

M2M Energy Saving Strategy in 5G Millimeter Wave System

Aiguo Shen

jimei University

Qiubo Ye

Jimei University

Guangsong Yang (✉ bieyun8409@163.com)

Jimei University <https://orcid.org/0000-0002-9423-3862>

Xinyu Hao

jimei university

Research Article

Keywords: 5G, M2M, BM-DRX, energy saving, delay

Posted Date: June 4th, 2021

DOI: <https://doi.org/10.21203/rs.3.rs-188319/v1>

License: © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

M2M Energy Saving Strategy in 5G Millimeter Wave System

Aiguo Shen¹, Qiubo Ye², Guangsong Yang^{2*} and Xinyu Hao²

¹Chengyi University college, Jimei University, Xiamen 361021, China

²School of Information Engineering, Jimei University, Xiamen 361021, China

Corresponding author: Guangsong Yang (e-mail: gsyang@jmu.edu.cn), QiuboYe(e-mail:qbye@jmu.edu.cn)

ABSTRACT

M2M (Machine to Machine) technology has a broad application prospect in 5G network, but one of the bottlenecks is the energy consumption of intelligent devices powered by battery. In this paper, we study the energy saving strategy in 5G millimeter wave system. Firstly, a Discontinuous Reception scheme based on Beam Measurement (BM-DRX) is proposed to avoid the unnecessary beamforming. Secondly, by modifying the frame structure and optimizing the beamforming, the time of beamforming is further shortened and the power consumption is also saved. Finally, based on the ETSI (European Telecommunications Standards Institute) data model, the beam misalignment events are regarded as Poisson distribution, and the semi-Markov process is used to analyze the BM-DRX. Simulation results show that the proposed scheme can not only meet the delay performance, but also save the energy consumption of the system.

INDEX TERMS 5G, M2M, BM-DRX, energy saving, delay

I. INTRODUCTION

In the Fifth Generation (5G) communication networks, some strategies are used to satisfy the demands of growing data capacity, data rate and provide the best quality of service requirements.

Firstly, in order to improve the data bandwidth and connection efficiency, achieve better download and upload speed and less delay, bands are specified in two Frequency Ranges (FR) in 3GPP Release 15. FR1 ranges from 450 MHz to 6000 MHz, known as cmWave. FR2 ranges from 24250 MHz to 52600 MHz, which are commonly referred to as mmWave.

Moreover, some technology such as beamforming are used in 5G network. References [1], [2] show that millimeter wave spectrum can support high-speed data rate by using beamforming technology with multi-antenna arrays. Efficient beamforming is helpful to improve spectrum efficiency, reduce system interference and enhance wireless communication security. At the same time, with the rapid development of electronics and computer, the intelligent devices can fulfill the requirement of higher bandwidth service [3]. M2M (Machine to Machine) communication is widely used in 5G Internet of Things (IoT) [4], including the fields of industrial vehicle network, automation, smart grid, telemedicine, etc. With the exponential growth of the number of M2M intelligent devices, the data flow is expanding rapidly. The increasing of M2M devices will not only affect Access Networks (ANs) but also Core Networks (CNs). Because most of the devices are powered by battery, such as intelligent wearable devices, UAVs (unmanned aerial vehicles), intelligent electric meters, the power saving of intelligent device is a crucial issue for the 5G M2M network. Thus, increasing energy efficiency in mobile networks will reduce the costs of capital and operational expenditures. It makes energy efficiency extremely important.

There are many energy saving technologies for 5G wireless networks. Some recent researches on green 5G technology and communication energy harvest are reviewed in reference [5]. Some new technologies are also discussed related to energy saving technology including User-Centric Design, intelligent devices On/Off switching, interference management, power control, etc. Discontinuous Reception (DRX) is also a kind of energy saving scheme in 4G network, which allow user equipments (UEs) to make signaling free transitions between sleep and awakened states. Due to 3GPP supports DRX integration in 5G network [6], so we study DRX related energy saving strategy of M2M in 5G Millimeter Wave System, combining with beamforming, optimization of 5G frame structure and etc..

In this paper, we focus on the following four aspects to improve the energy and delay performance of M2M communication in 5G network.

- 1) Beam strategy. In the multi-beam millimeter wave scenario, beamforming is unnecessary after each DRX sleep process. The user device measures the current beam pair's level after DRX sleep to decide whether to beamform. Specifically, a threshold value of beam pair level is set, if the measured level larger than it, the beam is aligned and the intelligent

device can effectively decode PDCCH data and signaling. Otherwise, the beam is of misalignment, and need beamforming.

- 2) Optimize 5G frame structure. Flexible 5G frame structure can realize the balance of spectrum efficiency, air interface delay and reliability [29], [30]. In this paper, short frame structure is adopted to reduce the time of beamforming and listening to PDDCH channel, so as to reduce power consumption and delay.
- 3) Optimize DRX configuration. Based on LTE-DRX, two sleep-ready timers are set for different sleep states (light sleep and deep sleep). In the sleep state of DRX, after a successful beamforming, it does not turn into the active state, but enters the sleep-ready state. When the sleep-ready timer expires with beam alignment and no data arrival, then go to sleep state. It can reduce the impact of the beam misalignment in the case of no data arrival, and turn into the sleep state as frequently as possible to save energy.
- 4) Select data model. In this paper, ETSI data model [31] is adopted, and Poisson process of beam misalignment events is defined to make the model closer to reality. A Semi-Markov model of eight states is established to evaluate the impact of beam misalignment events on the performance of the whole DRX scheme.

II. RELATED WORKS

A. ENERGY SAVING TECHNOLOGY

There are many energy saving methods in M2M systems by considering different protocol layers.

In physics layer, the power control is a main effect factor. In [7], an Energy Transfer and Transmission Adaptation (ENTRADA) method is proposed to determine the optimal transmission power of users. Suppose that each user is associated with a utility function which represents its QoS requirements. The distributed power control problem is defined as the utility maximization problem of each user to determine the optimal transmission power of the user and meet their QoS requirements. A wireless powered communication networking (WPCN) technology is discussed in [8], where the battery of wireless communication devices can be remotely replenished by means of microwave wireless power transfer (WPT) technology. An overview of the key networking structures and performance enhancing techniques is provided to build an efficient WPCN, and points out new and challenging future research directions for WPCN. Based on the wireless powered communication (WPC) technique, an energy-aware clustering and resource management framework is proposed to extend the operation time of the whole M2M network [9].

In data link layer, many energy saving methods are proposed. Reference [10] studies the energy-saving design by considering quality of service (QoS) in long-term evolution (LTE) network for M2M / H2H coexistence scenario. The problem of resource allocation is described as the maximization of bit capacity per joule based on effective capacity under statistical QoS configuration. An implicit weed optimization (IWO) algorithm is proposed, which can satisfy energy efficiency and QoS requirements. A MAC layer scheduling method combining with beam aware is proposed in [11] by considering the interval between channel measurement and data transmission. The BS processes the scheduling according to the result of channel measurement instead of every slot. The simulation results and mathematical expression both demonstrate that the beam-aware media access control (MAC) framework improves throughput under power constraint. A new scheduling algorithm is also proposed in [12] to improve battery life and ensure better spectrum efficiency by reducing energy consumption. Based on Non-orthogonal Multiple Access (NOMA) technology, [13] proposed a novel energy-efficient resource allocation algorithm to optimize the energy efficiency of M2M communication. Reference [14] considered a Wireless sensor networks with aggregated node and proposed an optimal partial aggregation technique for compromise of both energy and delay.

B. DRX METHODS AND BEAM ALIGNMENT

Since the mobile user device is significantly restricted by the battery capacity, most existing wireless mobile networks, such 3G and 4G mobile communication, employ discontinuous reception (DRX) to conserve the power of mobile stations (MSs) [6], [15]. In [16], DRX mechanism is applied to the IOT gateway which reduced the power consumption of IOT gateway and improves the energy efficiency.

