A Rate Adaptation Scheme with Enhanced Loss Differentiation for LoRaWAN Communications

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Abstract. As an emerging technology for long-range communication, LoRaWAN provides several data rates for transmission and the choice of data rates will affect the communication distance and the link quality. So how to allocate this communication resource in a network with a large amount of devices is a challenge. In this paper, we classify the reasons of packets loss as channel attenuation and data collision and then propose a rate adaptation scheme with enhanced loss differentiation. The proposed scheme can estimate two packet loss rates according to the channel attenuation probability model and data collision probability model respectively. And the selection of communication data rate is given by the balance of probabilities. Simulation results indicate that the proposed scheme is better than ADR and EXPLoRa on Data Extraction Rate and Goodput.

1. Introduction

THE interest of people towards Low-power wide-area networks (LPWAN) grew significantly, such as LoRaWAN and NB-IoT, all of them can provide large-scale and low-power networks for Internet of Things [1]. In this paper we specifically focus on LoRaWAN, which has the characteristics of easy deployment, low power consumption and long distances[2].

LoRa modulation supports multiple data rates through the selection of different Spreading Factors (SF), BandWidth (BW) and Code Rate (CR) [3]. In general, the larger value of Spreading factors will reduce the bit rate and take longer time to transmit information. At the same time, the signals with different SF are orthogonal to each other, so the data transmission of different SF can hardly collide [4]. In China, LoRaWAN specifies six kind of data rates (i.e., DR0-DR5), which represent six different Spreading factors choices.

LoRaWAN provided an adaptive data rate (ADR) scheme to maintain network connectivity [5]. In ADR, the end-device confirmed the receiving state of the message through the ACKs. There is a problem that ADR does not reflect the conflict status of the network. Once the packet loss is due to conflict, ADR will reduce the data rate and lead to longer transmission delay, so ADR may reduce the transmission efficiency and the throughput of LoRaWAN networks.

There are some studies about LoRaWAN. Firstly, in [6], the authors provided an overview of LoRa and had an in-depth analysis of its functional components. Based on the performance evaluations of physical and MAC layer, it can be found that the network performance will decrease significantly when the link load increase. Bor et al. In [7] provided a link behavior that communication range depend on...
2. System Description

In the actual application environment, the reasons of packet loss not only the channel attenuation, but also the interference between multiple transmission signals. Therefore, it is necessary to consider their impact on packet loss separately. We propose a rate adaptation scheme with enhanced loss differentiation, and it is composed of three parts, namely probability prediction of channel attenuation, probability prediction of data collision, data rate controller. The proposed scheme aim at choosing the data rate in a reliable way.

2.1. Probability Prediction of Channel Attenuation

In order to ensure the accuracy of packet loss probability prediction, a channel attenuation model is established. In general, when the signal is transmitted through the wireless channel, which can be affected by many kinds of fading. So an empirical channel path loss model is adopted in this paper, which composed of a linear path loss model $P_L$ and a lognormal shadowing model $P_S$:

$$PL(d) = P_L + P_S = PL(d_0) + 10\gamma \log_{10}(d / d_0) + X_\sigma$$

(1)

where $d$ is the reference distance, $\gamma$ is the path loss exponent. $PL(d_0)$ is the mean path loss at the distance $d_0$. $X_\sigma$ is a zero-mean normally distribution random variable with standard deviation $\sigma$ for shadowing.

