

## RESEARCH ARTICLE

# Energy-Efficient Traffic Steering in Millimeter-Wave Dual Connectivity Discontinuous Reception Framework

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**ABSTRACT** The Dual connectivity (DC) technology is a robust solution for Internet service providers (ISP) to evolve their legacy infrastructures with less cost to speed up the progress of fifth-generation (5G) services coverage. DC enables the traditional network to connect to multiple New Radio (NR) Node B (gNBs). A well-known scheme is the non-standalone (NSA) NR. In this case, the user equipment (UEs) could access the network via both the evolved Node B (eNB) and the gNB. However, some research has indicated that the UEs in such a configuration suffer from power consumption problems. UEs are typically configured with discontinuous reception (DRX) mechanism to save power. However, most current systems do not investigate and optimize the DRX parameters. To the authors' best knowledge, this work is the first to combine DRX with traffic steering for the UEs in the NSA NR system. A traffic steering algorithm is proposed to improve the coordination between the eNB and the gNB. We used a semi-Markov chain model to analyze power consumption and average delay. Compared with standard DRX operated in LTE, NR, and DC, we verified that the proposed model achieves power-saving gains without incurring an additional delay. The results indicated that the UE could save considerable power with an optimized system configuration.

**INDEX TERMS** Discontinuous reception (DRX), dual connectivity (DC), power saving, traffic steering.

## I. INTRODUCTION

To evolve the mobile communication network, Internet Service Providers (ISP) invest in their infrastructures to satisfy the increasing performance requirements. Most ISPs have established their stable infrastructure to provide mobile wireless network services. The 3rd Generation Partnership Project (3GPP) proposed several options for ISPs to upgrade their systems to the 5G New Radio (NR) system without tremendous costs. There are two solutions for the ISPs to construct their 5G NR systems: Standalone (SA) NR and Non-Standalone (NSA) NR. The NSA solution can be considered a transitional solution. It enables the ISPs to upgrade their existing network system by adding 5G NR Radio Access

Network (RAN) elements to the current core network (CN). In this case, user equipment (UE) subscribing to 5G network services can first access the web via upgraded 5G NR RAN. After that, the ISPs could later deploy the 5G NR CN and turn the system into the SA version.

A UE in the NSA system connects to the network with the dual connectivity (DC) technique. The UE maintains two links: one is to the master cell base station, and the other is to the secondary cell base station. In this work, we focus on Evolved Universal Terrestrial Radio Access Network (E-UTRAN) DC (EN-DC). In EN-DC, the master cell base station is the Long-Term Evolution (LTE) evolved Node B (eNB), and the secondary cell base station is the NR Node B (gNB). Both nodes connect to 4G evolved packet core (EPC), which serves as the CN in this deployment. Among the two links to the UE, the LTE link is more reliable for control

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signaling, but the transmission rate is lower. The NR link could provide a higher data rate, but the reliability is lower than the LTE cases.

However, after the NR NSA systems are broadly established worldwide, researchers discover power consumption issues in their measurements, experiments, and testbeds [1]. With beamforming technology applied to overcome severe pathloss problems in millimeter-wave (mmWave) communication, a gNB could only serve a limited number of beams during one period. UEs on other beams are unable to access NR resources. Since the UEs have no information on the beam serving pattern, they would keep decoding channels even if the gNB serves other beams. It makes the UEs waste a great amount of power.

Moreover, The UE can not reduce the wasted power by performing DRX, as the problem lies in the misalignment between the UE and the gNB. This indicates that there is still room for improving power consumption. Therefore, the UE's behavior when applying the DRX mechanism and DC technique simultaneously in EN-DC should be thoroughly investigated so that the UE can operate with an optimized system configuration.

We undertake research and analysis of the DRX mechanism for the UEs operating in EN-DC deployment in the NR NSA system. To the authors' best knowledge, this work is the first work focusing on coordinating DRX and traffic for the UEs operating in EN-DC. Our main contributions are listed as follows.

- We proposed a solution to improve the power-saving performance by introducing traffic steering into the EN-DC mechanism. The mechanism helps the master cell effectively offload the data to the secondary cell.
- We designed a traffic steering algorithm for the DC base stations to optimize the transmission delay when the UE is configured with the DRX mechanism.
- We proposed a performance model based on the semi-Markov chain model for the DRX. The analysis shows improvements on power consumption without incurring additional delay. It also provides insights into the impact of DRX parameters on power consumption and average delay.

## II. RELATED WORK

### A. DRX IN LTE AND NR NETWORKS

In LTE and LTE Advanced (LTE-A), various DRX mechanisms are proposed to fit in diverse traffic models and services. In [2], the authors improved the performance by optimizing the DRX parameters for various applications. Also, the impacts on different Radio Resource Control (RRC) modes were discussed. In [3], the authors analyzed the performance of LTE DRX with bursty traffic and adjustable DRX cycles. The results showed that LTE DRX outperformed Universal Mobile Telecommunications System (UMTS) DRX, and the trade-off relationship between power saving and the wake-up delay was investigated. In [4], the balance between power saving and delay was considered and

optimized. A switching mechanism was explored based on the traffic, enabling the UE to reduce energy consumption while maintaining reasonable latency. The authors further proposed guidelines for selecting parameters in different traffic types.

In [5], the authors proposed a new formula to evaluate the analytical model more accurately. Besides, a novel performance measure, relative power saving, was also introduced for evaluation. In [6], the authors analyzed the LTE/LTE-A DRX with mixed short and long cycles based on power consumption and relative power saving. They investigated the impact of changing DRX parameters and concluded that properly selecting parameters was helpful in reducing energy consumption while maintaining reasonable latency. In [7], the authors proposed a new approach to obtaining Power Saving Factor (PSF) and transmission delay. The method provides accurate results without making sophisticated mathematical calculations. In [8], the authors used a machine learning algorithm to predict inter-packet arrival time for machine-type communication (MTC) devices in a multi-access edge computing framework. The core idea is to predict the next packet arrival time based on the past arrival time with the bank-of-experts algorithm. Once the next arrival time is predicted, the UE could go to RRC\_IDLE mode directly without experiencing several short and long DRX cycles, and more power could be saved.

In 5G NR, beamforming technology is adopted to enhance signal power. It disadvantages the conventional DRX mechanism since the UE will temporarily lose the connection with the gNB, leading to difficulties in transmission and reception. Two types of solutions are proposed to deal with the misalignment problem. The first one is performing beam training, which enables the UE to find the best beam pair before transmission. The second solution considers the beam pattern and eliminates misalignment by turning off the radio frequency (RF) module while the UE and the gNB are mismatched.

In [9] and [10], the misalignment problem was resolved by performing beam training to find the best beam pair before entering the active state. Once the best beam pair has been found, the UE can make transmission and reception in the active period. In [11], a signaling-based DRX was proposed. This mechanism aims to reduce the time of performing beam searching. With the power saving indicator (PSI), the UE can avoid unnecessary beam training and save more power. The authors of [12] resolved the misalignment problem with a beam-aware DRX mechanism. As the gNB serves the beams periodically, the UE can stay dormant when out of the coverage and turn on the RF module only when necessary.

Aside from sequentially served beam patterns, the authors in [13] proposed a beam-aware DRX mechanism that considers dynamically served beam patterns. In this work, the beam pattern consists of a static-configured beam frame and a dynamic-configured beam frame. The UEs are sequentially served with a predefined beam pattern in a static-configured beam frame and turn on their RF modules only when served. Once the number of packets received in the static-configured

beam frame is no less than the threshold value, the gNB adds the beam to the candidate list. It will select the beam to serve in the following dynamic-configured beam frame. In [14], the authors proposed an algorithm that improves performance by adjusting the transmission time interval (TTI) length in different services. The algorithm configures the DRX parameters to optimize the power consumption.

### B. DRX IN DUAL CONNECTIVITY CONFIGURATION

Studies on power-saving mechanisms in dual connectivity configuration have been accomplished. In [15], a synchronized adaptive DRX sleep (SAS) scheme was proposed to simultaneously reduce the power consumption of a UE connected to a master eNB and a secondary eNB. The SAS scheme uses a flag as an indicator to determine the frequency of data traffic. If the traffic is frequent, the UE runs conventional DRX to avoid long delays. Otherwise, it circumvents several short periods of sleep to save more power at the cost of increasing delay. In [16], the authors discussed the scheme of aggregating LTE unlicensed bands (LTE-U) to boost throughput. Considering the coordination between LTE and LTE-U, a DRX scheme is proposed to reduce power consumption in unlicensed bands. Analysis based on a semi-Markov model also showed improvement in power saving.

In [17], a hybrid DRX mechanism that allows the UE to listen to the incoming data intimation from LTE signals was proposed. With the knowledge of incoming data intimation, the UE performs beam searching and beam alignment only when necessary to reduce unnecessary power consumption. Based on this hybrid DRX model, another hybrid DRX mechanism for light traffic was proposed in [18]. In this model, the light traffic is transferred over a low-quality mmWave link without performing beam alignment to reduce the time spent on beam searching and waiting for the inactivity timer. Aside from NSA architecture, [19] explored DRX on NR unlicensed bands (NR-U). The UE connects to a gNB and unlicensed bands simultaneously to enhance throughput. The authors designed a DRX scheme that synchronizes licensed and unlicensed bands to improve power efficiency. In [1], the authors conducted measurements studying the power consumption of the UE in NSA architecture. It was shown that a 5G system consumes more power than 4G due to the powerful hardware and inefficient solutions to power management. However, based on the results, the energy-per-bit of 5G is less than that of 4G, so 5G can be more energy-efficient than 4G with a well-designed power management scheme.