If the DRX scheme is directly moved to the 5G environment, especially the millimeter wave environment, it will have an adverse effect on DRX performance [17], [18]. Because beamforming is relatively time-consuming, data transmission needs to be carried out under the successful pairing of the beam pairs of the transmitter and the receiver, which makes the sleep time in the DRX scheme shorter and the supervision time of the PDCCH (Physical Downlink Control Channel) down link channel longer.

Many papers focus on the research of beam alignment and misalignment. Reference [19] describes the relationship between the moving speed of intelligent devices and the probability of beam misalignment in DRX state. When the moving speed of intelligent devices is 30km/h and the short sleep cycle interval of DRX is 100ms, the probability of beam misalignment is

0.1. When the short sleep cycle interval of DRX is 300ms, the probability of beam misalignment is less than 0.3. When the speed of the intelligent devices is 90km/h, the probability of beam misalignment is about 0.22 and 0.47 for the same DRX configuration. Therefore, under the DRX scheme, when the intelligent device moves slowly and in static state, the probability of beam misalignment is very low. In [20], directional-discontinuous reception (D-DRX) is proposed for millimeter-wave enabled 5G communications, to address alignment of directional beams between base station (BS) and intelligent user devices (UD) after a sleep cycle. When the best beam pair is searched, the beam search process is stopped instead of the full beam search, and the energy consumption is reduced by 10%.

An M2M paging scheme combined with DRX is proposed to reduce the network load and signaling overhead between BS and UD in 5G network [21], and then reduce power consumption. In [22], an interoperable hybrid H-DRX scheme is proposed in 4G/5G core network. When a 4G core network finds 5G data arriving, it sends beamforming prompt information to 5G intelligent user devices, so as to reduce unnecessary beam-forming and save power consumption. Because user devices need to be connected to 4G and 5G networks at the same time, they will also increase power consumption

Based on the study of [20], an extended HD-DRX scheme is proposed in [23], which adds a single active state of packet between the states of sleep and awake. In this state, user devices are allowed to receive packets during sleep within a certain threshold without switching to the active state to save power. Therefore, the user devices can directly receive short burst packets without beam searching procedure, thus reducing the beam searching time. In [24], a DRX scheme of beam sensing in M2M scenario is proposed. When the best matched beam pair is searched in DRX state, the beam pair is always used for data transmission, while other unauthorized beams are not used. Although this scheme can reduce the time of beamforming, it has poor flexibility without considering the changes of the surrounding environment. In [25], [26], a dynamic beam-aware DRX scheme is proposed, which could be applied along with dynamic mmWave beam configuration for better energy efficiency.

In [27], a fast beam tracking DRX scheme is proposed in the UAV scenario with D2D structure, focusing on analyzing system performance from sleep rate and average packet delay. In [28], under the DRX scheme of 5G, the method of beam training and feedback is adopted, which points out that frequent beamforming in DRX state is unnecessary. They use Poisson modeling to analyze the method, without considering the self-similarity of the data. The simulation shows that the energy saving effect is less than 80%, and the parameters need to be further optimized.

III. DESIGN OF MULTI-BEAM SLEEP SCHEME

A. SYSTEM MODEL

We consider a system shown in Figure 1 which consists of 5G base station (BS) with M beams and many small intelligent user devices (UD) with N beams, including sensors and actuators which are connected through the network. The network provides a communication means for sending and receiving data that is in a periodic form of M2M based communication. At a certain time, only one transmit and receive beam pair can be established between BS and a UD.

The purpose of beamforming is to find the best beam pair and establish connection between the BS and UDs.

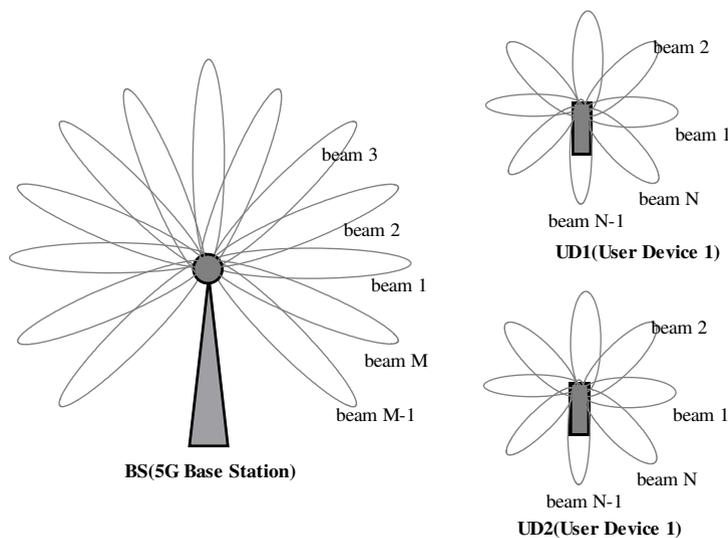


FIGURE 1. 5G M2M communication system with beamforming.

According to Friis free space path loss, RF coverage distance is inversely proportional to the carrier frequency square. In the 5G network, intelligent devices, base station gains, RF bandwidth, coding, and modulation techniques determine cell coverage. In our paper, the path loss can be estimated according to the specific channel model in reference [32].

Compared with 3G and 4G, 5G use millimeter wave which works in a higher frequency band, so it needs to overcome the huge path loss [33]. Fortunately, the millimeter wave antenna array can focus narrow beam and propagate towards the target direction by using beamforming technology, so as to reduce path loss and reduce interference [34], [35].

As shown in Figure 1, UD performs full beam search. It needs to search $M*N$ beam pairs, so as to find the best beam and transmit data with the best channel quality. To keep the beam alignment, the UD checks periodically the channel status on the given beam pair and appropriately changes the beam not to be misaligned.

There are many reasons of beam misalignment, such as the mobility of UD, the drastic changes of communication channel and the collision due to competing millimeter wave channel with other UD in beamforming.

B. BEAM AND FRAME STRUCTURE

Reference [9] tells us that in the case of low mobility of UD, the probability of beam misalignment is very low in DRX state, and Reference [4] shows that frequent beamforming is unnecessary in DRX state. In our scheme, a level threshold Th needs to be set, which is the minimum level value to ensure the beam pairing and data transmission between BS and UD. In the DRX state, UD immediately measures the current beam pair after its sleep. If the beam pair level is greater than Th , UD sends a feedback to BS to establish the channel between the BS and UD. Otherwise, beamforming is required until the beam pair level is greater than Th , instead of full beam search.

The beamforming time is related to the frame length L , which is at millisecond level in 5G standard. The time for full beam search is $M*N*L$, and the average statistical time required for best beam search is $M*N*L/2$. Assuming that the threshold level Th is half of the best beam level, and the level of each beam pair is not equal to each other, the average time required for the beam search is $M*N*L/4$.

5G supports flexible frame structure. As expected for 5G communication networks [29], shorter frame size will be used. The proposed solution encompasses flexible multiplexing of users on a shared channel with dynamic adjustment of the transmission time interval (TTI) in coherence with the service requirements per link. This allows optimization of the fundamental trade-offs between spectral efficiency, latency, and reliability for each link, as well as efficient machine type communication support. Reference [30] verified the advantages of DRX based on 2ms (TTI=0.02ms) short frame in terms of power saving and delay. Obviously, the short frame structure can reduce the beam search time, the power consumption of UD in DRX state and the delay caused by beamforming can also be reduced.

In this paper, we consider a variety of different frame structures, which can adapt to different application scenarios. We assume that the number of beams and time slots in the frame structure of 5G base station can meet the access needs of all intelligent devices in the cell, and the beamforming after beam misalignment can find the beam pair to establish the connection of the uplink and downlink channels.

C. BEAM MEASUREMENT BASED DRX SCHEME (BM-DRX)

In this section, we propose a beam measurement based DRX scheme (BM-DRX). UD measures the threshold of current beam pair after its DRX sleep. If the measured value is greater than the threshold Th , beam can be thought as aligned, and UD can effectively decode PDCCH data and signaling. If it is less than Th , it would be misaligned, and beamforming should be done.

