Analysis of communication reliability in NarrowBand-IoT oriented wireless sensor networks

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Abstract
The unstable link quality in wireless sensor networks (WSNs) directly affects the success rate of data transmission. The retransmission mechanism is one of the commonly used methods to solve this problem. However, too many retransmissions could lower the communication efficiency. Therefore, to reduce retransmissions while guaranteeing the communication reliability in WSNs, this study introduces the NarrowBand Internet of Things (NB-IoT) technology, and builds a network including both sensor and NB-IoT nodes. The NB-IoT node is designed to support both the radio frequency and the NarrowBand communication modes; thus it can communicate with both sensor nodes and NB-IoT base stations. Further, the communication reliability metrics considering both the link quality and the number of retransmissions in different communication modes are defined, based on which, an adaptive communication reliability algorithm is proposed to switch the communication modes of nodes. The simulation results verify that the proposed algorithm can achieve higher success rate with less end-to-end delay and flexibly control the cost on NB-IoT communication.

1 | INTRODUCTION

With the fast spread of communication technology, wireless sensor networks (WSNs) that can be self-organised and deployed randomly in unattended regions have a wide range of applications in Internet of Things (IoT) such as infrastructure construction, environmental monitoring, city surveillance, industrial control, and so forth [1].

In WSNs, link quality is a key factor affecting the network reliability. Poor link quality would cause dynamic change of packet loss and a large number of retransmissions [2], as well as asymmetric links which imposes significant impacts on the routing protocols [3].

In fact, the instability of wireless links is affected by many factors such as fading [4], shadowing and temperature [5]. Retransmission is the most commonly used technique to
improve it [6]. For example, in [7], a reliability model is designed to calculate the number of retransmissions by rigorous mathematical derivations. Authors in [8] analysed local and global network reliability with retransmissions based on the definitions of the betweenness centrality and dependency degree. In [9], a retransmission scheme was adopted to improve the network reliability in opportunistic communication. In [10], the number of retransmissions can be determined by the delay constraint of the applications.

The retransmission schemes are beneficial for improving communication reliability, but too many retransmissions could impair the communication efficiency. To address this issue, we introduce the NarrowBand IoT (NB-IoT) into WSNs to guarantee highly reliable communication. The NB-IoT technology has many advantages such as wide-area coverage, low power consumption, low-cost terminal, high reliability, high carrier-class network security [11, 12], and so forth. NB-IoT systems have been widely used in wireless applications such as shared bicycle, smart city, utilities management [13], smart parking system [14], smart grid [15], and service platform NB-IoTtalk [16], and so forth.

In NB-IoT systems, the NB-IoT uplink performance is crucial for communication reliability. In [17], the authors pointed out that the uplink of NB-IoT uses single-carrier frequency-division multiple access and described the packet error rate calculations for NB-IoTs by utilising symbol error rate. In some special scenarios, the quality of the direct link between NB-IoT nodes and base station (BS) may not satisfy the quality requirement for data transmission. For example, the NB-IoT system may fail to establish a link at all because of the severity of the interference presented by radar, or in the low power domain of the BS [18]. By adopting the retransmission scheme, the receiver processing gain and the chance of successful data transmission can be increased for uplink transmissions [19, 20].

Further, to avoid unnecessary cost incurred by mass retransmissions, the D2D relay has been proposed as a novel mechanism to effectively promote the network reliability of NB-IoT systems. In [21], vehicle-based relays are adopted to assist the NB-IoT communication, and rigorous mathematical analysis supported with comprehensive system level evaluations is provided to reveal their effects on connection reliability, transmission latency, and energy efficiency. Authors in [22] disclosed that D2D communication can be adopted as a routing extension to NB-IoT systems, which enables two-hop routes between NB-IoT user equipments and the serving BS via NB-IoT relays. In [23], the authors presented a social-aware relay selection scheme, in which the short-range low-power D2D communications are preferred, through encouraging long-range transmissions to be separated into multi-hop D2D transmissions, so that more opportunities can be created to increase spectrum utilisation and network reliability via cooperative communication.

