Multi-State Energy Efficiency Improvement Strategy for DRX Functional Devices

Tong Pei, Baoling Liu, Chen Dong, Bowen Cai and Fei Xu

September 29, 2021

Multi-State Energy Efficiency Improvement Strategy for DRX Functional Devices

Tong Pei[1], Baoling Liu[1], Dong Chen[1], Bowen Cai[2], Fei Xu[3]
[1]School of Information and Communication Engineering, Beijing University of Posts and Telecommunications, Beijing, China
[2]China Telecom Research Institute, Beijing, China
[3]Future Mobile Technology Lab, China Mobile Research Institude
Email: {peitong, blliu, dongchen}@bupt.edu.cn, caibw@chinatelecom.cn, xufei@chinamobile.com

***Abstract*—Ensuring the high efficiency of communication is one of the important properties of the Internet of Things (IoT) device network, which can be realized by Discontinuous Reception (DRX). In this paper, a strategy is proposed to schedule the user equipment (UE) with the base station knowing whether the packet is coming in the following 1 or 3 time slots, and this mechanism is added to an IoT device model with DRX function. This model operates on 5G standards and communicates with base stations. Packets are generated with a fixed length and a Poisson process. Based on this assumption, according to the cross-layer analysis model, this paper analyzes 1) the steady-state probability of each state, 2) the energy efficiency of this model, and 3) the improvement of energy efficiency relative to that of the single-mode circuit. It can be observed from the theoretical and simulation results that this model can improve the energy efficiency on the basis of the original strategy.**

***Index Terms*—DRX, energy efficiency, Internet of Things, Poisson process, 5G, Markov Chain**

I. INTRODUCTION

Due to the spread of communication technology, the number of Internet of Things (IoT) devices has exceeded the global population by three times in 2020. Most of these devices are powered by battery, requiring long battery life and low maintenance costs. Therefore, in order to effectively improve battery life, it is very important to reduce the battery consumption rate. The Discontinuous Reception (DRX) is one of the active topics in 3rd Generation Partnership Project (3GPP) standard, and it is also a very important technology in communication. It can make the equipment switch parts of the circuit from active to sleep, thus saving energy.

DRX periodically repeats both ”Sleep” and ”On Duration”, receiving data during ”On Duration” and saving energy by inactivity during ”Sleep”. In 4G Long Term Evolution (LTE), DRX is divided into two schemes. One is long DRX, which is suitable for low information arrival rate. This scheme ensures efficient system operation while tolerating certain information delay. The other is short DRX, which is suitable when the information arrival rate is high in order to ensure low latency. The UE can switch between the two states according to the timer and the surrounding environment.

In 5G New Radio (NR), the DRX mechanism still follows the same framework as LTE, but occupied with an added capability of multi-parameter set processing. By processing multiple parameter sets, NR can configure the timer of DRX, therefore preventing the DRX cycle from keeping a fixed parameter, and making the device more flexible to receive signals. Also, DRX will work with the new Radio Resource Control (RRC) mechanism to further reduce battery consumption.

In recent years, many organizations have studied the DRX mechanisms to improve the energy efficiency in various environments or in combination with different technologies. And a large number of articles have been published in relevant international academic conferences and important academic journals. Paper [1] proposes a new RRC state, namely RRC inactive state, in which the equipment temporarily suspends the connection to the Radio Access Network (RAN), while maintaining the connection to the core network. This state has 200% less latency cost than the idle state and 40% less power consumption than the connected state. Paper [2] proposes an online algorithm that is robust to the prediction error. The algorithm uses channel capacity prediction to adjust the configuration of resources and DRX to minimize the energy consumption of UE when streaming videos are being played and to create more sleep opportunities. It also prevents buffer overflows and reduces the possibility of video interruptions. Paper [3] proposes a four-states modeling, and analyzed the energy efficiency of the system, the steady-state probability and the retention time of the four states respectively. This system communicates with the base station by sending packets through the block-fading channel. The packets are generated by a Poisson process and the length of the packets are fixed.

The introduction of Dual Connectivity (DC) will lead to offset synchronization in traditional DRX, which impedes energy-saving. Paper [4] proposes a method named Synchronized Adaptive DRX Sleep (SAS), which maximized the overlapping Sleep time of DC. The core idea of the scheme is to synchronize DRX sleep from DC. It reduces energy consumption, but adds a certain amount of delay. In paper [5], the system is built as a four-states model. That paper optimized the original scheme. It configures the system according to the arrival of packets to reduce energy consumption. The paper takes into account the additional energy consumption generated at the UE's turning on and off, and adds a state named WRx (Wake-up Receiver)-ON as the state to decode

Physical Downlink Wake-up Channel (PDWCH) after each sleep cycle. After DRX is introduced into the 4G LTE, state of the original three DRX models can neither accurately capture the value of the electricity savings and time delay, nor capture found changing message arrival rate of these values. Paper [6] proposes a Device to Device (D2D) communication used in five-states DRX model, which uses a semi-Markov process. When data arrives during the sleep states, the system will switch to the discovery states, and complete the link setup procedure, and then process the data.

