e2e}^{j}	The end-to-end reliability when the data is sent to sink from the node j
β_i	The reliability of the i^{th} hop
δ	The minimum reliability that the applications requirement

receiving data is presented in formula (2). The parameters in the formula are shown in Table 1.

$$\begin{cases} E_{member} = lE_{elec} + l\varepsilon_{fs}d^2 \text{ if } d < d_0 \\ E_{member} = lE_{elec} + l\varepsilon_{amp}d^4 \text{ if } d > d_0 \end{cases} \tag{1}$$

$$E_R(l) = lE_{elec} \tag{2}$$

3.3. Problem statement

The problem this paper studies can be described as: how to design efficient transmission to minimize the delay, maximize the network lifetime and energy efficiency. Our design goal is to achieve high-reliability, low-latency and long lifetime in the networks, in the meanwhile, the reliability still should be guaranteed. So the goal of HTP approach can be stated as follows and the meanings of parameters in formulas are shown in Table 2.

$$\begin{cases} Minimize\ D_{e2e},\ \ Maximize\ \ell, Maximize\ \zeta, \\ \min\,(D_{e2e}) = \min\left(\sum_{i\subseteq route} d_i\right) \\ \max(\ell) = \max(E_{ini}/e_i) \\ \max\,(\zeta) = \max\left(\left(\sum_{0\le i\le n} e_i\right)/\left(\sum_{0\le i\le n} E_{ini}\right)\right) \\ \delta^{j}_{e2e\ j\in\{1..n\}} = \prod_{i\in pathj} \beta_i \ge \delta \end{cases} \tag{3}$$

4. A hybrid transmission protocol design

4.1. Background

SW-ARQ protocol, as Fig. 2 shows [11,13], reliability is assured in each hop. The transmitter sends a packet, if the transmitter receives an ACK from its subsequent node before the preset timeout occurs, it transmits a new packet. Otherwise, it retransmits the preceding packet. A receiver transmits an ACK for every packet it receives successfully including for duplicates.

Network coding based redundant transmissions (NCRT) approach can be seen from Ref. [18]. In this method, the redundancy level can be considered as the number of the coded packets. When selecting different vectors encoding the data packets, different encoding results can be got. The higher the level of redundancy is, the greater the probability of the node successfully receives the packets is. But the energy consumption is also increased. So redundancy level is determined according to the application requirements and the link loss rate.

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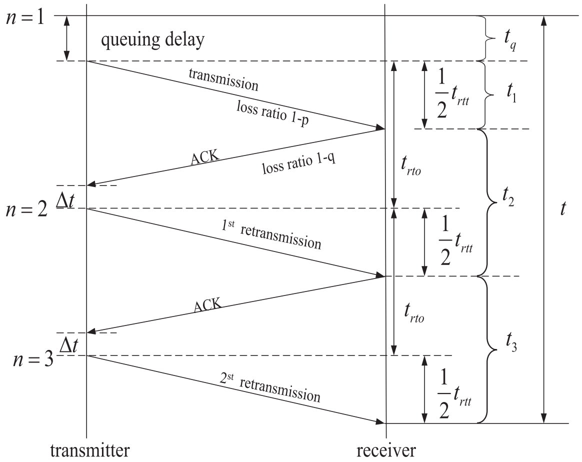

Fig. 2. SW-ARQ protocol.

4.2. The HTP approach design

4.2.1. The data sizes, reliability, energy consumption of SW-ARQ protocol

In the following, ς_i represents node i, the value of i increases with the increase of the distance to sink. In the linear network, ς_1 represents the nearest node to sink; in the planar network, ς_1 represents the nodes that are only one-hop to sink.

Theorem 1. *Under SW-ARQ protocol, no matter in planar network or linear network, for node ς_i, if it could guarantee the reliability to next hop greater than β, then the maximum number of retransmissions $R(\beta)$, the average number of transmissions $X(\beta)$ are express as follows*:

$$\begin{cases} R(\beta) = \left\lceil \frac{\log(1-\beta)}{\log(\overline{p})} \right\rceil \\ X(\beta) = \sum_{j=1}^{R(\beta)-1} jpq(1-pq)^{j-1} + R(\beta)\cdot(1-pq)^{R(\beta)-1} \end{cases} \tag{4}$$

Proof. Suppose that each sensed data has N backups. By the time independency assumption, the number of data send successfully to receiver with the probabilities of $P = \{p\}$ is binomially distributed with N and a success probability of p; thus, we can get the formula: $\delta(N,P) \cong P(X_{i,p} > 1) = 1 - (\overline{p})^N$. Let $\beta = \beta(N, P)$, $R(\beta) = N$, we can derive the following formula to calculate the maximum number of retransmissions for node ς_i to guarantee the reliability to next hop greater than β.

$$R(\beta) = \left\lceil \frac{\log(1-\beta)}{\log(\overline{p})} \right\rceil \tag{5}$$

Then the expected transmission times can be calculated as follows: it needs at least one time transmission that node ς_i transfers the packets to its next hop. If it transmits j times and the receiver doesn 't receive ACK in prior, the average number of transmissions $X(\beta)$ can express as:

$$X(\beta) = \sum_{j=1}^{R(\beta)-1} jpq(1-pq)^{j-1} + R(\beta)\cdot(1-pq)^{R(\beta)-1} \tag{6}$$

As well, this theorem is also completely applicable to the planar network □

Theorem 2. *If the probability of each node generating data packets are equal, the amount of data received and transmitted by each node, the number of ACK received and transmitted are expressed in the linear and planar network respectively as follows:*

$$\begin{cases} B_i^t = \sum_{k=i}^{\kappa}\left(X_k^i(\delta)\delta^{\frac{k-i}{k}}\right), B_i^r = pB_{i+1}^t = p\sum_{k=i+1}^{\kappa}\left(X_k^{i+1}(\delta)\delta^{\frac{k-i-1}{k}}\right) \\ B_l^t = \left(X_l^l\delta^{\frac{1}{h_l}} + X_{l+r}^l\cdot\frac{l+r}{l}\cdot\delta^{\frac{1}{h_l+1}} + X_{l+2r}^l\cdot\frac{l+2r}{l}\cdot\delta^{\frac{2}{h_l+2}} + \cdots + X_{l+zr}^l\cdot\frac{l+zr}{l}\cdot\delta^{\frac{z}{h_l+z}}\right)\lambda | l = hr + x,\ x + zr \le R \\ B_l^r = p\lambda\left(X_{l+r}^{l+r}\cdot\delta^{\frac{0}{h_l+1}} + X_{l+2r}^{l+r}\cdot\frac{l+2r}{l+r}\cdot\delta^{\frac{1}{h_l+2}} + \cdots + X_{l+(z+1)r}^{l+r}\cdot\frac{l+(z+1)r}{l+r}\cdot\delta^{\frac{z}{h_l+z+1}}\right) | l = hr + x,\ x + zr \le R \\ M_i^t = B_i^r,\ M_i^r = B_i^t pq; M_l^t = B_l^r,\ M_l^r = B_l^t pq \end{cases} \tag{7}$$

Proof. In the linear network, for the data that j-hop to node, we should ensure the reliability $\beta = \sqrt[j]{\delta}$ for each hop, so the end-to-end reliability can be guaranteed as δ.