The combination of different communication modes in a network can enhance the communication reliability [24], but it brings a problem of how to control the switching between the communication modes. The study in [25] provided a path selection algorithm that schedules data flows to NB-IoT slots when the TDMA slots are not available considering both time constraints and system costs, but it neglects the link reliability while switching the communication modes and lacks of retransmission control. In a heterogeneous network, to pursue a high success rate of data transmission with less delay, the communication reliability related to both the link reliability and number of retransmissions is a crucial precondition for communication mode switching.

In this study, the NB-IoT technology is introduced into WSNs to improve the communication reliability where the NB-IoT nodes are those nodes equipped with NB-IoT modules that can communicate with both sensor nodes and NB-IoT BSs. Besides, the NB-IoT nodes can communicate with each other and support both radio frequency (RF) and narrow band (NB) communication modes. The main contributions of this study are listed as follows:

We established a network model where the NB-IoT node can communicate with both the sensor nodes and the BS by adopting RF and NB communication modes, respectively.

We calculated the communication reliability metrics related to both the link quality and the number of retransmissions in different communication modes of nodes.

We developed an adaptive communication algorithm in which each node chooses its communication mode and next relay node according to the proposed communication reliability metrics of its neighbouring nodes.

The rest of this study is organised as follows. Section 2 provides the network model. Section 3 gives the detailed design of the proposed communication algorithm. The performance evaluation is presented in Section 4. And the study is concluded in Section 5.

## 2 | NETWORK MODEL

In our network model, a set of sensor nodes and a gateway (GW) are randomly deployed in a sensing area covered by a BS, and the GW is the data forwarding destination for each sensing node.

In the network, a certain amount of nodes equipped with NB-IoT modules are called NB-IoT nodes, which can communicate with both the sensor nodes and the BS via RF and NB communication modes, respectively. The NB-IoT nodes are preferred to transmit data via the RF communication mode, since too many transmissions through the NB communication mode could increase the network cost.

Data can be forwarded by sensor nodes in a multiple-hops way, or transmitted by NB-IoT nodes through the BS to the GW, where the communication radiuses for sensor nodes and NB-IoT nodes are \( r \) and \( R (r << R) \), respectively.

For sensor nodes in the network, a typical path is composed of multiple hops of sensor nodes via the RF communication mode, the intermediate sensor nodes between the source and destination on a path can act as relay nodes.

As the number of hops between nodes increases, the communication reliability will decrease. Compared with RF communication mode, the node using NB communication mode could build a one-hop direct link between itself and the BS. The high link quality between NB-IoT nodes and BS could improve the
communication reliability, and the link quality between BS and GW is assumed to be 1.

Furthermore, in case of the direct link between a NB-IoT node and the BS failures due to dynamic interferences, data uploading from the NB-IoT node to the BS can be extended to at most two hops, that is, the NB-IoT node will transmit its data to a nearby NB-IoT node first, which then relays the data to the BS, and this kind of two-hop route consists of a D2D RF link and a cellular NB link.

As shown in Figure 1, the path $P1 (a\rightarrow b\rightarrow c\rightarrow GW)$ represents that sensor node $a$ can establish its multi-hop path to GW by means of cooperation among sensor nodes using the RF communication mode. The path $P2 (d\rightarrow e\rightarrow BS\rightarrow GW)$ shows that sensor node $d$ first selects the NB-IoT node $e$ as its next hop, and then $e$ builds a direct link between itself and BS by adopting the NB communication mode. Moreover, in case that the direct link between NB-IoT node $f$ and BS fails, $f$ transmits data to a nearby NB-IoT node $g$ first by using the RF communication mode, then $g$ relays the data to BS. This kind of two-hop path consists of a D2D RF link from $f$ to $g$ and a cellular NB link from $g$ to BS, so that $P3 (f\rightarrow g\rightarrow BS\rightarrow GW)$ from node $f$ to GW can be established.

