IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received March 4, 2019, accepted March 24, 2019, date of publication April 9, 2019, date of current version April 18, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2909808

Discontinuous Reception for Multiple-Beam Communication

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This work was supported in part by the Swedish Research Council under Grant 2015-05306, in part by the National Natural Science Foundation of China under Grant 61771343, and in part by the project funded from the European Union's Horizon 2020 Research and Innovation Programme under the Marie Sklodowska-Curie grant agreement No. 752979.

ABSTRACT Discontinuous reception (DRX) techniques have successfully been proposed for energy savings in 4G radio access systems, which are deployed on legacy 2GHz spectrum bands with signal features of omnidirectional propagation. In upcoming 5G systems, higher frequency spectrum bands will also be utilized. Unfortunately higher frequency bands encounter more significant path loss, thus requiring directional beamforming to aggregate the radiant signal in a certain direction. We, therefore, propose a DRX scheme for multiple beam (DRXB) communication scenarios. The proposed DRXB scheme is designed to avoid unnecessary energy-and-time-consuming beam-training procedures, which enables longer sleep periods and shorter wake-up latency. We provide an analytical model to investigate the receiver-side energy efficiency and transmission latency of the proposed scheme. Through simulations, our approach is shown to have clear performance improvements over the conventional DRX scheme where beam training is conducted in each DRX cycle.

INDEX TERMS Discontinuous reception, beamforming, multiple-beam communication.

I. INTRODUCTION

According to [1], [2], "The capabilities of the 5th generation (5G) wireless access must extend far beyond previous generations of mobile communication. Examples of these capabilities include very high data rates, very low latency, ultra-high reliability, energy efficiency and extreme device densities; and will be realized by the development of the Long Term Evolution (LTE) system in combination with new radio-access technologies. Key technology components include extension to higher frequency bands, access/backhaul integration, device-to-device communication, flexible duplex, flexible spectrum usage, multi-antenna transmission, ultra-lean design, and user/control separation." In industry and academia it is generally understood that the success of 5G will depend on a diversity of spectrum assets, which span low, medium and high spectrum bands. In [3] the emphasis has generally been placed on high spectrum bands such as millimeter-wave bands, although bands below 6GHz will be key to providing the necessary coverage and bandwidth. To combat the poor propagation features of higher-frequency signals, multiple antennas are required at both the transmitter (Tx) and receiver (Rx) to realize beamforming for aggregating radiant signal power. As a drawback the derived directional beamforming needs additional overhead to maintain beam alignment [4].

Still data traffic often exhibits highly busty behavior which means a short period of transmission is normally followed by a long period of silence [5]. To improve the energy efficiency of the Rx, the discontinuous reception (DRX) strategy [5], [6] has been introduced into the LTE system to relieve the mobile receivers from having to continuously monitor the downlink control channel. The operation of the Rx is divided into two different states: an Active state and a DRX state, as shown in FIGURE 1(a). In the Active state, the Rx receives data packets from the Tx. Once the transmitted packet stream from the Tx ceases, the Rx is switched to the DRX state containing multiple DRX cycles.

Each DRX cycle is further divided into an On Duration state and a Sleep state as shown in FIGURE 1(b). Within the

The associate editor coordinating the review of this manuscript and approving it for publication was Jie Tang.

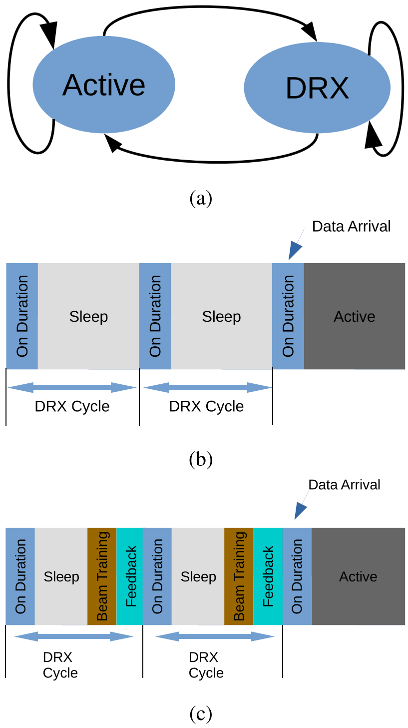


FIGURE 1. (a) The state transition process between Active and DRX states for the DRX strategy in LTE; (b) the LTE DRX cycles; (c) an improved DRX cycle with extra Beam Training and Feedback states.

On Duration state, the Rx monitors the downlink control channel. If a new data packet arrives at the Tx, the Rx switches its state back to the Active state and starts receiving the data packet. Otherwise, if there is no data arrival in the On Duration state, the Rx enters the Sleep state and turns off its reception circuits to save energy till the On Duration state in the next DRX cycle. The length of each DRX cycle and the Sleep state can be configured to meet different quality-of-service requirements. Longer sleep state leads to higher energy efficiency, but potentially also causes larger transmission latency, since if new data packets arrive at the Tx, they have to wait for the Rx to enter the On Duration state to be aware of them. Using adaptive approaches to trade off energy efficiency and wake-up latency has been investigated in [7]–[9].

In spite of the success of DRX in the LTE system, the scheme is not naturally applicable in a multiple-beam communication system since it does not have the mechanism to cope with issues related to beam alignment and misalignment. In fact, the choice of a particular beam pair between the Tx and Rx to conduct data packet transmission is in general sensitive to the mobility and rotation of mobile devices. The quality of an aligned beam pair is hence likely to deteriorate with time. Proper beam training should be conducted. But this is not taken into consideration by the legacy DRX scheme. As a result, in a multiple-beam communication scenario, a Rx with the DRX function may lose the available transmission channel after a Sleep state due to a beam misalignment event. To handle this problem, [10]–[12] propose to reduce the duration of the Sleep state, so that finding a proper beam pair and feedback of the index of the selected beam pair can be conducted in each DRX cycle, as shown in FIGURE 1(c). Even though the aligned beam pair can be updated with sufficient frequency, this approach may lead to other issues. For example, limiting the duration of the Sleep state may cause the Rx energy consumption to be significantly increased. The increase of energy consumption can be larger if there are a large number of potential beam pairs and thus more time in a DRX circle has to be used for beam training. In [13] and [14] it is shown that, after wireless devices are switched to sleep mode, power consumption only decreases gradually, rather than dropping sharply. For example, $10\,ms$ after entering into the sleep mode, a wireless device still consumes more than 10% of the power of being in active mode. This means that a very short duration of the Sleep state may not be able to achieve effective energy efficiency. In addition, running the beam training process in every DRX cycle may not be needed in practical situations when the probability that a beam misalignment event would occur is low. The simulation results presented in [11] show that, in a $100\,ms$ DRX cycle, the beam misalignment probability is only 0.1 when the user equipment (UE) velocity is $30\,km/h$, and in a $300\,ms$ DRX cycle, the probability is 0.38 when the UE velocity is $60\,km/h$. Therefore, adding the beam training and feedback functions to every DRX cycle will lead to unnecessary energy consumption. Recently, a hybrid-directional DRX scheme is studied in [15], where both the LTE and new radio beamforming links are maintained concurrently. Control signal is always transmitted via LTE over the legacy 2GHz band. Beam training is performed whenever the Active state is returned for data transmission over high-frequency spectrum band. This approach tends to balance energy usage and training. However, maintaining dual connectivity itself may consume more energy.

To address this problem, in this paper we propose a novel DRX scheme for multiple-beam system (termed DRXB). The basic idea is to allow the Rx to conduct the beam training and feedback of beam selection result only when beam misalignment between the Tx and Rx occurs. This procedure permits the system to balance the impact of beam training and the power-saving sleep mode.

To quantitatively analyze the performance of the proposed DRXB scheme, we model the behavior of a wireless device that employs the scheme by a semi-Markov chain. The stationary probability of each operating state and the transition probabilities between different states are calculated. Using these probability expressions, we further derive the *power saving factor*, defined as the duration proportion of the Sleep mode [16], and the *wake-up latency*, defined as the expected duration between the time instant that a data packet arrives at the Tx to the time instant that the Rx is able to receive this packet via an aligned beam pair. These two performance indicators can reflect the system energy efficiency and transmission latency, respectively. Through extensive simulations, the performance advantages of our DRXB scheme in terms of a significantly better achievable tradeoff between the power saving factor and wake-up latency, compared with the conventional strategy where the beam training process is conducted in each DRX cycle, are demonstrated.

The contributions of this paper are summarized as fellows.

- We propose a novel discontinuous reception scheme for downlink multiple-beam communication systems operated in the high-frequency bands. Compared to existing DRX solutions, our method can efficiently cope with the beam misalignment problem by conducting beam training only when necessary, which effectively balances energy efficiency and data package transmission latency.
- The random nature of data packet arrival and beam misalignment causes the performance analysis of the DRXB scheme to be very involved. To handle this issue, we propose a mathematical analytic model based on a semi-Markov chain that descries the Rx behavior, and derive the achievable power saving factor and wake-up latency of the DRXB scheme. The model allows the impact of different system parameters on the energy efficiency and transmission latency to be quantitatively evaluated.
- We carry out extensive simulations to verify the results of our analytical model. We provide illustration and discussion on how energy efficiency and transmission latency are affected by data arrival rate, beam misalignment rate, and the lengths of different operating states. Our results clearly exhibit the advantages of our scheme over the conventional DRX solution, and can be used to potentially support system design.

The remainder of the paper is organized as follows. In Section II, we present the system model, introduce the proposed DRXB scheme, and describe the semi-Markov chain modeling the Rx behavior. In Section III we derive the stationary probabilities and state holding time of the model. The energy efficiency and transmission latency of the system are investigated through quantitative analysis and simulations in Sections IV and V respectively. Our conclusions are drawn in Section VI.

II. DRXB AND ITS ANALYTICAL MODEL

In this section, we first present the considered multiple-beam communication scenario. Afterwards, we elaborate the DRXB scheme and introduce a semi-Markov chain model to describe the transitions among different states of the Rx. Finally, the transition probabilities are derived.

A. SYSTEM MODEL

We consider a high-frequency multiple-beam communication system that consists of a Tx (a base station) and a mobile Rx (a user device), as shown in FIGURE 2(a). The Tx is able to form M different beams to maintain its transmission coverage in different directions; but only one of the M beams is active for transmission to the Rx at a specific time instant. The Rx is configured with N beams to receive data that may come from different directions. Similarly, only one Rx beam is active at a specific time instant. Throughout the paper, the smallest unit of time duration for packet transmission from the Tx to the Rx and device operation (including packet/beam status detection, beam training, feedback, and switching states, etc.) is chosen to be 1 *ms*, which is the length of a subframe in LTE [5] and also in many new radio access technologies being actively discussed in current standardization activities [17], [18]. Furthermore, several timers are deployed in the Rx in order to control the durations of different states. The smallest unit of such down-counting timers is also set as 1 *ms*. We use *subframe* to denote the 1 *ms* unit of time resource throughout this paper.