Paper [7] proposes a system model based on the Channel Quality Indicator (CQI). This scheme can reduce the energy consumption by avoiding the unnecessary awakening of UE at certain moments. Compared with the original DRX model, the energy consumption used in stable network can be reduced by about 17%. Paper [8] proposes the concept of scheduling wake-up, and optimized the parameters of wake-up scheduling in offline mode and online mode respectively. Compared with the model without this scheduling scheme, both of these scheduling schemes can save energy. In paper [9], the collaboration between DRX and Joint Transmission (JT) is realized in the cloud RAN architecture to effectively improve system throughput and save energy. Paper [10] proposes a new DRX mechanism based on online learning, called AC-DRX (Actor Critic DRX). The proposed mechanism can reduce the energy consumption of machine type communication (MTC) service by adapting to the change of traffic mode. The simulation results showed that the AC-DRX mechanism is superior to the traditional DRX mechanism in controlling delay and saving energy. Paper [11] analyzes a mechanism of Licensed Assisted Access DRX (LAA-DRX). The scheme works on LTE networks. Compared with the original DRX scheme, LAA-DRX can improve the energy efficiency by nearly 4% and reduce the resource invocation by 58%. Paper [12] develops a new Hybrid Directional DRX mechanism (HD-DRX). The mechanism uses semi-Markov process to estimate the probability of various states of UE, saving 13% of power compared with the original directional DRX mechanism. Paper [13] proposes that HPC-DRX/TRTS (Highest Priority-Controlled DRX, Traffic Regulation plus Time Slicing). This scenario states that if the traffic has a low priority, it will not wake up the UE. Through analysis, the energy saving rate of this mechanism is superior to that of traditional DRX, Dynamically Adjustable DRX (DADRX) and combined DRX. Paper [14] proposes a new Energy Harvesting DRX (EH-DRX) mechanism. The purpose of this mechanism is to reduce the wake delay of wireless cellular networks as much as possible. Compared with the traditional DRX mechanism, the proposed mechanism can control the wake delay. Paper [15] proposes a grouping based DRX strategy with high efficiency and energy saving. This strategy will design a variety of DRX solutions for group leaders and group members, respectively, to achieve the purpose of improving the energy efficiency. Simulation results show that the proposed DRX mechanism is superior to the original DRX scheme in improving the energy efficiency.

The advantage of this strategy is that the base station will know whether data packets will be sent in the following 1 or 3 time slots according to the nature of the transaction, so as to manipulate UE to enter the sleep state to save energy or enter the wake state to receive data packets in time. Other strategies do not have this consideration of making a difference based on the nature of the transaction. It will play a certain positive role in the improvement of energy efficiency.

In this paper, we make the following contributions.

1) This scheme takes into account whether packets are coming or not in the following 1 or 3 time slots, which is not available in the previous system.

2) A seven-state DRX model is proposed, and its probability of stability, the energy efficiency and improvement of the energy efficiency are deduced.

3) The simulation results verify the accuracy of the derivation.

The remainder of this paper is organized as follows. In Section II, this paper describes the system model. Simulation results are presented in Section III followed by conclusion in Section IV.

II. DRX SYSTEM MODEL

Packets carry flags that are related to the time difference between the arrival of the next packet. When the base station sends packets from the cache, it knows whether there are any packets to send in the next 1 or 3 time slots. When the packet interval does not exceed one or three time slots, the value of FLAG1 is set as 1. Meanwhile, if the packet interval exceeds it, the value of FLAG2 is set as 1.

The system is divided into seven states. The seven states are: active state, long wake state, normal wake state, short sleep state, short sleep monitor state, long sleep state, long sleep monitor state. The seven-states transition diagram is shown in Fig. 1.

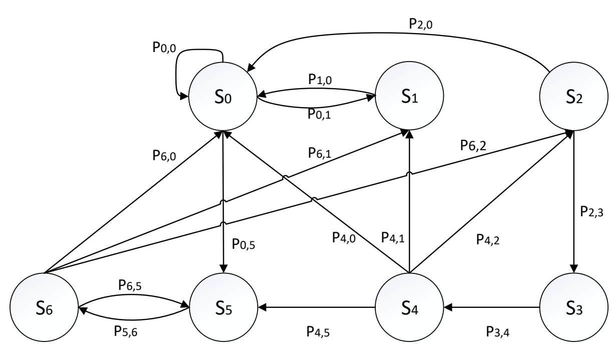

Fig. 1. State Transition Diagram.