In this study, each node switches its communication modes according to the communication reliability of its neighbouring nodes. To define and calculate different communication reliability metrics in different communication modes, we consider both the link quality and number of retransmissions, between sensor nodes, between NB-IoT nodes, and between NB-IoT nodes and BS.

3 | COMMUNICATION RELIABILITY ANALYSIS

This section presents the detailed analysis of communication reliability, which includes the definition of the reliability metrics and the design of adaptive communication reliability algorithm.

3.1 | Communication reliability metrics

This study mainly considers the link quality and the number of retransmissions between the neighbouring nodes with different communication modes to design specific communication reliability metrics. We denote the link quality between a sender and a receiver by $p$. When the sender is required to retransmit packets to the receiver only once, the communication reliability between them is computed by:

$$R(p, 1) = p^1$$

(1)

Based on Equation (1), a target reliability $\phi$ is set to represent the threshold of communication reliability between a sender and a receiver. If the communication reliability $R(p, 1)$ exceeds $\phi$:

$$R(p, 1) \geq \phi$$

(2)

It means that the sender does not need to retransmit packets to the receiver twice and more. If $R(p, 1) < \phi$, it indicates that the sender needs to retransmit packets to the receiver more than once to improve the communication reliability.

As for a sender and a receiver, when the given threshold for the number of retransmissions is $N_\phi$, the communication reliability between them can be computed by:

$$R(p, N_\phi) = 1 - (1 - p)^{N_\phi}$$

(3)

According to the different communication modes of nodes in the network, we can analyse and design different communication reliability metrics between the neighbouring sensor nodes, between the NB-IoT nodes and BS, and between the neighbouring NB-IoT nodes.

3.1.1 | Communication reliability between neighbouring sensor nodes

Based on Equation (3), it can be inferred that the communication reliability can be improved by increasing the link quality or the number of retransmissions. Therefore, to analyse the communication reliability between the neighbouring sensor nodes, we provide the methods to evaluate the actual link quality and number of retransmissions between them, respectively.

Usually, the link quality is estimated to measure the transmission capacity of wireless links between a sender and a receiver. It has a significant impact on the network performance, including latency, power consumption, and communication reliability.

The commonly used link quality evaluation metrics include: Packet reception rates (PRR), link quality indication (LQI), and received signal strength indication (RSSI). The PRR between a sender and a receiver is the ratio of the number of packets successfully received by the receiver to the number of packets sent by the sender over a period. The LQI is an estimate of energy detection value, and the RSSI reflects the signal to noise ratio.

To estimate the link quality between the neighbouring sensor nodes in the network, first, we analyse the relations between PRR and LQI. In fact, when the LQI value of a link is less than a small threshold, the wireless link will be unable to communicate. When the LQI of a link exceeds a great threshold, the PRR of the wireless link will remain stable. And if the LQI of a link
ranges from the small threshold to the great threshold, as the LQI increases, the PRR of the link gradually increases and they have an approximately linear relationship. Therefore, the PRR can be calculated as follows:

$$R(p, 1) = \begin{cases} 0, & LQI < \eta_{LQI} \\ \alpha LQI + \beta, & \eta_{LQI} \leq LQI < k_{LQI} \\ 100, & LQI \geq k_{LQI} \end{cases}$$

(4)

where $\eta_{LQI}$ is the upper limit of LQI with poor link quality, $k_{LQI}$ is the lower limit of LQI with good link quality, $\alpha$ and $\beta$ are constants that express the relationship between PRR and LQI.

Second, we analyse the relationship between RSSI and LQI, where the content of the sampled message is used to express the energy intensity of the message and the bit error rate of the message. As the LQI of a link increases, the RSSI of the link also increases, which further improves the link quality. It is worth noting that the RSSI increases faster than LQI. Thus, we give the description as follows:

$$PRR = \begin{cases} \text{unacceptable,} & \text{abs}(C_{RSSI}) \geq \lambda \\ \text{acceptable,} & \text{abs}(C_{RSSI}) < \lambda \end{cases}$$

(5)

where $\lambda$ is a threshold that is the ratio between the average value of RSSI ($\text{Aver}_{RSSI}$) and average value of LQI ($\text{Aver}_{LQI}$). To facilitate the link quality evaluation, the RSSI can be taken as an absolute value since it is always negative. In addition, $\sigma_0$ is the PRR requirement in the network, $C_{RSSI}$ and $C_{LQI}$ are the corresponding values of RSSI and LQI when $\text{PRR} = \sigma_0$, abs$(C_{RSSI})$ is the absolute value of $C_{RSSI}$.