We design two sleep-ready timers similar to LTE-DRX, which correspond to beamforming in light-sleep and deep-sleep respectively, so that UD can quickly turn to sleep and save energy. In Figure 2, OFF indicates that UD is asleep, and ON indicates that UD is active.

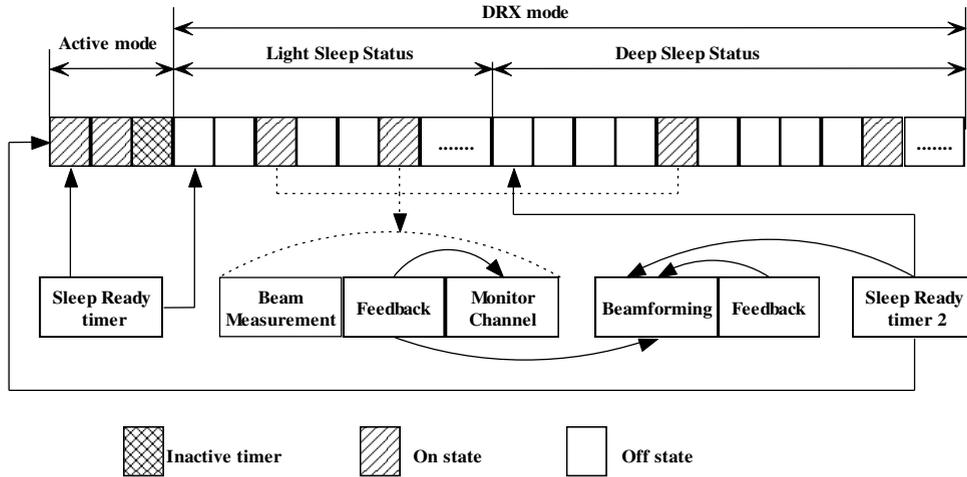


FIGURE 2. BM-DRX Scheme.

According to figure 2, the flow of BM-DRX scheme is as follows:

Step 1. Initialization stage of beamforming. Base station BS sends M beams, UD sends N beams, both sides search the best beam pair and establish wireless connection.

Step 2. Start the data transmission state, UD starts the inactive timer t_i . If the beam pair is aligned and the inactive timer times out, no data is sent to UD, and then go to step 3. Otherwise start the inactive timer, and go to step 2; if the beam is not aligned, go to step 1.

Step 3. Enter DRX energy-saving state. The sleep-ready timer 1 is started, and UD will continue to listen to the channel. If the beam pair is aligned and the sleep-ready timer times out, and no data arrives at UD, UD will shut down the RF unit, and turn to the light sleep state, then go to step 4; otherwise, go to step 2. If the beam pair is not aligned before the sleep-ready timer 1 times out, go to step 1.

Step 4. Enter the light sleep cycle state and start the light sleep timer. After sleep, BS-UD beam level should be measured at first. If the beam pair is not aligned, UD will turn to beam search state and execute step 5. If the beam pair is aligned, UD will send feedback to confirm ACK to BS and listen to channel state. If no data arrives at UD, continue to sleep; otherwise, execute step 2. If the light sleep timer times out and no data arrives at UD in the beam alignment state, turn to the long sleep cycle state and execute step 6.

Step 5. From light sleep state to beam search state for beamforming. If the beam pair is aligned, start the sleep-ready timer 1 and go to step 3.

Step 6. Enter deep sleep cycle state and start deep sleep timer. After sleep, BS-UD beam level should be measured at first. If the beam pair is not aligned, BS will turn to beam search state and go to step 7. If the beam pair is aligned, BS shall send feedback to confirm ACK to BS and listen to the channel state. If no data arrives at UD, continue to sleep; otherwise, go to step 2. If the beam pair is aligned and no data arrives at UD before the long sleep timer expires, start the sleep-ready timer 1, and go to step 3.

Step 7. From deep sleep state to beam search state for beamforming. If the beam pair is aligned, start the sleep-ready timer 2. If the sleep-ready timer 2 times out and no data arrives at UD, go to step 6; otherwise, go to step 2.

Based on the above discussion, we will study following 3 DRX schemes. If the beamforming strategy is full beam search, we call it F-BM-DRX. If the beamforming strategy is best beam search, we call it B-BM-DRX. If the beamforming strategy is based on the beam threshold Th , we call it T-BM-DRX.

Based on Figure 2, the algorithm of BM-DRX scheme is as follows:

Algorithm of BM-DRX scheme

Step 1. Initialization stage of beamforming

Step 2. Start timer t_i

for ($t_i=0; t_i = t_i + 1; t_i < t_{i_{max}} + 1$) do

if beam \leftarrow misaligned, goto step 1

else if data \leftarrow non-arrival, goto step2

else goto step1.

end

end

```

end
Step 3. Enter DRX mode, Start sleep-ready timer1  $t_p$ 
  for (  $t_p=0; t_p = t_p + 1; t_p < t_{p\max} + 1$  ) do
    if beam  $\leftarrow$  misaligned, goto step 1
    else if data  $\leftarrow$  non-arrival, goto step4
    else goto step2.
    end
  end
end
Step 4. Start light sleep timer1  $t_s$ 
  for (  $t_s=0; t_s = t_s + 1; t_s < t_{s\max} + 1$  ) do
    if beam  $\leftarrow$  misaligned, goto step 5
    else if data  $\leftarrow$  non-arrival, goto step6
    else goto step2.
    end
  end
end
step 5. Execute beamforming
  if beam  $\leftarrow$  misaligned, goto step 5
  else goto step 3
  end
Step 6. Start deep sleep timer1  $t_l$ 
  for (  $t_l=0; t_l = t_l + 1; t_l < t_{l\max} + 1$  ) do
    if beam  $\leftarrow$  misaligned, goto step 7
    else if data  $\leftarrow$  non-arrival, goto step3
    else goto step2.
    end
  end
end
step 7. Execute beamforming
  if beam  $\leftarrow$  misaligned, goto step 7
  else goto step 3
  end
end

```

IV. BM-DRX AND ITS ANALYTICAL MODEL

In the process of 5G M2M millimeter wave communication, beam misalignment is inevitable. Poisson distribution is suitable for describing the number of random events occurring in unit time (or space), such as the number of machine failures, the number of natural disasters, the number of product defects, the number of accidents on the highway etc.. In Reference [19], we know that under the DRX scheme, when the intelligent device moves slowly or in static state, the probability of beam misalignment is very low. The beam misalignment rate is also the number of misalignment per unit of time, so the hypothesis that beam misalignment events are Poisson is reasonable. In order to analyze the influence of beam misalignment on DRX performance, we assume that the beam misalignment events follow the Poisson distribution with parameter α which represents the misalignment rate [28]. Then the time interval of beam misalignment event indicates that the beam is not misaligned, which obeys the exponential distribution, and the mean value is $1/\alpha$. The misalignment rate represents the number of random beam misalignment events per unit time. We use ETSI data model instead of simple Poisson distribution. Some parameters are shown in Table I.

Table I Distribution of ETSI and beam misalignment parameters

Parameter	Distribution	Mean value
Inter-session idle time, t_{is}	Exponential	$1/\lambda_{is}$
Number of packet calls per session, N_{pc}	Geometric	μ_{pc}
Inter-packet call idle time, t_{ipc}	Exponential	$1/\lambda_{ipc}$

Number of packet calls per session, N_p	Geometric	μ_p
Inter-packet arrival time, t_{ip}	Exponential	$1/\lambda_{ip}$
Number of beam misalignments per session, N_α	Geometric	μ_α
Inter-misalignment idle time, t_α	Exponential	$1/\alpha$

According to the algorithm of BM-DRX scheme, we propose an eight states mathematical analytic model based on a semi-Markov chain to describe the UD behavior below.