S_0 is the active state, S_1 is the long wake state, S_2 is the normal wake state, S_3 is the short sleep state, S_4 is the short sleep monitor state, S_5 is the long sleep state, S_6 is the long sleep monitor state.

When the UE is in the active state, it consumes the most power. The active state is one of the most energy-intensive of the seven states. When no packet arrives and the previous packet's FLAG1 is the value of 1, the UE enters the long wake phase, in which the UE continuously monitors the Physical Downlink Control Channel (PDCCH) and becomes active if a packet arrives, until the corresponding long wake timer has exceeded its limit. Then the UE will close the transceiver circuit and enter the low-power short sleep state. When the short sleep timer exceeds the time limit, the PDCCH is monitored. In other words, the system goes into short sleep monitor state.

In the short sleep monitor state, the UE checks if any packets are coming during the current and sleep period. If one or more packets is received in the current slot, according to the FLAG1 and FLAG2 flags carried by it, the UE will enter the corresponding active state, long wake state, or long sleep state. If no packets arrive during monitoring while there are packets arrive during sleep, the UE enters a normal wake state. If the system still does not receive the data packet after the short sleep timer expires, the UE will enter the long sleep state.

Similarly, when the long sleep timer expires, the UE will monitor. It will then enter the long sleep monitor state, and check whether the packet has arrived. If a packet is received during monitoring, the system will go into the corresponding active state, long wake state, or long sleep state based on the value of FLAG1 and FLAG2. If no packet arrives during the monitoring period, but there is one or more packets arriving during the sleep period, the UE will enter a normal wake state. If the UE does not receive any data, it will enter the long sleep state. In the normal wake state, the UE will continuously monitor to the PDCCH and will enter the active state if a packet arrives before the normal wake timer expires.

When a packet receives FLAG1 as 1 during active state, it enters the long wake state. And when the value of FLAG2 is 1, it enters the long sleep state, which reduces battery energy consumption while ensuring a certain low latency.

In theory, the state transition matrix is listed according to the state transition probability in various cases, and the steady-state probability is obtained. Meanwhile, the corresponding state duration is obtained according to the arrival of different packets, so as to calculate the energy efficiency and the improvement relative to the single-state circuit. The state transition matrix is shown below,

$$P = \begin{pmatrix} p_{0,0} & p_{0,1} & 0 & 0 & 0 & p_{0,5} & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ p_{2,0} & 0 & 0 & p_{2,3} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ p_{4,0} & p_{4,1} & p_{4,2} & 0 & 0 & p_{4,5} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ p_{6,0} & p_{6,1} & p_{6,2} & 0 & 0 & p_{6,5} & 0 \end{pmatrix}; \tag{1}$$

$$\vec{\pi} = (\pi_0, \pi_1, \pi_2, \pi_3, \pi_4, \pi_5, \pi_6); \tag{2}$$

$$\pi_0 + \pi_1 + \pi_2 + \pi_3 + \pi_4 + \pi_5 + \pi_6 = 1; \tag{3}$$

$$\vec{\pi} * P = \vec{\pi}. \tag{4}$$

One example of an expression is given in a matrix. Let's take π_0 as an example to illustrate this. If the system is in the active state, the next step is to enter the long wake state, long sleep state, or to maintain the active state. The values of $p_{0,0}$, $p_{0,1}$, and $p_{0,5}$ are greater than or equal to 0, and the values in other cases are always 0. Therefore, 0 is directly filled in the matrix. Meanwhile, $p_{0,0}$ means the probability that the UE is currently in the active state, and at the same time the next state is the active state. $p_{0,1}$ means the probability that the UE is currently in the active state, and the next state is the long wake state. $p_{0,5}$ means the probability that the UE is currently in the active state, and the next state is the long sleep state. And so on for the other six states.

