

Energy Consumption Delay Evaluation of NB-IoT Terminal Based on Markov Model

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Energy Consumption Delay Evaluation of NB-IoT Terminal Based on Markov Model

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Abstract The energy consumption of terminal of Internet of Things has attracted much attention in the study of smart Internet of Things. How to simulate the energy consumption process of the terminal from the theoretical level, so as to analyze the energy consumption and delay of the terminal are important issues. In this paper, taking the power monitoring terminal as an example, a Markov model is established for the Narrow-Band Internet of Things (NB-IoT) terminal with periodic automatic reporting. The working state of the terminal includes PSM (Power Saving Mode), random access (RACH), data transport and receive (Tx/Rx), short eDRX (Extended Discontinuous Reception), long eDRX and terminal disconnection (ERROR). According to the proposed model, the effects of network quality, maximum possible number of RACH request times ($Rmax$) and data retransmission times (N_1, N_2) on terminal energy consumption and delay are analyzed. The numerical results show that network quality, maximum number of random access and maximum number of data retransmission directly affect the energy consumption and service quality of the terminal. Reasonable configuration of the above indicators can effectively improve the service life of the terminal and meet the customer's requirements for the terminal service quality under the condition of maximum power saving. The model provides a reference for energy consumption and delay optimization of NB-IoT terminal.

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1 Introduction

In the mobile communication technology industry, the research on terminal energy consumption optimization has never stopped. With the rapid development of Internet of things communication technology in recent years, intelligent devices emerge in endlessly. In order to make the terminal equipment work for a longer time, the energy consumption requirements of mobile communication are more and more stringent[1]. The general objectives of NB-IoT include supporting large-scale connectivity, enhancing coverage, reducing cost and complexity, ultra-low power consumption and flexible delay characteristics. In the power monitoring scenario, most of the power monitoring terminals are powered by batteries, and the number of terminals is huge, the deployment range is wide, and the deployment area is diverse[2], which makes the cost of replacing terminal batteries very high. Therefore, in order to effectively implement the technology, the energy consumption of terminal equipment must be controlled to a minimum. In order to reduce the energy consumption of the terminal, we can optimize the communication mechanism to reduce the unnecessary energy consumption in the communication process, so as to reduce the overall energy consumption of the terminal and prolong the service life of the terminal. Therefore, NB-IoT is optimized based on the discontinuous receiving mechanism of LTE system and introduces eDRX and PSM[3].

The performance of DRX is evaluated in[4–6], and it is found that DRX mechanism can effectively reduce terminal energy consumption; In [7–10], the authors have conducted modeling and Analysis on DRX mechanism. Tirronen et al.[11] discusses how DRX works in LTE and how it affects different machine to machine (M2M) traffic scenarios. Ramazanali et al.[12] establishes a Markov chain model of LTE / LTE-A DRX mechanism. The DRX cycle has long and short, and analyzes that under the condition of meeting the wake-up delay requirements, the maximum power saving can be achieved. Jin et al.[13] divides the time period for the steady-state power-saving operation into several independent parts and analyzes the power-saving operation in each part and thereafter combine the results into an aggregate result. In [14], a Markov model with terminal working state as state variable is established for NB-IoT extended discontinuous receiving mechanism, and the corresponding power consumption and delay model are given.

Although the power consumption of the terminal is reduced, there are also potential delays. In order to optimize DRX mechanism, predecessors have done a lot of mechanism innovation. In reference [15–20], the authors have studied the mechanism innovation of DRX. However, their methods mainly consider the influence between QoS and DRX parameters, and in the Internet of things devices, the control of energy consumption is often higher than the requirements of QoS. in [21], for 5g network, an energy-saving resource and sleep

planning scheme is proposed. In [22], LTE / LTE-A is considered to improve the current DRX and paging mechanism to achieve efficient and energy-saving IoT. In [23, 24], a flexible discontinuous reception scheme is proposed to minimize the wake-up delay. In [25], the author proposed and analyzed the modeling of battery power consumption in downlink data receiving of narrowband Internet of things devices.