### C. TRAFFIC STEERING

In [20], a unified traffic steering framework for LTE was proposed to optimize resource utilization. Based on the load, RAN is able to dynamically adjust the number of carriers, access points, or cells. If heavily loaded, the network side could configure more carriers or unlicensed bands to enhance throughput. On the other hand, access points or cells could be turned off for power saving if the traffic is light. In [21], a hierarchical software-defined network was proposed to enhance

coverage, mobility robustness, and throughput. Under this architecture, mmWave base stations and small cell base stations are responsible for network control, mobility management, and control signaling transmission, while ultra-dense mmWave access points provide flexibility in deployment and enhance total throughput. In [22], the authors investigated different protocol options, including hard handover, fast switch, and dual connectivity, to integrate LTE and NR networks. They showed that dynamically steering quality of service (QoS) flows to suitable channels and access points improves capacity and reliability. In [23], the authors proposed a Markov decision process to model traffic steering problems in 5G heterogeneous networks and solve them with a reinforcement learning algorithm. Based on different traffic types, the algorithm efficiently allocates resources and optimizes the connection quality experienced by users.

In this work, we investigated the possibility of improving DRX performance with traffic steering in Evolved Universal Terrestrial Radio Access Network (E-UTRAN) NR Dual Connectivity (EN-DC) deployment, which has not been done in the existing works. Table 1 organizes the contributions of the existing literature. Papers [15], [16], [17], [18], [19] considered DRX in dual connectivity architecture. However, either EN-DC architecture was not considered or traffic steering was not applied. Work [9], [10], [11] focused on resolving the NR beam alignment problem with beam training. Beam-aware mechanisms were proposed to resolve misalignment issues in the NR network [12], [13]. In this work, we proposed a DRX mechanism with a traffic steering algorithm that improves coordination between the UE, the eNB, and the gNB and reduces total UE power consumption. The algorithm not only considers coordination in control messages but also dynamically guides traffic to the eNB and the gNB based on beam information.

## III. BACKGROUND AND 3GPP STANDARDS

### A. DUAL CONNECTIVITY IN NR

From 4G LTE to 5G NR, the ISPs have to invest much money in upgrading the infrastructures to provide advanced network services. 3GPP had discussed the possible scenarios for deployments to speed up the evolution. It proposed using the dual connectivity technology to establish the devices' connections with 5G NR radio access network gNBs and the 4G LTE core network. DC lets the UE connect to two base stations simultaneously to improve data rate and mobility robustness. DC increases the throughput by aggregating the two base stations' wireless resources and improves the system robustness since it allows the network to separate the transmissions of control plane and user plane data.

In this work, we refer to the 3GPP-specified EN-DC architecture [24] shown in Figure 1 in this work. The UE connects to an eNB of a master cell group and a gNB of a secondary cell group. We use eNB to denote the master node eNB of the LTE network and gNB to represent the secondary node gNB of the NR network. The eNB connects the core network over the interface S1, which supports both control message traffic

TABLE 1. Summary of DRX related work.

Paper	Network	Connectivity	Target	Solution
[2]	LTE	Single	Performance analysis	<ul style="list-style-type: none"> <li>• Provide criteria for DRX parameter selection under various applications.</li> <li>• Analyze power consumption and delay with adjustable DRX cycles.</li> <li>• Formulate a trade-off relationship between energy saving and delay.</li> <li>• Optimize parameters based on the traffic pattern.</li> <li>• Provide guidelines in DRX parameter selection.</li> <li>• Provide in-depth analysis in power consumption and average delay.</li> <li>• Separate time period into parts to simplify calculation.</li> <li>• Use machine learning algorithm to predict next arrival time.</li> </ul>
[3]	LTE	Single	Performance analysis	
[4]	LTE	Single	Performance analysis	
[5]	LTE	Single	Performance analysis	
[6]	LTE	Single	Performance analysis	
[7]	LTE	Single	Numerical analysis	
[8]	LTE	Single	MTC DRX	
[9]	NR	Single	Beam management	
[10]	NR	Single	Beam management	
[11]	NR	Single	Beam management	
[12]	NR	Single	Beam alignment	
[13]	NR	Single	Beam alignment	
[14]	NR	Single	DRX with fixed TTI	
[15]	LTE	Dual	Dormancy alignment	<ul style="list-style-type: none"> <li>• Propose a synchronized DRX for two separate MAC entities.</li> <li>• Investigate benefits brought by alignment in sleep time.</li> <li>• Investigate power saving mechanism in LTE-U.</li> <li>• Propose a licensed band controlled DRX for unlicensed bands.</li> <li>• Propose a hybrid DRX with LTE as the controller.</li> <li>• Investigate improvements on DRX with data intimation in LTE.</li> <li>• Propose a way to receive light traffic in dormancy based on [17].</li> <li>• Propose a licensed band assisted DRX for NR unlicensed band.</li> <li>• Explore the possibility to be beam-aware and reduce beam searching procedure.</li> </ul>
[16]	LTE, LTE-U	Dual	DRX in LTE-U	
[17]	NR	Dual	Beam alignment	
[18]	NR	Dual	Beam alignment	
[19]	NR, NR-U	Dual	DRX in NR-U	

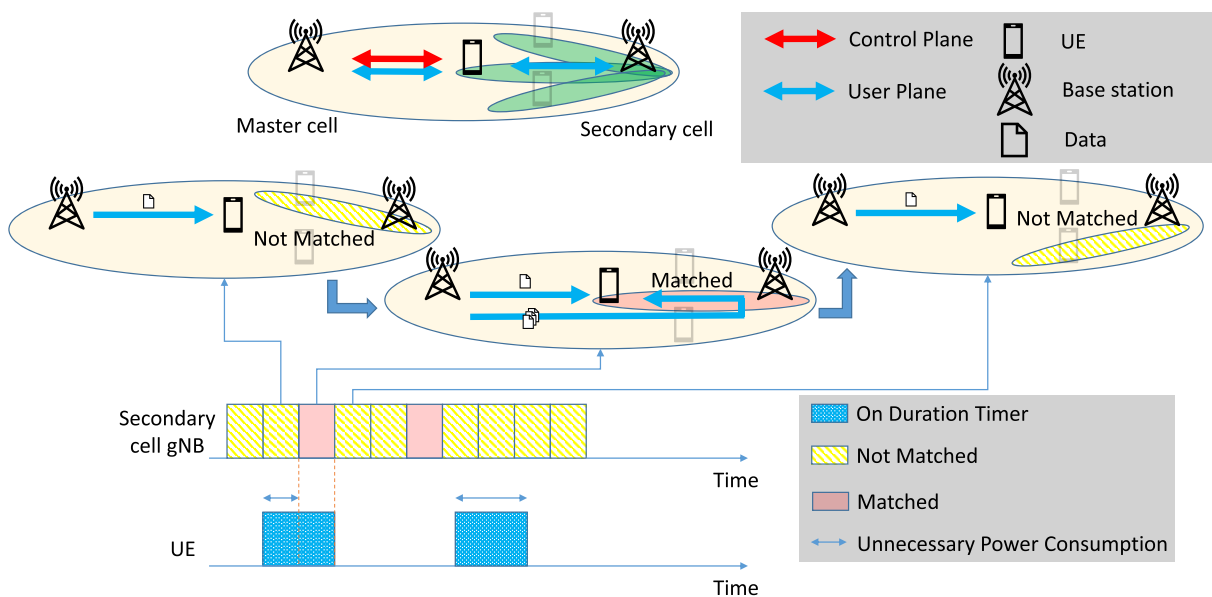


FIGURE 1. Unnecessary power consumption caused by the misalignment of beams in non-standalone dual connectivity scheme.

and user data traffic. On the other hand, the gNB connects to the core network via the interface S1-U, which handles only user plane traffic to maintain the system’s robustness. The eNB communicates with the gNB through interface X2, supporting control message traffic and user data traffic. The UE with DC configured connects to the eNB and the gNB.

**B. DRX MECHANISM**

DRX is introduced to reduce power consumption by turning on and off the RF module with predefined parameters. The predefined parameters are set by the RRC protocol, whose significant functions include UE power saving.

For a UE in the RRC\_IDLE state, its RF module remains off most of the time. It occasionally turns on the RF module to receive paging information, consuming only little energy. On the contrary, the UE consumes tremendous power in the RRC\_CONNECTED state, where it decodes channels for control messages and data. This work focuses on the DRX in the RRC\_CONNECTED state.

According to the 3GPP standard TS 38.300 [25], there are four main configurations in the DRX operation, including *Inactivity Timer*, *On Duration Timer*, *Short DRX Cycle*, and *Long DRX Cycle*. Figure 2 shows the DRX in the RRC\_CONNECTED state [26]. The UE turns on the

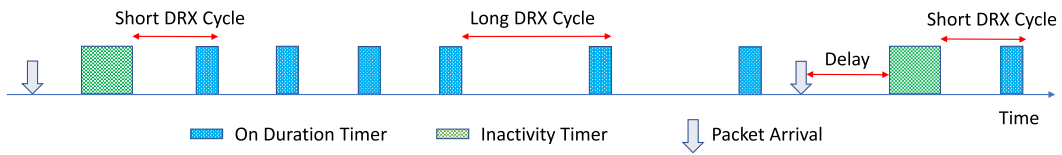


FIGURE 2. 3GPP defined DRX mechanism.