The row vector $\vec{\pi}$ represents the stationary probabilities of each of the seven states in turn. The sum of all stationary probabilities is 1. Assume that the incoming probability of the current time slot is p, the transition probabilities are shown as follows,

$$\begin{cases} p_{0,0} = p; \\ p_{0,1} = (1-p)p + (1-p)^2 p; \\ p_{0,5} = 1 - p - (1-p) * p - (1-p)^2 p; \\ p_{1,0} = 1; \\ p_{2,0} = p; \\ p_{2,3} = 1 - p; \\ p_{3,4} = 1; \\ p_{4,0} = p^2; \\ p_{4,1} = p^2(1-p)(2-p); \\ p_{4,2} = (1-p)[1-(1-p)^{t_s}]; \\ p_{4,5} = (1-p)^{t_s+1} + p(1-p)^3; \\ p_{5,6} = 1; \\ p_{6,0} = p^2; \\ p_{6,1} = p^2(1-p)(2-p); \\ p_{6,2} = (1-p)[1-(1-p)^{t_l}]; \\ p_{6,5} = (1-p)^{t_l+1} + p(1-p)^3. \end{cases} \tag{5}$$

And according to the above formula,

$$\begin{cases} p_{0,0}\pi_0 + p_{1,0}\pi_1 + p_{2,0}\pi_2 \\ +p_{4,0}\pi_4 + p_{6,0}\pi_6 = \pi_0; \\ p_{0,1}\pi_0 + p_{4,1}\pi_4 + p_{6,1}\pi_6 = \pi_1; \\ p_{0,2}\pi_0 + p_{1,2}\pi_1 + p_{4,2}\pi_4 + p_{6,2}\pi_6 = \pi_2; \\ p_{2,3}\pi_2 = \pi_3; \\ \pi_3 = \pi_4; \\ p_{0,5}\pi_0 + p_{4,5}\pi_4 + p_{6,5}\pi_6 = \pi_5; \\ \pi_5 = \pi_6. \end{cases} \tag{6}$$

After deduction, the theoretical stationary probabilities of the seven-states DRX system are

$$\begin{cases} A = -p_{0,0}p_{6,1}p_{2,3}p_{4,2}p_{6,0} + p_{0,0}p_{6,1}p_{6,0} + p_{6,1}p_{2,3}p_{4,2}p_{6,0} \\ -p_{6,1}p_{6,0} - p_{0,1}p_{6,0}p_{2,0}p_{6,2} - p_{0,1}p_{6,0}p_{2,3}p_{4,0}p_{6,2} \\ +p_{0,1}p_{6,0}p_{2,3}p_{4,0}p_{6,2} - p_{0,1}p_{6,0}p_{6,0} + p_{0,0}p_{6,2}p_{2,3}p_{4,1}p_{6,0} \\ -p_{6,2}p_{2,3}p_{4,1}p_{6,0} + p_{0,2}p_{6,0}p_{2,0}p_{6,1} + p_{0,2}p_{6,0}p_{2,3}p_{4,0}p_{6,1} \\ -p_{0,2}p_{6,0}p_{6,0}p_{2,3}p_{4,1}; \\ B = p_{6,1}p_{1,0}p_{2,3}p_{4,2}p_{6,0} - p_{1,0}p_{6,0}p_{6,1} - p_{2,0}p_{6,0}p_{6,2} \\ -p_{6,0}p_{2,3}p_{4,0}p_{6,2} + p_{2,3}p_{4,2}p_{6,0}p_{6,0} - p_{6,0}p_{6,0} \\ -p_{6,2}p_{1,0}p_{2,3}p_{4,1}p_{6,0} - p_{1,2}p_{6,0}p_{2,0}p_{6,1} \\ -p_{1,2}p_{6,0}p_{2,3}p_{4,0}p_{6,1} + p_{1,2}p_{6,0}p_{6,0}p_{2,3}p_{4,1}; \\ C = -p_{2,0}p_{6,5} + p_{2,0} - p_{2,3}p_{4,0}p_{6,5} \\ +p_{2,3}p_{4,0} + p_{2,3}p_{4,5}p_{6,0}; \\ \pi_0 = 1/(1 + \frac{A}{B} + (((A(p_{1,0}p_{6,5} - p_{1,0})(1 + 2p_{2,3})) \\ +(B(p_{0,0}p_{6,5} - p_{0,0} - p_{6,5} + 1 - p_{0,5}p_{6,0})(1 + 2p_{2,3})))/ \\ (BC)) + ((2Ap_{2,3}p_{4,5}(p_{1,0}p_{6,5} - p_{1,0}) \\ +2Bp_{2,3}p_{4,5}(p_{0,0}p_{6,5} - p_{0,0} - p_{6,5} \\ +1 - p_{0,5}p_{6,0}) + 2Bp_{0,5}C)/((1 - p_{6,5}) * B * C))); \\ \pi_1 = (\frac{A}{B})\pi_0; \\ \pi_2 = ((B(p_{0,0}p_{6,5} - p_{0,0} - p_{6,5} + 1 - p_{0,5}p_{6,0}) \\ +A(p_{1,0}p_{6,5} - p_{1,0}))/(BC))\pi_0; \\ \pi_3 = p_{2,3}\pi_2; \\ \pi_4 = \pi_3; \\ \pi_5 = ((Ap_{2,3}p_{4,5}(p_{1,0}p_{6,5} - p_{1,0}) + Bp_{2,3}p_{4,5} \\ (p_{0,0}p_{6,5} - p_{0,0} - p_{6,5} + 1 - p_{0,5}p_{6,0}) \\ +Bp_{0,5}C)/((1 - p_{6,5})BC))\pi_0; \\ \pi_6 = \pi_5. \end{cases} \tag{7}$$