Based on the above analysis, the link evaluation model can be constructed in Equation (6):

$$\begin{cases} PRR \geq \sigma_0 \\ PRR = \alpha LQI + \beta \\ \text{abs}(C_{RSSI}) = \lambda C_{LQI} \end{cases}$$

(6)

Each message transmitted in the network contains RSSI and LQI, therefore, in this model, the link change can be reflected in real-time. The estimated link quality between the neighboring sensor nodes $PSN_{N-SN}$ can be computed by:

$$PSN_{N-SN} = \text{abs}\left[\left(\frac{1}{n} \cdot \sum_{i=1}^{n} RSSI\right) / \left(\frac{1}{n} \cdot \sum_{i=1}^{n} LQI\right)\right]$$

(7)

In Equation (7), $n$ is the number of the sent packets in the process of statistics.

According to Equation (7), the link quality will be assumed to satisfy the given target reliability requirement if one of the following conditions is satisfied in Equations (8), (9) and (10) as follows:

Case 1:

$$\text{LQI} \geq k_{LQI}$$

(8)

Case 2:

$$\text{RSSI} \geq \psi_{RSSI}$$

(9)

where $\psi_{RSSI}$ is the lower limit of the RSSI with good link quality.

Case 3:

$$\begin{cases} \text{abs}(\text{Aver}_{RSSI}) / \text{Aver}_{LQI} \leq \alpha \times \text{abs}(\lambda C_{LQI}) / (\sigma_0 - \beta) \\ \eta_{LQI} \leq \text{LQI} < k_{LQI}, \ \zeta_{RSSI} \leq \text{RSSI} < \psi_{RSSI} \end{cases}$$

(10)

where $\zeta_{RSSI}$ is the lower limit of the RSSI with poor link quality.

The proof process for Equation (10) is given as follows: Based on Equation (5), when $\text{abs}(C_{RSSI}) / C_{LQI} \leq \lambda$, the link quality is reliable, thus, we have:

$$\text{abs}(\text{Aver}_{RSSI}) / \text{Aver}_{LQI} \leq \lambda$$

(11)

According to Equation (6), if the link quality between nodes maintains a high reliability, the relation between $\text{Aver}_{RSSI}$ and $\text{Aver}_{LQI}$ has to satisfy that:

$$\text{abs}(\text{Aver}_{RSSI}) / \text{Aver}_{LQI} \leq \text{abs}(C_{RSSI}) / C_{LQI}$$

(12)

By combining $PRR = \sigma_0$ with Equation (6), the PRR can be formulated as:

$$PRR = \alpha C_{LQI} + \beta = \sigma_0$$

(13)

Here

$$C_{LQI} = (\sigma_0 - \beta) / \alpha$$

(14)

Based on Equations (6) and (12), we have:

$$\text{abs}(\text{Aver}_{RSSI}) / \text{Aver}_{LQI} \leq \alpha \times \text{abs}(\lambda C_{LQI}) / (\sigma_0 - \beta)$$

(15)

According to Equation (10), the link quality is unreliable when $\text{LQI} < \eta_{LQI}$ or $\text{RSSI} < \zeta_{RSSI}$, the retransmission scheme is used, and increasing the number of retransmissions can improve the communication reliability.