S1, UD is in the active state;

S3, S8, UD enters the sleep-ready state, and listens for any incoming data;

S2, S5, S7, UD is in beamforming states, and sends feedback to BS;

S4, UD is in a light sleep state and periodically wakes up to listen for any incoming data;

S6, UD is in a deep sleep state and periodically wakes up to listen for any incoming data.

A. STATIONARY DISTRIBUTION

There are two situations of new packet call, one belongs to the current session process, and the other belongs to the beginning of the next session process. The number of packet calls obeys the memoryless geometric distribution. Packet data traffic consisting of packet service sessions is considered where each session comprises of one or more packet calls depending on the applications. The number of packet calls obeys the memoryless geometric distribution. When no data arrives at UD, the probability of interval t_{is} is $q_1 = 1/\mu_{pc}$, and the probability of t_{ipc} is $q_2 = 1 - 1/\mu_{pc}$ [36].

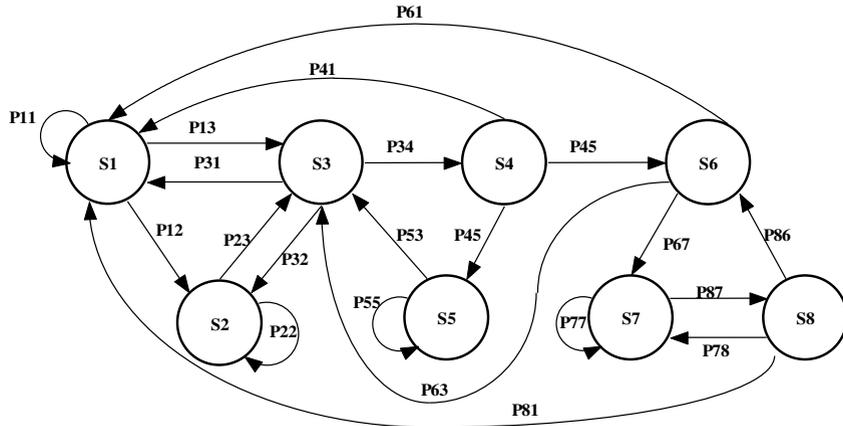


FIGURE 3. Markov chain of BM-DRX.

In state S1, RX is active. When no data arrives at RX, turn on the inactivity timer. Before the timeout of the inactivity timer, there are two possible events, i.e., beam misalignment and beam alignment. In the first event, the Rx goes to state S2 (i.e., transition S1→S2), and the transition probability is p_{12} . In second event, if any data arrives, then transit to S1 with transition probability p_{11} ; if no data arrives, the data interval may be a session interval or a packet call interval, then transit to S3 with transition probability p_{13} . The transition probabilities can be calculated as:

$$p_{11} = [q_2(1 - e^{-\lambda_{ipc}t_i}) + q_1(1 - e^{-\lambda_{is}t_i})]e^{-\alpha t_i} \quad (1)$$

$$p_{13} = (q_2e^{-\lambda_{ipc}t_i} + q_1e^{-\lambda_{is}t_i})e^{-\alpha t_i} \quad (2)$$

$$p_{12} = 1 - e^{-\alpha t_i} \quad (3)$$

In state S3, before the timeout of sleep-ready timer, when the beam is misaligned, then transit to state S2 with transition probability p_{32} . When the beam is aligned, if there is data arrival, then transit to S1 with a transition probability p_{31} . Otherwise, transit to S4 with a transition probability p_{34} . The analysis process of state S8 is the same as that of state S3. The duration of timer 2 and timer 1 is t_p , so the transition probabilities are as follows:

$$p_{31} = p_{81} = [q_2(1 - e^{-\lambda_{ipc}t_p}) + q_1(1 - e^{-\lambda_{is}t_p})]e^{-\alpha t_p} \quad (4)$$

$$p_{34} = p_{86} = (q_2e^{-\lambda_{ipc}t_p} + q_1e^{-\lambda_{is}t_p})e^{-\alpha t_p} \quad (5)$$

$$p_{32} = p_{87} = 1 - e^{-\alpha t_p} \quad (6)$$

In state S4, before timeout of the light sleep timer t_s , when the beam is not aligned, it transits to state S5 with transition probability p_{45} . When the beam is aligned, if there is data arrival, then transit to S1 with a transition probability p_{41} ; Otherwise, transit to deep-sleeping S6 with a transition probability p_{46} . The transition probabilities are as follows:

$$p_{41} = [q_2(1 - e^{-\lambda_{ipc}t_s}) + q_1(1 - e^{-\lambda_{is}t_s})]e^{-\alpha t_s} \quad (7)$$

$$p_{46} = (q_2e^{-\lambda_{ipc}t_s} + q_1e^{-\lambda_{is}t_s})e^{-\alpha t_s} \quad (8)$$

$$p_{45} = 1 - e^{-\alpha t_s} \quad (9)$$

In state S6, before timeout of the deep sleep timer t_l , when the beam is not aligned, it transits to state S7 with transition probability p_{67} . When the beam is aligned, if there is data arrival, then transit to S1 with a transition probability p_{61} . Otherwise, transit to sleep-ready state S3 with a transition probability p_{63} . The transition probabilities are as follows:

$$p_{61} = [q_2(1 - e^{-\lambda_{ipc}t_l}) + q_1(1 - e^{-\lambda_{is}t_l})]e^{-\alpha t_l} \quad (10)$$

$$p_{63} = (q_2e^{-\lambda_{ipc}t_l} + q_1e^{-\lambda_{is}t_l})e^{-\alpha t_l} \quad (11)$$

$$p_{67} = 1 - e^{-\alpha t_l} \quad (12)$$

In the beamforming states of S2, S5 and S7, if beam alignment is successful, then transit to sleep-ready states of S3 or S8 instead of S1, then listen to the channel, which helps to extend the sleep time. The transition probabilities are as follows:

$$p_{22} = p_{55} = p_{77} = 1 / \mu_\alpha \quad (13)$$

$$p_{23} = p_{53} = p_{78} = 1 - 1 / \mu_\alpha \quad (14)$$

According to the above state transition probability matrix, the stationary distribution π_i of each state can be obtained by using the following equation.

$$\begin{cases} \sum_{i=1}^8 \pi_i = 1 \\ \sum_{j=1}^8 \pi_j p_{ji} = \pi_i \end{cases} \quad (15)$$

B. ENERGY MODEL

The power consumption of UD depends on the average holding time of each Markov state. The longer the holding time of sleep state is, the lower the energy consumption of UD is. We use $T_i (i \in \{1, 2, \dots, 8\})$ to express the holding time of the Markov chain state of DRX.

The duration of T_1 in state S1 consists of two parts, the service time of $\mu_p - 1$ packets and the inactive time t_i^* ($t_i^* \leq t_i$). t_i^* includes the time of beam-alignment and misalignment. So the average holding time of state S1 is

$$E[T_1] = E[t_a] + E[t_i^*] = \frac{\mu_p - 1}{\lambda_{ipc}} + (q_2 \frac{1 - e^{-\lambda_{ipc}t_i}}{\lambda_{ipc}} + q_1 \frac{1 - e^{-\lambda_{is}t_i}}{\lambda_{is}})e^{-\alpha t_i} + (t_i + \frac{e^{-\alpha t_i} - 1}{\alpha})(1 - e^{-\alpha t_i}) \quad (16)$$

In the state S3, T_3 includes the time of beam-alignment and misalignment, then

$$E[T_3] = E[t_p^*] = (q_2 \frac{1 - e^{-\lambda_{ipc}t_p}}{\lambda_{ipc}} + q_1 \frac{1 - e^{-\lambda_{is}t_p}}{\lambda_{is}})e^{-\alpha t_p} + (t_p + \frac{e^{-\alpha t_p} - 1}{\alpha})(1 - e^{-\alpha t_p}) \quad (17)$$

The analysis method for T_8 of state S8 is the same as that for T_3 . We assume the duration of timer 1 and timer 2 are the same as t_p , i.e., $E[T_8] = E[T_3]$.