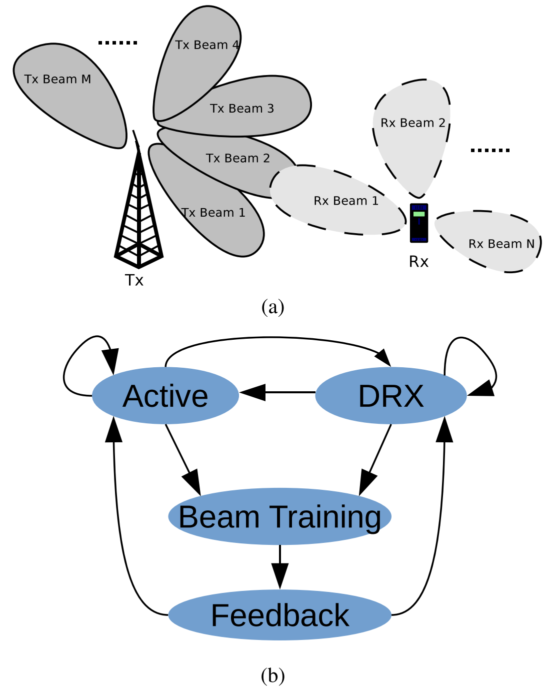


FIGURE 2. (a) System model and (b) the state transitions of our DRXB scheme.

The data packets intended for the Rx are generated randomly. They arrive at the Tx following a Poisson process with parameter λ, termed *packet arrival rate*. Thus the inter-arrival time between two adjacent packets (denoted by t_p) is exponentially distributed with mean value $1/\lambda$. We assume that the Tx and Rx can exchange their status (i.e., whether the Tx has a new packet arrival and whether the Rx is ready for reception) through the downlink control channel [19] with negligible time, as long as the Rx is operating in the Active or the On Duration state.

When the Rx is in the Active state, a data packet can be delivered from the Tx to the Rx when their beams are properly chosen to be *aligned*, which means the link quality of the Tx-Rx beam pair is sufficiently good (normally considered to be better than a certain threshold [11], [12]). However, due to the movement of the Rx or change of the environment, this link quality may be degraded to be unsatisfactory. In such a case, a beam *misalignment* occurs. This event can be detected by the Rx (if it is operating in the Active or the On Duration state) via measuring the strength of the beam reference signal from the Tx [20]–[22]. In this case, the Rx cannot receive any data from Tx, until a new pair of aligned beams is found after a beam-training procedure. Assume that the beam misalignment events occur according to a Poisson process with parameter α, termed *beam misalignment rate*. Then the time duration between two consecutive misalignment events (denoted by t_m) follows an exponential distribution with mean value $1/\alpha$. Such an inter-misalignment interval t_m is independent of the packet arrival interval t_p.

If a beam misalignment occurs, the link quality of an established Tx-Rx beam pair is insufficient to support the desired data packet transmission. A beam training procedure is needed to rediscover an aligned pair of Tx-Rx beams. The basic idea of beam training is that the Rx measures the link qualities using its N receiving beams against all the M transmitting beams, by the beam management reference signal (BMRS) or channel-state information reference signal (CSI-RS) sent from the Tx [23]–[25]. The BMRS and CSI-RS are predefined signals occupying specific communication resource for the purpose of Tx-Rx beam pair quality estimation. A pair of Tx-Rx beam is considered to be aligned if the link quality is sufficiently good. A number of training algorithms that lead to different energy and time consumption have been proposed recently [26]–[31]. In this paper, the time demanded by the beam training procedure is denoted by $T_B\, ms$. After the aligned beam pair is found, the Rx uses a feedback signal to notify the Tx of the index of the selected transmitting beam [19], the time consumption of which is $T_F\, ms$. Note that after the Rx feeds back the beam training decision, a successful transmission link between the Tx and the Rx may still be unable to be established, potentially because beam misalignment occurs again during the feedback process or the Tx does not even receive the feedback signal [20].

As stated in Section I, the conventional DRX scheme adopted in LTE contains two Rx states. The Active state allows the Rx to receive packets from the Tx. The DRX state is formed by multiple DRX cycles, each of which consists of an On Duration state and a Sleep state. In the On Duration state the Rx is capable of monitoring the downlink control channel and in the Sleep state, the Rx's reception circuits are switched off to reduce energy consumption. Since the beam misalignment problem is not taken into account, this DRX scheme cannot be directly adopted in high-frequency multiple-beam systems. However the designing principle can still be applicable for new radio systems [32]. For instance, [10]–[12] propose to add two extra states in each DRX cycle to deal with potential beam misalignments in multiple-beam systems: The Beam Training state permits the Rx to carry out the beam training procedure and the Feedback state allows the Rx to send the training result back to the Tx. The structure of this DRX cycle is illustrated in FIGURE 1(c). However, including such two states in each DRX cycle reduces the length of the Sleep state. The energy consumption can hence be much higher than that of the LTE DRX scheme, especially when the numbers of Tx and Rx beams are large (the beam training process consumes more time). Since in general beam misalignment does not occur frequently, forcing every DRX cycle to have Beam Training and Feedback states is not really necessary.

Therefore, we propose to separate the Beam Training and Feedback states from the DRX cycles, and allow the Rx to carry out beam training and the corresponding feedback procedure only when misalignment events happen. The proposed scheme is termed DRXB and the potential transitions among the states are displayed in FIGURE 2(b). Compared with FIGURE 1(a), it is clear that the transitions between the Active and DRX states remain the same. However if a beam misalignment occurs when the Rx is operating in the Active state, the Rx goes to the Beam Training state and then the Feedback state so that a new aligned beam pair can be found. Afterwords, the Rx re-enters the Active state and is ready for receiving packets from the Tx. Beam misalignment may also happen when the Rx is in the DRX state. Specifically, in the On Duration state, the Rx monitors the downlink control channel to check if there is an incoming data packet at the Tx and also uses the beam reference signals to measure the quality of the current serving Tx-Rx beam pair. If the link quality becomes lower than the pre-determined threshold, the Rx switches to the Beam Training and Feedback states. After a new aligned beam pair is identified, the Rx goes back to the DRX state and waits for new packet arrivals. Clearly, if the signal propagation environment is stable such that there is no beam misalignment event, the DRXB scheme is identical to the LTE DRX scheme.

In the considered multiple-beam communication system, beam misalignment does occur randomly. Since the durations of the Beam Training and Feedback states are not fixed in each DRX cycle, the performance analysis of the DRXB scheme is very involved. In what follows, we model the behavior of the Rx as a semi-Markov chain. Through the stationary and transition probabilities, the system performance with regard to energy efficiency and transmission latency can be analyzed.

B. DRXB SEMI-MARKOV CHAIN DESCRIPTION

Let the maximum lengths of the Active, On Duration, and Sleep states be controlled by an Inactivity Timer, an On Duration Timer, and a Sleep Timer, respectively. As long as the Rx enters an Active state, the Inactivity Timer starts to count down from T_0 (by the smallest unit of 1 *ms*). If the timer reading successfully reaches zero (i.e., without any interruption caused by new data arrival or by beam misalignment), the Rx switches to the DRX state. Similarly, whenever the Rx enters an On Duration state, the On Duration Timer starts counting down from T_{ON}. The Rx goes to the Sleep state after the On Duration Timer successfully reaches zero without any interruption. Finally, the Sleep state has a fixed length.

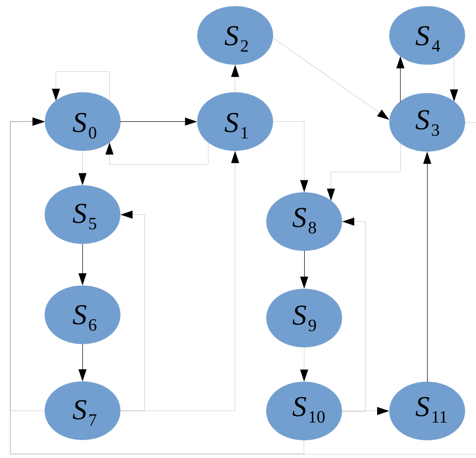
After the Sleep Timer counts down from T_S to zero, the Rx switches to the next On Duration state.

Due to the random nature of packet arrival and beam misalignment events, the counting-down process of the Inactivity Timer and the On Duration Timer can be interrupted. Although these two events may occur at any time instant, the Rx can be aware of them and take corresponding actions only when it is operating in an Active state or an On Duration state (in which the Rx receiving circuit is turned on). Specifically, in these two states, when a new data packet arrives at the Tx, the Rx switches to a new Active state and starts receiving the packet if the Tx-Rx beam pair is an aligned pair. The Inactivity Timer is reset to T_0. When a beam misalignment event occurs, the Rx goes to the Beam Training and Feedback states to reestablish the aligned beam pair. Afterwards, the Rx reenters the Active state or On Duration state as it operated before the beam misalignment event occurred.

To facilitate performance analysis, we further transform the illustration of the state transitions of the DRXB scheme from FIGURE 2(b) to FIGURE 3(a), as a semi-Markov chain. More specifically, we separate the Active state in FIGURE 2(b) into two different forms, based on the causes that activate them. The Active state S_0 is generated after the Rx detects a new packet arrival at the Tx. The Active state S_7 is generated after the Rx conducts beam training (through the Beam Training state S_5 and the Feedback state S_6) to reestablish the aligned Tx-Rx beam pair when beam misalignment interrupts an Active state (either S_0 or S_7). In addition, the On Duration state included in the DRX state in FIGURE 2(b) is separated into three different forms, S_1, S_3, and S_{10}. The On Duration state S_1 is generated when the Inactivity Timer of an Active state (either S_0 or S_7) successfully reaches zero. The On Duration state S_3 is generated when the Sleep Timer of a Sleep state (S_2, S_4, or S_{11}) successfully reaches zero, and the On Duration state S_{10} is generated after the Rx conducts beam training (through the Beam Training state S_8 and the Feedback state S_9) to reestablish the aligned Tx-Rx beam pair when beam misalignment interrupts an On Duration state (S_1, S_3, or S_{10}). Since the Rx switches to the Sleep state only after it successfully goes through an un-interrupted On Duration state (i.e., the On Duration Timer reaches zero), we separate the Sleep state included in the DRX state in FIGURE 2(b) are each separated into two forms. The Rx goes to the Beam Training state S_5 and the Feedback state S_6 when beam misalignment interrupts the Active state S_0 or S_7, and goes to the Beam Training state S_8 and the Feedback state S_9 when beam misalignment interrupts the On Duration state S_1, S_3, or S_{10}.