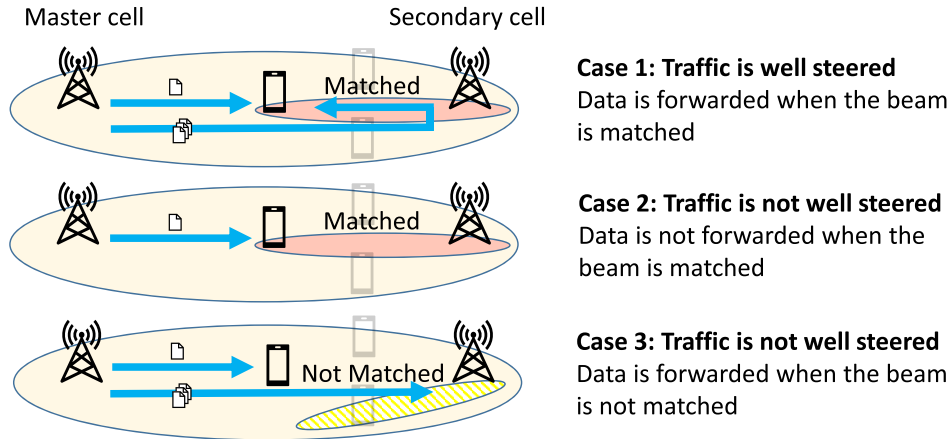


FIGURE 3. Traffic steering issue in mmWave Dual connectivity schemes.

RF module to monitor the physical downlink control channel (PDCCH) for downlink transmission when the *On Duration Timer* is running. If no packet arrives before the expiry of the *On Duration Timer*, the UE turns off the RF module to save power. If it receives new data, it starts the *Inactivity Timer* and stays active for fear of missing follow-up packets. The UE restarts *Inactivity Timer* if more packets arrive before the timer's expiry. Suppose both the *On Duration Timer* and the *Inactivity Timer* expire. In that case, the UE has the opportunity for DRX and can stay in dormancy before the next trigger of the *On Duration Timer*.

The trigger of the *On Duration Timer* is controlled by the DRX cycle. Typically, the UE has to reset its *On Duration Timer* at the beginning of every DRX cycle. When receiving new downlink traffic from the base station, the UE would first apply the *Short DRX Cycle*. In each DRX cycle, the UE periodically wakes up to monitor PDCCH during the on period. If the base station has no buffered packet to transmit, the UE turns off its RF module and sleeps. Otherwise, the UE receives the buffered packets and starts its *Inactivity Timer*. If the UE does not receive any downlink packet for a couple of short DRX cycles, it moves to *Long DRX Cycle* until the next downlink packet. If there is any new packet transmission, the UE returns to the short DRX cycle and receives the packet.

In EN-DC, the UE is configured with two medium access control (MAC) entities: one for the eNB and another for the gNB. The network could also configure the DRX mechanism for the UEs. According to the 3GPP standard [24], the two MAC entities apply separated DRX configurations, i.e., the

LTE connection follows one set of DRX configurations, and the NR connection follows another.

IV. DESIGN ISSUES

A. TRAFFIC STEERING ISSUE IN NR DUAL CONNECTIVITY

As the requirement for enhanced mobile broadband grows, the NR network applies beamforming technology to increase the transmission rate. It helps the transmitter concentrate its transmission power on its target. Furthermore, the beamforming technology benefits the transmission range and quality of the communications over the mmWave band. The pathloss in mmWave communications is larger than in conventional sub-6GHz communications. Therefore, beamforming can significantly increase the received power and help the devices to overcome the severe pathloss in the mmWave band by concentrating the transmission power. However, the directionality of links brings difficulties to MAC protocols. The gNB can not simultaneously transmit data to the UEs on different beams in the NR network. This constraint complicated the scheduling algorithm in the gNB. Considering UE distribution and random traffic arrival, the gNB might consequently serve its UEs with a random order of the beams and skip sending on the beams without UEs.

Because of the link directionality in the NR transmissions, especially for mmWave communications, the traffic steering issue in DC becomes critical for optimizing the network performance. As shown in Figure 3, there are three cases in the NR NSA EN-DC scheme. Case 1 shows successful traffic steering. The traffic data for the UE are forwarded

to the secondary gNB just when the gNB is going to serve matched beam direction. The throughput and latency could be optimized best without overwhelming the gNB's buffer.

In contrast, cases 2 and 3 are the ones without traffic steering. In case 2, the gNB serves the matched beam, but the UE's data are not forwarded to the gNB. In case 3, the traffic data are forwarded, but the gNB is not serving the matched beam.

### B. LINK DIRECTIONALITY ISSUE IN NR DRX

In NR DRX, link directionality is also a critical issue. The UE decodes PDCCH when *On Duration Timer* or *Inactivity Timer* is running. However, with beamforming technology, the gNB only serves a certain beam in a period, leading to the misalignment shown in Figure 1. Since the UE has no information about the gNB's selected beam, it decodes the channel even if the gNB is beamforming in other directions and consumes extra power. On the other hand, if the UE has information on the beam pattern, it can keep the RF module off and save more power. Moreover, the packet delay increases significantly since the gNB will buffer the packets for the UE until the next serving time.

## V. PROPOSED MECHANISM

To resolve the misalignment issue and improve DRX performance in EN-DC, we propose a traffic steering algorithm that coordinates the UE, the eNB, and the gNB. A DRX mechanism that considers coordination of the LTE and NR modules is designed to incorporate with the traffic steering algorithm and reduce power consumption.

### A. TRAFFIC STEERING ALGORITHM

In EN-DC, the UE connects to the eNB and the gNB simultaneously. The link to the eNB is reliable and used for transferring control messages and user data. On the other hand, the link to the gNB provides a higher data rate but suffers from link directionality issues, as stated in Section IV-B. To enjoy the high transmission rate in NR while maintaining stable connectivity through LTE, we propose a traffic steering algorithm that dynamically steers user traffic based on the NR beam pattern. If the UE and the gNB are matched, user traffic will be delivered through gNB, which decreases transmission delay and allows the UE to enter dormancy earlier. Otherwise, if they are not matched, the eNB is responsible for transmission since it always connects to the UE.

In Figure 4, we present the algorithm with two signal flow diagrams: matched scenario in (a) and mismatched scenario in (b). No matter the scenario, the algorithm starts with coordinating the nodes. In the first step, the gNB will generate its beam serving pattern and pass it to the eNB through the X2 interface. The eNB then forwards beam information and control messages to UE. Due to the misalignment issue, downlink control messages are sent via the eNB. After receiving control messages, the UE responds to the eNB. The eNB then negotiates with the gNB for resource allocation. At this step, coordination has been completed, and information is

shared among all nodes. The UE, the eNB, and the gNB know whether the UE and the gNB are matched or not at this point. If it is the matched scenario, the UE is able to connect to the gNB. After connection establishment completes, the UE can receive packets from the gNB. The eNB will also forward buffered data to the gNB for transmission. On the other hand, if the UE and the gNB are not matched, NR resources are unavailable, and the LTE link is used to transfer data. The gNB will move the data to the eNB to avoid additional delay.

### B. PROPOSED DRX MECHANISM

The main idea of the proposed DRX goes as follows: if the UE and the gNB are matched when there are packets in the queue, the algorithm steers to enable the NR link for transmission; otherwise, it utilizes LTE to deliver the data traffic. The algorithm also helps the eNB decide the amount of data to forward to the gNB. Figure 5 shows the illustration of the proposed DRX. There are four parameters, *Inactivity Timer*, *On Duration Timer*, *Sleep*, and *Reception*. In our model, we only consider the Long DRX Cycle denoted by DRX Cycle in the figure. It consists of one *On Duration Timer* and one *Sleep*. Without packet arrival before the *On Duration Timer* expires, the UE will turn off its LTE and NR RF modules and enter dormancy for power saving. On the other hand, any packet arrival before the expiry of the *On Duration Timer* makes the UE decode PDCCH and physical downlink shared channel (PDSCH) for incoming data.