In the state of S4, T_4 is the sum of short cycles (t_{ds}) of UD. If timer t_s expires and no data arrives, the light sleep period lasts for $N_s = t_s / t_{ds}$ short cycles. Before t_s timeout, the light sleep period lasts for N_{si}^* ($N_{si}^* < N_s$) short cycles due to arrival of downlink data or misalignment. Different transition probabilities p_{41} and p_{45} correspond to N_{s1}^* and N_{s5}^* respectively, therefore

$$E[T_4] = E[n_{ds}]t_{ds} = (p_{46}N_s + p_{41}E[N_{s1}^*] + p_{45}E[N_{s5}^*])t_{ds} \quad (18)$$

Since t_{ipc} , t_{is} and t_α follow the memoryless exponential distribution, we can assume that N_s^* follows the geometric distribution with the mean value of $\frac{1}{p_n}$. Therefore,

$$E[N_s^*] = \left(\frac{q_1}{\Pr[t_{is} \leq t_{ds}]} + \frac{q_2}{\Pr[t_{ipc} \leq t_{ds}]} \right) e^{-\alpha t_{ds}} \quad (19)$$

$$E[N_{s5}^*] = \frac{(1 - e^{-\alpha t_{ds}})}{\Pr[t_\alpha \leq \tau]} \quad (20)$$

The analysis of state S6 is similar to that of state S4. T_6 is the sum of the long cycles (t_{dl}) of UD. If timer t_l times out and no data arrives, the deep sleep period lasts for $N_l = \frac{t_l}{t_{dl}}$ long cycles. Before the timeout of t_l , the deep sleep period lasts for $N_l^* (N_l^* < N_l)$ long cycles due to arrival of downlink data or misalignment. Different transition probabilities p_{61} and p_{67} correspond to N_{l1}^* and N_{l7}^* respectively. Therefore, we can obtain the following equations.

$$E[T_6] = E[n_{dl}]t_{dl} = (p_{63}N_l + p_{61}E[N_{l1}^*] + p_{67}E[N_{l7}^*])t_{dl} \quad (21)$$

$$E[N_{l1}^*] = \left(\frac{q_1}{\Pr[t_{is} \leq t_{dl}]} + \frac{q_2}{\Pr[t_{ipc} \leq t_{dl}]} \right) e^{-\alpha t_{dl}} \quad (22)$$

$$E[N_{l7}^*] = \frac{1}{\Pr[t_m \leq \tau]} (1 - e^{-\alpha t_{dl}}) \quad (23)$$

States S2, S5 and S7 all represent the process from beam search to beam pairing success. t_m mainly depends on the number of beam pairs and the algorithm of beam search and feedback.

$$E[T_2] = E[T_5] = E[T_7] = t_b + t_f \quad (24)$$

We define the probability of DRX semi Markov process in state S4 and S6 as the energy-saving parameter P_s . Since each DRX cycle contains a fixed monitoring cycle τ , the effective sleep time of each DRX cycle is $t_{ds} - \tau$ or $t_{dl} - \tau$. Then, $E[T_4]$ and $E[T_6]$ can be written as follows:

$$E[T_4^\#] = (p_{46}N_s + p_{41}E[N_{s1}^*] + p_{45}E[N_{s5}^*])(t_{ds} - \tau) \quad (25)$$

$$E[T_6^\#] = (p_{63}N_l + p_{61}E[N_{l1}^*] + p_{67}E[N_{l7}^*])(t_{dl} - \tau) \quad (26)$$

According to the above analysis, we can obtain the energy saving parameter of UD as follows:

$$P_s = \frac{\pi_4 E[T_4^\#] + \pi_6 E[T_6^\#]}{\sum_{i=1}^8 \pi_i E[T_i]} \quad (27)$$

C. DELAY MODEL

The BM-DRX sleep scheme will inevitably lead to a certain transmission delay, because some data must save at BS cache before sending to UD. Assume UD can service the arrived data timely in active state, the delay mainly results in the state of light-sleep, deep-sleep and beamforming. The probability of these three states is P_{L4} , P_{D6} and P_{Bj} respectively, therefore

$$P_{L4} = \frac{\pi_4 E[T_4^\#]}{\sum_{i=1}^8 \pi_i E[T_i]} \quad (28)$$

$$P_{D6} = \frac{\pi_6 E[T_6^\#]}{\sum_{i=1}^8 \pi_i E[T_i]} \quad (29)$$

$$P_{Bj} = \frac{\pi_j E[T_j]}{\sum_{i=1}^8 \pi_i E[T_i]} \quad (j = 2, 5, 7) \quad (30)$$

We use $d_i (i \in \{2, 4, 5, 6, 7\})$ to express the delay corresponding to the Markov chain at state S_i of DRX, then the total average waiting delay is

$$E[D] = P_{B2}E[d_2] + P_{L4}E[d_4] + P_{B5}E[d_5] + P_{D6}E[d_6] + P_{B7}E[d_7] \quad (31)$$

In state S4, the delay mainly depends on whether beam is aligned in this state. If beam is aligned, UD will find the arrival of data after sending feedback ACK to BS. Assuming that the arrived data of UD in the sleep state obeys even-distributed, the delay in alignment state is:

$$da_4 = \left(\frac{t_{dsc} + t_m + t_f}{2}\right)e^{-\alpha(t_{dsc} + t_m + t_f)} = \left(\frac{t_{dsc} + t_m + t_f}{2}\right)e^{-\alpha(t_{dsc} + t_m + t_f)} \quad (32)$$

If the misalignment occurs in state S4, then the delay will be increased. The data will be detected by UD after successful beamforming and sending feedback ACK to BS. If the beam misalignment occurs in the feedback stage after beamforming, it needs to go through N times of beamforming to the cyclic state of transmitting feedback. The parameter N obeys the memoryless geometric distribution, and the probability is $p_n = e^{-\alpha t_f}$ [28]. Therefore, the delay in misalignment state is:

$$d_{m4} = \left(\frac{t_{dsc} + t_m + t_f}{2} + \frac{t_b + t_f}{p_n}\right)(1 - e^{-\alpha(t_{dsc} + t_m + t_f)}) = \left(\frac{t_{dsc} + t_m + t_f}{2} + \frac{t_b + t_f}{e^{-\alpha t_f}}\right)(1 - e^{-\alpha(t_{dsc} + t_m + t_f)}) \quad (33)$$

In summary, the total average delay in the S4 state is

$$E[d_4] = da_4 + d_{m4} = \left(\frac{t_{dsc} + t_m + t_f}{2}\right)e^{-\alpha(t_{dsc} + t_m + t_f)} + \left(\frac{t_{dsc} + t_m + t_f}{2} + \frac{t_b + t_f}{e^{-\alpha t_f}}\right)(1 - e^{-\alpha(t_{dsc} + t_m + t_f)}) \quad (34)$$

Similar to delay analysis in S6 state, the average delay in the S4 state can be estimated as:

$$E[d_6] = \left(\frac{t_{dsc} + t_m + t_f}{2}\right)e^{-\alpha(t_{dsc} + t_m + t_f)} + \left(\frac{t_{dsc} + t_m + t_f}{2} + \frac{t_b + t_f}{e^{-\alpha t_f}}\right)(1 - e^{-\alpha(t_{dsc} + t_m + t_f)}) \quad (35)$$

In state S2, if beam-alignment occurs in feedback state, the delay is $(t_b + t_f)/2$. If the beam misalignment occurs in the feedback state, the analysis is the same as S4. Therefore,

$$E[d_2] = \frac{t_b + t_f}{p_n}(1 - e^{-\alpha t_f}) + \frac{t_b + t_f}{2} = \frac{t_b + t_f}{2}(2e^{\alpha t_f} - 1) \quad (36)$$

We can use the same methods to analyze delay in state S5, S7 and state S2.

$$E[d_2] = E[d_5] = E[d_7] \quad (37)$$

When equations (34), (35), (37) and (40) are introduced into equation (31), the delay model of the whole BM-DRX scheme can be obtained.