The expected retransmission times for the data at j-hop distance to node transmits to i-hop distance to node can be expressed as follows:

$$X_j^i(\delta) = \sum_{j=1}^{R(\sqrt[j]{\delta})-1} jpq(1-pq)^{j-1} + R(\sqrt[j]{\delta}) \cdot (1-pq)^{R(\sqrt[j]{\delta})-1} \tag{8}$$

The probability of data at j-hop distance to node transmits to i-hop distance to node is $\delta^{\frac{j-i}{j}}$, so the number of data packets with node j that node i needs to transmit is $X_j^i(\delta)\delta^{\frac{j-i}{j}}$. Node i needs to transmit the data packets with node number from i to κ(κ is the total number of nodes). Thus the number of data packets that node i sends is:

$$B_i^t = X_i^i(\delta)\ \delta^{\frac{0}{i}} + X_{i+1}^i(\delta)\ \delta^{\frac{1}{i+1}} + X_{i+2}^i(\delta)\ \delta^{\frac{2}{i+2}} + \ldots + X_\kappa^i(\delta)\ \delta^{\frac{\kappa-i}{\kappa}} = \sum_{k=i}^{\kappa}\left(X_k^i(\delta)\delta^{\frac{k-i}{k}}\right) \tag{9}$$

The amount of ACK that is required to send is calculated as follows: when a node receives a packet, it returns an ACK. So, the number of ACK is equal to the number of received data packets. The number of received data packets is the number of packets that send by a previous node multiplied by p (because of packets loss). So we can get the following formula to calculate the number of ACK that node i transmits:

$$M_i^t = B_i^r = pB_{i+1}^t = p\sum_{k=i+1}^{\kappa}\left(X_k^{i+1}(\delta)\delta^{\frac{k-i-1}{k}}\right) \tag{10}$$

For node i, B_i^t is the number of packets that it sends to the download nodes, p represents the probability of packets successful delivery by download nodes, and each packet return an ACK, the probability of ACK successful return is q. So the number of received ACK is:

$$M_i^r = B_i^t pq \tag{11}$$

In the flat circular network with a radius of R. Assume the network sense radius is r, according to the above proof that it is easy to think: let $j = \lceil \frac{l+nr}{r} \rceil$, when a packet transmits from $l + nr$ distance to sink to l distance to sink, the expected retransmission times can be expressed as:

$$X_{l+nr}^l(\delta) = 1 + \sum_{j=2}^{R(\sqrt[j]{\delta})-1} jpq(1-pq)^{j-1} + R(\sqrt[j]{\delta}) \cdot (1-pq)^{R(\sqrt[j]{\delta})-1} \tag{12}$$

The previous research had given the formula to calculate the data sizes that each ring nodes undertake under the condition that regardless the link loss rate:

$$\zeta_l = \left(1 + \frac{l+r}{l} + \frac{l+2r}{l} + \cdots + \frac{l+zr}{l}\right)\lambda | l = hr + x, x + zr \le R \tag{13}$$

We define the nodes that have same distance to sink are in the same ring. By this time, because the sense radius is r, so the hops to sink for the ring nodes that are l distance to sink can represent as: $h_l = \lceil \frac{l}{r} \rceil$. Thus, the number of data packets that the ring nodes send is:

$$B_l^t = \left(X_l^l\delta^{\frac{1}{h_l}} + X_{l+r}^l \cdot \frac{l+r}{l} \cdot \delta^{\frac{1}{h_l+1}} + X_{l+2r}^l \cdot \frac{l+2r}{l} \cdot \delta^{\frac{2}{h_l+2}} + \cdots + X_{l+zr}^l \cdot \frac{l+zr}{l} \cdot \delta^{\frac{z}{h_l+z}}\right)\lambda |\ l = hr + x,\ \ x + zr \le R \tag{14}$$

As well, the number of data packets that the ring nodes receive is:

$$B_l^r = M_l^t = pB_{l+r}^t = p\lambda\left(X_{l+r}^{l+r} \cdot \delta^{\frac{0}{h_l+1}} + X_{l+2r}^{l+r} \cdot \frac{l+2r}{l+r} \cdot \delta^{\frac{1}{h_l+2}} + \cdots + X_{l+(z+1)r}^{l+r} \cdot \frac{l+(z+1)r}{l+r} \cdot \delta^{\frac{z}{h_l+z+1}}\right) \tag{15}$$

Like formula (10), the number of received ACK packets in the planar network is:

$$M_l^r = B_l^t pq \tag{16}$$

□

4.2.2. The data sizes, reliability, energy consumption of NCRT approach

Theorem 3. *For each node, we can calculate the reliability and energy consumption, the amount of data that is being received and transmitted in accordance with following formulas. In the formula,* p_0 *represents the reliability of the node transmits a data to next hop,* λ *is the probability of each node generating a data packet in a sample cycle.*

$$\begin{cases} p_o = \sqrt{1 - p_l^{m+2} - (m+2)\cdot p_l^{m+1}\cdot(1-p_l)} \\ \zeta_l^{e,t} = \left(\left(2 + \frac{l+r}{l}p_o + \frac{l+2r}{l}(p_o)^2 + \cdots + \frac{l+zr}{l}(p_o)^{z-1}\right)(m+1)\right)\lambda | l = hr + x,\ \ x + zr \le R \\ \zeta_l^{e,r} = \left(\frac{l+r}{l}p_o + \frac{l+2r}{l}(p_o)^2 + \cdots + \frac{l+zr}{l}(p_o)^{z-1}\right)(m+1)\lambda | l = hr + x,\ \ x + zr \le R \\ E_l^e = \zeta_l^{e,r}e_u^r + \zeta_l^{e,t}e_u^t \end{cases} \tag{17}$$