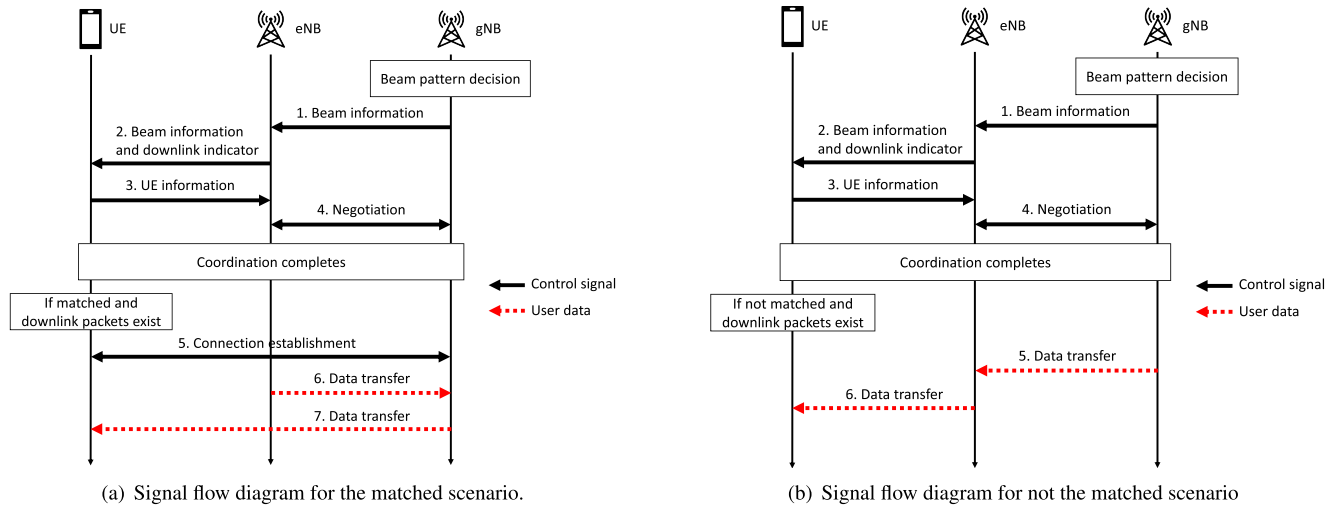
We use *Reception* to refer to the time spent on receiving downlink data. At this stage, the eNB, the gNB, and the UE coordinate to determine the mode of transmission. If the UE and the gNB are matched, the UE can receive data via the NR link. Otherwise, data are transferred via the LTE link. After transmission finishes, the UE extends the *Inactivity Timer* with the LTE module to decode PDCCH for future follow-up packets. Once any packet arrives before the *Inactivity Timer* expires, the UE will immediately decode PDCCH and PDSCH again. Otherwise, the UE will enter the *Sleep* period if the *Inactivity Timer* expires. The UE turns off the LTE and NR modules during the *Sleep* period to save power. The arrivals are buffered until it wakes up. After waking up, the UE starts the *On Duration Timer*. If buffered packets exist, the UE moves to *Reception* to decode them.

In our model, we consider finite transmission time, so the following scenarios occur:

- 1) When the eNB is transmitting, the gNB starts to serve the UE.
- 2) The gNB plans to serve other UEs in the next beam period without completing the current transmission.

For (1), we assume that the gNB will take over the transmission and deliver the remaining packets to the UE. For (2), since the gNB plans to serve other UEs, we let the eNB continue the transmission.

In the proposed model, data reception is taken into consideration for two reasons. First, there is a difference in power consumption between decoding PDCCH and receiving data. The UE consumes more power in receiving data. Second,



**FIGURE 4.** Signal flow diagram of the proposed traffic steering algorithm. In (a), at the beginning, the gNB coordinates with the UE through the eNB. If the UE and the gNB are matched, the UE can establish connection with the gNB. The buffered packets are delivered to the UE with the gNB. In (b), the gNB passes its beam pattern to the UE through the eNB. If the UE and the gNB are not matched, the gNB is unable to serve the UE and the eNB is responsible for data transmission.

the UE connects to two base stations with different data rates. Therefore, we include data reception in our model to highlight the difference between the two links and investigate the impact on power consumption. With this enhancement, power consumption could be investigated more thoroughly. It also helps us analyze the data rate’s impact on power consumption.

Compared with the 3GPP-defined DRX, the proposed DRX saves more power in two ways. First, with the proposed traffic steering algorithm, the issue in Section IV-B could be avoided. The UE turns on the NR RF module only in a matched scenario and would not waste power on decoding channels when not being served. Second, with the LTE module as an anchor, the UE can receive information via the LTE link. The NR link no longer needs to monitor downlink channels for information. Therefore, it could stay dormant without periodically waking up to monitor the channel. With these two merits, the proposed DRX could save more power than the 3GPP-defined DRX model.

**VI. ANALYTICAL MODEL AND FORMULATION**

**A. SYSTEM MODEL**

We consider a scheme consisting of an eNB and a mmWave gNB.  $M$  UEs are uniformly scattered in the coverage of the LTE cell. Among these UEs, there exist  $N$  UEs also covered by the mmWave NR cell. We assume each UE has a downlink traffic flow whose packet arrival follows Poisson Process. The packet arrival rate is  $\lambda$ . We assume the packet size is  $K$ . The gNB concentrates its power in a certain direction to enhance transmission quality, leading to the inability to serve all UEs simultaneously. Thus, we assume the gNB serves the UEs randomly. It randomly selects the UEs on the same beam to serve for a beam period  $T_b$ .

Furthermore, we assume the gNB would ignore the beams without UEs to save resources. For the transmission rate, we denote  $\mu_{LTE}$  and  $\mu_{NR}$  as LTE throughput and NR

throughput, respectively. Besides, to solve the extra power consumption caused by the link directionality, we assume a UE could get the beam information from its master cell. Notations for the analytical model are listed in Table 2

**TABLE 2.** Notations used in analytical model and formulation.

Symbol	Meaning
$M$	Number of UEs in LTE cell
$N$	Number of UEs in NR cell
$N_b$	Beam number of a gNB
$K$	Packet size
$X \sim \exp(\lambda)$	Inter-arrival time with rate $\lambda$
$\mu_{LTE}$	LTE link throughput
$\mu_{NR}$	NR link throughput
$T_b$	Beam period
$T_1$	Inactivity Timer
$T_2$	On Duration Timer
$T_3$	Sleep Duration
$S_i$	Markov chain state $i$
$P_{m,n}$	Transition probability from $S_m$ to $S_n$
$\pi_i$	Steady state probability of $S_i$
$E\{S_i\}$	Expected holding time of $S_i$
$PS_{A,B}$	Consumed power of behavior $A$ with mode $B$
$R_i$	Time proportion of state $i$
$R_{A,B}$	Time proportion of behavior $A$ with mode $B$
$A_n$	State after $n$ steps
$B$	Number of buffered bits
$\tau$	Transition matrix of the Markov chain
$D_{Buffer}$	Buffering delay

**B. FORMULATION**

In this section, we use a semi-Markov chain model to analyze the performance of our proposed model. First, We will construct a four-state semi-Markov chain model and define the meaning of each state. Then, we will derive transition and steady-state probability based on the actions of the UE. To find the actual time proportion of each component, we further calculate the expected holding time in each state. Finally,

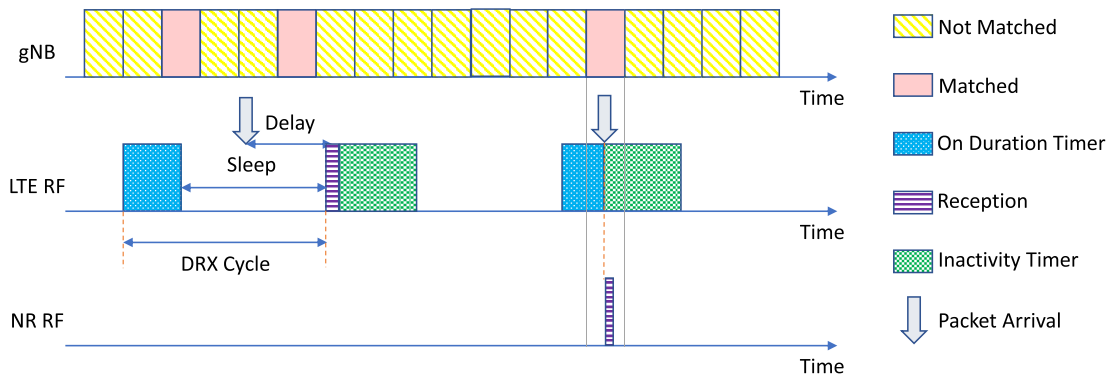


FIGURE 5. The proposed DRX mechanism.

we calculate the time spent on each state, followed by the derivation of relative power consumption.

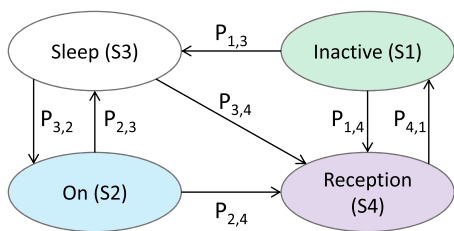


FIGURE 6. The semi-Markov chain model for the proposed DRX mechanism.

C. SEMI-MARKOV CHAIN MODEL

A semi-Markov chain model that evaluates the performance of the proposed mechanism is proposed. As shown in Figure 6, the semi-Markov chain model includes four states, *Inactive*(S1), *On*(S2), *Sleep*(S3), and *Reception*(S4). We describe the details of each state in the following passages.

1) INACTIVE (S1)

At *Inactive*, the UE starts the *Inactivity Timer* with length  $T_1$ . Before it expires, the UE keeps monitoring PDCCH with the LTE module. If there is any packet arrival before the timer expires, the UE starts to receive data and enter *Reception*. Otherwise, the UE enters dormancy.

2) ON (S2)

At *On*, the UE monitors PDCCH with the LTE module for  $T_2$ . Similar to *Inactive*, the UE switches to *Reception* if any packet arrives before the timer expires. Otherwise, it moves to *Sleep*.