Table II Notation list

Symbol	Meaning
t_i	The length of the inactive timer
t_m	The period of beam measurement when UD wakes up from sleep in DRX mechanism
t_f	The feedback time of beam measurement results
t_p	The length of the sleep-ready timer
t_b	The period of beam forming
t_s	The length of the light sleep timer
t_l	The length of the deep sleep timer
τ	The period when UD wakes up from sleep in each DRX cycle

t_{dsc}	The period when UD sleeps in each light sleep DRX cycle
t_{dlc}	The period when UD sleeps in each deep sleep DRX cycle
t_{ds}	The period consists of τ and t_{dsc}
t_{dl}	The period consists of τ and t_{dlc}
N_s	The number of light sleep DRX cycles
N_l	The number of deep sleep DRX cycles

V. SIMULATION AND ANALYSIS

In this paper, Matlab is used for numerical simulation, and the simulation parameters are set as follows: $\lambda_{is} = 1/2200$, $\lambda_{ipc} = 1/30$, $\lambda_{ip} = 10$, $\mu_{pc} = 5$, $\mu_p = 25$, $\mu_\alpha = 10$, $t_i = 20\text{ms}$. 5G flexible frame structure can be adapted to different applications. In order to be more realistic, we consider the frame structure parameters of 5G NS-3 [37]. The frame structure length are $L=10\text{ms}$, 6ms and 4ms . The corresponding sub-frame TTIs are 1ms , 0.6ms , 0.4ms . $N_s = N_l = 10$, $t_f = t_m = L$, $t_i = 20\text{ms}$, $\tau = 4*L$. $t_s = t_{so} + i*\text{stepsize}$, $t_l = t_{lo} + i*\text{stepsize}$, step size= 10ms , $t_{so} = 300\text{ms}$, $t_{lo} = 400\text{ms}$. Transmitting beam of BS is $M=16$ (half power beamwidth 7°), and transmitting beam of UD is $N=8$ (half power beamwidth 15°).

Figure 4 shows the relationship between sleep-ready timer t_p and energy saving factor. On the same misalignment rate, the larger the sleep cycle (t_{ds} or t_{dl}) is, the longer the sleep time is, and the better the energy saving effect is. Under the same conditions, the energy saving effect of T-BM-DRX is the best, the energy saving performance of B-BM-DRX is the second, and that of F-BM-DRX is the worst. With the increase of t_p , the energy-saving effect is almost the same.

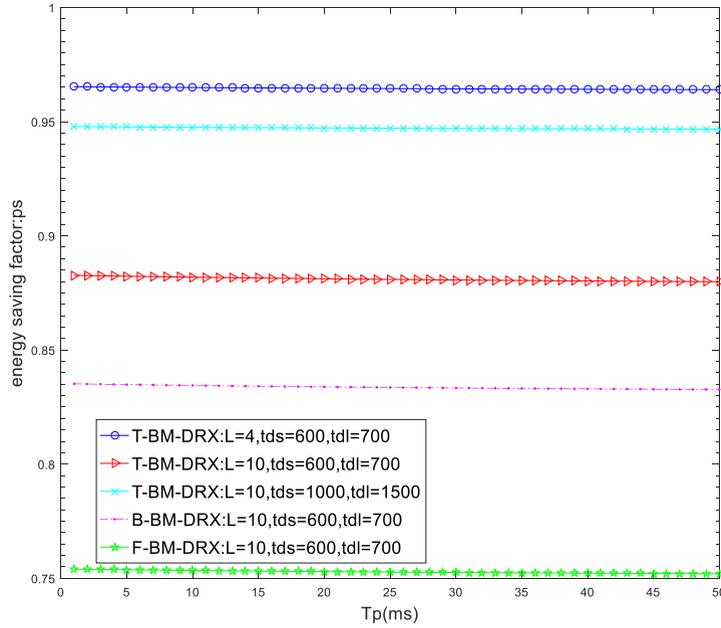


FIGURE 4. Relationship between sleep-ready timer and energy saving.

Figure 5 shows the effect of beam misalignment rate on DRX energy saving performance under three different BM-DRX parameter settings. The energy-saving effect of various DRX schemes decreases with the increase of beam misalignment. Under the same parameter settings, the energy-saving performance of F-BM-DRX decreases sharply with the increase of misalignment rate, while that of B-BM-DRX is relatively slow, and that of T-BM-DRX is the slowest. The energy-saving performance of BM-DRX with short frame is better than that of BM-DRX with long frame. Compared with BM-DRX with frame length 10ms , the energy-saving effect of F-BM-DRX with frame length 4ms is improved by at least 10% .

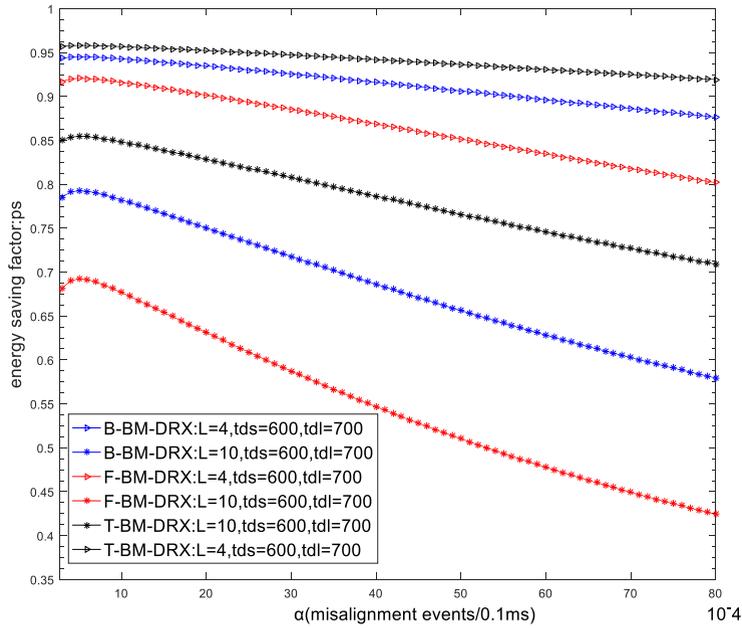


FIGURE 5. Effects of beam misalignment rate on energy saving.

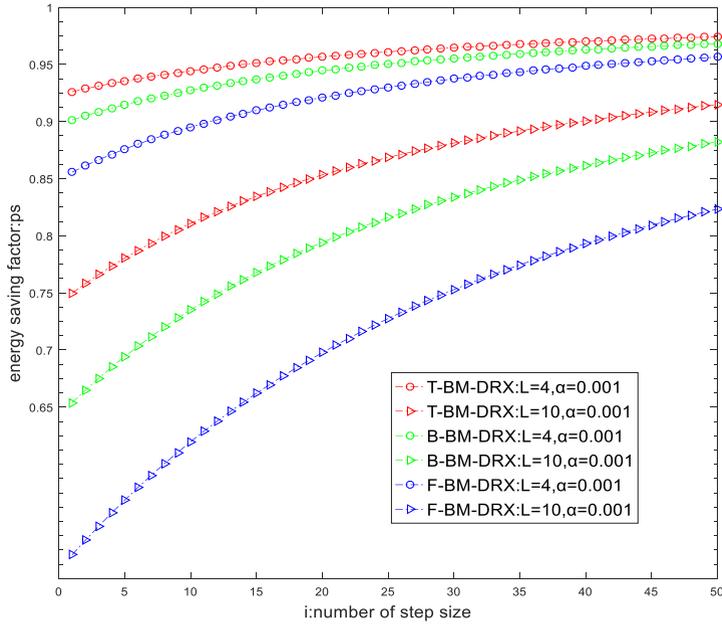


FIGURE 6. Effects of t_{ds} and t_{dI} on energy saving.

The greater the misalignment rate is, the more significant the improvement in energy saving effect is. T-BM-DRX frame length 4ms has the best energy-saving performance, and the energy saving parameter is above 92%.