By combining Equations (3) with (7), the estimated number of retransmissions $N_{PSN_{N-SN}}$ between the neighboring nodes can be given by:

$$\phi \geq PSN_{N-SN}$$

$$N_{PSN_{N-SN}} = \log_{1 - PSN_{N-SN}} (1 - \phi)$$

(16)
By combining Equations (3, 7) and (16), the communication reliability \( R_{SN-SN} \) between the neighbouring sensor nodes via the RF communication mode can be computed by:

\[
\begin{align*}
R_{SN-SN} &= 1 - (1 - R_{SN-SN})^\phi \\
p_{SN-SN} &= ab \left( \frac{1}{n} \cdot \sum_{i=1}^{n} R_{RSSI} \right) / \left( \frac{1}{n} \cdot \sum_{i=1}^{n} L_{QI} \right) \\
N_{SN-SN} &= \left| \log_{10}(1 - p_{SN-SN}) \right| (1 - \phi) \\
\phi &\geq p_{SN-SN}
\end{align*}
\]

(17)

### 3.1.2 Communication reliability between NB-IoT nodes and BS

As for the communication reliability between NB-IoT nodes and BS, we define that the link quality \( P_{NB-BS} \) between NB-IoT nodes and BS as a function of signal to Interference plus noise ratio (SINR). The SINR is the ratio of the strength of the received useful signal to the strength of the received interference signal (including noise and interference). The greater the SINR the better the quality of the wireless channel which is calculated by:

\[
p_{NB-BS} = f (\psi (d))
\]

(18)

It is worth noting that the function \( f (\psi (d)) \) depends on the path loss, wireless channel and so on, and \( d \) is the given distance between NB-IoT nodes and BS.

In Equation (18), \( \psi (d) \) can be expressed as a Gaussian random variable:

\[
\psi (d) = N (\beta (d, \eta), \sigma)
\]

(19)

where \( \sigma^2 \) is the variance of the Gaussian random variable, and the mean value \( \beta (d, \eta) \) of the Gaussian random variable is calculated as:

\[
\beta (d, \eta) = P_t - P_{L} (d_0) - 10 \eta \log_{10} (d/d_0) - P_a
\]

(20)

where \( d_0 \) is the reference distance, it also can be described as SINR, the attenuation of the wireless signal is expressed as path loss \( P_{L} (d) \), \( P_{L} (d) \) is the ratio of transmit power \( P_t \) to received power \( P_r \), \( \eta \) is the path loss constant.

By using the lognormal channel model, the SINR is given by:

\[
\text{SINR} = P_t - P_{L} (d_0) - 10 \eta \log_{10} (d/d_0) + X_0 - P_a
\]

(21)

where \( P_{L} (d_0) \) denotes the received signal strength of \( d_0 \), \( P_a \) is the interference power in the channel, and \( X_0 \) follows lognormal.

When the direct link between a NB-IoT node and BS is unstable, the retransmission scheme is used to improve the communication reliability, and the estimated number of retransmissions \( N_{NB-BS} \) between them is calculated as follows:

\[
N_{NB-BS} = 2^{\ln \log_{10}(1 - P_{NB-BS})} \frac{(1 - \phi)}{\ln 2}
\]

(22)

By combining Equations (3, 19) and (22), the communication reliability \( R_{NB-BS} \) between the NB-IoT node and BS by using the NB communication mode can be calculated as follows:

\[
\begin{align*}
R_{NB-BS} &= 1 - (1 - P_{NB-BS})^\phi \\
p_{NB-BS} &= f (\psi (d)) \\
N_{NB-BS} &= 2^{\ln \log_{10}(1 - P_{NB-BS})} \frac{(1 - \phi)}{\ln 2} \\
\phi &\geq p_{NB-BS}
\end{align*}
\]

(23)

### 3.1.3 Communication reliability between neighbouring NB-IoT nodes

The calculation of link quality between the neighbouring NB-IoT nodes is the same as that between the sensor nodes in Equation (7).