It is worth noting that the Markov state transition matrix is defined as an immediate state transition in the next slot, whereas in this DRX system, some states are not of the same duration. For example, long sleep and short sleep scenarios require the system to sleep for a period of time that consists of multiple time slots. So the states need to be standardized.

Let T_0, T_1, T_2, T_3, T_4, T_5, and T_6 be the average durations of the seven states. The length of a time slot is T_s. In general, T_s =1ms. Then,

$$\begin{cases} T_0 = T_s; \\ T_1 = \frac{p}{p+(1-p)p}T_s + \frac{2p}{p+(1-p)p}T_s; \\ T_2 = T_s; \\ T_3 = t_sT_s; \\ T_4 = T_s; \\ T_5 = t_lT_s; \\ T_6 = T_s. \end{cases} \tag{8}$$

Let T be the system time, thus

$$\begin{cases} T = \pi_0T_0 + \pi_1T_1 + \pi_2T_2 + \pi_3T_3 + \pi_4T_4 + \pi_5T_5 + \pi_6T_6; \\ \pi_0 = \frac{T_0\pi_0}{T}; \\ \pi_1 = \frac{T_1\pi_1}{T}; \\ \pi_2 = \frac{T_2\pi_2}{T}; \\ \pi_3 = \frac{T_3\pi_3}{T}; \\ \pi_4 = \frac{T_4\pi_4}{T}; \\ \pi_5 = \frac{T_5\pi_5}{T}; \\ \pi_6 = \frac{T_6\pi_6}{T}. \end{cases} \tag{9}$$

III. SIMULATION RESULTS

In this system, two configurations are set as: t_a=1ms, t_i=1ms, t_s=3ms, t_l=5ms; t_a=3ms, t_i=3ms, t_s=5ms, t_l=10ms.

In these configurations, t_a is the long arousal duration, t_i is the normal arousal duration, t_s is the short sleep duration, and t_l is the long sleep duration.

FLAG1 will be set as 1 if the next packet arrives no later than t_a; FLAG2 will be set as 1 if the next packet arrives later than t_a.

There are two reasons for choosing these two configurations. One is that the configuration of paper [3] is referred to; the other is that the strategy is based on the fact that the base station will know whether packets will be sent in the next few time slots according to the continuity of transactions. The number of time slots itself should be kept in the order of single digits.

The simulations of these two configurations are carried out respectively. The steady-state probability, the energy efficiency and increment are shown at the end of the section.

A. Probability of Stability

In order to verify the alignment of theory and simulation, the system uses a fixed configuration, t_a = 1ms, t_i = 1ms, t_s= 3ms, t_l= 5ms. The results after simulation are shown in Fig. 2 and Fig. 3, in which solid lines represent the theoretical results, while markers represent simulation results. It can be observed that the markers and soild lines fit well, which can verify the correctness of the theory.

The data packets sent by the base station are usually of a fixed length. Furthermore, the scheme assumes that the data packets sent by the source to the UE follow a Poisson distribution with λ parameter. Assume that two flags occupy two bits, the valid length of the packet is L=498bits. And the data arrival amount per unit slot is D[n] (n =1, 2, 3...). Meanwhile, the amount of data arriving between time slots is not related. Therefore, the probability of i (i =1, 2, 3...) data packets arriving in a unit time slot is

$$P(D = i\ packets\ per\ slot) = \frac{\lambda^i}{i!}e^{-\lambda}. \tag{10}$$

Data arrival rate μ is

$$\mu = \frac{\lambda L}{T_s}. \tag{11}$$

Packet probability p for the current time slot is

$$p = 1 - P(D=0) = 1 - e^{-\lambda}. \tag{12}$$

Meanwhile, it can be observed from the Fig. 2 and Fig. 3 that, along with the increase of λ value, the stationary probability of π_0 gradually increases; the stationary probability of π_1, π_2, π_3, and π_4 first increases and then decreases; and the stationary probability of π_5 and π_6 gradually decreases.