Proof. Under NCRT protocol, we assume the maximum network hops is $\hbar$, the minimum end-to-end reliability that meets the application requirements is $\hat{p}$, then the reliability of the node transmits a packet to next hop can express as:

$$(p_o)^{\hbar} \ge \hat{p}\ | p_o = \sqrt{1 - p_l^{m+2} - (m+2)\cdot p_l^{m+1}\cdot(1-p_l)} \tag{18}$$

That is:

$$(p_o)^{\hbar} \ge \hat{p} \Rightarrow \sqrt{1 - p_l^{m+2} - (m+2)\cdot p_l^{m+1}\cdot(1-p_l)} \ge \sqrt[\hbar]{\hat{p}} \tag{19}$$

Then we can get the redundancy level m under NCRT approach:

$$p_l^{m+1}\left(p_l + (m+2)(1-p_l)\right) = 1 - \sqrt[\hbar]{(\hat{p})^2} \tag{20}$$

Take the logarithm on both sides, that is:

$$m\log p_l + \log\left[p_l + (m+2)(1-p_l)\right] = \log\frac{\left(1 - \sqrt[\hbar]{(\hat{p})^2}\right)}{p_l} \tag{21}$$

Because the values of m are integers, so based on the formula (21), we can easily get a value of m that meets the conditions. At this time, for a node in the l distance to sink, it sends the amount of data:

$$\zeta_l^{e,t} = \left(\left(2 + \frac{l+r}{l}p_o + \frac{l+2r}{l}(p_o)^2 + \cdots + \frac{l+zr}{l}(p_o)^{z-1}\right)(m+1)\right)\lambda\ | l = hr + x,\ \ x + zr \le R \tag{22}$$

It receives the amount of data:

$$\zeta_l^{e,r} = \left(\frac{l+r}{l}p_o + \frac{l+2r}{l}(p_o)^2 + \cdots + \frac{l+zr}{l}(p_o)^{z-1}\right)(m+1)\lambda | l = hr + x,\ \ x + zr \le R \tag{23}$$

Thus, for a node in the l distance to sink, its energy consumption can express as:

$$E_l^e = \zeta_l^{e,r}e_u^r + \zeta_l^{e,t}e_u^t \tag{24}$$

□

According to the proof of Theorems 1–3 and the calculation formulas, we proposed a concrete algorithm about HTP approach, the specific steps of it is:

(1) First, according to the requirement of end-to-end reliability p_e, we can calculate the average reliability $\hat{p}$ of each hop. We assume that the first h hops in the network are the high energy consumption areas. For the first $h + 1$ hops in the network, based on SW-ARQ protocol, we calculate the expected retransmission times N, the data sizes and energy consumption at this time. From the $(h + 2)$ *th* hop, we set the parameters under NCRT approach. And according to the reliability $\hat{p}$ we can calculate the node 's redundancy level m. Then we can calculate the data sizes and energy consumption for each node.
(2) For the first ring nodes, let $N_1 = N_1 - 1$, calculating the reliability $p_1$to next hop and its energy consumption at this time. While from the last ring, outside-in improving the node 's redundancy level, satisfying the condition that energy consumption in these areas are still smaller than the consumption in the center nodes and $m_i < 30$ (because $m_i = 30$, the reliability for the nodes to next hop is almost equal to 1, so when $m_i \ge 30$, improving it has no effect on improving the reliability, it only increases energy consumption). Calculating the reliability p_i, it needs to satisfy the formula $p_1\ p_2\ \cdots\ p_n \ge p_e$.
(3) Repeat the second step until it can 't meet the requirements. Then, $N_1 = N_1 + 1$.
(4) Until the $(h + 1)$ *th* ring nodes, we do the same action as the first ring nodes. When we get a minimum retransmission times N_1, N_2, ..., N_{h+1}, the algorithm comes to an end. By this time, the retransmission times N_1, N_2, ..., N_{h+1} in the first $(h + 1)$rings and the redundancy levels m_l after the $(h + 2)$ *th* ring are the significant signals that we desire.

The pseudo-code of HTP protocol represents as Algorithm 1.

Before starting the algorithm, we calculate the energy consumption for each node under SW-ARQ protocol. And we find out the first h hops in the network of high energy consumption areas. So, for the first $(h + 1)$hops, we adopt SW-ARQ protocol; from the $(h + 2)$ *th* hop, we adopt NCRT approach.

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Algorithm 1
The calculation of the retransmission times and redundancy level.

Algorithm1: Attaining retransmission times $N_1, N_2, \ldots, N_{h+1}$ in the first $(h+1)$ rings and redundancy levels m_I after the $(h+2)$ *th* ring to maximum network lifetime. In the meantime, reliability is higher and delay is lower.
Input: link loss rate p_l, package delivery probability p_e, network radius R, node's initial energy E_{init} and relevant energy model parameters, the node's sensing range r, h represents the areas that with high energy consumption in WSN.
Output: the retransmission times $N_1, N_2, \ldots, N_{h+1}$ and the redundancy levels m_I

1: initialization. The expected number of retransmissions in the first $(h+1)$ rings: $N_1 = N_2 = \cdots = N_{h+1} = N$
The redundancy level for the nodes in after the $(h+2)$ *th* ring: $m_{h+2} = m_{h+3} = \cdots = m_n = m$
The reliability $p_1 = p_2 = \cdots = p_n = \sqrt[n]{p_e}$
2: $i = i + 1$
3: **For** $(i \le h+1)$
4: **While** $(N_i \ne 0)$
5: $N_i = N_i - 1$
6: According to Theorem 1, 2 calculate the reliability p_i and energy consumption E_i for the nodes in the i^{th} ring
7: According to Theorem 1, 2 calculate the energy consumption E_1 for the nodes in the first ring
8: **While** $(p_1\ p_2 \cdots p_i \cdots p_n \le p_e)$
9: According to Theorem 3 calculate the energy consumption $E_{h+2}, E_{h+3}, \ldots, E_n$. Finding out the minimum energy consumption ring I $(I > h+1)$
10. Improve the node's redundancy level $m_I = m_I + 1$. Recalculating the reliability p_I and the energy consumption E_I, E_{I-1}
11. **If** $(E_I < E_1 \&\& E_{I-1} < E_1 \&\& m_I < 30)$
12: **If** $(p_1\ p_2 \cdots p_n \ge p_e)$
13: goto 4;
14: **Else**
15: goto 9;
16: **End if**;
17: **Else**
18: $N_i = N_i + 1$
19: **End if**;
21: **End while**;
22: **End while**;
23: **End for**;
23: **Output**: $N_1, N_2, \ldots, N_{h+1}, m_{h+2}, m_{h+3}, \ldots, m_n$
24: **END**

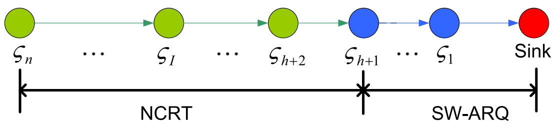

Fig. 3. A simple model in linear network under HTP approach.