Further, the standard deviation of shadow fading $\sigma$ can be calculated by the deviation of actual measured path loss $P_c(d)$ and expected path loss $P_L(d)$. $P_c(d)$ can be obtained by measuring the received signal strength indicator (RSSI), signal-to-noise ratio (SNR), effective omnidirectional radiation power ($P_{tx}$), and receiving antenna gain (G).

$$P_c(d) = RSSI + SNR + P_t + G$$

(2)

$$\sigma = \text{std}(P_c(d) - P_L(d))$$

(3)

According to the above path loss model, we can obtain the receiving signal strength $P_r(d)$ by transmitting power $P_t$ and antenna gain $G$:

$$P_r(d) = P_t + G - PL(d)$$

(4)

The minimum receiving sensitivity $S_{DR[i]}$ of the receiver at different data rates is introduced as the threshold. The receiver can decode the packet only when the receiving signal intensity of the packet is greater than $S_{DR[i]}$. Therefore, irrespective of conflict, the probability of a packet loss due to channel attenuation is got as follows:
\[ P_f (d, DR[i]) = P\left\{ P_x(d) > S_{\text{DR[i]}}(d) \right\} = P\left\{ P_x + G - PL(d) > S_{\text{DR[i]}}^x(d) \right\} = P\left\{ P_x < S_{\text{DR[i]}}^x + P_p(d) - P_{in} - G \right\} \]

\[ S_{\text{DR[i]}} = -174 + 10 \log(BW) + NF + SNR \]

where \( NF \) is the noise factor of receiver, \( BW \) is bandwidth, \( SNR \) is the adjustable signal to noise ratio at different rates. And \( SNR \) is determined by the data rate, the higher the data rate, the higher the \( SNR \) value, as shown in Table I. Thanks to that \( P_x \) satisfies the logarithmic normal distribution of the zero mean of standard deviation. So the probability is calculated as follows.

\[ P_f (d, DR[i]) = \Phi \left( \frac{\ln\left[ S_{\text{DR[i]}} + P_p(d) - P_{in} - G \right]}{\sigma} \right) \]

where, \( \Phi(*) \) represents the cumulative distribution function of the standard normal distribution.

2.2. Probability Prediction of Data Collision

Owing to the robust modulation scheme used in LoRa, it is possible that concurrent transmission of LoRa can transfer successfully depend on the timing of the interference.

With the study on the interference of LoRa modulation, we can get the following conclusions: first, if the interference starts after the preamble and the RSSI of the interference packet is the same level or lower than the interfered packet, the interference packet will be transmitted correctly. Secondly, if the last six symbols of the transmission preamble are received successfully, the receiver can synchronize with the transmitter correctly. Finally, if the interference signal occurs after the preamble and header transmission of the interfered signal and the interference signal has a higher RSSI, the interfered signal will be received with the wrong payload. So we classifies the interference into the seven situations according to the timing of the signal interference, as shown in Fig. 1.

![Figure 1: The possible cases that interfered packet transmission](image)

Next, in order to have a better quantification of the data conflicts between end-devices, we design the packet loss situation in various cases is shown in Table II. Then we can establish a simulation model to determine the relationship between the number of end-devices and the packet loss rate in the LoRaWAN network with a single gateway.

There are \( g \) end-devices within the range of gateway communication, and each device contains \( n \) packets to be sent in a period of time according to the message rate \( v \). Then generate a vector of data rate used by each transmitter \( DR[i][j] \), which are from 0 to 5 with \( i = 1, \ldots, g \) and \( j = 1, \ldots, n \). and then generate a vector \( CHAN[i][j] \) representing the channel used by the jth packet of the ith node, which have the range of 1 to \( m \) and \( m \) is number of channels that can be used by the current network settings. The selection of channels is random.
Table 2. Status of The Packet For Different Cases

| Situation | The status of the interfered packet receiving |
|-----------|--------------------------------------------|
| 1#        | Received correctly                          |
| 2#        | Lost                                       |
| 3#        | Lost                                       |
| 4#        | Lost                                       |
| 5#        | Lost                                       |
| 6#        | Lost                                       |
| 7#        | Received correctly (Interferer RSSI <= Interfered RSSI) |
|           | Lost (Interferer RSSI > Interfered RSSI)    |

To determine the state of the conflict, the following operations will be continued:
1) For each packet \(i\), iterate all possible interference \(k\) (\(k \leq g\) and \(k \neq i\))
2) If \(\text{DR}[i][j] = \text{DR}[k][j]\) and \(\text{CHAN}[i][j] = \text{CHAN}[k][j]\), the time of packet transmission is taken into account;
3) Check whether the transmission of interference \(k\) starts before the end of header of packet \(i\), or finishes after the end of last 6 symbols of preamble. If these conditions are established, the data packet \(i\) would be lost;
4) Otherwise, if the finish of interference \(k\) transmission happen after the preamble and header transmission of the packet \(i\), and the RSSI of interference \(k\) is below packet \(i\), the packet \(i\) will be received correctly.