The above literature evaluates the impact of DRX mechanism on terminal energy consumption and time delay, and does not consider whether the terminal is disconnection or not. In this paper, a Markov model is established for NB-IoT terminal by adding the terminal disconnection state while refining the working state of the terminal. The main contributions of this article are summarized as follows:

- In order to describe the process of terminal energy consumption more accurately, a Markov model is established for the NB-IoT terminal with periodic automatic reporting. The working state of the terminal includes PSM, RACH, Tx/Rx, short eDRX, long eDRX and ERROR.
- According to the proposed Markov model, the energy consumption and time delay analysis model is derived. In addition, the influence of network quality, maximum possible number of RACH request times and Tx/Rx times on terminal energy consumption and delay are analyzed in this paper.

The numerical results show that network quality, maximum number of random access and maximum number of data retransmission directly affect the energy consumption and service quality of the terminal. Reasonable configuration of the above indicators can effectively improve the service life of the terminal and meet the customer's requirements for the terminal service quality under the condition of maximum power saving.

This paper is organized as follows. Section II introduces the Markov model and each state of the terminal. Section III provides the theoretical analysis of terminal energy consumption and delay. Section IV presents the numerical analysis results of the above models. Section V makes a conclusion of our work.

2 NB-IoT terminal energy consumption model

The scenario envisaged in this paper is that the NB-IoT terminal periodically sends up data. Sleep the rest of the time. Access connections are made periodically. As mentioned above, the working status of a NB-IoT terminal can be divided into six types: PSM, random access, data receiving and sending, short eDRX, long eDRX and terminal disconnection. As shown in Fig. 1, The states are described as follows: (among them, PSM, RACH, Tx/Rx, short eDRX long eDRX, and ERROR are represented by S1, S2, S3, S4, S5 and S6 respectively.)

S1: This status indicates that the device has just been powered on or transferred to after data reporting is successful, after entering S1, start the report cycle timer T1. S2 (RACH) is entered when abnormal conditions occur or the reporting cycle arrives.

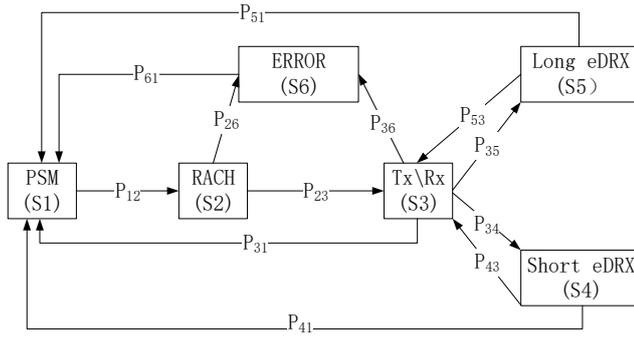


Fig. 1 State transition of NB-IoT terminal

S2: In this state, random access is performed. After entering S2, if the access is unsuccessful for $Rmax$ consecutive times, it is judged that the device has a fatal error such as network disconnection. The device enters S6 state, otherwise it will jump to S3 state.

S3: This state refers to the reporting and receiving of data, after entering S3, start the data transceiver timer T3. If the data is reported successfully, it will jump to S1 state. If the terminal still does not receive the ACK after the T3 timer expired, it means that the data upload failed. If the number of failures is less than or equal to N_1 , jump to S4, otherwise jump to S5.

S4: This state is eDRX short cycle. After entering S4, start the short cycle timer T4, When T4 is expired, the terminal will jump to S1 when receiving ACK, otherwise it will jump to S3.

S5: This state is eDRX long cycle. After entering S5, start long cycle timer T5, When T5 is expired and the terminal receives an ACK, it indicates that the data is sent successfully and jumps to S1; otherwise, it indicates that the data transmission fails. If the number of failures is greater than or equal to N_2 , it means that the device has a fatal error such as network disconnection and jumps to S6 state, otherwise it will jump to S3.