Based on the above analysis, by combining Equations (3), (7) and (22), the communication reliability \( R_{NB-NB} \) and the estimated number of retransmissions \( N_{NB-NB} \) between the neighbouring NB-IoT nodes can be calculated as follows:

\[
\begin{align*}
R_{NB-NB} &= 1 - (1 - P_{NB-NB})^\phi \\
p_{NB-NB} &= ab \left( \frac{1}{n} \cdot \sum_{i=1}^{n} R_{RSSI} \right) / \left( \frac{1}{n} \cdot \sum_{i=1}^{n} L_{QI} \right) \\
N_{NB-NB} &= 2^{\ln \log_{10}(1 - P_{NB-NB})} \frac{(1 - \phi)}{\ln 2} \\
\phi &\geq p_{NB-NB}
\end{align*}
\]

(24)

### 3.2 Adaptive communication reliability algorithm

In this section, an adaptive communication reliability algorithm is designed to switch different communication modes of nodes, that is, RF and NB modes, with considering both the link quality and the number of retransmissions.

There are two cases for a node to select relay nodes when using the adaptive communication reliability algorithm:

Case 1: If the current node is a sensor node, it will select a neighbour with the greatest communication reliability and taking less RF hops to the GW than itself. As shown in Figure 2(a), the neighbour node \( b \) has the greatest communication reliability \( R_{b-a} \) and taking less RF hops to the GW than node \( a \) in all neighbours of sensor node \( a \), thus, node \( b \) is selected as the next relay node.
Figure 2: The adaptive communication mode switching

Case 2: If the current node is a NB-IoT node, it will select a neighbour with the greatest communication reliability and taking less RF hops to the GW than itself in its sensor neighbours. As shown in Figure 2(b), the neighbour $e$ has the greatest communication reliability $R_{SN-e}$ and taking less RF hops to the GW than node $d$, further if $N_{SN-e}$ is not greater than the given threshold $N_{\phi}$, node $e$ will be selected as the next relay node. If $N_{SN-e}$ cannot satisfy the requirement of $N_{\phi}$, node $d$ will build a direct link between itself and the BS via the NB communication mode and calculate the communication reliability $R_{NB-BS}$ as shown in Figure 2(c).

Furthermore, as shown in Figure 2(d), in case that the communication reliability of the direct link between NB-IoT node $d$ and the BS also cannot satisfy the requirement of $N_{\phi}$ due to dynamic interferences, the NB-IoT node $d$ first transmits data to a nearby NB-IoT node $f$ with the greatest communication reliability $R_{NB-f}$, which then relays the data to the BS.

The detailed design of the adaptive communication reliability algorithm is shown in Algorithm 1.

From Equation (3), it can be seen that the number of retransmissions, link quality and communication reliability are interrelated and influence each other. The switching method of communication modes in the proposed adaptive communication reliability algorithm can indirectly limit the link quality of the selected communication mode via directly controlling the number of retransmissions and communication reliability; thus it can not only promote the success rate but also reduce the transmission delay.

4 | PERFORMANCE EVALUATION

Our simulations are performed with MATLAB R2014b. The parameters in the simulations are shown in Table 1.

There are two kinds of network deployment in the simulations, as shown in Figures 3(a) and 3(b), in which the numbers of sensor nodes are set as 500 and 1500, respectively. In each kind of network deployment, the pre-set number of sensor nodes, 80 NB-IoT nodes, one BS and one GW are deployed randomly in an area of $500 \times 500$ m$^2$. In addition, in Equation (3), $p$ is set to 0.5, $\phi$ is varied from 0.5 to 0.95 and $N_{\phi}$ can be calculated according to $p$ and $\phi$.

In the simulations, we compare the proposed method, the path selection algorithm in [25] (denoted by method 2) and ZigBee protocol (denoted by method 1) where the sensor nodes communicate with each other only via RF mode, on performance of success rate, end-to-end delay and cost on NB-IoT communication, respectively.
4.1 Success rate

The success rate is defined as the percentage of packets that are successfully delivered from sensor nodes to the GW. The success rate of the three methods are compared in the network deployments of Figures 3(a) and 3(b), and the simulation results are shown in Figures 4 and 5.