The behaviors of the Rx affected by the random occurrence of data packet arrival and beam misalignment are as follows. Without loss of generality, let us start from the case where the Rx has identified an aligned Tx-Rx beam pair from the measurements of the beam reference signals while also being aware of an incoming data packet via the downlink control channel. The Rx enters the Active state S_0 and receives the packet from the Tx using the paired beams. At the same time, the Inactivity Timer starts counting down from T_0. Following the above discussions, three possible events can occur to force the Rx to change its operating state. If a new data packet arrives at the Tx (which can be immediately detected by the Rx since the Rx continuously monitors the downlink control channel via the aligned Tx-Rx beam pair), the Rx restarts the Active state S_0 (i.e., transition $S_0 \rightarrow S_0$) to receive the packet and then reset the Inactivity Timer to T_0. However, if a beam misalignment occurs before new data arrival, the Rx goes to the Beam Training state S_5 (i.e., transition $S_0 \rightarrow S_5$) in order to search for a new pair of aligned Tx-Rx beams. Finally, if neither new packet arrival nor beam misalignment occurs before the Inactivity Timer expires (reaches zero), the Rx switches its operation state to the DRX state: It enters the On Duration state S_1 (i.e., transition $S_0 \rightarrow S_1$) and activates the On Duration Timer.

Now consider the case that the Rx is in the Beam Training state S_5. After finding the new aligned Tx-Rx beam pair (using time T_B), the Rx goes to the Feedback state S_6 (i.e., transition $S_5 \rightarrow S_6$) and sends the index of the beam pair to the Tx. The duration of this state is T_F. Note that a new packet may arrive at the Tx at any time instant during the states S_5 and S_6, and a beam misalignment event may reappear during the state S_6. But the Rx is unable to be aware of them. After the feedback completes, the Rx switches to the Active state S_7 (i.e., transition $S_6 \rightarrow S_7$). The Inactivity Timer of the state is activated to count down from T_0. Similar to the



(a)

Notation	States
S_0, S_7	Active (continuous reception)
S_1, S_3, S_{10}	On Duration
S_2, S_4, S_{11}	Sleep
S_5, S_8	Beam Training
S_6, S_9	Feedback

(b)

FIGURE 3. (a) The semi-Markov chain diagram for the proposed DRXB scheme and (b) state descriptions.

case in S_0, three potential events can cause the Rx to change its operating state. If the beam pair remains aligned and a new data packet arrives at the Tx (occurs in the Beam Training state S_5, the Feedback state S_6, or the Active state S_7), the Rx enters the Active state S_0 (i.e., transition $S_7 \rightarrow S_0$) and starts the packet reception process. On the other hand, if Rx discovers a beam misalignment (occurs either in the Feedback state S_6 or the Active state S_7) first, it leaves for the Beam Training state S_5 (i.e., transition $S_7 \rightarrow S_5$) to find the new aligned beam pair. Finally, if the Inactivity Timer successfully expires without being interrupted by packet arrival or beam misalignment, the Rx switches to the On Duration state S_1 (i.e., transition $S_7 \rightarrow S_1$).

The possible events that affect the behavior of the Rx in the state S_1 are similar to those in S_0, except that now the state's maximum length is controlled by an On Duration Timer. A new packet arrival at the Tx forces the Rx to enter the Active state S_0 (i.e., transition $S_1 \rightarrow S_0$). But if the Rx discovers a beam misalignment first, it carries out the beam training procedure to reestablish a satisfactory transmission link. In this case, the Rx switches to the Beam Training state S_8 and then the Feedback state S_9 (i.e., transitions $S_1 \rightarrow S_8$ and $S_8 \rightarrow S_9$). If the On Duration Timer successfully counts down from T_{ON} to zero without facing any data arrival or beam misalignment, the Rx turns off its receiving circuit and enters the Sleep state S_2 (i.e., transition $S_1 \rightarrow S_2$). Discontinuous reception is utilized to reduce energy consumption. After the Sleep Timer expires, the Rx starts a new DRX state by entering the On Duration state S_3 (i.e., transition $S_2 \rightarrow S_3$).

Being an On Duration state, S_3 can transit to an Active state, a Beam Training state, or a Sleep state. But different from the state S_1, new packet arrival or beam misalignment may also occur during the Sleep state (S_2 or S_4) before S_3. Since the Rx receiving circuit is off in a Sleep state, detecting such events can be done only when the Rx starts operating in S_3. If beam misalignment is discovered, the Rx turns to the Beam Training state S_8 (i.e. transition $S_3 \rightarrow S_8$) and then the Feedback state S_9 (i.e. transition $S_8 \rightarrow S_9$). Otherwise, if a new packet arrival is detected before beam misalignment, the Rx immediately changes its state to the Active state S_0 (i.e. transition $S_3 \rightarrow S_0$) in order to conduct packet reception. Again, as long as the On Duration Timer expires successfully, a Sleep state, i.e., state S_4, is activated to save device energy, until the Sleep Timer counts down to zero and the Rx reenters S_3. This process leads to the state transitions $S_3 \rightarrow S_4$ and then $S_4 \rightarrow S_3$.

Finally, let us focus on what happens after the Beam Training state S_8 and Feedback state S_9. Because these two states are triggered due to beam misalignment detected by the Rx in an On Duration state (S_1, S_3, or S_{10}), after S_9 is completed the Rx enters an On Duration state S_{10} (i.e., transition $S_9 \rightarrow S_{10}$). It turns on its receiving circuit to detect whether the current Tx-Rx beam pair is no longer aligned, which may happen at any time instant in the states S_9 and S_{10}. If misalignment does occur, the Rx changes its state to S_8 to conduct another round of beam pair selection (i.e. transition $S_{10} \rightarrow S_8$). On the other hand, if a new packet arrival (which may occur at any time instant in the states S_8, S_9 and S_{10}) is discovered when the Tx-Rx beam pair is still aligned, the Rx goes to the Active state S_0. If these two events do not happen until the On Duration Timer expires, the Sleep state S_{11} is activated (i.e. transition $S_{10} \rightarrow S_{11}$) till another DRX cycle (i.e. transition $S_{11} \rightarrow S_3$).

Clearly, following the above discussions the behavior of the Rx can be described by the semi-Markov chain model displayed in FIGURE 3(a). The next subsection presents the transition probabilities of the model.

C. STATE TRANSITION PROBABILITY

Use $p_{i,j}$ ($i, j \in \{0, 1, \cdots, 11\}$) to denote the probability that the Rx transits its state from S_i to S_j. Recall that the two independent exponentially-distributed random variables t_p and t_m are used respectively to denote the interval between two consecutive packet arrivals and that between two consecutive beam misalignment events.

Let us start from the case that the Rx has detected a data packet arrival and entered the Active state S_0. As mentioned earlier, three different events can cause the Rx to change its state. The transition $S_0 \rightarrow S_0$ occurs when a new data packet arrives at the Tx before the occurrence of a beam misalignment event and also before the expiry of the Inactivity Timer. Due to the memoryless property of the exponential distribution, such conditions can be written as $0 \leq t_p < T_0$ and $0 \leq t_p < \lfloor t_m \rfloor$ for $t_m > 0$, where $\lfloor \cdot \rfloor$ denotes floor operation. $\lfloor \cdot \rfloor$ is used here because if data arrival and beam misalignment happen in the same subframe, Rx would transfer to the Beam Training state. Therefore, the transition probability $p_{0,0}$ can be calculated as

$$\begin{aligned} p_{0,0} &= \Pr\left\{0 \leq t_p < T_0, t_p < \lfloor t_m \rfloor\right\} \\ &= \sum_{k=1}^{T_0} \Pr\left\{k-1 \leq t_p < k, t_m \geq k\right\} \\ &= -\frac{\left(e^{\lambda}-1\right)\left(e^{-T_0(\alpha+\lambda)}-1\right)}{e^{\alpha+\lambda}-1}. \end{aligned} \tag{1}$$

In addition, the event that a beam misalignment occurs before a new data packet arrival and also before the expiry of the Inactivity Timer leads to transition $S_0 \rightarrow S_5$. The Rx goes to the Beam Training state S_5 to search for a new pair of Tx-Rx beams. Following the above discussion, the associated transition probability $p_{0,5}$ is

$$\begin{aligned} p_{0,5} &= \Pr\left\{0 \leq t_m < T_0, t_p \geq \lfloor t_m \rfloor\right\} \\ &= \sum_{k=1}^{T_0} \Pr\left\{k-1 \leq t_m < k, t_p \geq k-1\right\} \\ &= \frac{\left(e^{\alpha}-1\right) e^{\lambda-T_0(\alpha+\lambda)}\left(e^{T_0(\alpha+\lambda)}-1\right)}{e^{\alpha+\lambda}-1}. \end{aligned} \tag{2}$$

If the Inactivity Timer successfully expires without being interrupted by beam misalignment or new data arrival, the transition $S_0 \rightarrow S_1$ occurs. The transition probability $p_{0,1}$

is

$$p_{0,1} = \Pr\left\{t_p \geq T_0, t_m \geq T_0\right\} = e^{-(\alpha+\lambda)T_0}. \tag{3}$$