S6: This state is proposed for the first time in this paper. In practical applications, NB-IoT terminals are often disconnected due to a variety of unpredictable reason, including network signals, hardware problems, external environment, and software systems. In this state, it indicates that the device has a fatal error (such as device disconnection). After the device restarts, it will jump to S1 state.

Suppose that the probability of each random access failure is p_r , the average backoff time is T_r , and the feedback information time follows the exponential distribution of the parameter λ_r .

Suppose the probability of data transmission failure is p_t , and the average transmission time is T_t . After each successful data transmission, the response time follows the exponential distribution of the parameter λ_t .

Let p_{ij} is the state transition probability from state S_i to state S_j . Then the transition probability matrix is shown in equ.1:

$$\begin{aligned}
& (q_1 \ q_2 \ q_3 \ q_4 \ q_5 \ q_6) \begin{pmatrix} 0 & p_{12} & 0 & 0 & 0 & 0 \\ 0 & 0 & 1-p_{26} & 0 & 0 & p_{26} \\ 1-p_{34}-p_{35}-p_{36} & 0 & 0 & p_{34} & p_{35} & p_{36} \\ 1-p_{43} & 0 & p_{43} & 0 & 0 & 0 \\ 1-p_{53} & 0 & p_{53} & 0 & 0 & 0 \\ p_{61} & 0 & 0 & 0 & 0 & 0 \end{pmatrix} \\
& = (q_1 \ q_2 \ q_3 \ q_4 \ q_5 \ q_6)
\end{aligned} \tag{3}$$

$$P = \begin{pmatrix} 0 & p_{12} & 0 & 0 & 0 & 0 \\ 0 & 0 & 1-p_{26} & 0 & 0 & p_{26} \\ 1-p_{34}-p_{35}-p_{36} & 0 & 0 & p_{34} & p_{35} & p_{36} \\ 1-p_{43} & 0 & p_{43} & 0 & 0 & 0 \\ 1-p_{53} & 0 & p_{53} & 0 & 0 & 0 \\ p_{61} & 0 & 0 & 0 & 0 & 0 \end{pmatrix} \tag{1}$$

Since state 1 is awakened after an abnormal event or the end of sleep, it must enter state 2 after being awakened, so $p_{12} = 1$;

p_{26} is the probability from state 2 to state 6 after continuous $Rmax$, so $p_{26} = p_r^{Rmax}$;

The condition from state 3 to state 4 is that as long as the number of consecutive failures in state 3 is less than N_1 , then all of them will jump to state 4. As long as there is a success, it will no longer enter, then there are N_1-1 cases, therefore, $p(3,4) = \sum_{n=1}^{N_1-1} p_t^n (1-p_t)^{N_2-n}$, in the same way, $p(3,5) = \sum_{n=N_1}^{N_2-1} p_t^n (1-p_t)^{N_2-n}$, $p(3,6) = p_t^{N_2}$, $p(3,1) = 1 - p(3,4) - p(3,5) - p(3,6)$.

p_{43} , p_{53} are the probability of data transmission failure, that is p_t , $p_{41} = p_{51} = 1 - p_t$;

p_{61} means that the system needs to be restarted in case of a major error. It is an inevitable event from state 6 to state 1, so $p_{61} = 1$.

Suppose that the steady-state probability of each state is $[q_1 \ q_2 \ q_3 \ q_4 \ q_5 \ q_6]$. According to the steady-state condition, the following formula can be obtained, and the steady-state probability of each state can be obtained by combining the equ.2 and equ.3.

$$\sum_{k=1}^6 q_k = 1 \tag{2}$$

3 Energy consumption and delay analysis of NB-IoT terminal

Let E_p and D_p be the total energy consumption and total delay of the system in the business process, $E_p(k)$ and $D_p(k)$ be the average energy consumption and average delay in the state S_k , for $k \in \{1, 2, 3, 4, 5, 6\}$, then E_p and D_p can

be given in equ.4 and equ.5:

$$E_p = \sum_{k=1}^6 q_k E_p(k) \quad (4)$$

$$D_p = \sum_{k=1}^6 q_k D_p(k) \quad (5)$$

3.1 Energy consumption analysis

For state 1, since the research is oriented to one session process, the starting point is from the expiration of the data reporting cycle timer or the triggering of abnormal events, and then it will immediately go to state 2. Therefore, the time spent in state 1 can be ignored, so that $E_p(1)$ can be given in equ.6:

$$E_p(1) = 0 \quad (6)$$

For state 2, it is assumed that the energy consumed by each random access process is