3) SLEEP (S3)

At this state, the UE turns off its RF modules for  $T_3$  to save power. Every packet arrival is buffered at the base station until the UE wakes up. Upon waking up, the UE enters *On* to decode the PDCCH channel. If there is any buffered

packet, it will immediately move to *Reception* to receive data. For simplicity, we assume that the UE directly moves to *Reception* from *Sleep* if buffered data exist.

4) RECEPTION (S4)

The UE turns on its RF modules to receive data and control messages in this state. Before transmission starts, the eNB, the gNB, and the UE will coordinate. The NR module is utilized for transmission if the UE and the gNB are matched in the next beam period. Otherwise, the packets are transmitted through the LTE network. Besides, we utilize the first-come-first-served (FCFS) policy for buffered data. New arrivals are queued at the end of the old ones. After receiving all buffered data, the UE enters *Inactive* to monitor PDCCH for fear of missing follow-up packets.

As mentioned in Section V, the UE is expected to switch between the LTE and the NR modules based on the beam serving pattern. Therefore, the UE is expected to use the LTE and NR modules.

D. TRANSITION PROBABILITY OF THE SEMI-MARKOV CHAIN MODEL

This section derives the transition probability of the semi-Markov chain model. Let  $P_{n,m}$  denotes the transition probability from  $S_n$  to  $S_m$ , where  $n, m \in \{1, 2, 3, 4\}$ . The derivation of these parameters is as follows:

1) FROM S1

At *S1*, the UE monitors PDCCH for downlink indicators. If the *Inactivity Timer* expires before any packet arrival, the UE moves to *S3*.

Since the inter-arrival time follows an exponential distribution,

$$P_{1,3} = Pr\{X > T_1\} = e^{-\lambda T_1}. \tag{1}$$

On the contrary, any indicator of packet arrival moves the UE to *S4*.

$$P_{1,4} = 1 - e^{-\lambda T_1}. \tag{2}$$



2) FROM S2

At S2, the UE keeps monitoring PDCCH with the LTE module. It moves to S3 if there is no packet arrival; otherwise, it enters S4. The probabilities are

$$P_{2,3} = Pr\{X > T_2\} = e^{-\lambda T_2}, \tag{3}$$

$$P_{2,4} = (1 - e^{-\lambda T_2}). \tag{4}$$

3) FROM S3

The UE turns off its RF modules at S3. Packet arrivals are buffered until the UE wakes up. If there is no buffered packet, the UE moves to S2 to listen to PDCCH. On the contrary, the UE moves to S4 if there is any buffered packet. The probabilities are

$$P_{3,2} = Pr\{X > T_3\} = e^{-\lambda T_3}, \tag{5}$$

$$P_{3,4} = Pr\{X < T_3\} = 1 - e^{-\lambda T_3}. \tag{6}$$

4) FROM S4

The UE turns on its RF modules to receive buffered packets. After the reception, the UE switches to S1 to monitor PDCCH. The probability is

$$P_{4,1} = 1. \tag{7}$$

**E. STEADY STATE PROBABILITY**

We use a balanced equation to derive the steady-state probability of the semi-Markov chain model. Let  $\tau$  denote the transition matrix. It can be written as follows:

$$\tau = \begin{bmatrix} 0 & 0 & P_{1,3} & P_{1,4} \\ 0 & 0 & P_{2,3} & P_{2,4} \\ 0 & P_{3,2} & 0 & P_{3,4} \\ P_{4,1} & 0 & 0 & 0 \end{bmatrix}. \tag{8}$$

Let  $\pi_i, \forall i \in \{1, 2, 3, 4\}$  denote the steady-state probability of  $S_i$  and  $\vec{\pi}$  represents the steady-state vector. In the long term, the probability becomes steady, and we could write down the balance equation

$$\vec{\pi} = \vec{\pi} \tau. \tag{9}$$

By doing matrix multiplication, the following equations could be obtained.

$$\begin{cases} \pi_1 = \pi_4 P_{4,1} \\ \pi_2 = \pi_3 P_{3,2} \\ \pi_3 = \pi_1 P_{1,3} + \pi_2 P_{2,3} \\ \pi_4 = \pi_1 P_{1,4} + \pi_2 P_{2,4} + \pi_3 P_{3,4}. \end{cases} \tag{10}$$

Using the fact that probabilities add up to 1, we can obtain

$$\sum_{i=1}^4 \pi_i = 1. \tag{11}$$

With these equations, we can derive the steady-state probability of each state.

$$\begin{cases} \pi_1 = \frac{P_{4,1}(1 - P_{2,3}P_{3,2})}{P_{4,1}P_{1,3}(1 + P_{3,2}) + (1 + P_{4,1})(1 - P_{2,3}P_{3,2})} \\ \pi_2 = \frac{P_{4,1}P_{1,3}P_{3,2}}{P_{4,1}P_{1,3}(1 + P_{3,2}) + (1 + P_{4,1})(1 - P_{2,3}P_{3,2})} \\ \pi_3 = \frac{P_{4,1}P_{1,3}}{P_{4,1}P_{1,3}(1 + P_{3,2}) + (1 + P_{4,1})(1 - P_{2,3}P_{3,2})} \\ \pi_4 = \frac{1 - P_{2,3}P_{3,2}}{P_{4,1}P_{1,3}(1 + P_{3,2}) + (1 + P_{4,1})(1 - P_{2,3}P_{3,2})}. \end{cases} \tag{12}$$

**F. EXPECTED HOLDING TIME**

This part provides the derivation of the expected holding time in a certain state. Let  $E\{S_i\}$  represent the expected holding time of  $S_i$ . The derivation goes as follows:

1) S1

If there is no packet arrival before the *Inactivity Timer* expires, the UE will stay at S1 for  $T_1$  and enter dormancy. Otherwise, it moves to S4 when any packet arrives. So,  $E\{S1\}$  can be divided into two parts based on the arrival time. Its value is

$$\begin{aligned} E\{S1\} &= \int_0^{T_1} t\lambda e^{-\lambda t} dt + \int_{T_1}^{\infty} T_1\lambda e^{-\lambda t} dt \\ &= \frac{1 - e^{-\lambda * T_1}}{\lambda}. \end{aligned} \tag{13}$$

2) S2

Similar to S1, the UE enters S3 if there is no packet arrival before the timer expires. Otherwise, it enters S4 if the packet arrives before the *On Duration Timer* expires. The length is  $T_2$ , thus

$$\begin{aligned} E\{S2\} &= \int_0^{T_2} t\lambda e^{-\lambda t} dt + \int_{T_2}^{\infty} T_2\lambda e^{-\lambda t} dt \\ &= \frac{1 - e^{-\lambda T_2}}{\lambda}. \end{aligned} \tag{14}$$

3) S3

The UE turns off the RF modules to save power. Any packet arrival is buffered at the base stations until the UE wakes up later. During dormancy, the UE will not be interrupted by downlink messages. So  $E\{S3\}$  is equal to the length of the sleep timer  $T_3$ .

$$E\{S3\} = T_3. \tag{15}$$

4) S4

In this state, all buffered packets are delivered to the UE via the LTE and NR links. Since the final goal is to evaluate the power consumption, we have to find the expected holding time  $E\{S4\}$  and identify the proportion of time spent on the LTE and NR modules, which denote  $E\{S4\}_{LTE}$  and  $E\{S4\}_{NR}$ , respectively. In the following, we propose

a numerical method that approximates  $E\{S4\}$  and finds  $E\{S4\}_{LTE}$  as well as  $E\{S4\}_{NR}$ .

Since the UE receives all buffered packets at S4,  $E\{S4\}$  is significantly influenced by the number of buffered packets. Depending on the previous state, the number of buffered packets varies. If the last state is S1 or S2, where the UE listens to PDCCH, only one packet is waiting for transmission upon entering S4. However, if the previous state is S3, the number of buffered packets follows the Poisson process. Let  $A_n$  represent the state after  $n$  steps. The probability that the previous state is  $Sm$  can be written as

$$Pr\{A_{n-1} = Sm \mid A_n = S4\}, m \in \{1, 2, 3\}. \quad (16)$$

After applying Bayes' theorem to (16), it becomes

$$\frac{Pr\{A_n = S4 \mid A_{n-1} = Sm\}Pr\{A_{n-1} = Sm\}}{Pr\{A_n = S4\}}. \quad (17)$$

In the long term, the system reaches a steady-state, and steady-state probability represents the probability of staying at each state.

$$Pr\{A_{n-1} = Sm\} = \pi_m. \quad (18)$$

Substituting into (17), the probability that the previous state is  $Sm$  can be expressed as

$$Pr\{A_{n-1} = Sm \mid A_n = S4\} = \frac{\pi_m P_{m,4}}{\pi_4}. \quad (19)$$

Therefore, by the law of total expectation, the expected holding time of S4 could be written as

$$\begin{aligned} E\{S4\} &= \left(\frac{\pi_1 P_{1,4}}{\pi_4}\right) \times E\{S4 \mid A_{n-1} = S1\} \\ &+ \left(\frac{\pi_2 P_{2,4}}{\pi_4}\right) \times E\{S4 \mid A_{n-1} = S2\} \\ &+ \left(\frac{\pi_3 P_{3,4}}{\pi_4}\right) \times E\{S4 \mid A_{n-1} = S3\}. \end{aligned} \quad (20)$$

In Figure 7, we propose a numerical method to approximate the data transmission process. This method finds  $E\{S4\}$  conditioned on arbitrary previous states. Furthermore, the proportion of time spent on LTE and NR can also be derived.