5. The performance analysis of HTP approach

5.1. Delay analysis

Adopting HTP protocol in the network, that is, according to the energy consumption of nodes in WSNs, we adopt SW-ARQ protocol in the first $h+1$ hops while adopting NCRT approach from the $(h+2)$ *th* hop (like Fig. 3 shows). Thus, the total network latency composes the delay of SW-ARQ protocol and the delay of NCRT. So:

$$D = d_i + D_i \tag{25}$$

d_i and D_i can be calculated from 5.1.1 and 5.1.2 later. Therefore, the whole network latency D can be expressed as:

$$D = \sum_{i=1}^{h+1}\left(i\sum_{k=1}^{A_i(\delta)}\left(\frac{1}{2}t_{rtt} + (k-1)t_{rto}\right)\right) + \sum_{h+2}^{n}\left(\frac{1}{2}t_{rtt} + m_i \cdot s\right) \tag{26}$$

5.1.1. The delay of SW-ARQ protocol

Theorem 4. *Adopt SW-ARQ protocol, for node ς_i that is i-hop distance to sink, the delay of it transmits packets to sink is:*

$$d_i = i\sum_{k=1}^{A_i(\delta)}\left(\frac{1}{2}t_{rtt} + (k-1)t_{rto}\right) \tag{27}$$

Proof. Like Fig. 3 shows, for node ς_i that is i-hop distance to sink, in order to meet the reliability requirements, the maximum retransmission times of it can denote as:

$$A_i(\delta) = \left\lceil \frac{\log(1-\delta^{1/i})}{\log(\overline{p})} \right\rceil \tag{28}$$

The delay of the data packets on any node for node ς_i is: $\sum_{k=1}^{A_i(\delta)} (\chi_k \nu_k)$ | where χ_k represents the packet is successfully sent until the k- th time. ν_k is the delay for k times transmissions.

The probability of a data packet is successfully sent until the k- th ($k \le A_i(\delta)$) time is: $(\overline{p})^{k-1}p$, at this time, the delay of receiver receives the packet is:

$$\frac{1}{2}t_{rtt} + (k-1)t_{rto} \tag{29}$$

So the delay of the data packets on any node for node ς_i is:

$$\sum_{k=1}^{A_i(\delta)} \left(\frac{1}{2}t_{rtt} + (k-1)t_{rto}\right) \tag{30}$$

Thus the end-to-end delay for node ς_i is:

$$d_i{=}i\sum_{k=1}^{A_i(\delta)} \left(\frac{1}{2}t_{rtt} + (k-1)t_{rto}\right) \tag{31}$$

It is similar in planar network, the end-to-end delay for ring nodes that are i-hop distance to sink can also denote as:

$$d_i = i\sum_{k=1}^{A_i(\delta)} \left(\frac{1}{2}t_{rtt} + (k-1)t_{rto}\right); \text{And } A_i(\delta) = \left\lceil \frac{\log(1-\delta^{1/i})}{\log(\overline{p})} \right\rceil \tag{32}$$

So, we can get the formula of end-to-end delay under SW-ARQ protocol, that is:

$$d_i = i\sum_{k=1}^{A_i(\delta)} \left(\frac{1}{2}t_{rtt} + (k-1)t_{rto}\right) \tag{33}$$

□

5.1.2. The delay of NCRT approach

Theorem 5. *Adopt NCRT approach, for node ς_i that is i-hop distance to sink, its hop-to-hop delay can express as:*

$$D_i = \frac{1}{2}t_{rtt} + m_i \cdot s \tag{34}$$

Where m_i represents the redundancy level of node ς_i and s represents the transmission interval.

Proof. Under NCRT approach, for node ς_i that is i-hop distance to sink, the delay of it to next hop consists of the queuing delay t_q, transmission delay $\frac{1}{2}t_{rtt}$ and send delay $m \bullet s$ (m is its redundancy level), that is:

$$D_i = t_q + \frac{1}{2}t_{rtt} + m_i \cdot s \tag{35}$$

We ignore the queuing delay t_q in this paper. So, the delay to next hop under NCRT approach can express as:

$$D_i = \frac{1}{2}t_{rtt} + m_i \cdot s \tag{36}$$

□

5.2. Lifetime analysis

Theorem 6. *E_{ini} represents the node's initial energy. ζ_l is the data sizes that the node undertakes without considering the link loss rate. n is the maximum retransmission times under SW-ARQ protocol. Then, the network lifetime of HTP approach is as:*

$$\Omega = \begin{cases} \dfrac{E_{ini}}{n\zeta_l E_{elec} + n(\zeta_l+1)E_{elec} + n(\zeta_l+1)\varepsilon_{fs}d^2} (\text{if}(d < d_0)) \\ \dfrac{E_{ini}}{n\zeta_l E_{elec} + n(\zeta_l+1)E_{elec} + n(\zeta_l+1)\varepsilon_{amp}d^4} (\text{if}(d > d_0)) \end{cases} \tag{37}$$

Proof. According to the previous research, without considering the link loss rate, we had known the amount of data that the node in the l distance to sink is received can be denoted as:

$$\zeta_l = \left(1 + \frac{l+r}{l} + \frac{l+2r}{l} + \cdots + \frac{l+zr}{l}\right)\lambda | l = hr + x, x + zr \le R \tag{38}$$