Now focus on the case that the Rx is in the Beam Training state S_5. It is easy to see that the transition $S_5 \rightarrow S_6$ and the consequent transition $S_6 \rightarrow S_7$ are both determined processes. As a result, we have the transition probabilities $p_{5,6}$ and $p_{6,7}$ as

$$p_{5,6} = p_{6,7} = 1. \tag{4}$$

After entering the Active state S_7, the Rx turns on its receiving circuit to detect the incoming packet and beam alignment status. Two events would lead to the transition $S_7 \rightarrow S_0$. First, after the beam training process in S_5, the new beam pair can remain aligned even after the Inactivity Timer of S_7 expires (i.e., $t_m \geq T_F + T_0$). Then if at any point of time during the states S_5, S_6, and S_7 a new packet arrives at the Tx (i.e., $0 \leq t_p < T_B + T_F + T_0$), this event will be detected by the Rx in the state S_7. The Rx's state will be changed to S_0. Further, a beam misalignment may occur during the state S_7, but a new data packet arrives before that. The condition can be written as $T_F + 1 \leq t_m < T_F + T_0$ and $0 \leq t_p < T_B + \lfloor t_m \rfloor$, where we take into account that the smallest time unit for the Rx to make operations is 1 *ms* so that if beam misalignment happens at the first millisecond of S_7 the Rx inevitably changes its state to the Beam Training state S_5. Consequently, the transition probability $p_{7,0}$ can be expressed as

$$\begin{aligned}
p_{7,0} &= \Pr\left\{t_m \geq T_F + T_0, 0 \leq t_p < T_B + T_F + T_0\right\} \\
&\quad + \Pr\left\{T_F + 1 \leq t_m < T_F + T_0, t_p < T_B + \lfloor t_m \rfloor\right\} \\
&= \left(e^{\lambda(T_B+T_F+T_0)} - 1\right) e^{-\lambda T_B - (\alpha+\lambda)(T_F+T_0)} \\
&\quad + \sum_{k=T_F+2}^{T_F+T_0} \left(e^{-\alpha(k-1)} - e^{-\alpha}\right)\left(1 - e^{-\lambda(T_B+k-1)}\right) \\
&= \left(\left(e^{\alpha+\lambda} - 1\right)\left(e^{\alpha T_0} - e^{\alpha}\right) e^{\lambda(T_B+T_F+T_0)} + \left(e^{\alpha} - 1\right)\right. \\
&\quad \left. \cdot \left(e^{\alpha+\lambda} - e^{T_0(\alpha+\lambda)}\right)\right) \frac{e^{-\alpha-\lambda T_B-(\alpha+\lambda)(T_F+T_0)}}{e^{\alpha+\lambda} - 1} \\
&\quad + e^{-\alpha T_F - \alpha T_0}\left(1 - e^{-\lambda(T_B+T_F+T_0)}\right).
\end{aligned} \tag{5}$$

Furthermore, the transition $S_7 \rightarrow S_5$ is caused as long as the Rx detects a beam misalignment in the state S_7. This happens when: 1) $0 \leq t_m < T_F + 1$, which means the misalignment event happens during the Feedback state S_6 or at the first millisecond of the Active state S_7; and 2) $T_F + 1 \leq t_m < T_F + T_0$ and $T_B + \lfloor t_m \rfloor \leq t_p$, which means that the misalignment event happens after the first millisecond of S_7 but before any new packet arrival and also before the expiry of the Inactivity Timer. Hence the transition probability $p_{7,5}$ is

$$\begin{aligned}
&p_{7,5} \\
&= \Pr\left\{T_F + 1 \leq t_m < T_F + T_0, t_p \geq T_B + \lfloor t_m \rfloor\right\} \\
&\quad + \Pr\left\{0 \leq t_m < T_F + 1\right\} \\
&= \sum_{k=T_F+2}^{T_F+T_0} \left(e^{-\alpha(k-1)} - e^{-\alpha k}\right) e^{-\lambda(T_B+k-1)} - e^{-\alpha(T_F+1)} + 1 \\
&= \frac{\left(e^{\alpha} - 1\right)\left(e^{T_0(\alpha+\lambda)} - e^{\alpha+\lambda}\right) e^{-\lambda(T_0+T_B+T_F)-\alpha(1+T_F+T_0)}}{e^{\alpha+\lambda} - 1} \\
&\quad - e^{-\alpha(T_F+1)} + 1.
\end{aligned} \tag{6}$$

Finally, if no date packet arrives in the states S_5, S_6 and S_7, and no beam misalignment occurs in the states S_6 and S_7, the Rx goes to the On Duration state S_1 after the Inactivity Timer of S_7 expires. This leads to the transition probability $p_{7,1}$ as follows:

$$\begin{aligned}
p_{7,1} &= \Pr\left\{t_p \geq T_B + T_F + T_0, t_m \geq T_F + T_0\right\} \\
&= e^{-\lambda T_B - (\alpha+\lambda)(T_F+T_0)}.
\end{aligned} \tag{7}$$

As mentioned in Section II-B, the behavior of Rx in S_1 is actually similar to that in the Active state S_0. The difference is that the maximum state duration is T_{ON} *ms*. Hence we can follow the analysis for $p_{0,0}$ to derive the transition probability $p_{1,0}$ as the probability that a new packet arrives before the beam pair becomes misaligned and also before the On Duration Timer expires:

$$\begin{aligned}
p_{1,0} &= \Pr\left\{0 \leq t_p < T_{\text{ON}}, t_p < \lfloor t_m \rfloor\right\} \\
&= -\frac{\left(e^{\lambda} - 1\right)\left(e^{-(\alpha+\lambda)T_{\text{ON}}} - 1\right)}{e^{\alpha+\lambda} - 1}.
\end{aligned} \tag{8}$$

Similarly, the transition probability $p_{1,8}$ is the probability that beam misalignment occurs before any new packet arrival and also before the expiry of the On Duration Timer:

$$\begin{aligned}
p_{1,8} &= \Pr\left\{0 \leq t_m < T_{\text{ON}}, t_p \geq \lfloor t_m \rfloor\right\} \\
&= \frac{\left(e^{\alpha} - 1\right) e^{\lambda-(\alpha+\lambda)T_{\text{ON}}}\left(e^{(\alpha+\lambda)T_{\text{ON}}} - 1\right)}{e^{\alpha+\lambda} - 1}.
\end{aligned} \tag{9}$$

If nothing happens within the whole duration of S_1, the Rx goes to the Sleep state S_2. The transition probability $p_{1,2}$ is thus

$$p_{1,2} = \Pr\left\{t_p \geq T_{\text{ON}}, t_m \geq T_{\text{ON}}\right\} = e^{-(\alpha+\lambda)T_{\text{ON}}}. \tag{10}$$

The transition from S_2 to the On Duration state S_3 is a determined process, which leads to

$$p_{2,3} = 1. \tag{11}$$

The difference between the two On Duration states S_1 and S_3 is that the former state follows an Active state (either S_0 or S_7) but the latter is a consequence of completing a Sleep state (S_2, S_4, or S_{11}). Hence any change of packet arrival or beam alignment status appeared in both the precedent Sleep state and S_3 would affect the behavior of the Rx in S_3. Now, there are two events that lead to the transition $S_3 \rightarrow S_0$. First, for the complete duration of the precedent Sleep state and S_3, the Tx-Rx beam pair remains aligned (i.e., $t_m \geq T_S + T_{\text{ON}}$) and a packet arrives before the On Duration Timer expires (i.e., $0 \leq t_p < T_S + T_{\text{ON}}$). Second, the beam misalignment may occur in S_3 (but not within the first millisecond, i.e., $T_S + 1 \leq t_m < T_{\text{ON}} + T_S$) but packet arrival happens before that (i.e., $0 \le t_p < \lfloor t_m \rfloor$). Hence the transition probability $p_{3,0}$ is calculated by

$$\begin{aligned} p_{3,0} &= \Pr\left\{T_S + 1 \le t_m < T_{\mathrm{ON}} + T_S, t_p < \lfloor t_m \rfloor\right\} \\ &\quad + \Pr\left\{T_{\mathrm{ON}} + T_S \le t_m, t_p < T_{\mathrm{ON}} + T_S\right\} \\ &= \left(e^{\alpha+\lambda} - 1\right)^{-1} \left(\left(e^{\alpha} - 1\right)\left(e^{\alpha+\lambda} - e^{(\alpha+\lambda)T_{\mathrm{ON}}}\right)\right. \\ &\quad \left. - \left(e^{\alpha+\lambda} - 1\right)\left(e^{\alpha} - e^{\alpha T_{\mathrm{ON}}}\right) e^{\lambda(T_{\mathrm{ON}}+T_S)}\right) \\ &\quad \times e^{-\alpha-(\alpha+\lambda)(T_{\mathrm{ON}}+T_S)} \\ &\quad + \left(e^{\lambda(T_{\mathrm{ON}}+T_S)} - 1\right) e^{-(\alpha+\lambda)(T_{\mathrm{ON}}+T_S)}. \end{aligned} \tag{12}$$

If a beam misalignment event, which may happen in either the precedent Sleep state or S_3, is detected by the Rx in S_3, the state is changed to the Beam Training state S_8. The cause of such a transition can be either $0 \le t_m < T_S + 1$, which means that the beam misalignment occurs during the precedent Sleep state or at the first millisecond of S_3 (in this case, the Rx inevitably goes to S_8 at the second millisecond), or $T_S + 1 \le t_m < T_{\mathrm{ON}} + T_S$ and $t_p > \lfloor t_m \rfloor$, which means that the beam misalignment occurs after the first millisecond of S_3 but still before a new packet arrives. We have the transition probability $p_{3,8}$ as

$$\begin{aligned} p_{3,8} &= \Pr\left\{T_S + 1 \le t_m < T_{\mathrm{ON}} + T_S, t_p \ge \lfloor t_m \rfloor\right\} \\ &\quad + \Pr\left\{0 \le t_m < T_S + 1\right\} \\ &= \sum_{k=T_S+2}^{T_{\mathrm{ON}}+T_S} \left(e^{-\alpha(k-1)} - e^{-\alpha k}\right) e^{-\lambda(k-1)} - e^{-\alpha(T_S+1)} + 1 \\ &= \frac{\left(e^{\alpha} - 1\right)\left(e^{(\alpha+\lambda)T_{\mathrm{ON}}} - e^{\alpha+\lambda}\right) e^{-\alpha-(\alpha+\lambda)T_{\mathrm{ON}}-(\alpha+\lambda)T_S}}{e^{\alpha+\lambda} - 1} \\ &\quad - e^{-\alpha(T_S+1)} + 1. \end{aligned} \tag{13}$$