Assuming there are buffered packets that add up to  $B$  bits upon entering S4. A node with a capital  $B$  inside denotes the starting point. According to the proposed model, the probability of matching the gNB and the UE in the next beam period is  $1/N$ . In this case, the state transits along with the blue dotted arrow to the upper right node; otherwise, it goes lower right with the solid red arrow. With the NR link, the gNB can send  $\mu_{NR}T_b$  bits to the UE within a beam period. On the other hand, the LTE link supports transferring  $\mu_{LTE}T_b$  bits to the UE.

However, new packets still arrive when the transmission is ongoing. Since the arrival follows the Poisson process, the expected number of arrivals within a beam period is  $\lambda T_b$ . So, a total of  $\lambda T_b K$  bits is expected to arrive at the buffer in a beam period. That is, only  $\mu_{NR}T_b - \lambda T_b K$  bits reduce at the buffer if the NR link is used, and  $\mu_{LTE}T_b - \lambda T_b K$  bits reduce if the LTE

TABLE 3. Relative power model in a time slot in 3GPP TR38.840. [27].

Power State	FR1	FR2
Only PDCCH	100	175
PDCCH + PDSCH	300	350
Deep Sleep	1	1

link is applied. At the end of the beam period, the UE, eNB, and gNB coordinate again to determine the module in the next beam period. Regardless of current states, the probability of the UE being served by the gNB in the next beam period is  $1/N$ . The state transition follows the blue dotted arrow if the UE and gNB match. Otherwise, it goes with the solid red arrow. This process continues until there is no data left in the buffer, and the traversed nodes form a path starting at  $B$ .

Since the UE stays in each node for a beam period, the expected holding time for that path is the number of traversed nodes times beam period  $T_b$ . Finally, we can find the expected holding time conditioned on the buffer bits  $B$  by adding up the expected holding time on each path weighted by their probability of occurrence. To find  $E\{S4\}$ , we need to identify the value  $B$ . According to the previous discussion, if the previous state is S1 or S2, there will be only one buffered packet, and  $B$  is equal to  $K$ . If the last state is S3,  $B$  equals  $K$  times the number of arrivals within dormancy, which follows the Poisson process. Also, the UE selects either the LTE link or the NR link in a beam period, so  $E\{S4\}_{LTE}$  and  $E\{S4\}_{NR}$  can be easily found by counting the number of corresponding nodes.

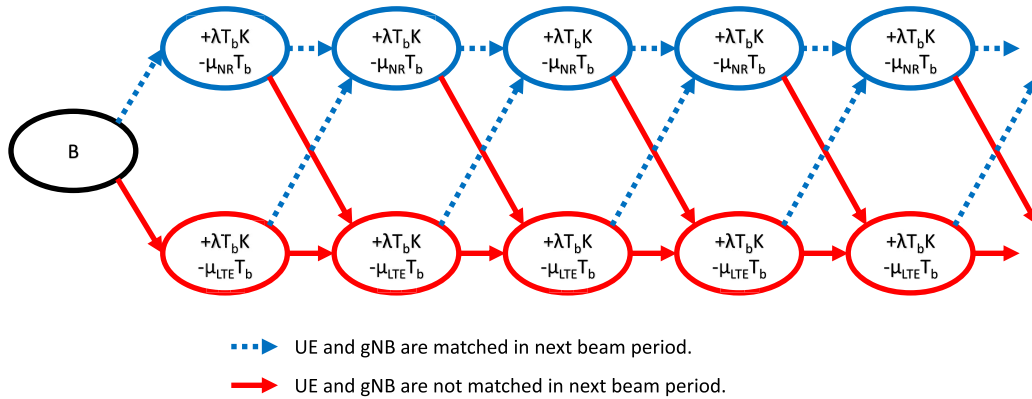
### G. POWER CONSUMPTION

In this section, we calculate the relative power consumption of the proposed model. The relative power consumption is the power of a certain state multiplied by the proportion of time spent on it. Table 3 lists the relative power model for the frequency range 1 (FR1) and frequency range 2 (FR2) at different states. FR1 refers to the lower frequency band of 5G, while FR2 refers to the higher frequency band. In the model, FR1 replaces the power model of LTE due to the difficulty in searching suitable LTE power model. For the LTE model, the subcarrier spacing is 15 kHz, and one subframe consists of two slots. On the contrary, for the NR model in the third numerology, the subcarrier spacing equals 120 kHz, and there are eight slots within a subframe. Since power in Table 3 is measured in one timeslot. We also consider the difference in frame structure when calculating the relative power.

We use  $PS_{D,FRx}$ ,  $PS_{DS,FRx}$ , and  $PS_{Sleep,FRx}$  to represent the relative power state of decoding PDCCH, decoding PDCCH and PDSCH, and sleep in  $FRx$  mode, respectively, where  $FRx$  is either FR1 or FR2.

The proportion of time spent on each state can be derived from Sections VI-E and VI-F. Let  $R_n$  denote the proportion of time spent on  $Sn$ , and it can be written as

$$R_n = \frac{\pi_n E\{Sn\}}{\sum_{i=0}^{i=4} \pi_i E\{Si\}}, \quad n \in \{1, 2, 3, 4\}. \quad (21)$$



**FIGURE 7.** The numerical method used to approximate the expected holding time at S4 and find out the time spent on the LTE and NR modules.

Having the proportion of time spent on  $S_n$ , we can further derive the proportion of time spent on each power state. We use  $R_{D,LTE}$ ,  $R_{DS,LTE}$ , and  $R_{Sleep,LTE}$  to denote the proportion of time spent on decoding only PDCCH, decoding PDCCH and PDSCH, and dormancy in LTE mode. Likewise,  $R_{D,NR}$ ,  $R_{DS,NR}$ , and  $R_{Sleep,NR}$  denote the corresponding states in NR mode.

1) TIME DISTRIBUTION OF THE LTE MODULE

At S1 and S2, the LTE module is used to monitor PDCCH. At S3, the UE enters dormancy and turns off the LTE RF module. At S4, if the UE and the gNB are matched, data are transferred over the NR link. At this moment, the LTE module is decoding PDCCH for downlink indicators and control messages. On the contrary, if the gNB does not serve the UE, the UE will use the LTE link for data reception. Therefore,

$$R_{D,LTE} = R_1 + R_2 + R_4 \times \frac{E\{S4\}_{NR}}{E\{S4\}}, \quad (22)$$

$$R_{DS,LTE} = R_4 \times \frac{E\{S4\}_{LTE}}{E\{S4\}}, \quad (23)$$

$$R_{Sleep,LTE} = R_3. \quad (24)$$

2) TIME DISTRIBUTION OF THE NR MODULE

The NR module is only used for data reception and is not responsible for monitoring PDCCH. Only when the NR link is available will the UE utilize the NR link to receive the buffered data. The time distribution for the NR module is as follows:

$$R_{D,NR} = 0, \quad (25)$$

$$R_{DS,NR} = R_4 \times \frac{E\{S4\}_{NR}}{E\{S4\}}, \quad (26)$$

$$R_{Sleep,NR} = 1 - R_4 \times \frac{E\{S4\}_{NR}}{E\{S4\}}. \quad (27)$$

With the time proportion spent on each state and the power model, the relative power consumption of the UE with the

**TABLE 4.** Default parameters.

Parameter	Default Value
Number of UEs in LTE cell	20
Number of UEs in NR cell	10
Beam number of a gNB	20
Packet size	1000 bytes
Arrival rate $\lambda$	$\lambda = 0.1ms^{-1}$
LTE link throughput	133 Mbps [28]
NR link throughput	692 Mbps [28]
Beam period	0.125 ms
Inactivity Timer	10 ms
On Duration Timer	10 ms
Sleep Duration	680 ms

proposed DRX is

$$R_{D,LTE}PS_{D,FR1} + R_{DS,LTE}PS_{DS,FR1} + R_{Sleep,LTE}PS_{Sleep,FR1} + R_{DS,NR}PS_{DS,FR2} + R_{Sleep,NR}PS_{Sleep,FR2}. \quad (28)$$

In Section VII, we will evaluate the performance of the proposed model based on this relative power consumption.

H. AVERAGE PACKET DELAY

Two kinds of delay exist in the model, including buffering and transmission delays. Buffering delay refers to the delay incurred by packets buffered at the base stations. On the other hand, a finite data rate leads to transmission delay. However, the transmission delay is much smaller than buffering delay, so the model only considers buffering delay. At S3, the UE turns off the RF modules, and arrivals are queued at the base stations. Before being delivered, the buffered packet waits for the UE to wake up and for previous packets to be sent. However, as the transmission delay is small enough, we only consider the impact of dormancy.

For a packet arrival, the probability of seeing the UE in dormancy is  $R_3$ , and the expected remaining time before waking up follows a uniform distribution. Let  $D_{Buffer}$  be the

TABLE 5. Reference configuration for FR1 and FR2.