So that, the percentage of lost packets resulting from conflict can be calculated. There are a lot of training and the percentage of packet loss in \(K\)th training is expressed as follows:

\[
C_k = \frac{\sum_{i=1}^{N} \sum_{j=1}^{K} C_{ij}}{nN} \times 100\% \quad c = \begin{cases} 0, & \text{packet was not collided} \\ 1, & \text{packet was collided} \end{cases}
\]  

(8)

Therefore, the total percentage value can be expressed as:

\[
C_{tot} = \frac{\sum_{i=1}^{K} C_i}{K}
\]

(9)

Therefore, the probability fitting curve of data loss under different network load can be generated. We can get the relation curve \(f_{\text{SCH,DR}[i]}(N)\) between the number of EDs and the packet loss rate for each data rate and with the single channel, reference message rate \(v_c\) and reference payload \(M_c\).

Next, we introduce the variable parameters, such as message rate \(v\), payload size \(M\), and the number of channel \(CN\), into the relation curve \(f_{\text{SCH,DR}[i]}(N)\). Then simulate the change of message rate, number of channels and payload size as the change of the number of EDs.

\[
P_i(N, DR[i]) = f_{\text{SCH,DR}[i]}(N \times r_p, M / CN)
\]

(10)

where:

\[
v_p = v / v_c
\]

(11)

\[
r_p = ToA(M) / ToA(M_c)
\]

(12)

2.3. Data Rate Controller

According to the method mentioned above, we can get a pair of probability of packets loss \([P_p(DR[i]), P_l(N, DR[i])]\) at different rates according to the packet loss probability model of channel attenuation data conflict. Where \(i\) represents the identifier of the optional data rate, which is DR0–DR5. So we can get 6 pair of probabilities at different rates.
In order to ensure the reasonable distribution of data rate, making the overall packet loss probability under each rate reaches equilibrium. In data rate controller, we get the value of the root mean square of each pair of probability. And the data rate with the lowest value is selected as the current rate. The related operations can be expressed as follows:

\[
DR_i = \min \left( \left\{ h(DR_{i|j}) \right\} \right) \\
h(DR_{i|j}) = \left[ \begin{array}{c}
p(P_i; P_j | DR_0) \\
\vdots \\
p(P_i; P_j | DR_5) \\
\end{array} \right] = \left[ \begin{array}{c}
\sqrt{\frac{P_i^2 + P_j^2}{2}} | DR_0 \\
\vdots \\
\sqrt{\frac{P_i^2 + P_j^2}{2}} | DR_5 \\
\end{array} \right] \\
\]

(13)

3. PERFORMANCE ANALYSIS

3.1. Network Model

In order to test and verify the performance of the adaptive rate selection scheme proposed in this paper, we use MATLAB to simulate the performance of proposed scheme compare with the adaptive rate (ADR) scheme and the EXPLoRa scheme.