The following transitions $S_8 \rightarrow S_9$ and $S_9 \rightarrow S_{10}$ are determined processes, which lead to

$$p_{8,9} = p_{9,10} = 1. \tag{14}$$

Furthermore, if the On Duration Timer of S_3 successfully counts down to zero, the Rx goes to another Sleep state S_4, and stays there for T_S *ms* before switching back to S_3. The transition probabilities $p_{3,4}$ and $p_{4,3}$ are as follows:

$$\begin{aligned} p_{3,4} &= \Pr\left\{t_p \ge T_{\mathrm{ON}} + T_S, t_m \ge T_{\mathrm{ON}} + T_S\right\} \\ &= e^{-(\alpha+\lambda)(T_{\mathrm{ON}}+T_S)}, \end{aligned} \tag{15}$$

$$p_{4,3} = 1. \tag{16}$$

Finally, we consider what happens when the Rx is operating in the On Duration state S_{10}. In fact, the state transition probability analysis in this state is similar to that in the state S_7, except that the duration of S_{10} is at most T_{ON} *ms* and if the On Duration Timer successfully reaches zero, the Rx switches to the Sleep state S_{11} and turns off its receiving circuit. Then we can follow the analysis of $p_{7,0}$ and attain the transition probability $p_{10,0}$ as

$$\begin{aligned} & p_{10,0} \\ &= \Pr\left\{t_m \ge T_F + T_{\mathrm{ON}}, 0 \le t_p < T_B + T_F + T_{\mathrm{ON}}\right\} \\ &\quad + \Pr\left\{T_F + 1 \le t_m < T_F + T_{\mathrm{ON}}, 0 \le t_p < T_B + \lfloor t_m \rfloor\right\} \\ &= \sum_{k=T_F+2}^{T_F+T_{\mathrm{ON}}} \left(e^{-\alpha(k-1)} - e^{-\alpha k}\right)\left(1 - e^{-\lambda(T_B+k-1)}\right) \\ &\quad + \left(e^{\lambda(T_B+T_F+T_{\mathrm{ON}})} - 1\right) e^{-\lambda T_B-(\alpha+\lambda)T_F-(\alpha+\lambda)T_{\mathrm{ON}}} \\ &= e^{-\alpha-\lambda T_B-(\alpha+\lambda)(T_F+T_{\mathrm{ON}})} \left(\left(e^{\alpha} - 1\right)\left(e^{\alpha+\lambda} - e^{(\alpha+\lambda)T_{\mathrm{ON}}}\right)\right. \\ &\quad \left. - \left(e^{\alpha+\lambda} - 1\right)\left(e^{\alpha} - e^{\alpha T_{\mathrm{ON}}}\right) e^{\lambda(T_B+T_F+T_{\mathrm{ON}})}\right) \\ &\quad \times \left(e^{\alpha+\lambda} - 1\right)^{-1} + \left(e^{\lambda(T_B+T_F+T_{\mathrm{ON}})} - 1\right) \\ &\quad \times e^{-\lambda T_B-(\alpha+\lambda)(T_F+T_{\mathrm{ON}})}. \end{aligned} \tag{17}$$

Similarly, following the analysis of $p_{7,5}$ we can derive the probability that the Rx changes its state from S_{10} to S_8 when a beam misalignment event is detected. The associated transition probability $p_{10,8}$ is

$$\begin{aligned} & p_{10,8} \\ &= \Pr\left\{T_F + 1 \le t_m < T_F + T_{\mathrm{ON}}, t_p \ge T_B + \lfloor t_m \rfloor\right\} \\ &\quad + \Pr\left\{0 \le t_m < T_F + 1\right\} \\ &= \frac{\left(e^{\alpha} - 1\right)\left(e^{\alpha+\lambda} - e^{(\alpha+\lambda)T_{\mathrm{ON}}}\right) e^{-\alpha-\lambda T_B-(\alpha+\lambda)(T_F+T_{\mathrm{ON}})}}{1 - e^{\alpha+\lambda}} \\ &\quad + 1 - e^{-\alpha(T_F+1)}. \end{aligned} \tag{18}$$

If the On Duration Timer of S_{10} successfully expires, the Rx goes to S_{11} and waits for T_S *ms* before switching back to the On Duration state S_3. The probabilities for these two state transitions $S_{10} \rightarrow S_{11}$ and $S_{11} \rightarrow S_3$ are as follows:

$$\begin{aligned} p_{10,11} &= \Pr\left\{t_p \ge T_B + T_F + T_{\mathrm{ON}}, t_m \ge T_B + T_F\right\} \\ &= e^{-\lambda T_B-(\alpha+\lambda)(T_F+T_{\mathrm{ON}})}, \end{aligned} \tag{19}$$

$$p_{11,3} = 1. \tag{20}$$

Now we have completed the presentation of the semi-Markov chain model describing the behavior of the Rx in our DRXB scheme. The state transition probabilities which define the semi-Markov chain have also been derived. In the next section, we use these results to further calculate the state stationary probabilities as well as the state holding time of the model, in order to facilitate the performance analysis of the DRXB scheme.

III. STATIONARY PROBABILITY AND STATE HOLDING TIME

Before studying the performance of the DRXB scheme in terms of energy efficiency and transmission latency, we derive the stationary probabilities π_i, and state holding time H_i for S_i, where $i = 0, 1, 2, \cdots, 11$. The state holding time H_i is the average time duration of state S_i of the Rx that is observed in a long time duration, before the Rx transfers to another state S_j where $j \neq i$.

A. STATIONARY PROBABILITY

According to the semi-Markov chain model in FIGURE 3(a), we have the balance equations as follows:

$$\begin{aligned}
\pi_0 &= \pi_0 p_{0,0} + \pi_1 p_{1,0} + \pi_3 p_{3,0} + \pi_7 p_{7,0} + \pi_{10} p_{10,0},\\
\pi_1 &= \pi_0 p_{0,1} + \pi_7 p_{7,1},\\
\pi_j &= \pi_{j-1} p_{j-1,j}, \quad j = 2, 4, 6, 7, 9, 10, 11,\\
\pi_3 &= \pi_2 p_{2,3} + \pi_4 p_{4,3} + \pi_{11} p_{11,3},\\
\pi_5 &= \pi_0 p_{0,5} + \pi_7 p_{7,5},\\
\pi_8 &= \pi_1 p_{1,8} + \pi_3 p_{3,8} + \pi_{10} p_{10,8}.
\end{aligned}$$

Substituting (1)-(20) into the above equations with condition $\sum_{i=0}^{11} \pi_i = 1$ leads to stationary probabilities π_0, $\pi_1, \cdots, \pi_{11}$.

B. STATE HOLDING TIME

We start with the calculation of the holding time H_0 for state S_0. There are three possible cases of how state S_0 may terminate:

- Neither data packet arrival nor beam misalignment happens before the expiry of the Inactivity Timer ($t_p \geq T_0, t_m \geq T_0$). The corresponding holding time for this case is T_0;
- A data packet arrives at the kth subframe, i.e. time range $(k-1, k)$, before the expiry of the Inactivity Timer ($k \leq T_0$) and before misalignment happens ($k \leq t_m$). Thus, the packet is received successfully, which leads to the transition from S_0 to S_0 after which the Inactivity Timer is restarted to count down from T_0. Note that after $S_0 \to S_0$, the holding time of S_0 continues accumulating since the Rx is still in S_0. The corresponding holding time for this case is k (the time that the Rx will stay in S_0) plus H_0, the time that the Rx has been in state S_0, which brings a total of $k + H_0$ *ms* for this case;
- Beam misalignment happens at the kth subframe before the expiry of Inactivity Timer ($k \leq T_0$) and before any packet arrival ($k \leq t_p$). This leads to the transition from S_0 to S_5 and the corresponding holding time is k *ms*, $0 \leq k \leq T_0$.

According to the above discussion, the state holding time for S_0 is calculated as follows,

$$\begin{aligned}
H_0 &= \sum_{k=1}^{T_0} k \cdot \Pr\left\{k-1 \leq t_m < k, t_p \geq k-1\right\} + T_0 \cdot p_{0,1}\\
&\quad + \sum_{k=1}^{T_0} (H_0 + k) \cdot \Pr\left\{k-1 \leq t_p < k, t_m \geq k\right\}\\
&= \sum_{k=1}^{T_0} k \left(e^{-\alpha(k-1)} - e^{-\alpha k}\right) e^{-\lambda(k-1)} + T_0 e^{-T_0(\alpha+\lambda)}\\
&\quad + \sum_{k=1}^{T_0} (H_0 + k)\, e^{-\alpha k} \left(e^{-\lambda(k-1)} - e^{-\lambda k}\right). \qquad (21)
\end{aligned}$$

By solving the Equation (21), we have

$$H_0 = \frac{e^{\alpha+\lambda}\left(e^{T_0(\alpha+\lambda)} - 1\right)}{e^{(T_0+1)(\alpha+\lambda)} - e^{\lambda+T_0(\alpha+\lambda)} + e^{\lambda} - 1}. \qquad (22)$$

The analysis for S_1 considers cases as follows:

- The holding time of S_1 is T_{ON} when neither misalignment nor new data packet occurs before the expiry of the On Duration Timer, with probability $p_{1,2}$;
- The holding time of S_1 is k for $0 < k \leq T_{\mathrm{ON}}$ in the following two situations:
  - Misalignment occurs at the kth subframe of On Duration state and no data arrives before the $(k-1)$th subframe ($t_p \geq k-1$). The Rx cannot be notified of data arrival if beam misalignment and data arrival occur in the same subframe;
  - Data packet arrives at the kth subframe of On Duration state and no misalignment occurs before this subframe ($t_m \geq k$).

Thus, H_1 is expressed by

$$\begin{aligned}
H_1 &= \sum_{k=1}^{T_{\mathrm{ON}}} k \cdot \Pr\left\{k-1 \leq t_p < k\right\} \Pr\left\{t_m \geq k\right\} + p_{1,2} \cdot T_{\mathrm{ON}}\\
&\quad + \sum_{k=1}^{T_{\mathrm{ON}}} k \cdot \Pr\left\{k-1 \leq t_m < k\right\} \Pr\left\{t_p \geq k-1\right\}\\
&= \sum_{k=1}^{T_{\mathrm{ON}}} k \left(e^{-\alpha(k-1)} - e^{-\alpha k}\right) e^{-\lambda(k-1)}\\
&\quad + \sum_{k=1}^{T_{\mathrm{ON}}} k e^{-\alpha k} \left(e^{-\lambda(k-1)} - e^{-\lambda k}\right) + T_{\mathrm{ON}} e^{-(\alpha+\lambda)T_{\mathrm{ON}}}\\
&= \frac{e^{-(\alpha+\lambda)T_{\mathrm{ON}}}\left(e^{(\alpha+\lambda)(T_{\mathrm{ON}}+1)} - e^{\alpha+\lambda}\right)}{e^{\alpha+\lambda} - 1}. \qquad (23)
\end{aligned}$$

The Sleep states hold for the same period, i.e.,

$$H_2 = H_4 = H_{11} = T_S. \qquad (24)$$

The state holding time H_3 of On Duration state S_3 is different from H_1 because data packet arrival and beam misalignment may happen during the Sleep state S_2, S_4 or S_{11} prior to S_3. There are also three possible cases for H_3:

- Neither data packet arrival nor beam misalignment occurs in its prior Sleep state and On Duration state ($t_p \geq T_S + T_{\mathrm{ON}}$ and $t_m \geq T_S + T_{\mathrm{ON}}$). The holding time for S_3 in this case is therefore T_{ON};
- If beam misalignment happens during the time interval $(0, T_S + 1)$, the Rx transfers to S_8 after the 1st subframe of S_3. The time interval $(T_S, T_S + 1)$ here is the 1st subframe of S_3. Therefore, if beam misalignment occurs in $(T_S, T_S + 1)$ or the prior Sleep state, the Rx does not have an aligned beam pair and cannot receive data at all. In this case, the holding time for this case is 1. If a data packet arrives in the prior Sleep state or the 1st subframe of S_3, and misalignment does not occur before the 1st subframe of S_3, i.e. $t_p < T_S + 1$ and $t_m \geq T_S + 1$,

Rx transfers to S_0 right after the 1st subframe of S_3 and the holding time for this case is 1;

- If a data packet arrives at the kth subframe of S_3 before any beam misalignment i.e. $k-1 \le t_p < k, t_m \ge k$ or misalignment happens at the kth subframe of S_3 before any data packet arrives, i.e. $k-1 \le t_m < k$, $t_p \ge k-1$, Rx transfers to S_0 or S_8 respectively after the kth subframe. Thus the holding time for this case is k, where $k = T_S+2, T_S+3, \cdots, T_S+T_{\mathrm{ON}}$.