E_{RACH} . The average number of random access failures is $\bar{R} = \sum_{j=0}^{R_{max}} j(p_r)^j$, so that $E_p(2)$ can be given in equ.7:

$$E_p(2) = E_{RACH} \bar{R} = E_{RACH} \sum_{j=0}^{R_{max}} j(p_r)^j \quad (7)$$

For state 3, it is assumed that the energy consumed in each data sending and receiving process is E_T . In this state, the average number of data transmission is $\bar{N} = \sum_{j=0}^{N_2} j(p_t)^j$, so that $E_p(3)$ can be given in equ.8:

$$E_p(3) = E_T \bar{N} = E_T \sum_{j=0}^{N_2} j(p_t)^j \quad (8)$$

For state 4, it is assumed that the average power is W_4 and the sleep time is T_4 . Since state 3 determines the average number of data transfers, the average number of times to enter this state is $\bar{N}_4 = P(3,4) \bar{N}$, so that $E_p(4)$ can be given in equ.9:

$$E_p(4) = W_4 T_4 \bar{N}_4 \quad (9)$$

For state 5, it is assumed that the average power is $W_5 = W_4$ and the sleep time is T_5 . Since state 3 determines the average number of data transfers, the average number of times to enter this state is $\bar{N}_5 = P(3,5) \bar{N}$, so that $E_p(5)$ can be given in equ.10:

$$E_p(5) = W_5 T_5 \bar{N}_5 \quad (10)$$

For state 6, the system is restarted in this state, and the energy consumption required to restart the system is assumed to be E_r . After the system restarts, the system enters the PSM, and in this case, the reporting data process is restarted immediately, so that $E_p(6)$ can be given in equ.11:

$$E_p(6) = E_r \quad (11)$$

3.2 Delay analysis

For state 1, the PSM cycle is assumed to be T_p . Since the research is oriented to a session process, it will jump to state 2 immediately after the end of the data reporting cycle or the triggering of abnormal events, therefore, the time spent in state 1 can be ignored, so that $D_p(1)$ can be given in equ.12:

$$D_p(1) = 0 \quad (12)$$

For state 2, since the average backoff time in each random access process is T_r , the feedback information time obeys the exponential distribution of parameter λ_r , so that $D_p(2)$ can be given in equ.13:

$$D_p(2) = (1 - p_r^{R_{\max}}) \left(T_r \bar{R} + \int_0^{T_r} t \lambda_r e^{-\lambda_r t} dt \right) + p_r^{R_{\max}} R_{\max} T_r \quad (13)$$

Where, the first half represents the average delay of random access success, and the second half represents the average delay of random access failure.

For state 3, the average transmission time of each data transmission is T_t . After each successful data transmission, the response time follows the exponential distribution of the parameter λ_t , so that $D_p(3)$ can be given in equ.14:

$$D_p(3) = (1 - p_{34} - p_{35} - p_{36}) \left(T_t \bar{N} + \int_0^{T_t} t \lambda_t e^{-\lambda_t t} dt \right) + (p_{34} + p_{35} + p_{36}) N_2 T_t \quad (14)$$

Where, the first half represents the average delay of successful data transmission, and the second half represents the average delay of data transmission failure.

For state 4, the sleep time is set as T_4 , and the response time for each successful data transmission follows the exponential distribution of parameter λ_t , so that $D_p(4)$ can be given in equ.15:

$$D_p(4) = \bar{N}_4 T_4 + \int_0^{T_4} t \lambda_t e^{-\lambda_t t} dt + \int_{T_4}^{\infty} T_4 \lambda_t e^{-\lambda_t t} dt \quad (15)$$

The first half represents the average delay of receiving the ACK response before the end of sleep, and the second half represents the average delay of not receiving the ACK response after the end of sleep.