Also, the network lifetime is determined by the largest energy consumption node. In WSN, the center nodes undertake a large amount of data, and their energy consumption is big. So the network lifetime determined by the lifetime of the center nodes. For the center nodes, we can use formula (38) to calculate the data sizes ζ_l that they undertake. Under HTP approach, the center nodes adopt SW-ARQ protocol. If the number of maximum retransmission is n, when the data is successfully delivery, the amount of data that it is transmitted can express as:

$$\zeta_l^t = n(\zeta_l + 1) \tag{39}$$

The amount of data that the center node is received can express as:

$$\zeta_l^r = n\zeta_l \tag{40}$$

So according to the formula (1) we can calculate the energy consumption of sending data is:

$$E_l^t = \begin{cases} n(\zeta_l + 1)E_{elec} + n(\zeta_l + 1)\varepsilon_{fs} d^2 (\text{if}(d < d_0)) \\ n(\zeta_l + 1)E_{elec} + n(\zeta_l + 1)\varepsilon_{amp} d^4 (\text{if}(d > d_0)) \end{cases} \tag{41}$$

According to the formula (2) we can calculate the energy consumption of receiving data is:

$$E_l^r = n\zeta_l E_{elec} \tag{42}$$

Thus the total energy consumption for the node is:\

$$E_l = E_l^t + E_l^r \tag{43}$$

Because each node 's initial energy is E_{ini}, so the whole network lifetime can be described as:

$$\Omega = \frac{E_{ini}}{E_l} \tag{44}$$

Bring the formulas (41)–(43) to (44), we can get the network lifetime as follows:

$$\Omega = \begin{cases} \dfrac{E_{ini}}{n\zeta_l E_{elec} + n(\zeta_l + 1)E_{elec} + n(\zeta_l + 1)\varepsilon_{fs} d^2} (\text{if}(d < d_0)) \\ \dfrac{E_{ini}}{n\zeta_l E_{elec} + n(\zeta_l + 1)E_{elec} + n(\zeta_l + 1)\varepsilon_{amp} d^4} (\text{if}(d > d_0)) \end{cases} \tag{45}$$

□

5.3. Reliability analysis

Theorem 7. *The end-to-end reliability under HTP approach can express as:*

$$p_{e2e} = \prod_{i=1}^{h+1} \left(1 - (1-p)^{A_i(\delta)}\right) \prod_{i=h+2}^{H} \sqrt{1 - {p_l}^{m_i+2} - (m_i + 2){p_l}^{m_i+1} \cdot (1 - p_l)} \tag{46}$$

A_i (δ) represents the maximum retransmission times for node i under SW-ARQ protocol, m_i is the redundancy level of node i under NCRT protocol.

Proof. According to the relevant literature: when the network adopts the SW-ARQ protocol, the relations between the maximum retransmission times A (δ) and the reliability δ can express as:

$$A(\delta) = \left\lceil \frac{\log(1-\delta)}{\log\left(1 - \prod_{i=0}^{h} p\right)} \right\rceil \tag{47}$$

The maximum retransmission times A_i (δ) of node i transmits packet successful to next hop can express as:

$$A_i(\delta) = \left\lceil \frac{\log\left(1 - \delta^{1/i}\right)}{\log(1-p)} \right\rceil$$

So, under SW-ARQ protocol, the reliability to next hop can express as:

$$\delta_i = 1 - (1-p)^{A(\delta_i)} \tag{48}$$

Table 3
Linear network experiment environment.

Property	Value
The number of nodes	10
Sink	Located at one end of the network
Arrangement of nodes	Equal distance linearly ordered
The distance between nodes	60 m
The initial energy of each node	5000000 NJ
Network transmission radius	80 m
The energy consumption of nodes	Follow the energy consumption model

Table 4
Planar network experiment environment.

Property	Value
The number of nodes	1000
Sink	Only one, located in the network center
Arrangement of nodes	Randomly arranged in a circular network
Network radius	500 m
Network transmission radius	80 m
The initial energy of each node	50000000 NJ
The energy consumption of nodes	Follow the energy consumption model

Table 5
Experiment parameters.

Parameter symbol	Parameter settings
The length of ACK	20 bit
round-trip time t_{rtt}	200 ms
retrainsmission time out t_{rto}	250 ms
Waiting time $\Delta\ t$	50 ms
The transmission interval s	5 ms

Also, under NCRT approach, the reliability p_i to next hop can denote as:

$$p_i = \sqrt{1 - {p_l}^{m_i+2} - (m_i + 2) \cdot {p_l}^{m_i+1} \cdot (1 - p_l)}$$

Thus, for a wireless sensor network that the maximum hops of it is H, the end-to-end reliability is:

$$p_{e2e} = \prod_{i=1}^{h+1} \left(1 - (1 - p)^{S_h(\delta_i)}\right) \prod_{i=h+2}^{H} \sqrt{1 - {p_l}^{m_i+2} - (m_i + 2){p_l}^{m_i+1} \cdot (1 - p_l)} \tag{49}$$

□

6. Experimental results

In order to evaluate the performance of the approach which we proposed, we simulate the network behavior on Omnet ++ experimental platform [25]. Experiments include linear network and planar network. The simulation environment in experiment is as Tables 3 and 4.

And the experiment parameters are set as Table 5.

6.1. Energy efficiency

Fig. 4 shows the analyzing and experimental results in linear network. As seen in the figure, the HTP approach is well balanced the energy consumption. For HTP approach, compared with SW-ARQ, the center nodes ’ energy consumption can reduce over 15 percent; and compared with NCRT approach, our approach prolongs the lifetime of network over 100%. Fig. 5 presents the analyzing and experimental results in circular network. In the planar network, HTP protocol which we proposed can balance the whole network energy consumption. And compared with SW-ARQ protocol, the center nodes’ energy consumption can reduce over 20 percent; compared with NCRT approach, it can save energy at least double. In conclusion, HTP approach can effectively reduce the center nodes’ energy consumption. It can improve the energy efficiency and balance the whole network’s energy consumption.