As a result, the holding time for state S_3 is

$$\begin{aligned}
H_3 &= p_{3,4} \cdot T_{\mathrm{ON}} + \Pr\{0 \le t_m < T_S+1\} \cdot 1 \\
&\quad + \Pr\left\{0 \le t_p < T_S+1, t_m \ge T_S+1\right\} \cdot 1 \\
&\quad + \sum_{k=T_S+2}^{T_{\mathrm{ON}}+T_S} (k-T_S) \Pr\left\{k-1 \le t_p < k\right\} \Pr\{t_m \ge k\} \\
&\quad + \sum_{k=T_S+2}^{T_{\mathrm{ON}}+T_S} (k-T_S) \Pr\{k-1 \le t_m < k\} \Pr\left\{t_p \ge k-1\right\} \\
&= T_{\mathrm{ON}} e^{-\alpha(T_{\mathrm{ON}}+T_S)} e^{-\lambda(T_{\mathrm{ON}}+T_S)} \\
&\quad + e^{-\alpha(T_S+1)} \left(1-e^{-\lambda(T_S+1)}\right) + 1 - e^{-\alpha(T_S+1)} \\
&\quad + \sum_{k=T_S+2}^{T_{\mathrm{ON}}+T_S} e^{-\alpha k} \left(e^{-\lambda(k-1)} - e^{-\lambda k}\right)(k-T_S) \\
&\quad + \sum_{k=T_S+2}^{T_{\mathrm{ON}}+T_S} e^{-\lambda(k-1)} \left(e^{-\alpha(k-1)} - e^{-\alpha k}\right)(k-T_S) \\
&= \frac{e^{\alpha+\lambda} - e^{-(\alpha+\lambda)(T_{\mathrm{ON}}+T_S-1)} + e^{-(\alpha+\lambda)T_S} - 1}{e^{\alpha+\lambda}-1}. \qquad (25)
\end{aligned}$$

For H_5 and H_6, the time needed for beam training and feedback is determined by the total number of Tx-Rx beam pairs that the training procedure needs to measure, and the employed training and feedback algorithms (with different complexity and measurement/feedback accuracy, see e.g. [26]–[28]). For a particular system, T_B and T_F are in general fixed. Therefore, we have

$$H_5 = T_B, \qquad (26)$$
$$H_6 = T_F. \qquad (27)$$

The holding time H_7 is different from H_0 because there is no self-loop transition as $S_0 \to S_0$ for state S_7, and there are Beam Training state S_5 and Feedback state S_6 before S_7. We assume that the Rx can always find an aligned Tx-Rx beam pair after the Beam Training state. The training result is reported to the Tx during the Feedback state to recover communication. Meanwhile, data still possibly arrives at the Tx while the Rx is in Beam Training state S_5 or Feedback state S_6. Beam misalignment can possibly happen during Feedback state S_6 even though the Tx-Rx beam pair has been updated right ahead the Feedback states. Therefore, the holding time for H_7 is summarized as following:

- Neither data arrival happens throughout S_5, S_6 and S_7, i.e. $t_p \ge T_B+T_F+T_0$, nor beam misalignment occurs throughout S_6 and S_7, i.e. $t_m \ge T_F+T_0$. In this case, the Rx transfers to S_1 from S_7 after the expiry of Inactivity Timer of S_7 and the holding time is T_0;
- If beam misalignment happens during the time interval $(0, T_F+1)$, the Rx detects the beam misalignment at the 1st subframe of S_7 and transfers to S_5 after this subframe. The holding time is 1 ms. If data packet arrives in S_5, S_6 or the 1st subframe of S_7 and misalignment does not occur before the 1st subframe of S_7, i.e. $0 \le t_p < T_B+T_F+1$ and $t_m \ge T_F+1$, the Rx transfers to S_0 after this subframe. The holding time for this case is also 1 ms;
- If data packet arrives at the kth subframe of S_7 before any beam misalignment event i.e. $k-1 \le t_p - T_B - T_F < k$ subject to $t_m - T_F \ge k$, or beam misalignment happens at the kth subframe of S_7 before any data packet arrival i.e. $k-1 \le t_m - T_F < k$ subject to $t_p - T_F - T_B \ge k-1$, the Rx transfers to S_0 or S_5 respectively after the kth subframe. Thus the holding time for these two cases is $k - T_B - T_F$, where $k = T_B+T_F+2, T_B+T_F+3, \cdots, T_B+T_F+T_{\mathrm{ON}}$.

Thus, the holding time for S_7 is

$$\begin{aligned}
&H_7 \\
&= \Pr\{t_m \ge T_F+1\} \Pr\left\{0 \le t_p < T_B+T_F+1\right\} \cdot 1 \\
&\quad + T_0 \cdot p_{7,1} + \Pr\{t_m < T_F+1\} \cdot 1 \\
&\quad + \sum_{k=T_B+T_F+2}^{T_B+T_F+T_0} \Big(\Pr\left\{t_p \ge k-1\right\} \Pr\{k-T_B-1 \le t_m < k-T_B\} \\
&\quad + \Pr\left\{k-1 \le t_p < k\right\} \Pr\{t_m \ge k-T_B\}\Big)(k-T_B-T_F) \\
&= \frac{e^{\alpha-\lambda(T_B-1)-(\alpha+\lambda)(T_F+T_0)} - e^{-\lambda T_B-(\alpha+\lambda)T_F}}{1-e^{\alpha+\lambda}} + 1. \qquad (28)
\end{aligned}$$

The calculation for S_{10} is similar to that of S_7, which is expressed as follows

$$\begin{aligned}
&H_{10} \\
&= \Pr\{t_m \ge T_F+1\} \Pr\left\{0 \le t_p < T_B+T_F+1\right\} \cdot 1 \\
&\quad + p_{10,11} \cdot T_{\mathrm{ON}} + \Pr\{0 \le t_m < T_F+1\} \cdot 1 \\
&\quad + \sum_{k=T_B+T_F+2}^{T_B+T_F+T_{\mathrm{ON}}} (k-T_B-T_F) \\
&\quad \times \Big(\Pr\left\{k-1 \le t_p < k\right\} \Pr\{t_m \ge k-T_B\} \\
&\quad + \Pr\left\{t_p \ge k-1\right\} \Pr\{k-T_B-1 \le t_m < k-T_B\}\Big) \\
&= \frac{e^{\alpha-\lambda(T_B-1)-(\alpha+\lambda)(T_F+T_{\mathrm{ON}})} - e^{-\lambda T_B-(\alpha+\lambda)T_F}}{1-e^{\alpha+\lambda}} + 1. \qquad (29)
\end{aligned}$$

The state holding time for both S_8 and S_9 is constant.

$$H_8 = T_B, \qquad (30)$$
$$H_9 = T_F. \qquad (31)$$

So far, we have obtained the holding time for all states.

IV. ENERGY EFFICIENCY AND TRANMISSION LATENCY

Following the analysis of the DRX scheme in LTE [16], we define the *power saving factor* ε as the duration proportion of Sleep state, i.e., the expected holding time of the Sleep state (state holding time weighted by stationary probability) over the expected holding time of all states:

$$\varepsilon = \frac{\pi_2 H_2 + \pi_4 H_4 + \pi_{11} H_{11}}{\sum_{i=0}^{11} \pi_i H_i}. \tag{32}$$

The power saving factor indicates, at any time instant, the probability that the Rx is in the Sleep state. A larger value of ε means that the Rx turns off its receiving circuit more often. Hence ε reflects the achievable energy efficiency.

Similarly, the duration proportion of the Beam Training and Feedback states can also be defined as the ratio of the expected holding time of these two states to the expected holding time of all states:

$$\phi = \frac{\pi_5 H_5 + \pi_6 H_6 + \pi_8 H_8 + \pi_9 H_9}{\sum_{i=0}^{11} \pi_i H_i}. \tag{33}$$

ϕ is termed beam training consumption factor and will be used to help analyze the transmission latency performance.

In addition to energy efficiency, the latency occurred in the data packet transmission from the Tx to the Rx is another important performance indicator of a scheme. Such a transmission latency can be represented by the *wake-up latency*, defined as the expected interval from the time instant that a data packet arrives at the Tx but the Rx is unable to receive it because the Rx is in a Sleep, Beam Training, or Feedback state, to the first subframe of an Active state when the Rx is capable of receiving the packet using an aligned Tx-Rx beam pair. In what follows, the wake-up latency is denoted by D. When a data packet arrives at the Tx, if the Rx is in a Sleep state, the expected conditional wake-up latency is denoted as d_S, and if the Rx is in a Beam Training or Feedback state, the expected conditional wake-up latency is denoted as d_M. Clearly, we have

$$D = \epsilon d_S + \phi d_M. \tag{34}$$

For our DRXB scheme, the wake-up latency can be studied in the following two cases:

1) Data packet arrives at the Tx when the Rx is in a Sleep state S_2, S_4 or S_{11}. There are two alternative cases depending on the beam misalignment event:
   - If there is no beam misalignment during the Rx's Sleep state, via downlink control channel the Rx would detect the data packet waiting for transmission at the Tx as soon as the On Duration state comes. In this case, the state transition is shown as the path $1 \rightarrow 2$ in FIGURE 4. Since data packets arrive following a Poisson process, the arrival time of a data packet follows a uniform distribution over given time interval (Section 2.3 [33]). Thus the expectation of wake-up latency is $(T_S + 1)/2$ if $t_m > T_S + 1$. In this case, the expectation of wake-up latency is $\Pr\{t_m > T_S + 1\}(T_S + 1)/2$;

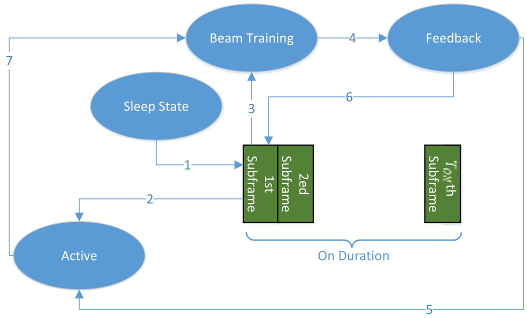


FIGURE 4. State transitions related to wake-up latency.