For state 5, the sleep time is set as T_5 , and the response time for each successful data transmission follows the exponential distribution of parameter λ_t , so that $D_p(5)$ can be given in equ.16:

$$D_p(5) = \bar{N}_5 T_5 + \int_0^{T_5} t \lambda_t e^{-\lambda_t t} dt + \int_{T_5}^{\infty} T_5 \lambda_t e^{-\lambda_t t} dt \quad (16)$$

The first half represents the average delay of receiving the ACK response before the end of sleep, and the second half represents the average delay of not receiving the ACK response after the end of sleep.

For state 6, the state indicates that the terminal needs to restart the system, so the average delay is given in equ.17:

$$D_p(6) = T_6 \quad (17)$$

Table 1 Simulation parameters.

Parameter	Value	Parameter	Value	Parameter	Value
T_L/h	12	E_r/J	0.2	T_5/ms	1000
W_1/mW	0.02	T_6/ms	5000	T_4/ms	3000
W_4/mW	100	T_r/ms	8	$p_r, p_t/ms$	0-1
W_5/mW	100	T_p/h	1/12	$1/\lambda_r, 1/\lambda_t/ms$	5
$E_{RACH}, E_T/J$	0.05	T_t/ms	8	-	-

4 Numerical analysis of energy consumption and delay of NB-IoT terminal

Considering the energy consumption of a single NB-IoT terminal, in order to maximize the service life of the terminal, it means that the energy consumption should be as small as possible in a fixed time. Assuming that the energy consumption in the time period T_L is E , so that E can be given in equ.18:

$$E = \frac{T_L}{T_P} (E_p + W_1) \frac{1}{p_{suc}} \quad (18)$$

Where p_{suc} is the success rate of a single service, which can be expressed as shown in equ.19:

$$p_{suc} = 1 - p(1, 2)p(2, 6)p(6, 1) - p(1, 2)p(2, 3)p(3, 6)p(6, 1) \quad (19)$$

Consider the delay of a NB-IoT terminal to complete a single service successfully. If the data is sent successfully, it means the end of a session. Because the success rate of a single business is p_{suc} , it takes an average of $1/p_{suc}$ sessions for a single business success. Suppose that the delay of successful transmission of a single service is D , so that D can be given in equ.20:

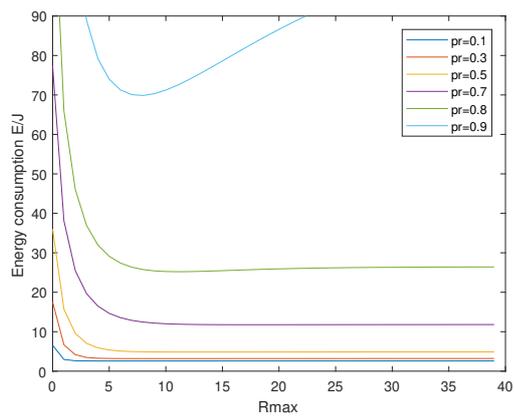
$$D = \frac{1}{p_{suc}} D_p \quad (20)$$

Where, T_6 represents the time required to restart the system. According to reference [2,14], the reference values of parameters required for simulation are shown in Table 1.

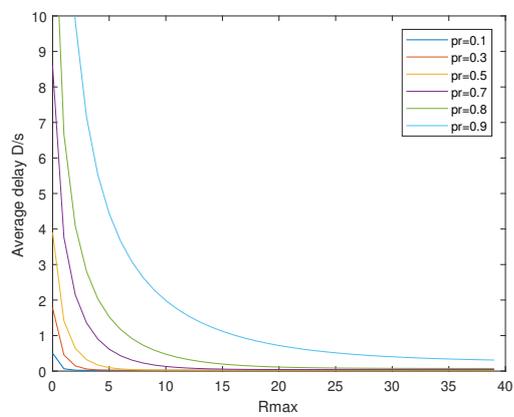
Based on the above assumptions, simulation analysis is carried out to verify the effectiveness of the model.