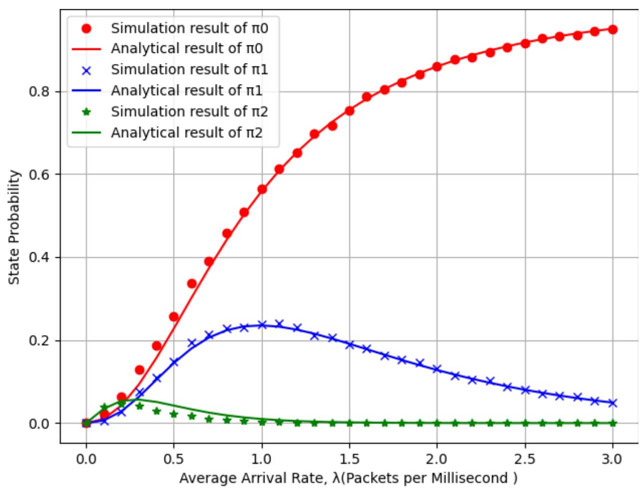

Fig. 2. Stationary probability π_0,π_1,π_2.

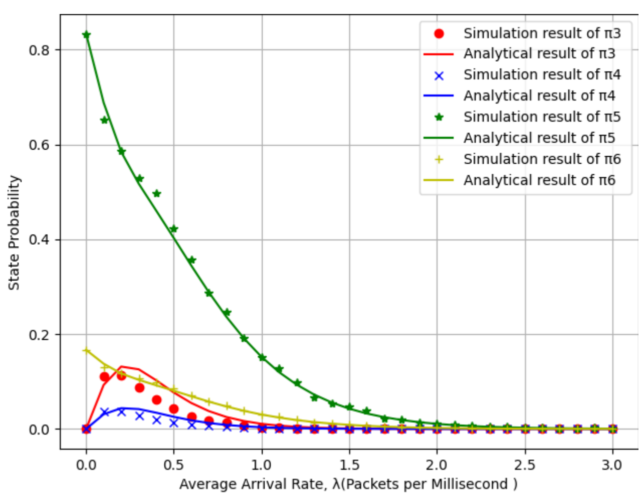

Fig. 3. Stationary probability π_3,π_4,π_5,π_6.

B. Energy Efficiency

Energy efficiency η is defined as the amount of data that the UE can receive per unit of the energy consumed. The unit of energy efficiency is bit/J. Circuit power consumption is P_c=0.1W, and transmission power consumption is P_{tx}=46dBm. The total energy consumption E and the energy efficiency η are calculated by the following formulas:

$$E = TP_{tx} + (\pi_0 T_0 + \pi_1 T_1 + \pi_2 T_2 + \pi_4 T_4 + \pi_6 T_6)P_c; \tag{13}$$

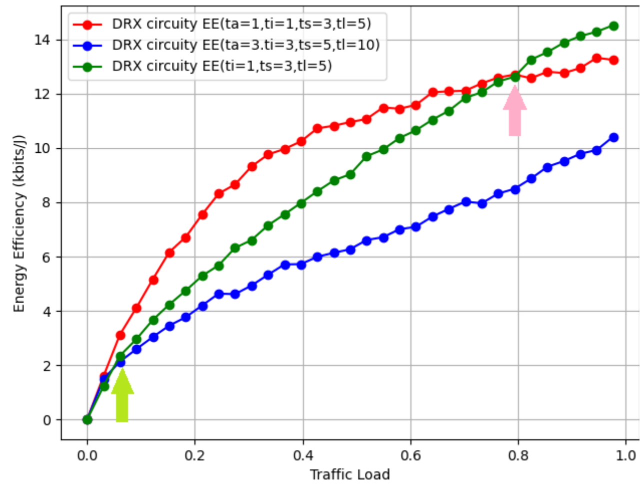

Fig. 4. Energy efficiency results with parameter of m=2.

$$\eta = \frac{\mu T}{E}. \tag{14}$$

This scheme sets the UE to work in the block-fading channel. The time slot is T_s, whose value is equal to the fading time. Nakagami-m block fading channel, which is widely used in wireless channel modeling, is modeled for simulation. The shape parameter is m. Let m=2. The probability distribution of the signal-to-noise ratio (SNR) attenuation of this channel is as follows:

$$f_\gamma(\gamma) = \frac{\gamma^{m-1}}{\Gamma(m)}(\frac{m}{\bar{\gamma}})^m exp(-\frac{m}{\bar{\gamma}}\gamma)(\gamma \geq 0). \tag{15}$$

The service rate is:

$$S[n] = T_s C[n] = T_s B_c log_2(1+\gamma[n]). \tag{16}$$

Here, B_c=180kHz, the average SNR $\bar{\gamma}$=10dB. According to these two formulas, the average service rate can be obtained by generating random numbers and then calculating the mean value.