In the MATLAB, we consider a two-dimensional space with gateway as the center, and end-devices is deployed in the network area with radius R, and the end-devices is randomly distributed in this region. The attributes of each end-device include coordinate axis position, the distance from gateway, current usage data rate, and so on. In order to meet the actual application requirements, set the same initial data rate for each end-device at the beginning of the simulation. Other network parameters are shown in table III.

| Parameters            | Value       |
|-----------------------|-------------|
| Carrier Frequency     | 471.5MHz    |
| Bandwidth             | 125 kHz     |
| Code Rate             | 4/5         |
| Payload Size          | 20 bytes    |
| Message Rate (msg/min)| 1/60,1/30,1/10,1/5,1/3,1/2,1,2,4,6,12 |
| The number of EDs     | 500,2000    |
| Path loss parameter   | \( d_i=40m \), \( \gamma=2.67 \), \( \sigma=1 \) |

3.2. Comparison of Data Extraction Rate

First of all, in order to analysis of the performance of the adaptive rate selection scheme proposed in this paper, we use the Data Extraction Rate (DER) as a performance index. The DER is defined as the ratio of the number of messages that be received correctly by the gateways to the number of messages from all end-devices in a given time period. We will compare the DER of the different schemes. In simulation, there are 2000 end-devices that distributed in a circular range of 3500m around a single gateway. In this scene, we get the measured DER when the message rate is increased with the initial data rate of each ED is set to DR3 and DR5 respectively. the DER behavior is shown in Fig. 2 for the three approaches: i) ADR, ii) EXPLoRa and iii) Proposed scheme.

In the first coordinate system of Fig. 2, it can be seen that the varying trend of DER is gradually decreasing when the message rate is increased from one packet per hour to a packet every 5 seconds. Compared with the ADR, EXPLoRa can only improve DER performance at higher message rate, that is, EXPLoRa has good performance in the case of network congestion. Compared with the ADR and the EXPLoRa, the presented scheme in this paper has a significant improvement in DER performance
at any message rate. Similarly, the same conclusion can be obtained with the initial rate of the EDs at DR5.

![Figure 2. DER of function of the message rate](image)

On the other hand, comparing the two cases in Fig. 2, the selection of the initial rate will affect the network performance in ADR. However, the proposed method in this paper is not limited by the initial data rate, and in the case of the change of initial data rate, there is none impact of network performance. Therefore, the proposed scheme has high practicability. Next, Fig. 3 shows how the DER varies when the range of the EDs distribution varies. The message rate is set to 1/2 (i.e. 1 packet every two minutes) and there are 500 EDs in a network. Extending the coverage range from 500m to 3500m.

![Figure 3. DER as a function of the range of EDs positions](image)

It not only shows the change of DER under three schemes, but also shows the variation of DER with distribution range at a single data rate. It can be indicated that the maximum transmission distance of each data rate by the turning point of DER curve. According to the simulation results, when the distribution of EDs is less than 1000 meters, the performance of proposed method is better than the ADR and similar to the EXPLORa. However, once the range is longer than 1000m, the DER of the ADR and the EXPLORa are both lower than the proposed method, and the difference is more obvious with the extend of range.

3.3. Comparison of Goodput

The next evaluation is the goodput as a function of the message rate by using different rate adaptation schemes. We set the scenario with 2000 EDs positioned within a range of 3500m. Each ED sends the messages forward with an increasing message rate. The result is shown in Fig. 4.

We note that with the increase of message rate, the goodput of the three schemes shows a trend of decreasing. In the ADR scheme, because the rate selection tends to be lower data rate, the goodput is not significantly improved as the message rate increases. The goodput of EXPLORa would first have a noticeable improvement with the increase of the message rate, then, it goes down rapidly because of a lot of conflict. Compared with EXPLORa, the proposed method tries to ensure the data transmission at the fastest data rate. So it has better performance than the EXPLORa in goodput, especially in the case of lower message rate.
4. SCONCLUSION
This paper has presented a rate adaptation scheme with enhanced loss differentiation. In this scheme, the reasons of packet loss is classified as path loss and data conflict, then the selection of data rate is made by combining the probability of packet loss with two reasons. Through the simulation analysis, the proposed scheme can reduce the access conflicts through reasonable data rate selection, as well as to improve the data extraction rate and the goodput. In the proposed scheme, we consider the application scenario of periodic reporting, and the event-driven application needs to be studied in future work.

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