   - Otherwise, if beam misalignment does happen during Rx's Sleep state, the Rx would not be able to receive the data packet due to the lack of available communication link. In this case, the wake-up latency is extended by the time used for beam training and feedback ($T_B + T_F + 1$), as shown by the path $1 \rightarrow 3 \rightarrow 4 \rightarrow 6 \rightarrow 2$ in FIGURE 4. If beam misalignment occurs in the Feedback state, the wake-up latency $(T_S + 1)/2$ of the Sleep state may be further extended by n rounds of beam training and feedback as the path $\cdots 6 \rightarrow 3 \rightarrow 4 \cdots$ in FIGURE 4. The random variable n follows a geometric distribution with parameter $\Pr\{t_m > T_F + 1\}$ and we have the expectation $E[n] = 1/\Pr\{t_m > T_F + 1\}$. The wake-up latency for this case is thus $\left(\frac{(T_B+T_F+1)}{\Pr\{t_m>T_F+1\}} + \frac{T_S+1}{2}\right)\Pr\{t_m < T_S + 1\}$.

Following the above analysis, the expected conditional wake-up latency d_S can be calculated as:

$$\begin{aligned} d_S &= \left(\frac{T_B + T_F + 1}{\Pr\{t_m > T_F + 1\}} + \frac{T_S+1}{2}\right)\Pr\{t_m < T_S+1\} \\ &\quad + \frac{T_S + 1}{2}\Pr\{t_m > T_S + 1\} \\ &= \left(1 - e^{-\alpha(T_S+1)}\right)\left((T_B + T_F + 1)\,e^{\alpha(T_F+1)} \right. \\ &\quad \left. + \frac{T_S + 1}{2}\right) + \frac{T_S + 1}{2} e^{-\alpha(T_S+1)}. \end{aligned} \tag{35}$$

2) Data packet arrives at the Tx when the Rx is in the Beam Training state S_5 or Feedback state S_6. Then the data packet is received successfully at the first subframe of the subsequent Active state S_7 (shown as the transition path $7 \rightarrow 4 \rightarrow 5$ in FIGURE 4) if beam misalignment does not happen during S_6. In this case the latency expectation is $\frac{T_B+T_F+1}{2}$. Otherwise, the wake-up latency may be extended by $n(T_B+T_F+1)$ if beam misalignment happens in S_6 with probability $\Pr\{t_m < 1 + T_F\}$, similar to case 1). For S_8 and S_9, the analysis can be conducted similarly. As a result, the expected conditional wake-up latency d_M can be

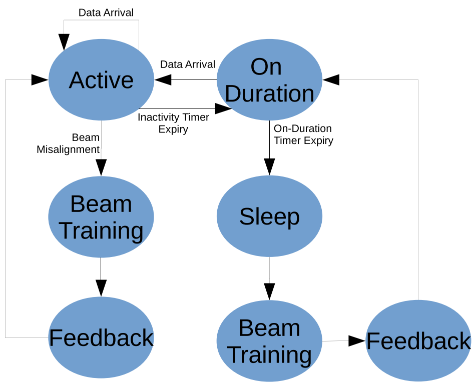


FIGURE 5. The DRXR scheme used as numerical comparison reference.

derived as

$$d_M = \frac{T_B + T_F + 1}{\Pr\{t_m > T_F + 1\}} \Pr\{t_m < 1 + T_F\} + \frac{1}{2}(T_B + T_F + 1) = \frac{1}{2}(T_B + T_F + 1)\left(2e^{\alpha(T_F+1)} - 1\right). \quad (36)$$

Substituting Equations (35) and (36) into (34) leads to the overall wake-up latency achieved by our DRXB scheme. Clearly, there exists a tradeoff between the power saving factor and wake-up latency. If one adjusts system parameters (e.g., increasing the length of Sleep state T_S) to improve energy efficiency, the transmission latency is inevitably increased. In the next section, we will show through simulations that, for the same system setup, our DRXB achieves a notably better tradeoff between these two performance indicators, compared with a reference scheme.

V. NUMERICAL RESULTS

In this section, we present numerical results to evaluate the performance of the proposed DRXB scheme in certain typical system setups. Specifically, the power saving factor and wake-up latency of the DRXB scheme are found by both analytical results as presented in the previous sections and Monte Carlo simulation (labeled by "Sim"). We let all simulations start from the Active state S_0. Each simulation runs for 10^6 *ms*, i.e. 10^6 subframes. Numerical values of the system parameters are chosen following existing literature on the legacy DRX scheme [11], [12], [16] or on high-frequency beamforming systems [12], [15].

The direct comparison between our proposed DRXB scheme and the legacy DRX scheme of LTE [5] is not meaningful, since the legacy DRX scheme designed for LTE does no have policy coping with the beam misalignment problem in multiple-beam communication systems. To demonstrate the efficiency of our proposed DRXB scheme and have a fair comparison, we consider a DRX reference (DRXR) scheme adapted from [10]–[12]. Its state transition behaviors are illustrated in FIGURE 5. The basic idea is to insert a Beam Training state and a Feedback state in every

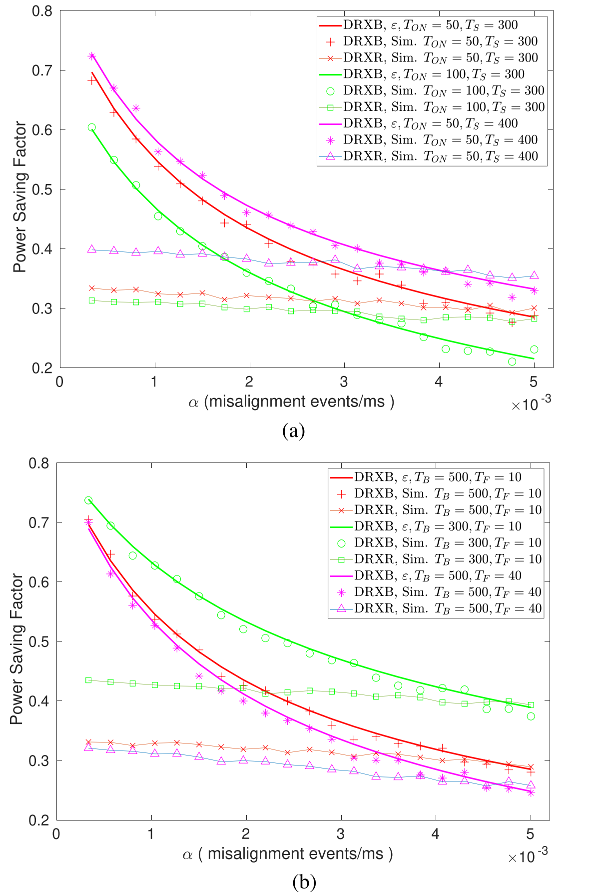


FIGURE 6. Power saving factor versus misalignment rate. (a) Comparison for different On Duration state and Sleep state lengths, with $\lambda = \frac{1}{1000}$, $T_F = 10$, and $T_B = 500$. (b) Comparison for different Beam Training state and Feedback state lengths, with $\lambda = \frac{1}{1000}$, $T_{ON} = 50$, and $T_S = 300$.

DRX cycle, as shown in FIGURE 1(c), and also allow the Rx to carry out beam training if beam misalignment occurs in the Active state. By this means, a new communication link can be reestablished after the system experiences a beam misalignment event. However, as we mentioned in Section I, in practice beam misalignment may not appear frequently. Demanding the Rx to conduct beam training in every DRX cycle may not be necessary and thus wastes system resources.

FIGURE 6 shows the power saving factor against the beam misalignment rate α. Clearly, for our DRXB scheme, simulation results match well with analytical results, which verifies the accuracy of the latter. In addition, when α is relatively small, the DRXB scheme achieves a notably larger power saving factor than the DRXR scheme, due to the fact that beam training is carried out only when beam misalignment occurs. This implies a significantly higher device energy efficiency. The performance gain becomes larger when α is smaller, because the Rx can enjoy a larger chance of entering the Sleep state if there is no need to update the aligned beam pair. When the beam misalignment rate is very large, from the figure it can be seen that our DRXB scheme may have a smaller power saving factor compared with the DRXR scheme, because the Rx may frequently conduct beam training in the Active and On Duration states which reduces the opportunity it enters the Sleep state. But this observation does not necessarily mean that the DRXR scheme outperforms our DRXB scheme, since both energy efficiency and transmission latency are important and there is tradeoff between them. The only way that the Rx can be aware of new data packet arrival at the Tx is through the downlink control channel using an aligned beam pair. If beam misalignment occurs frequently, the beam training has to be conducted frequently. Otherwise, the Tx cannot timely notify the Rx to prepare for reception, which would not give a good balance between energy efficiency and transmission latency. It can be seen later on in FIGURE 8 that under the same parameter settings, our DRXB scheme has smaller wake-up latency for the same range of α.

The impact of the lengths of the On Duration Timer and the Sleep Timer on the power saving factor is shown in FIGURE 6(a). It is seen that choosing a smaller value of T_{ON} or a larger value of T_{S} results in a larger energy efficiency. But as we will show later, such choices also lead to longer wake-up latency, since when new data packet arrives at the Tx, with a higher probability the Rx is in the Sleep state. There is a tradeoff between the achievable energy efficiency and transmission latency. Designing proper system parameters should take both indicators into consideration. With the same values of T_{ON} and T_{S}, the DRXB scheme have better performance than the DRXR scheme, because it is an opportunistic approach and activates beam training only when beam misalignment really happens.

For fixed $T_{\mathrm{ON}} = 50$ and $T_{\mathrm{S}} = 300$, the impact of the lengths of the Beam Training state and Feedback state is shown in FIGURE 6(b). It can be seen that reducing the values of T_B and T_F leads to higher energy efficiency since more time can be reserved for the Sleep state. However, a shorter beam training period in general comes from simpler training and feedback methods, and thus may not be able to provide sufficient estimation reliability. The selection of T_B and T_F, i.e., the training and feedback solutions, can be directed by our analytical solutions. Again, for the same values of T_B and T_F, our DRXB scheme in general achieves better power saving factors than the DRXR scheme, especially when α is small. If the beam training time is large, which happens normally when the number of potential Tx-Rx pairs is large, the performance advantage becomes more notable. This can again be attributed to that DRXB is designed to perform the time-consuming and energy-consuming beam training and feedback procedure only if beam misalignment happens.