As can be seen from Fig. 4, along with the increase of λ value, the energy efficiency keeps improving. Traffic load is the ratio of average data arrival rate to average service rate. When the traffic load is between 0 and 1, the energy efficiency of the first set of configuration is greater than that of the second set of configuration.

The first set of seven-states DRX system is configured as t_a=1ms, t_i=1ms, t_s=3ms, t_l=5ms, and the second set is configured as t_a=3ms, t_i=3ms, t_s=5ms, t_l=10ms. The green curve serves as a comparison curve with the same configuration as the four-states DRX system, as described in paper [3], t_i=1ms, t_s=3ms, t_l=5ms. If the condition with known packet interval model is removed, the system will delete the long wake state, short sleep monitor state, and long sleep monitor state. And this scheme will be consistent with the four-states scheme. Compared with the four-states scheme in paper [3], the seven-states system with DRX function is more applicable.

It can be observed that when the traffic load is over high, the energy efficiency of the four states is the highest. The first configuration of the seven-states scheme is the most energy-efficiency when the traffic load is in the middle. When the traffic load is low, the second configuration of the seven-states scheme has the highest energy efficiency.

The reasons are as follows:

When the traffic load is less than 0.05, the data arrival rate is low. The intersection point is indicated by green arrows in Fig. 4. The second set of configuration in the seven-states scheme can make the system sleep more in order to save energy.

When the traffic load exceeds 0.05 and gradually increases, the energy efficiency of the original four-states DRX system will fall between the energy efficiency of the first configuration and the second configuration of the seven-states DRX system. This is because the first configuration of the seven-states DRX scheme can enable the system to receive the next packet a time slot as short as possible. However, the second set of configuration has a relatively long wake-up time. Although it can minimize the delay caused by packets coming during the sleep state, the relatively long wake-up state will result in lower energy efficiency than the original four-states scheme.

In Fig. 4, the red line and the green line intersect at a point. The intersection point is indicated by pink arrows. The point's horizontal coordinate is 0.79. Focus on the right side of the intersection, the energy efficiency of the four-states scheme is higher than that of the seven-states scheme, due to, t_{i}=1ms in the four-states scheme. Each slot has a high probability of a packet arriving. While, the system in the seven-states scheme takes longer to wake up, because it considers avoiding as far as possible the situation that packets arrive while sleeping. In some cases, the packets in the first time slot and the second time slot of the long wake-up state are not collected. However, in order to reduce the delay (t_{a}=3ms), the system is still kept in the wake-up state to monitor PDCCH, so that the third time slot can receive and decode the data packet immediately. Therefore, their energy efficiency is relatively lower than that of a four-state DRX system.

C. Improvement of the Energy Efficiency

Improvement refers to the improvement of the energy efficiency of the seven-states system relative to that of the single-mode circuit at the λ value.

As can be seen from Fig. 5, along with the increase of λ value, the amount of improvement first increases and then decreases, and the amount of improvement in configuration 1 is always larger than that in configuration 2.

IV. CONCLUSION

The paper discussed an IoT device with DRX function, and designed a UE scheduling strategy with known packet interval model. Under these conditions, the scheme analyzes the stationary probability of each state, the energy efficiency, and the improvement of energy efficiency relative to the single-mode circuit, based on the cross-layer analysis model. According to the observation, this scheme can improve the energy efficiency on the basis of single-mode circuit. There are some challenges to this strategy. FLAG1 and FLAG2 Settings are dependent on whether the base station is in continuous packets. This strategy does not take into account what to do if something unexpected happens.

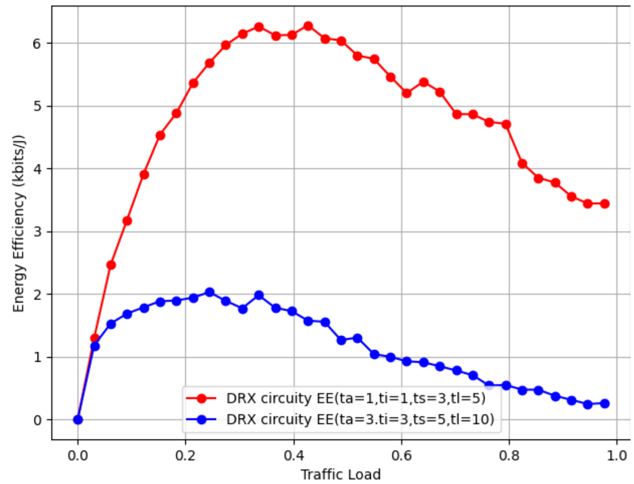

Fig. 5. Improvment results with parameter of m=2.