The impact of $Rmax$ on terminal energy consumption, delay and service success rate is analyzed. Since the $Rmax$ is directly affected by the degree of network congestion, $p_r = \{0.1, 0.3, 0.5, 0.7, 0.8, 0.9\}$ is used to represent the degree of network congestion. In order to ensure that the analysis results can be more affected by $Rmax$ and ensure the correctness of the analysis, $p_t = 0.5$ is selected as the network environment parameter of the simulation. Other parameters remain unchanged, and the simulation results are shown in Fig. 2.

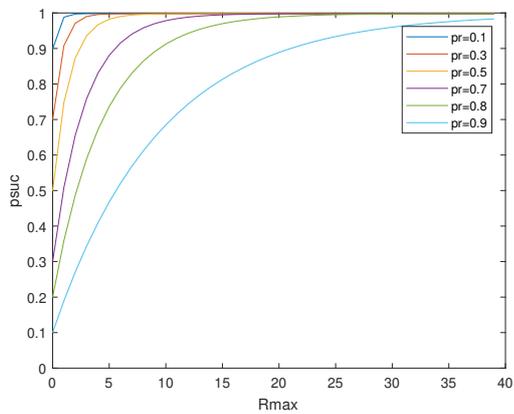
As shown in Fig. 2, when the network congestion is not serious, because the state of disconnection and restart is added, when $Rmax$ is too small,



(a) Relationship between energy consumption and Rmax.



(b) Relationship between average delay and Rmax.



(c) Relationship between business success rate and Rmax.

Fig. 2 The influence of Rmax on terminal in time T_L

it may lead to unsuccessful access and continuous restart. At this time, the energy consumption will be very high. With the increase of $Rmax$, the access success rate will increase and the energy consumption will decrease. When $Rmax$ reaches a suitable value, the energy consumption becomes stable, even if the given $Rmax$ increases, it will not increase energy consumption, in this case, the access can be successful without reaching the maximum value of $Rmax$. However, if the network congestion degree is above $p_r = 0.7$, as shown in Fig. 2, with the increase of $Rmax$, the service success rate gradually increases, but at the same time, the terminal energy consumption starts to rise. Due to the increase of service success rate, the number of system restarts is continuously reduced, and the delay will be correspondingly reduced. That is also verified that the degree of network congestion is an important factor to determine the terminal energy consumption and delay.

Fig. 3 describes the relationship curves of average terminal power consumption, average delay, service success rate and network transmission quality in time respectively. Assume that represents the theoretically ideal network transmission quality, and represents that the network is unavailable. At the same time, assume that the network congestion degree is good, namely, is the threshold of random access times. As can be seen from the figure, with the deterioration of network transmission quality, the average power consumption and average delay of terminals are increasing. When it reaches 0.7 or above, the average power consumption and average delay of terminals rise more and more obviously, while the success rate of services declines more and more obviously. When the power consumption exceeds 0.8, the average power consumption and average delay increase exponentially. The curve reflected in the figure is consistent with the actual phenomenon, which reflects the correctness of the model from the side.

The following describes the relationship curve between terminal energy consumption and delay, service success rate and data retransmission times N_1 and N_2 in T_L time. Where N_1 represents the threshold for entering into long-cycle sleep. When the cumulative number of data transmission failures reaches N_1 , it will be transferred to eDRX long-term sleep, otherwise it will enter eDRX short-cycle sleep. N_2 refers to the threshold of system restart. When the cumulative number of data transmission failures reaches N_2 , it will enter state 6. Then $N_2 - N_1$ represents the number of times in eDRX for long-cycle sleep.