Figure 6 shows the effect of long and short cycle (t_{ds} and t_{dI}) in two sleep states on energy saving performance of BM-DRX scheme. Under the same parameter settings, the energy saving effect of BM-DRX is more significant with the increase of the length of long and short cycle. The energy-saving effect of BM-DRX with short frame is better than that of BM-DRX with long frame. When $\alpha = 0.001$, short frame length $L=4$ ms, t_{ds} is greater than 300ms and t_{dI} is greater than 400ms, the energy-saving effect of T-BM-DRX and B-BM-DRX is above 90%.

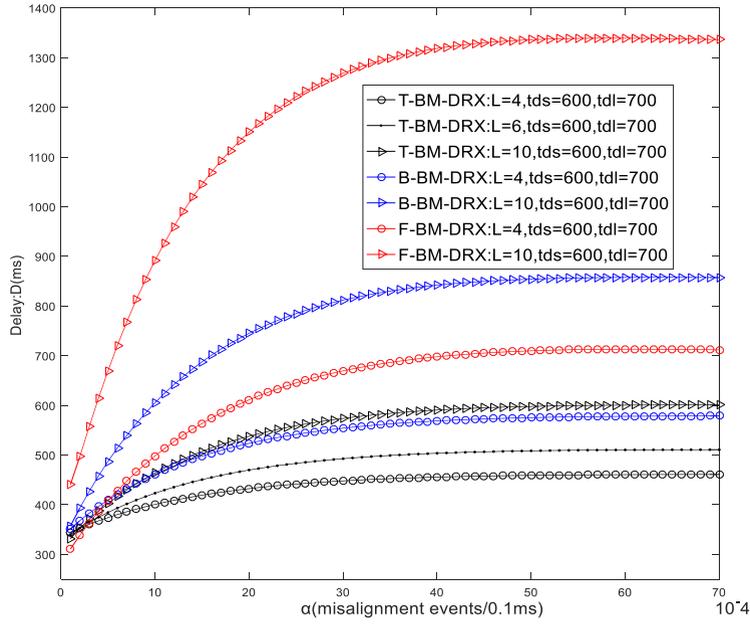


FIGURE 7. Effects of misalignment rate on delay.

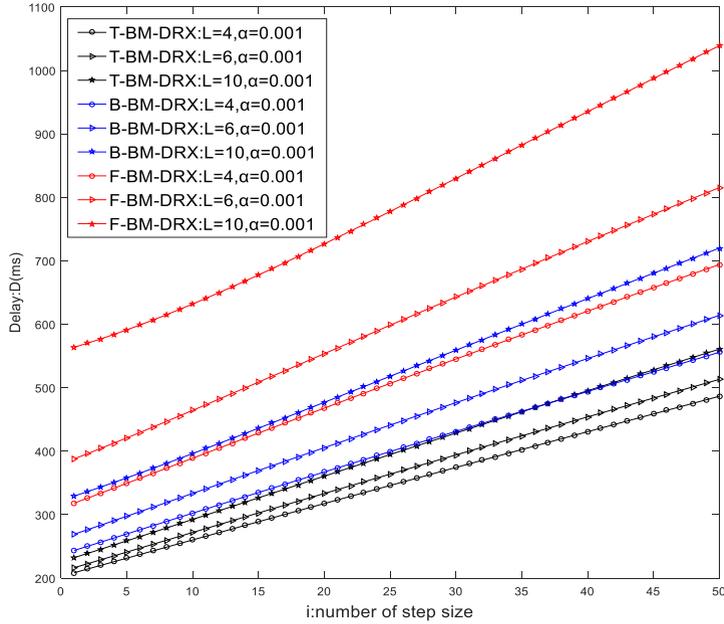


FIGURE 8. Effects of t_{ds} and t_{dl} on delay.

Figure 7 shows the relationship between delay and misalignment rate in BM-DRX scheme. The delay of BM-DRX increases with the increase of misalignment rate. This is because the beam misalignment leads to too much beamforming, and the data arriving at UD can only be found in the sleep state after the successful beamforming, which makes the delay longer. Under the same parameter settings, the delay performance of T-BM-DRX is the best, B-BM-DRX is the second, and F-BM-DRX is the worst. The delay performance of BM-DRX with short frame structure is better than that of BM-DRX with long frame structure. Figure 8 shows the effect of long and short cycle sleep intervals (t_{ds} and t_{dl}) in two sleep states on the delay performance of BM-DRX scheme. Under the same parameter settings, the time delay of BM-DRX increases with the increase of the length of

long and short cycle. Using short frame structure, BM-DRX shows better delay performance, where the short frame improves the delay performance of F-BM-DRX most obviously.

In summary, we have the following conclusions,

- 1) The sleep-ready timer can make UD go to sleep quickly to save energy.
- 2) Under the same conditions, T-BM-DRX has the best energy saving and delay effect, B-BM-DRX is the second, and F-BM-DRX is the worst.
- 3) Beam misalignment has a negative impact on the delay and energy saving of BM-DRX scheme. At low beam misalignment rate, adopting short frame can reduce the impact of beam misalignment and improve the performance of DRX system.
- 4) Short frame can improve the delay and energy-saving performance of the system. Especially in F-BM-DRX scheme, the energy-saving effect is very significant.
- 5) With the increase of long or short cycle, energy is saved but delay is prolonged in BM-DRX. Therefore, it is necessary to select parameters to find a tradeoff between delay and energy saving, according to the specific service QoS requirements.
- 6) With low beam misalignment, T-BM-DRX scheme with short frame $L=4\text{ms}$ can achieve more than 92% energy saving effect, and the delay can be less than 300ms.

VI. CONCLUSION

Except the ultra-low delay requirements in some scenarios such as the Internet of vehicles and UAVs, the millisecond delay in 5G can meet the QoS requirements of the vast number of M2M Internet of things services.

In our proposed scheme, unnecessary beamforming is avoided, and several methods are used to reduce the time of beamforming and reduce the adverse effects caused by beam misalignment. In the case of low beam misalignment rate, our scheme can effectively improve the delay and energy saving performance of DRX. 5G short frame structure can reduce beam search time, and UD power consumption in DRX state and delay caused by beamforming can also be reduced. When $\alpha = 0.001$, short frame length $L=4\text{ms}$, $t_{ds} = 600\text{ms}$, $t_{dl} = 700\text{ms}$, the energy-saving effect of T-BM-DRX can achieve about 96% energy saving effect, and the delay can be less than 400ms. Short frame structure with short time slot is suitable for URLLC (Ultra Reliable and Low Latency Communication).

However, in the M2M scenario, because UD competes to access BS channel, the short frame structure not only optimizes the flexibility of M2M communication throughput, but also affects multi-user UD access. UD competes with BS channel (beam) and causes beam misalignment, thus the system delay is increased. In the future, we will further study how to find the best short frame structure to obtain better system performance.

VII. ACKNOWLEDGEMENT

This work is partially supported by National Key Scientific Research Program of China under Grant No. 2018YFC1406603, Education and scientific research project for young and middle-aged teachers in Fujian Province (No. JAT191159), Chengyi Youth Scientific Research Fund (No. CK19061), and Fujian Natural Science Fund (No. 2019J01718).