ACKNOWLEDGMENT

This research is funded by Beijing University of Posts and Telecommunications-China Mobile Research Institute Joint Innovation Center(Project Number: R207010101125D9) and Fundamental Research Funds for the Central Universities (Project Number: 2021RC01).

REFERENCES

[1] A. Khlass, D. Laselva and R. Jarvela, "On the Flexible and Performance-Enhanced Radio Resource Control for 5G NR Networks," in *2019 IEEE 90th Vehicular Technology Conference (VTC2019-Fall)*, 2019, pp. 1-6.

[2] F. Moradi, E. Fitzgerald, M. Pióro and B. Landfeldt, "Flexible DRX Optimization for LTE and 5G," *IEEE Transactions on Vehicular Technology*, vol. 69, no. 1, pp. 607-621, Jan. 2020.

[3] B. Cai, Y. Chen and I. Darwazeh, "Analyzing Energy Efficiency for IoT Devices with DRX Capability and Poisson Arrivals," in *2019 26th International Conference on Telecommunications (ICT)*, 2019, pp. 254-259.

[4] L. Sharma, B. B. Kumar and S. Wu, "Performance Analysis and Adaptive DRX Scheme for Dual Connectivity," *IEEE Internet of Things Journal*, vol. 6, no. 6, pp. 10289-10304, Dec. 2019.

[5] S. Rostami, S. Lagen, M. Costa, M. Valkama and P. Dini, "Wake-Up Radio Based Access in 5G Under Delay Constraints: Modeling and Optimization," *IEEE Transactions on Communications*, vol. 68, no. 2, pp. 1044-1057, Feb. 2020.

[6] F. Moradi, E. Fitzgerald and B. Landfeldt, "Modeling DRX for D2D Communication," *IEEE Internet of Things Journal*, vol. 8, no. 4, pp. 2574-2584, Feb. 2021.

[7] M. Matin and M. I. Hossain, "A New Adaptive Discontinuous Reception (DRX) Model for Power Saving in LTE System," in *2019 22nd International Conference on Computer and Information Technology (ICCIT)*, 2019, pp. 1-6.

[8] S. Rostami, H. D. Trinh, S. Lagen, M. Costa, M. Valkama and P. Dini, "Wake-Up Scheduling for Energy-Efficient Mobile Devices," *IEEE Transactions on Wireless Communications*, vol. 19, no. 9, pp. 6020-6036, Sep. 2020.

[9] J. Liang, C. Hsu, J. Chen, K. Wu and Y. Tseng, "Three-Stage DRX Scheduling for Joint Downlink Transmission in C-RAN," *IEEE Wireless Communications Letters*, vol. 9, no. 2, pp. 129-133, Feb. 2020.

[10] J. Zhou, G. Feng, T. P. Yum, M. Yan and S. Qin, "Online Learning-Based Discontinuous Reception (DRX) for Machine-Type Communications," *IEEE Internet of Things Journal*, vol. 6, no. 3, pp. 5550-5561, Jun. 2019.

[11] M. K. Maheshwari, A. Roy and N. Saxena, "DRX over LAA-LTE-A New Design and Analysis Based on Semi-Markov Model," *IEEE Transactions on Mobile Computing*, vol. 18, no. 2, pp. 276-289, Feb. 2019.

[12] M. K. Maheshwari, M. Agiwal, N. Saxena and A. Roy, "Hybrid Directional Discontinuous Reception (HD-DRX) for 5G Communication," *IEEE Communications Letters*, vol. 21, no. 6, pp. 1421-1424, Jun. 2017.

[13] M. Li and H. Chen, "Energy-Efficient Traffic Regulation and Scheduling for Video Streaming Services Over LTE-A Networks," *IEEE Transactions on Mobile Computing*, vol. 18, no. 2, pp. 334-347, Feb. 2019.

[14] M. Lee and T. Lee, "Energy Harvesting Discontinuous Reception (DRX) Mechanism in Wireless Powered Cellular Networks," *IET Communications*, vol. 11, no. 14, pp. 2206-2213, Sep. 2017.

[15] S. Xu, Y. Liu and W. Zhang, "Grouping-Based Discontinuous Reception for Massive Narrowband Internet of Things Systems," *IEEE Internet of Things Journal*, vol. 5, no. 3, pp. 1561-1571, Jun. 2018.