Configuration	FR1	FR2
Direction	Downlink	Downlink
Mode	TDD	TDD
Subcarrier spacing	30 kHz	120 kHz
Bandwidth	100 MHz	100 MHz

buffering delay

$$\begin{aligned}
 D_{Buffer} &= R_3 \times \int_0^{T_3} \frac{T_3 - t}{T_3} dt \\
 &= \frac{\pi_3 T_3}{2}.
 \end{aligned}
 \tag{29}$$

VII. ANALYSIS RESULTS AND DISCUSSIONS

We conduct the simulation in Python. The model has  $M$  UEs in the LTE cell and  $N$  UEs in the NR cell. The eNB’s throughput is evenly distributed to each UE, and the gNB is restricted to serve one UE with all resources at a time. For the NR frame structure, we refer to the third numerology of the frame structure, and the beam period is equal to one slot. The following paragraphs show the simulation results under different parameters, and we compare the proposed model with LTE DRX and NR DRX. The default simulation parameters are listed in Table 4.

Standard DRX specified in 3GPP serves as the baseline in our work. We simulate it on three kinds of networks, including LTE, NR, and EN-DC. LTE DRX, NR DRX, and EN-DC DRX are used to denote them, respectively. The differences between these operations lie in the connection reliability and throughput. In LTE DRX, the UE could always connect to the eNB, enabling the UE to receive downlink indicators immediately. However, the data rate is lower. On the contrary, the gNB provides a higher data rate with a less reliable link. The UE loses connection to the gNB once it serves other beams. In this case, the UE could not receive downlink information even if it is active. In baseline EN-DC DRX, the UE connects to the eNB and the gNB with separate MAC entities. Each entity runs its own DRX operation without any coordination. MAC entity for LTE operates LTE DRX, and the other one runs NR DRX.

A. EFFECT OF DRX CYCLE

We simulate the model with different DRX cycles ranging from 80 ms to 1280 ms. The arrival rate is set to 0.1 ms<sup>-1</sup>, and we configure 10 and 20 UEs in the NR and LTE cells, respectively. In Figure 8, we show the power consumption of the proposed model, LTE DRX, and NR DRX with different DRX cycles. With a longer DRX cycle, the UE turns off the RF modules for a longer period. As a result, the UE consumes less power, and the battery life extends. In LTE DRX, the UE only connects to the LTE network, whose throughput is lower than the NR, and it takes more time for the UE to receive a packet. In the proposed model, the UE simultaneously connects to the eNB and the gNB, enabling itself to utilize

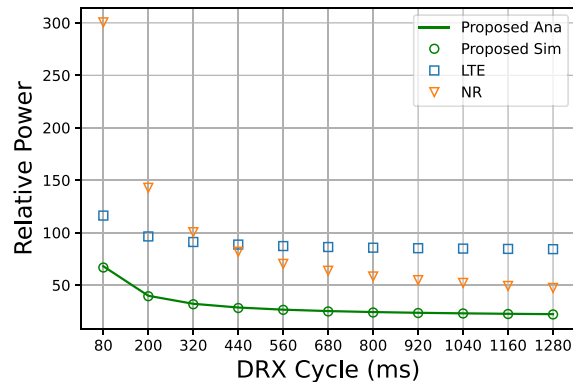


FIGURE 8. Power consumption with different length of DRX cycle and number of UEs in NR cell.

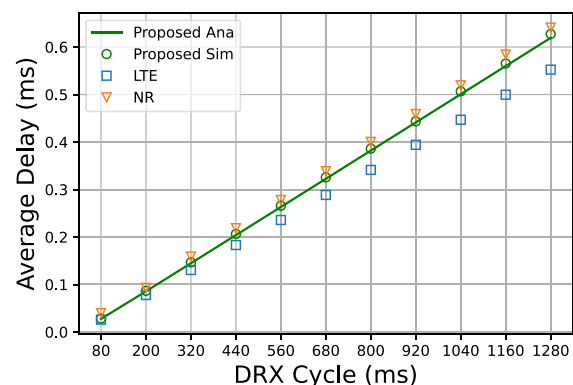


FIGURE 9. Average delay with different length of DRX cycle and number of UEs in NR cell.

NR for faster transmission. Since the UE consumes the most power when decoding PDCCH and PDSCH, the proposed model helps save more power by significantly reducing the transmission time.

Besides, the proposed DRX model helps the UE save more power than the NR DRX since it enables the UE to monitor PDCCH with the LTE module rather than the NR module. The number of time slots within an LTE subframe is four times less than that in NR. So, even if the UE takes advantage of the high data rate, it consumes more power to monitor PDCCH with the NR module.

Figure 9 shows the average delay in the proposed DRX, LTE DRX, and NR DRX. The average delay consists of two parts, buffering delay and transmission delay. Buffering delay refers to the time a packet waits at the base station, and transmission delay is the time required to send a packet over the air interface. Generally speaking, as the UE would stay in dormancy, buffering delay is far greater than the transmission delay. Therefore, no matter which network architecture is considered, the average delays are almost the same.

B. EFFECT OF ARRIVAL RATE

In this section, we evaluate the performance under different arrival rates ranging from 10 ms<sup>-1</sup> to 400 ms<sup>-1</sup>. The DRX

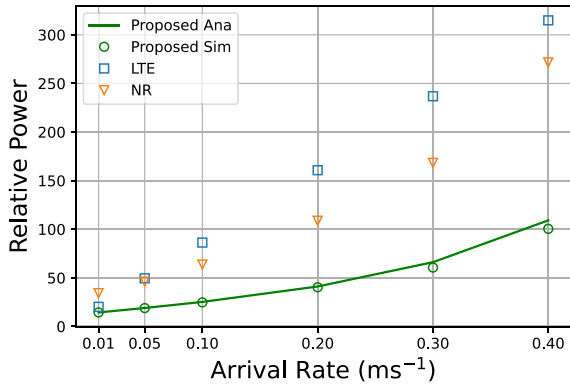


FIGURE 10. Power consumption under different arrival rate.

cycle is set to 680 ms. In Figure 10, we present the relationship between power consumption and arrival rate. Each time a packet arrives, the transmission is initiated if the UE is monitoring PDCCH. Otherwise, it will receive the packet after waking up from dormancy. As the arrival rate represents how frequently packets arrive, it has a significant impact on power consumption. With a higher arrival rate, packets arrive more frequently, and it takes the UE more time to complete reception. It increases power consumption as reception is the most power-consuming activity. Moreover, the *Inactivity timer* restarts more frequently as the arrival rate increases, leading to more UE power consumption.

Aside from consuming more power, it is observed that the UE with LTE DRX consumes the most power and the difference between the three mechanisms becomes larger as the arrival rate increases. The reason lies in the fact that data rate also plays an important role. With the higher data rate, the NR link can deliver more data to the UE than the LTE link. Therefore, the UE configured with LTE DRX spends more time receiving data and consumes the most power. As for the proposed DRX and NR DRX, the difference stems from the module used for monitoring PDCCH. In NR DRX, the NR module is utilized for monitoring every channel, including PDCCH. On the other hand, the LTE module is applied to decode downlink control messages in the proposed model. Due to the difference in frame structures, the NR module consumes more power than the LTE module. This lets the proposed DRX model be power-efficient. When the arrival rate is high, packets arrive more frequently, and more packets are queued at the base station. Under this condition, the impact of data rate on transmission time would be more significant as there are lots of packets waiting to be scheduled. Besides, the *Inactivity timer* restarts more often as the arrival rate increases. These factors enlarge the difference in power consumption between the three mechanisms.

In Figure 11, it is observed that the average delay decreases as the arrival rate increases. When the arrival rate increases, the UE needs to spend more time decoding PDCCH since the *Inactivity Timer* is more likely to restart. Thus, the average delay decreases as the UE monitors the channels more often.

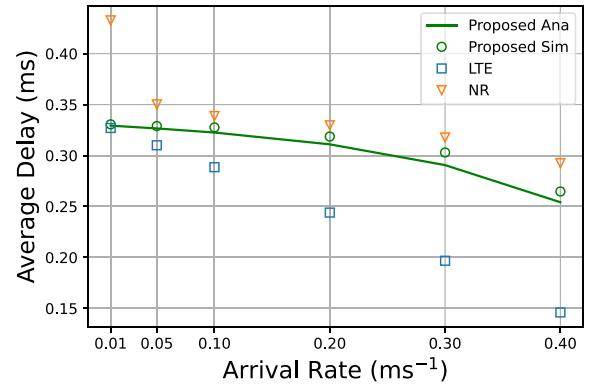


FIGURE 11. Average delay under different arrival rate.

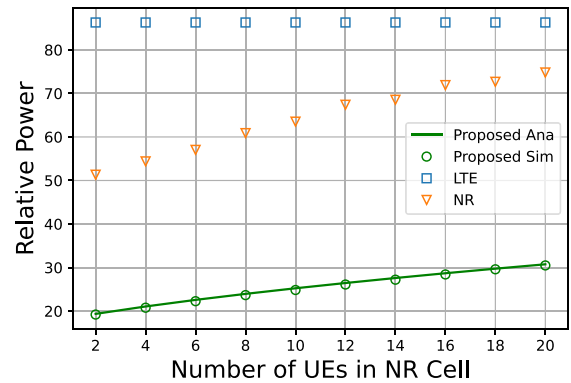


FIGURE 12. Power consumption under different number of UEs.