In both of Figures 4 and 5, the proposed method has higher success rate than methods 1 and 2. This is because nodes in method 1 communicate with each other only via the RF communication mode and have no alternative communication mode when their link quality are unreliable; nodes in method 2 can switch RF communication mode to NB-IoT communication mode when the RF communication mode is not available but without considering the link quality; and nodes in the proposed method take the communication reliability as the condition of communication mode switching and, thus, can effectively reduce the transmission failures because of unreliable link quality.

Figures 4 and 5 also show that with increase of \( \phi(N_\phi) \), the success rate of the proposed method remains stable. This is because when \( \phi(N_\phi) \) is small, the success rate of the proposed method can be maintained by communication mode switching, and when \( \phi(N_\phi) \) is great, the success rate of the proposed method can be maintained by retransmission.
From the comparison between results of Figures 4 and 5, it is can be seen that, with increase of number of sensor nodes, there is only slight change for the success rate of the proposed method, but the success rate decrease of methods 1 and 2 are obvious. The significant success rate drop of method 1 also results from that it has no alternative communication mode. The success rate change of method 2 can be explained from the network deployment of Figure 3(b) where the greater number of sensor nodes brings lower link quality, but method 2 cannot switch the communication modes of nodes according to the communication reliability.

4.2 End-to-end delay

In this section, we quantify the end-to-end delay, which is measured as the average time of sending packets from the sensor nodes to the GW. The end-to-end delay of the tree methods are compared in the network deployments of Figures 3(a) and 3(b), and the simulation results are shown in Figures 6 and 7.

In Figures 6 and 7, the end-to-end delay of the proposed method is less than that of other methods. This result has following reasons: (1) The proposed method can avoid unreliable transmissions via communication mode switching and communication reliability control; (2) the proposed method can reduce the number of retransmissions by setting $\phi (N_\phi)$.

Figures 6 and 7 also show that with increase of $\phi (N_\phi)$, the end-to-end delay of the proposed method increases. This is because in the proposed method, when $\phi (N_\phi)$ is smaller, nodes will be limited to perform less retransmissions and there will be more nodes using the NB-IoT communication mode, thus the end-to-end delay is less.

From the comparison between results of Figures 6 and 7, it is can be seen that with increase of number of sensor nodes, the end-to-end delay of all methods increase. This is because more sensor nodes bring lower link quality and more retransmissions.

4.3 Cost on NB-IoT communication

In this section, we quantify the cost on NB-IoT communication, which is measured as the ratio of packets sent from the sensor nodes to the GW via NB-IoT communication mode. The cost on NB-IoT communication of the proposed method and method 2 are compared in the network deployment of Figures 3(a) and 3(b), and the simulation results are shown in Figures 8 and 9.

In Figures 8 and 9, when $\phi (N_\phi)$ is small, the proposed method has more cost on NB-IoT communication than method 2, but when $\phi (N_\phi)$ is great, the proposed method has less cost on NB-IoT communication than method 2. This can be explained by that, when $\phi (N_\phi)$ is small, the limitations
to retransmission and link quality in the proposed method are stricter than those in method 2, and thus there are more nodes using the NB-IoT communication mode in the proposed method. Conversely, when $\phi(N_2)$ is great, the limitations to retransmission and link quality in the proposed method are lesser than those in method 2, thus there are less nodes using the NB-IoT communication mode in the proposed method. It also can be seen that the proposed method can flexibly control the cost on NB-IoT communication by adjusting $\phi(N_2)$.

From the comparison between results of Figures 8 and 9, it is can be seen that with increase of number of sensor nodes, the cost on NB-IoT communication in both methods increase. This is also because more sensor nodes bring lower link quality and more retransmissions, thus more nodes use the NB-IoT communication mode.

5 | CONCLUSION

In this study, we introduce the NB-IoT technology into WSNs to reduce the number of retransmissions while guaranteeing the network communication reliability. By defining different communication reliability metrics in different communication modes of nodes, an adaptive communication reliability algorithm is proposed to improve the communication reliability. Both theoretical and experimental analysis have been provided to validate the flexibility and effectiveness of the proposed algorithm, in addition, simulation results demonstrate that the proposed algorithm outperforms the existing methods both in network reliability and network efficiency.

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