In Fig. 4, $p_r, p_t, Rmax = (0.8, 0.8, 5)$ are taken as the basic simulation parameters. As shown in Fig. 4, when the network quality is poor, with the increase of retransmission time-
s, although the terminal energy consumption and delay are declining, the success rate is very low. Further, with the increase of retransmission times, the success rate will slightly increase, but the final success rate is still very low, while the terminal energy consumption and average delay are rising. This is due to the terminal constantly trying to retransmit, which is consistent with the actual situation.

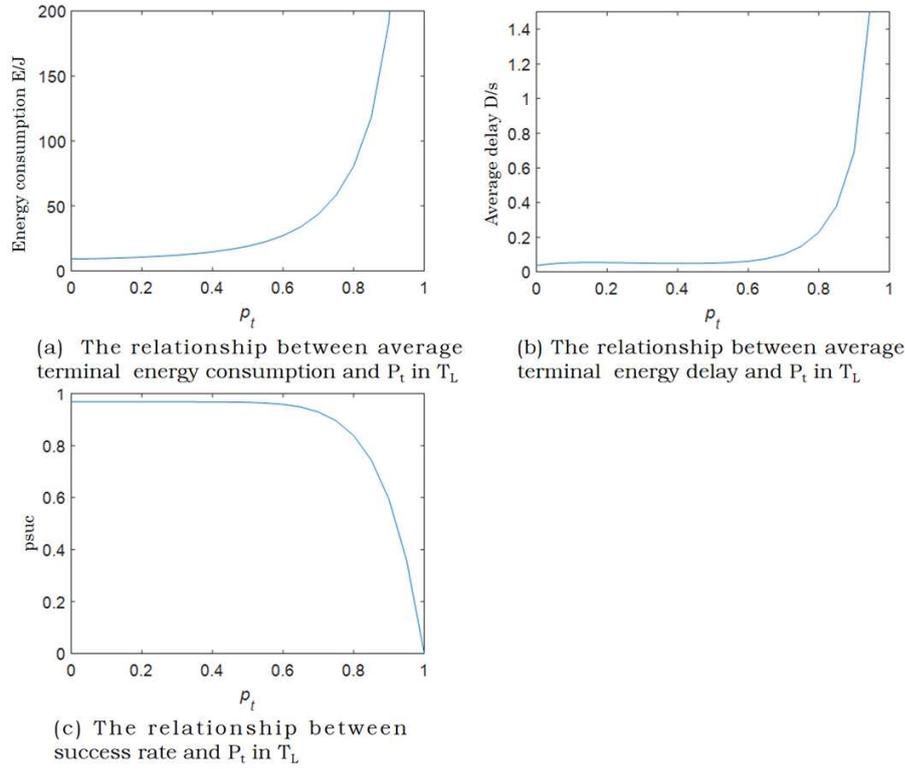
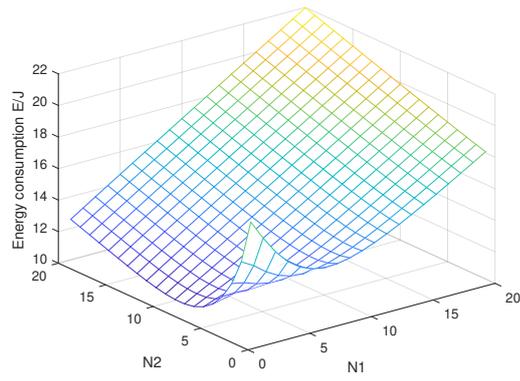


Fig. 3 Performance analysis under different network quality

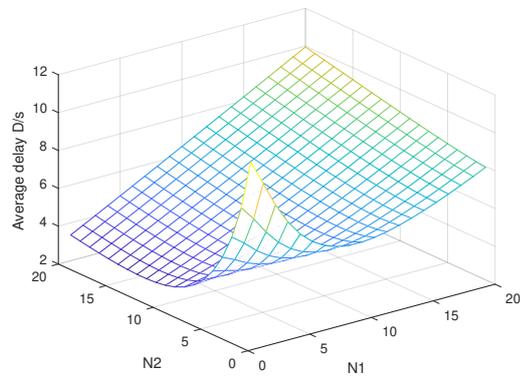
Through the analysis of section 2 and section 3, it can be seen that the addition of terminal offline state makes the model more detailed for the working state of the terminal. In practical application, when $Rmax$, N_1 and N_2 are configured, the rationality of parameter configuration can be verified by the model, which provides an important reference value for the impact of terminal energy consumption and delay in different scenarios.