### C. EFFECT OF NUMBER OF UES IN NR CELL

In Figure 12, we change the number of UEs in the NR cell and observe the power consumption variation. As we have discussed above, the proposed DRX enables the UE to take advantage of NR's high throughput and use the LTE module to monitor PDCCH. Hence, it consumes less power than LTE DRX and NR DRX. In the model, the gNB serves the UEs in random order and serves only one UE with all resources at a time. The probability of being served is inversely proportional to the number of UEs in the NR cell. As the number increases, the UE is less likely to be served and lose the opportunity to connect to the NR network. Therefore, the power consumption increases as more UEs enter the NR cell. In LTE DRX, the UE only connects to the eNB, so the power consumption is independent of the number of UEs in the NR cell. In NR DRX, as the number increases, the probability of being served also decreases, resulting in an increase in power consumption.

In Figure 13, we show the average delay under different numbers of UEs in NR cells. It is shown that the average delay slightly decreases since the UE is less likely to be served when crowded. So, the UE connects to LTE more often and spends less time on dormancy, giving rise to the drop in average delay.

### D. EFFECT OF TRAFFIC STEERING

In the EN-DC structure, user traffic can be transferred to the UE via the LTE and NR links. In the experiment, we split

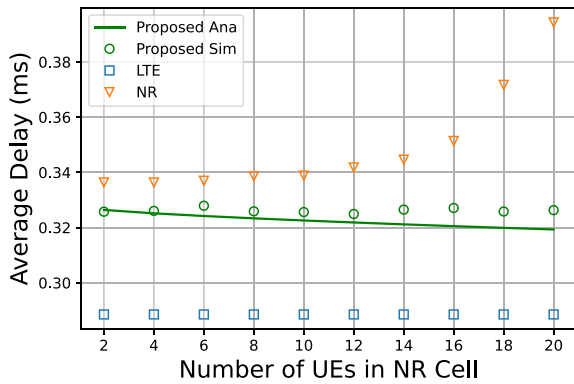


FIGURE 13. Average delay under different number of UEs.

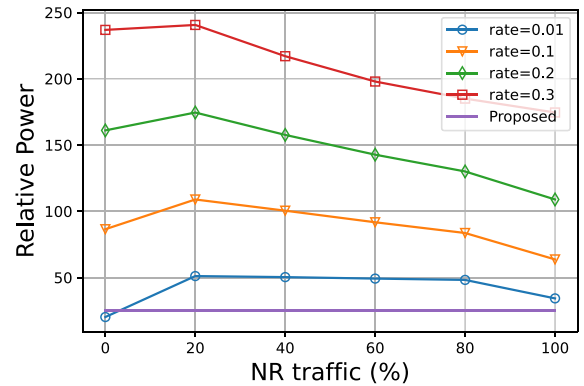


FIGURE 14. Power consumption of the UE under different traffic flow patterns.

user traffic into two flows with a predefined ratio. One flow routes through the eNB and the other is guided to the gNB, and there is no data exchange between them. The UE runs two separated DRXs on the LTE circuitry and the NR circuitry to save power. In Figure 14, we demonstrate the experiment result. If the user traffic routes through the LTE network only, the power consumption is relatively low since the NR module is off most of the time. However, when 20 percent of the traffic is allocated to the NR network, both the LTE module and the NR module receive data, decode channels, and extend timers. This inevitably consumes more power. With higher throughput, NR enables faster data transmission than LTE. So, as more and more data are transferred to the NR network, the power consumption decreases instead. When the arrival rate is high, this phenomenon becomes more obvious. The proposed DRX mechanism considers data exchange and coordination between the eNB and the gNB. It allows the UE to use NR resources when available and maintain a reliable connection to LTE in case NR is unavailable, resulting in better performance compared with simple traffic steering.

As shown in Figure 15, the average delay is not sensitive to traffic steering. The main reason lies in the fact that most of the delays are incurred by the UE's dormant period instead of the network. When the UE stays in dormancy, it can not decode channels, resulting in a massive buffering delay. It is much longer than the transmission delay or delay incurred by beam directionality. So, the average delay changes only subtly as the load is gradually shifted to the NR network.

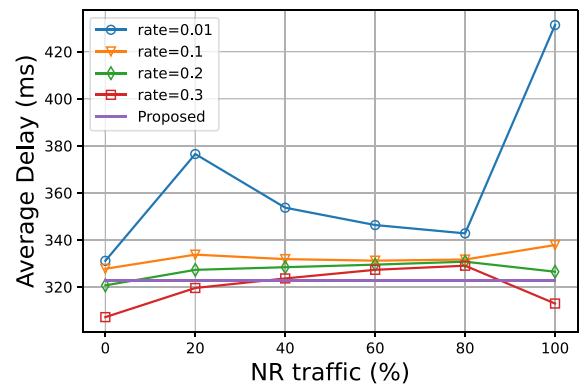


FIGURE 15. Average delay under different traffic flow patterns.

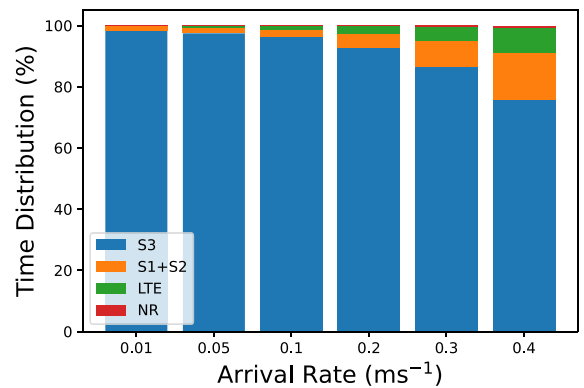


FIGURE 16. The time distribution on each state.

### E. TIME AND POWER DISTRIBUTION UNDER DIFFERENT ARRIVAL RATES

In Figure 16, we present the time distribution to the arrival rate. The labels LTE and NR denote the state of utilizing LTE and NR for transmission, respectively. When the arrival rate is low, the UE spends more time on dormancy(S3) because of the little traffic loading. As the arrival rate grows, the UE needs to handle more downlink traffic, so it spends more time receiving packets. However, even if the UE spends almost 10 % time on LTE when the arrival rate is  $0.4 \text{ ms}^{-1}$ , the proportion of NR is still less than 1 percent. Two reasons

lead to the huge difference in time distribution. The first one is that the probability of using the LTE link is higher. Since the gNB needs to serve all covered UEs, the chance for a UE to be served is small. The second reason is the difference in throughput. Since the NR link provides a higher data rate, the reception process is more likely to finish while utilizing the NR link.

In Figure 17, we present the energy distribution under different arrival rates. Similarly, LTE and NR labels represent the state of receiving data with LTE and NR,

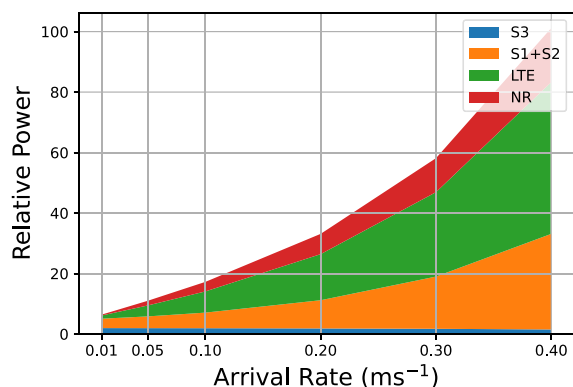


FIGURE 17. The power distribution of each state.

respectively. With the arrival rate increasing, the UE needs to spend more time receiving data, so the proportions of LTE and NR increase. Meanwhile, although the UE spends the most time on dormancy, as shown in Figure 16, it consumes little power as the RF modules are turned off. The most power-consuming behavior is receiving data with the RF modules, which occupy only a tiny fraction of time instead. The UE spends less than 1 percent of the time on reception with NR, but it accounts for nearly 10 percent of energy consumption when the arrival rate is  $0.4 \text{ ms}^{-1}$ . Similarly, the UE spends about half of the power on reception with LTE, but it only takes 5 percent of the time. Therefore, although the UE seldom decodes PDCCH and PDSCH, it accounts for most power consumption.

## VIII. CONCLUSION

Currently, most operational 5G systems are deployed in EN-DC, enabling the UE to connect simultaneously to the eNB and the gNB. However, the directionality in the NR system brings disadvantages as the UE may keep monitoring downlink channels due to insufficiency of beam information. This makes the UE consume unnecessary power and drains its battery. In this work, we propose a DRX mechanism along with a traffic steering algorithm that dynamically guides user traffic to the eNB or the gNB based on the gNB's beam pattern. With the eNB as an anchor, the beam information can be shared within each node, and the UE could resolve the misalignment issue and reduce power consumption with DRX.

The analysis is based on a semi-Markov chain model, and simulation results demonstrate the improved power-saving performance compared with standard 3GPP DRX operated on LTE, NR, and EN-DC. Nonetheless, as shown in Figure 17, the UE still spends most power on LTE, leaving room for further study on power allocation for each link. In the future, we will extend our work from the analysis of the single UE to the whole network. We will explore the possibility of combining DRX with multi-connectivity-enabled user association technology to optimize power efficiency on both the LTE and NR modules.

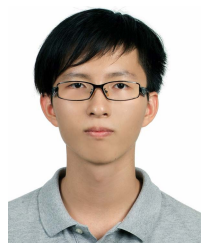
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