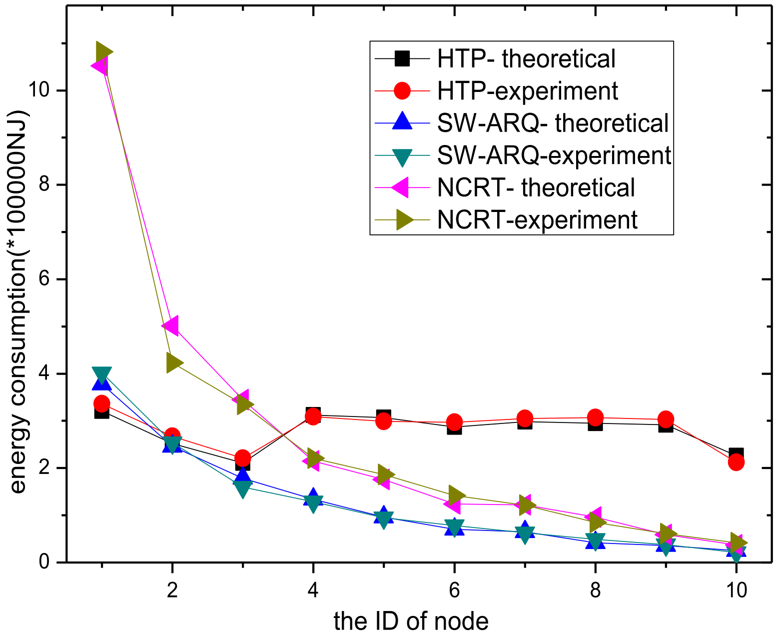

Fig. 4. The energy consumption for each node ($p = 0.5$, $p_e = 70\%$).

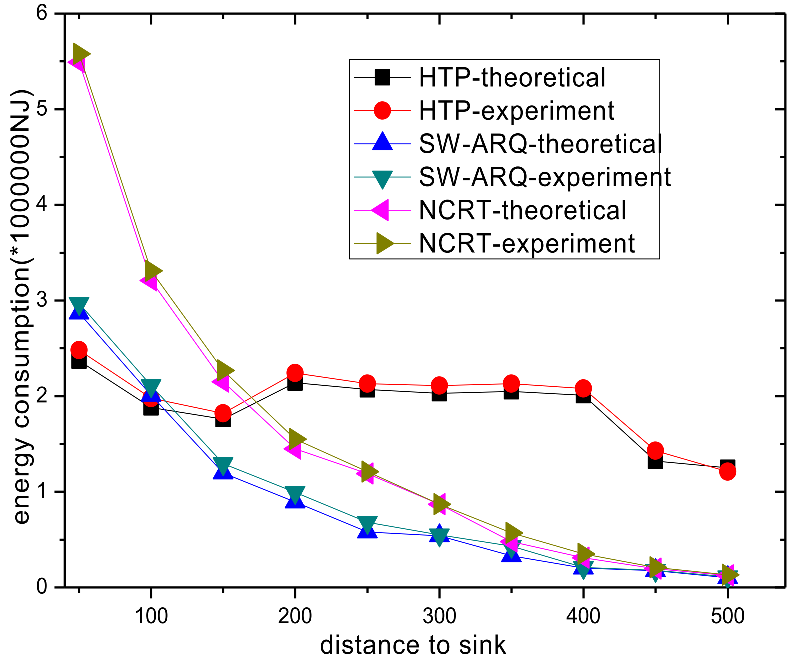

Fig. 5. The energy consumption for each node ($p = 0.5$, $p_e = 70\%$).

6.2. Network lifetime

Fig. 6 shows the network lifetime comparison in case that the network link loss rate is 50% and the end-to-end reliability are 50%, 70% and 90%, respectively. According to the comparison of the graph, HTP method proposed by us can have a higher network lifetime. Fig. 7 shows the network lifetime comparison in case that the end-to-end reliability is greater than or equal to 70%, and the network link loss rate is 0.1, 0.3 and 0.5, respectively. As can be seen from the graph, HTP protocol still has a higher network lifetime. Therefore, both under the same link loss rate or the same reliability, HTP approach still have a higher network lifetime than the other two methods. Thus, HTP approach which we proposed is better.

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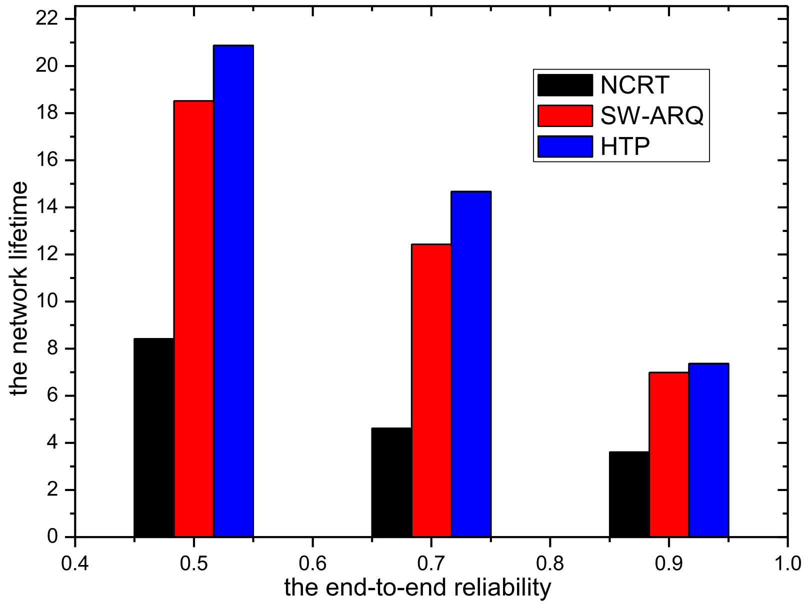

Fig. 6. The network lifetime under different mechanism ($p = 0.5$).

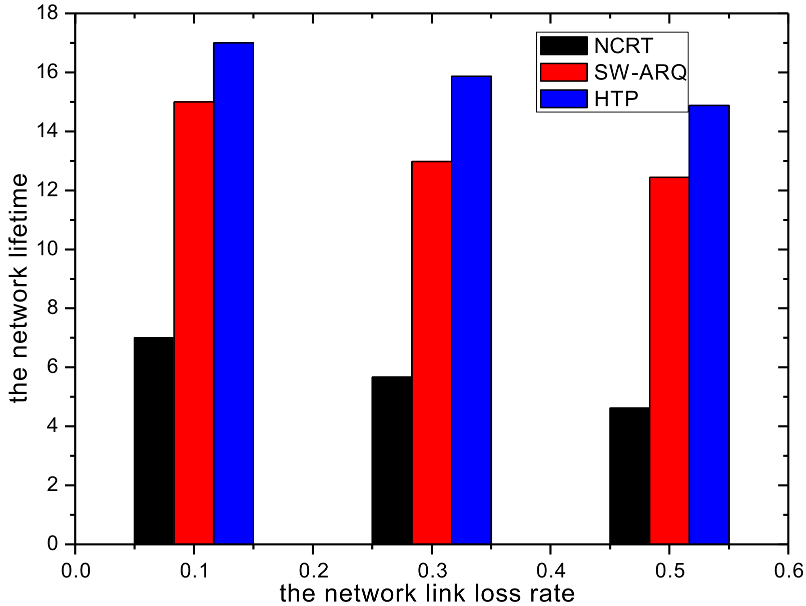

Fig. 7. The network lifetime under different mechanism ($p_e = 70\%$).