FIGURE 7 shows how the power saving factor changes when the data packet arrival rate λ varies. For our DRXB scheme, the power saving factor decreases as data traffic becomes heavier, i.e. λ increases, because the Rx more frequently operates in the Active state to receive data. Comparing DXRB with DRXR, generally speaking the former outperforms the latter. The performance advantage becomes larger when the data packet arrival rate is smaller. This is because the DRXB scheme does not need to perform beam training in each DRX cycle and thus more time can be reserved for the Sleep state.

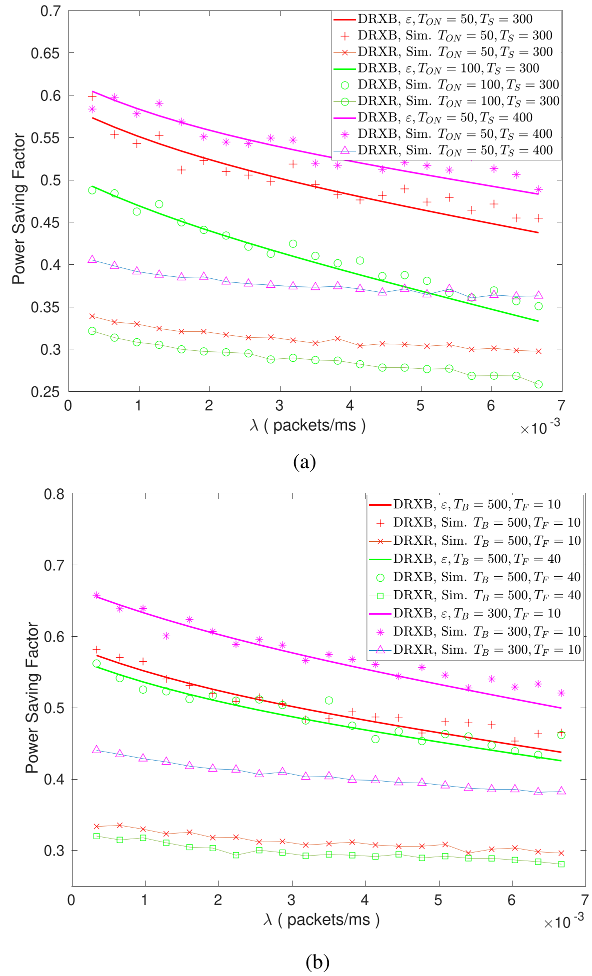


FIGURE 7. Power Saving Factor versus data arrival rate. (a) Comparison for difference On Duration state and Sleep state lengths, with $\alpha = \frac{1}{1000}$, $T_0 = 50$, $T_F = 10$, and $T_B = 500$. (b) Comparison for different Beam Training state and Feedback state lengths, with $\alpha = \frac{1}{1000}$, $T_0 = 50$, $T_{\mathrm{ON}} = 50$, and $T_S = 300$.

FIGURE 8 illustrates how system parameters affect the data packet transmission latency. Specifically, FIGURE 8(a) and FIGURE 8(b) display the relationship between the wake-up latency and the beam misalignment rate of the system. It can be clearly seen that the DRXB scheme achieves smaller wake-up latency, especially when α is small and beam training is needed with relatively low frequency. For our DRXB scheme, a larger beam misalignment rate leads to larger transmission latency since the beam training has to be conducted before data delivery. Having a larger value of T_{ON} and smaller value of T_S results in better performance in terms of wake-up latency, which is opposite to the case for the power saving factor shown in FIGURE 6(a), as expected. Shorter durations of Beam Training and Feedback states also lead to smaller transmission latency. Hence one needs to balance different performance indicators when choosing beam training and feedback strategies.

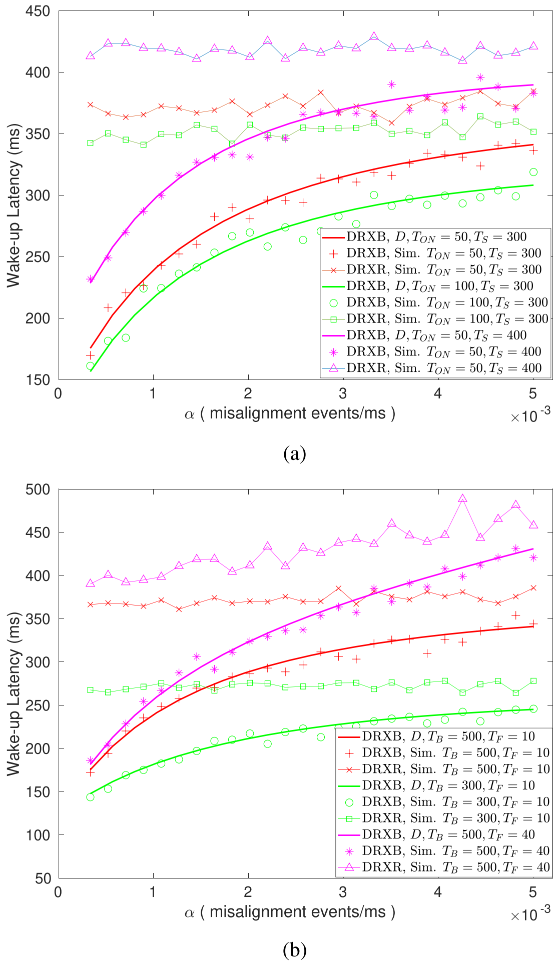


FIGURE 8. Wake-up latency versus beam misalignment rate. (a) Comparison for different On Duration state and Sleep state lengths, with $\lambda = \frac{1}{1000}$, $T_0 = 50$, $T_F = 10$, and $T_B = 500$. (b) Comparison for different Beam Training state and Feedback state lengths, with $\lambda = \frac{1}{1000}$, $T_0 = 50$, $T_{ON} = 50$, and $T_S = 300$.

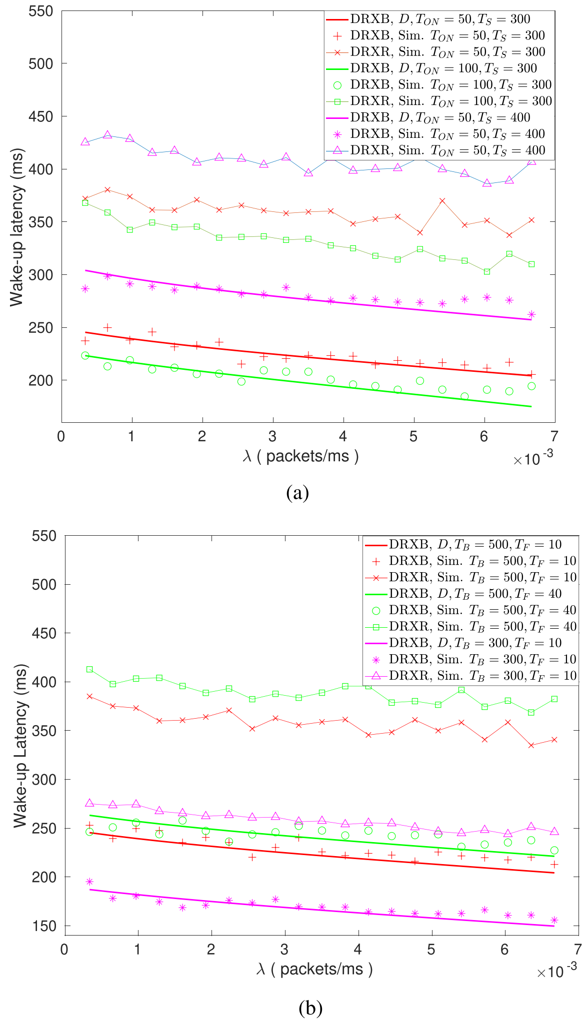


FIGURE 9. Wake-up latency versus data packet arrival rate. (a) Comparison for different On Duration state and Sleep state lengths, with $\alpha = \frac{1}{1000}$, $T_0 = 50$, $T_F = 10$, and $T_B = 500$. (b) Comparison for different Beam Training state and Feedback state lengths, with $\alpha = \frac{1}{1000}$, $T_0 = 50$, $T_{ON} = 50$, and $T_S = 300$.

FIGURE 8(a) shows that larger T_{ON} leads to smaller wake-up latency and longer sleep time results in longer wake-up latency (it leads to larger power saving factor as shown in FIGURE 6(a).) FIGURE 8(b) shows the small wake-up latency can also be achieved when the time needed for beam training and feedback decreases. Change of Feedback time T_F may not produce significant difference of wake-up latency when α is small but would result in non-negligible difference when α is large and the Feedback state is more frequently entered.

The relationship between the wake-up latency and packet arrival rate, under different system setups, is shown in FIGURE 9. In general, systems with heavier data traffic have smaller wake-up latency, since the Rx devices rarely have opportunities to enter the energy-saving Sleep state. They can rapidly respond to new data packet arrival at the Tx. Certainly, this also leads to a smaller power-saving factor, as shown previously. From the figures, it is easy to see that the proposed DRXB scheme achieves much smaller transmission latency compared with the DRXR scheme. This is again because DRXB is an opportunistic scheme that avoids unnecessary beam training procedures. Combining the results demonstrated in FIGURE 6-FIGURE 9, we can clearly see that our DRXB scheme can attain a notably better performance in terms of the overall tradeoff between energy efficiency and data transmission latency than the DRXR scheme, due to its opportunistic nature in incorporating discontinuous reception and beam training to jointly consider the characteristics of bursty data traffic and beam misalignment issues in high-frequency multiple-beam communication systems.

VI. CONCLUSION

We have proposed a novel discontinuous reception technique suitable for multiple-beam communication systems in high-frequency spectrum bands. The scheme jointly takes into account the nature of bursty data traffic and time-varying Tx-Rx link quality. Compared with conventional DRX solutions, it allows the Rx to frequently turn off its receiving circuit to realize discontinuous reception and also to conduct beam training only when beam misalignment happens. This brings the opportunity to avoid unnecessary energy consumption. We have presented an analytic model to the proposed DRXB scheme so that the relationship between system performance, in terms of power saving factor and wake-up latency, and various system parameters can be quantitatively established. Extensive simulation results have shown that our method can achieve a notably better tradeoff between energy efficiency and data transmission latency than conventional methods.

ACKNOWLEDGMENT

This work reflects only the authors' view and the EU Commission is not responsible for any use that may be made of the information it contains.

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