Actual, in NB-IoT, there are relatively few studies using Markov model to analyze terminal energy consumption and delay model. The innovation point proposed in this paper is closer to the actual application state. A better parameter combination can be obtained through simulation analysis. In view of the comparative experiment, the model proposed in this paper is compared with the model without S6 state as well as the general model, and many parameters eDRX are idealized. The energy consumption and delay under different network quality are compared.

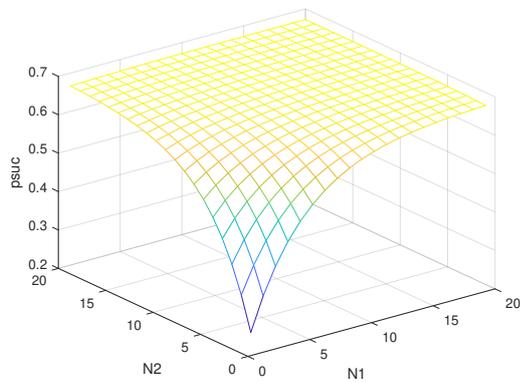
It can be seen that under different network performance, the algorithm proposed in this paper has advantages in energy consumption and is in hibernation state when the connection cannot be made. But its delay performance deteriorates. Because the terminal is off line inevitably cause delay to increase.



(a) Relationship between energy consumption and N_1 , N_2 .



(b) Relationship between average delay and N_1 , N_2 .



(c) Relationship between business success rate and N_1 , N_2 .

Fig. 4 The influence of N_1 , N_2 on terminal in time TL T_L

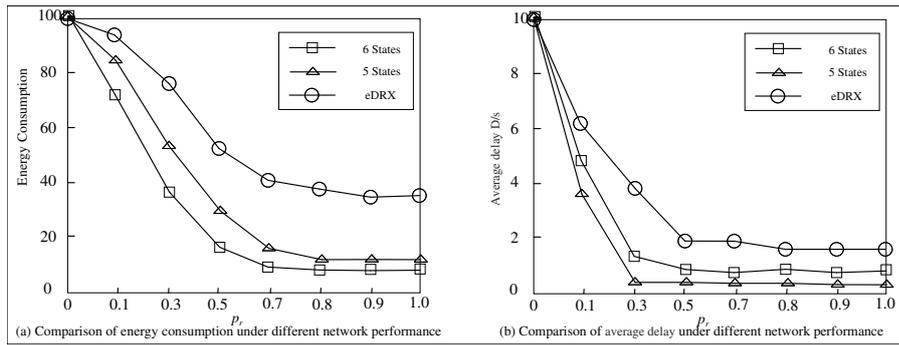


Fig. 5 Comparison between energy consumption and delay of similar algorithms

The six-state transition proposed in this paper is more perfect, such as sleep mechanism, and has better performance than the traditional eDRX.

5 Conclusion

In order to analyze the energy consumption and time delay of NB-IoT terminal, Markov chain is introduced to model and analyze the working state of NB-IoT terminal. Taking power monitoring terminal as an example, PSM, RACH, Tx/Rx, short eDRX, long eDRX and ERROR are taken as the state variables of Markov model, and the influence of network quality, maximum possible number of RACH request times and Tx/Rx times on terminal energy consumption and delay are analyzed. The numerical results show that the Markov model proposed in this paper is accurate and effective for NB-IoT terminal energy consumption and delay analysis. And also from the simulation results, when the success rate of random access is low, the appropriate increase of maximum possible number of RACH request times helps to reduce the energy consumption and delay of the terminal, which provides an important reference value for the later optimization of terminal energy consumption and delay.

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