6.3. Reliability

Fig. 8 shows the contrast of end-to-end reliability under three different methods in linear network, and Fig. 9 shows the same comparison in planar network. The prerequisite for comparison is under the same lifetime. No matter in the linear or the planar network, with the increase of link loss rate, the end-to-end reliability decreases. But the end-to-end reliability of HTP approach is higher than the other two methods all the time. So, the HTP approach which we proposed can improve the network reliability effectively, thus improving the whole network performance.

6.4. Delay

Fig. 10 shows the contrast of the delay under different link loss rates in linear network, and Fig. 11 shows the same comparison in planar network. The prerequisite for comparison is under the same reliability. Similarly, the prerequisite for

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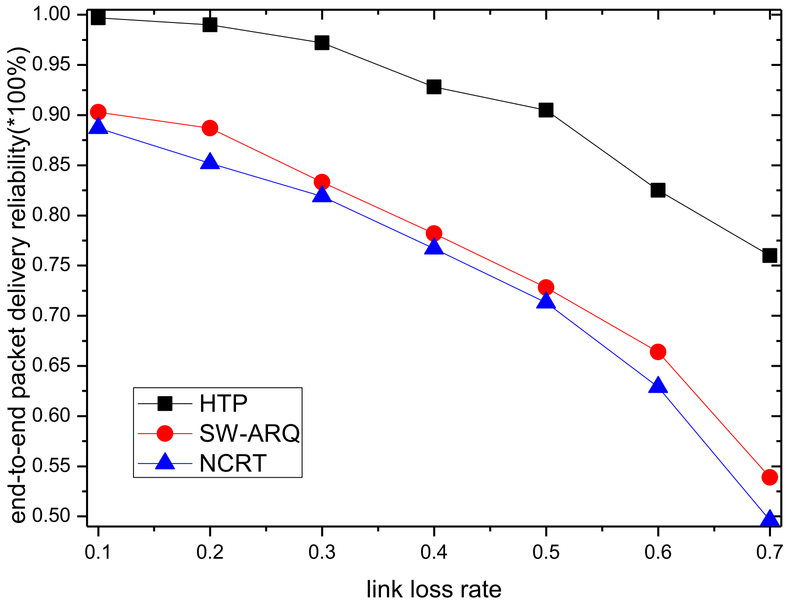

Fig. 8. The end-to-end reliability under the same lifetime in the linear network.

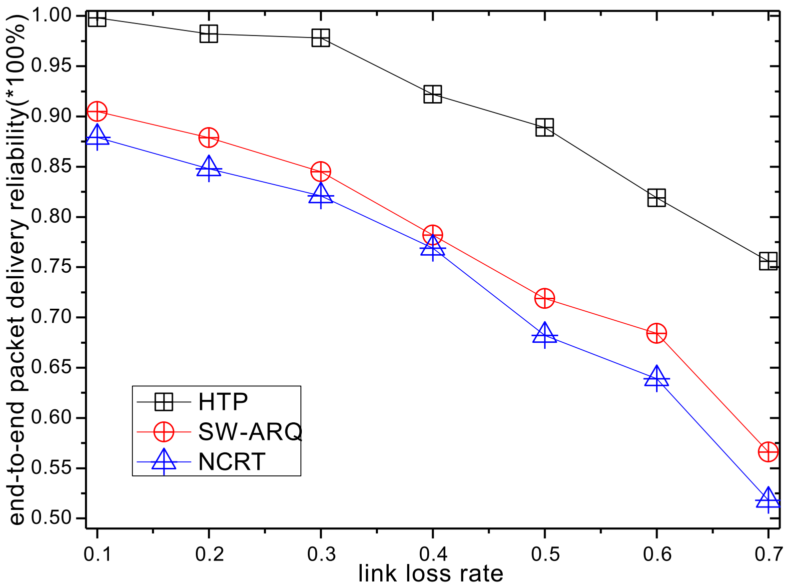

Fig. 9. The end-to-end reliability under the same lifetime in the flat network.

Fig. 12 and Fig. 13's comparison is under the same lifetime. From the figure, with the increase of the link loss rate, the delay increases. But the delay of SW-ARQ protocol increases rapidly, and the other two methods' delay increase slowly. The delay of HTP approach is slightly greater than the delay of NCRT approach, but is far less than the delay of SW-ARQ protocol. For HTP, integrated its contribution to the network, this increase of delay is negligible.

7. Conclusion

Industrial wireless sensor networks have drawn much attention by researchers, and the network performance, such as network lifetime, energy efficiency, the end-to-end reliability and delay are all the key issues for it. But they are also restricted to each other, and it is difficult to optimize them simultaneously. In this paper, we proposed a hybrid transmission protocol (HTP) to maximize the network lifetime with reliability guaranteed for WSNs. The proposed scheme can attain a high end-to-end reliability, long network lifetime and high energy efficiency with a little longer delay as a price. What's

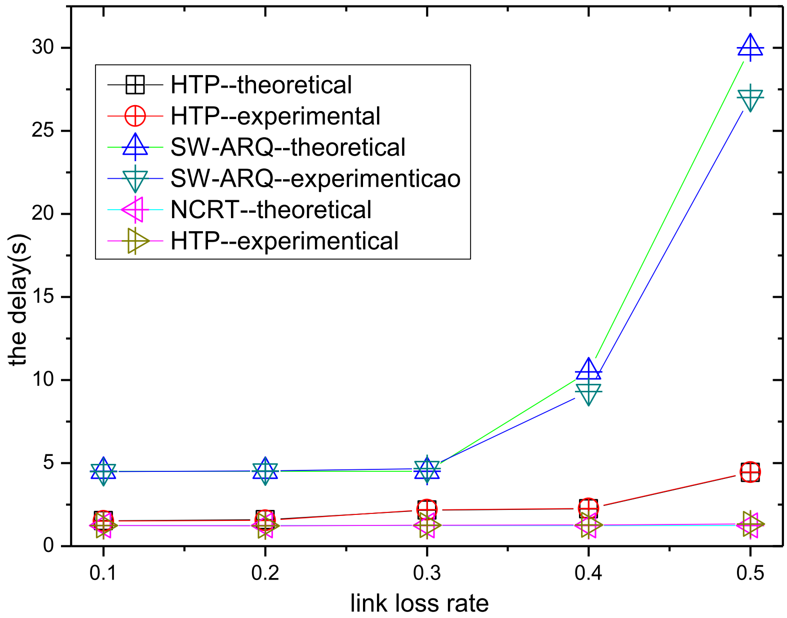

Fig. 10. The delay under different mechanism ($p_e \geq 70\%$, planar network).