REFERENCES

- [1] Agiwal, Mamta, Abhishek Roy, and Navrati Saxena. 2016. "Next Generation 5G Wireless Networks: A Comprehensive Survey." IEEE Communications Surveys and Tutorials 18 (3): 1617–55.
- [2] Weng, Chung-Wei, Biswa P. S. Sahoo, Hung-Yu Wei, and Chia-Hao Yu. 2018. "Directional Reference Signal Design for 5G Millimeter Wave Cellular Systems." IEEE Transactions on Vehicular Technology 67 (11): 10740–51.
- [3] Ericsson White Paper: 5G System, document Uen 284 23-3251, Rev B, Ericsson, Jan. 2017.
- [4] Ratasuk, Rapeepat, et al. "NB-IoT system for M2M communication." 2016 IEEE wireless communications and networking conference. IEEE, 2016.
- [5] Wu Q, Li G Y, Chen W, et al. 2017. "An Overview of Sustainable Green 5G Networks." IEEE Wireless Communications, 24(4): 72-80.
- [6] Yang, Shun-Ren, Sheng-Ying Yan, and Hui-Nien Hung. 2007. "Modeling UMTS Power Saving with Bursty Packet Data Traffic." IEEE Transactions on Mobile Computing 6 (12): 1398–1409.
- [7] Vamvakas P, Tsiropoulou E E, Vomvas M, et al. 2017. "Adaptive power management in wireless powered communication networks: a user-centric approach." IEEE Sarnoff symposium, 1-6.
- [8] Bi S, Zeng Y, Zhang R, et al. 2016. "Wireless powered communication networks: an overview." IEEE Wireless Communications, 23(2): 10-18.
- [9] Tsiropoulou E E, Mitsis G, Papavassiliou S, et al. 2018. "Interest-aware energy collection & resource management in machine to machine communications." ad hoc networks, 48-57.
- [10] Aijaz A, Tshangini M, Nakhai M R, et al. 2014. "Energy-Efficient Uplink Resource Allocation in LTE Networks with M2M/H2H Co-Existence Under Statistical QoS Guarantees." IEEE Transactions on Communications, 62(7): 2353-2365.
- [11] Weng, Chung-Wei, Kuang-Hsun Lin, Biswa P. S. Sahoo, and Hung-Yu Wei. 2018. "Beam-Aware Dormant and Scheduling Mechanism for 5G Millimeter Wave Cellular Systems." IEEE Transactions on Vehicular Technology 67 (11): 10935–49.
- [12] Rekhissa H B, Belleudy C, Bessaguet P. 2019. Power Efficient Packet Scheduling for M2M Devices over LTE/LTE-A Technologies[C]//2019 IEEE 24th International Workshop on Computer Aided Modeling and Design of Communication Links and Networks (CAMAD). IEEE, 1-4.
- [13] Selvam, K., & Kumar, K. 2020. Optimal Resource allocation in NOMA-based M2M communication using Hybrid Rider Optimization with FireFly: Power Saving Strategy of IoT. INTERNATIONAL JOURNAL OF COMMUNICATION SYSTEMS, 33(12).

- [14] Raja Basha, A., & Yaashuwanth, C. 2019. Optimal partial aggregation based energy delay compromise technique for wireless sensor network. *IETE Journal of Research*, 65(6):855-871.
- [15] Mihov, Yakim Y., Kiril M. Kassev, and Boris P. Tsankov. 2010. "Analysis and Performance Evaluation of the DRX Mechanism for Power Saving in LTE." In 2010 IEEE 26-Th Convention of Electrical and Electronics Engineers in Israel, 520-24.
- [16] Chandroth, J., Saxena, N., Roy, A., & Rastogi, E. 2021. A New Design and Analysis of Power Saving for IoT Gateway. *IETE Technical Review*, 1-9.
- [17] 3GPP, TS 36.300 V14.1.0, "Evolved Universal Terrestrial Radio Access(E-UTRA) and Evolved Universal Terrestrial Radio Access Network (E-UTRAN); Overall description; Stage 2(Release 14)", Dec. 2016.
- [18] Moradi, F., Fitzgerald, E., & Landfeldt, B. 2021. Modeling DRX for D2D Communication. *IEEE Internet of Things Journal* 8(4):2574-2583.
- [19] Kwon, Sang-Wook, June Hwang, Anil Agiwal, and Hyunjeong Kang. 2014. "Performance Analysis of DRX Mechanism Considering Analogue beam-forming in Millimeter-Wave Mobile Broadband System." In 2014 IEEE Globecom Workshops (GC Wkshps), 802-7.
- [20] Agiwal, M., M.K. Maheshwari, N. Saxena, and A. Roy. 2016. "Directional-DRX for 5G Wireless Communications." *Electronics Letters* 52 (21): 1816-18.
- [21] Chang, Chia-Wei, and Jyh-Cheng Chen. 2017. "UM Paging: Unified M2M Paging with Optimal DRX Cycle." *IEEE Transactions on Mobile Computing* 16 (3): 886-900.
- [22] Maheshwari, Mukesh Kumar, Mamta Agiwal, Navrati Saxena, and Abhishek Roy. 2017. "Hybrid Directional Discontinuous Reception (HD-DRX) for 5G Communication." *IEEE Communications Letters* 21 (6): 1421-24.
- [23] Philip, Ninu Rachel, and B. Malarkodi. 2019. "Extended Hybrid Directional DRX with Auxiliary Active Cycles for Light Traffic in 5G Networks." *Transactions on Emerging Telecommunications Technologies* 30 (1).
- [24] Ho, Cheng-Hsiang, An Huang, Ping-Jung Hsieh, and Hung-Yu Wei. 2017. "Energy-Efficient Millimeter-Wave M2M 5G Systems with Beam-Aware DRX Mechanism." In 2017 IEEE 86th Vehicular Technology Conference (VTC-Fall), 1-5.
- [25] Huang A, Lin K H , Wei H Y. 2020. "Beam-Aware Cross-Layer DRX Design for 5G Millimeter Wave Communication System." *IEEE Access* 8:77604-17.
- [26] Philip, N. R., & Balakrishnan, M. 2020. Beam-aware energy harvesting discontinuous reception in machine-to-machine millimeter-wave 5G communications. *International Journal of Communication Systems*, 33(16):e4567.
- [27] Zhang, Zhi, Qingyu Zhu, and Ping Zhang. 2019. "Fast Beam Tracking Discontinuous Reception for D2D-Based UAV MmWave Communication." *IEEE Access* 7: 110487-98.
- [28] Liu, Dong, Chao Wang, and Lars Kildehøj Rasmussen. 2019. "Discontinuous Reception for Multiple-Beam Communication." *IEEE Access* 7: 46931-46.
- [29] Pedersen, Klaus I., Gilberto Berardinelli, Frank Frederiksen, Preben Elgaard Mogensen, and Agnieszka Szufarska. 2016. "A Flexible 5G Frame Structure Design for Frequency-Division Duplex Cases." *IEEE Communications Magazine* 54 (3): 53-59.
- [30] Sallam, Mustafa M., Hala B. Nafea, and Fayez Wanis Zaki. 2018. "Comparative Study of Power Saving and Delay in LTE DRX, Directional-DRX and Hybrid-Directional DRX." *Wireless Personal Communications*, 98 (4): 3299-3317.
- [31] ETSI, "Universal Mobile Telecommunications System (UMTS); Selection Procedures for the Choice of Radio Transmission Technologies of the UMTS," Technical Report UMTS 30.03, version 3.2.0, Apr. 1998.
- [32] Singhal, C., & De, S. (2017). Resource allocation in next-generation broadband wireless access networks. In *Advances in Wireless Technologies and Telecommunication (AWTT)*, Book Series.
- [33] Rappaport, Theodore S., et al. "Overview of millimeter wave communications for fifth-generation (5G) wireless networks—With a focus on propagation models." *IEEE Transactions on Antennas and Propagation* 65.12 (2017): 6213-6230.
- [34] Zhang, Jing, et al. "5G millimeter-wave antenna array: Design and challenges." *IEEE Wireless communications* 24.2 (2016): 106-112.
- [35] V. W. Wong, R. Schober, D. W. K. Ng and L. Wang, *Key Technologies for 5G Wireless Systems*, Cambridge, U.K.: Cambridge Univ. Press, 2017.
- [36] Fowler, Scott, Ahmed Omar Shahidullah, Mohammed Osman, Johan M. Karlsson, and Di Yuan. 2015. "Analytical Evaluation of Extended DRX with Additional Active Cycles for Light Traffic." *Computer Networks* 77: 90-102.
- [37] M. Mezzavilla et al., 2018, "End-to-End Simulation of 5G mmWave Networks," *IEEE Communications Surveys & Tutorials*, 20(3):2237-2263.