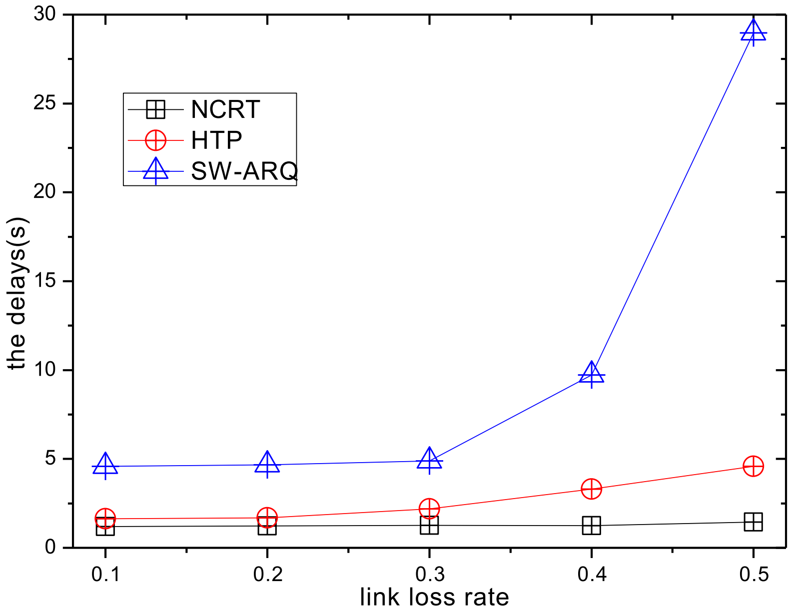

Fig. 11. The delay under different mechanism ($p_e \geq 70\%$, linear network).

more, the HTP scheme can be easily adopted by vary network coding based data collection scheme which provides an easily implementable solution for reliable and high lifetime data collection in WSNs. We use Omnet++ network simulator for simulation, and theoretical analysis to evaluate the performance of the proposed scheme. Through our research, the evaluation results indicate that: for HTP approach, under the same reliability, compared with SW-ARQ protocol, the network lifetime can be improved by 15%–30%; compared with NCRT approach, the lifetime can be improved by over 100%. Similarly, under the same lifetime, compared with the other two methods, HTP approach can improve the reliability by 12%–45%. In terms of delay, the delay of HTP is far less than the delay of SW-ARQ protocol, but it is slightly higher than the delay of NCRT approach. When the link loss rate is small, the delay of HTP is almost equal to the delay of NCRT approach. Comprehensive analysis showed that HTP approach is an effective data collection scheme.

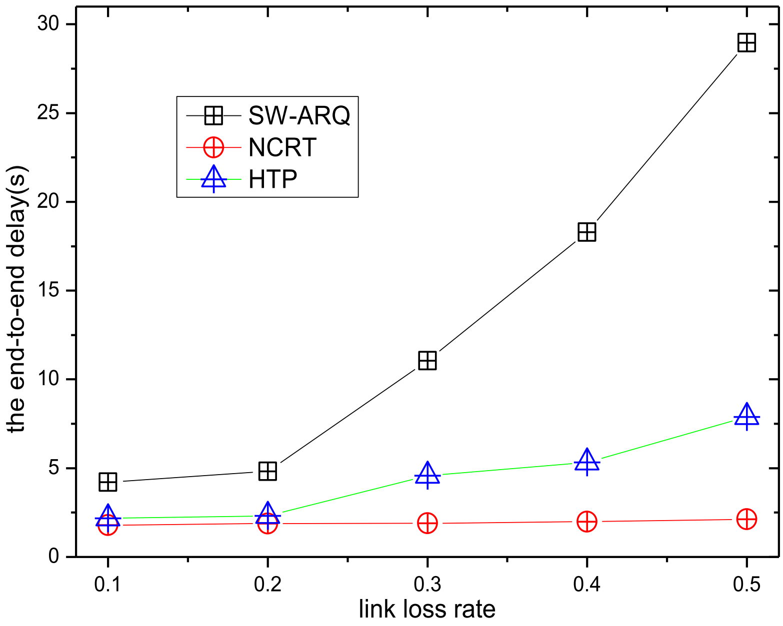

Fig. 12. The delay under the same lifetime (linear network).

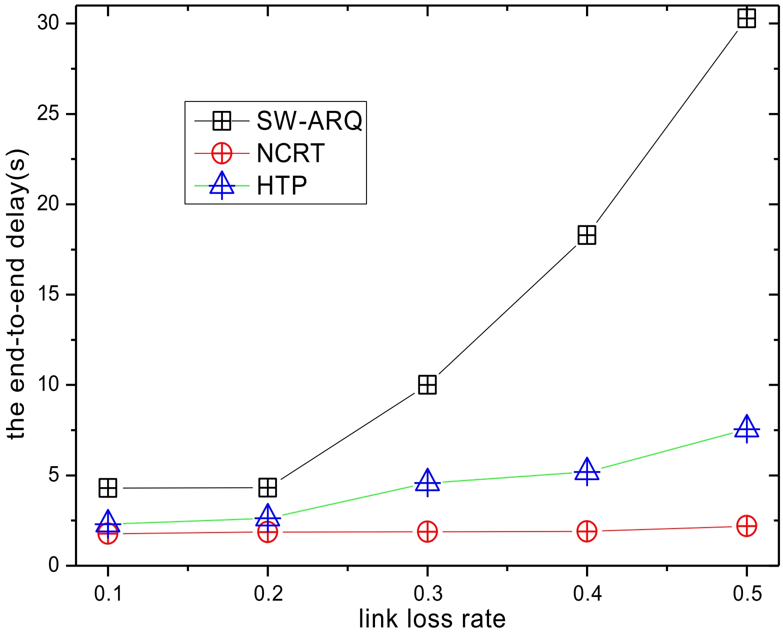

Fig. 13. The delay under the same lifetime (planar network).

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