DRX in NR Unlicensed for B5G Wireless: Modeling and Analysis

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Abstract—The proliferation in the demand of high data rate and improved performance has urged the wireless vendors to think of extending 5G New Radio (NR) in unlicensed bands. The unlicensed band is typically used by Wi-Fi/Wi-Gig, resulting in the reduced probability of the availability of channel for transmission of data. The User Equipment (UE) has to keep its radio circuitry ON and wait until it gets access to the unlicensed channel again. This process escalates the energy expense of the battery-constrained mobile devices. Discontinuous Reception (DRX) introduced in LTE and 5G can also be used in NR-Unlicensed (NR-U) to reduce the UE’s energy consumption. In this article we introduce a DRX mechanism over NR-U networks for both Standalone (SA) and Non-Standalone (NSA) deployment modes. We used two different flavors, Beam-Search and Beam-Aware, to model the DRX mechanism. Hence, the proposed DRX mechanisms are: Standalone DRX with Beam-Search (SBS-DRX), Standalone DRX with Beam-Aware (SBA-DRX), Non-Standalone DRX with Beam-Search (NSB-DRX), and Non-Standalone DRX with Beam-Aware (NBA-DRX). Semi-Markov based modeling is used to show the estimation of power-saving, average delay, and resource utilization in the proposed NR-U DRX mechanism. Mathematical analysis and simulation results indicate that DRX in NR-U significantly improves the UE’s power-saving, average delay, and resources utilized by the network. The power-saving achieved with SBA-DRX is 21.13% and 24.84% higher than 5G NR DRX for both Trace 1 and Trace 2, respectively. Moreover, the delay achieved with NBA-DRX is 19.16% less than NBS-DRX with 18% less resource utilization.

Index Terms—5G NR, NR-Unlicensed (NR-U), Standalone NR-U, Non-Standalone NR-U, Discontinuous Reception (DRX), Beam-Search, Beam-Aware, semi-Markov.

1 INTRODUCTION

O

ver the past few years, cellular networks have witnessed an escalating trends in number of smartphones, tablets, IoT devices, and various other smart devices supporting multimedia applications. According to Ericsson’s forecast, by 2025, 5G network will have up to 2.8 billion subscriptions contributing 65% of the total world’s population. This is likely to generate 30% of the world’s total mobile data traffic [1]. 5G New Radio (NR) potentially supports different applications like Ultra-Reliable Low Latency Communication (URLLC), enhanced Mobile Broadband (eMBB), and massive Machine Type Communication (mMTC). The vision of 5G lies in providing multi-Gbps UL/DL speed, superior user experience, and ubiquitous availability, leading to seamless connectivity for a myriad of heterogeneous devices [2]. 5G/Beyond 5G (B5G) is essentially a paradigm shift that includes carrier frequencies in the mmWave spectrum, massive bandwidth, extremely dense heterogeneous network, directional air interface, cloud technologies, etc. [2, 3].

Besides improving the quality of life, the introduction of smart devices has also led to an enormous growth in data traffic that has almost saturated the resources in the existing cellular networks. Since the scarce and almost-saturated licensed spectrum has limitations like cost constraints, the wireless industry has entered its next phase of evolution by giving attention to the unlicensed bands [4]. Consequently, 3GPP Release 16, introduced the applicability of NR access technology to unlicensed spectrum (NR-U) [5]. NR-U supports all major 5G features such as wide-band carriers, flexible numerologies, dynamic TDD, beamforming, and dynamic scheduling/HARQ timing. The abundance of spectrum available in unlicensed band can create new opportunities for the application requiring multi-Gbps data rate for a large number of users. It has the potential to support diverse services, such as industrial IoT, private networks, enhanced Vehicle-to-Everything (eV2X) communication, etc. by extending the bandwidth resources on unlicensed band. The unlicensed spectrum access can be considered as a supplementary service to cater the demand for increased wireless broadband applications. The unlicensed frequency bands for NR-U are classified as: (i) sub-7 GHz bands which include 2.4, 3.5, 5, and 6 GHz bands and (ii) mmWave bands which comprise 37 GHz and 60 GHz bands. The 60 GHz band is an attractive candidate for NR-U since it is currently not very crowded and can offer a large amount of contiguous bandwidth [6].

Motivation: The unlicensed band is shared between Wi-Fi and cellular technologies. The gNB has to sense the unli-
licensed channel and intimate the UE about the unlicensed channel. Even if the gNB gets access to the channel, it is available for only Maximum Channel Occupancy Time (MCOT). Since the unlicensed channel is shared between Wi-Fi and other operators, the availability of the unlicensed band for the UE cannot be guaranteed every time the data arrives. Intuitively, the spectrum sharing reduces the probability of channel availability for data transmission over cellular network. The UE waits for the availability of the unlicensed channel, causing additional power consumption of the UE. This motivated us to explore DRX over NR-U to save the battery of the UE by temporarily shutting off its radio circuitry. DRX allows the UE to transit to Sleep state, if there is no packet transmission/reception during the Active state [7, 8].

The conventional DRX in 5G consists of Active, Short sleep, Beam-Search, and Long Sleep states [7]. It does not consider channel access mechanism and MCOT, making it unsuitable for NR-U. In this article, we investigate Discontinuous Reception (DRX) over 5G NR-U networks in both SA and NSA deployment modes. We model the DRX mechanism in NR-U by leveraging the two existing beamforming methods: (i) Beam-Search; (ii) Beam-Aware. In the Beam-Search scenario, if the selection of the optimal beam pair requires a substantial amount of time, greater than MCOT, the UE will possibly miss the access to unlicensed channel. This motivates us to explore the scenario where the information of the optimal beam pair is known to the network, i.e., Beam-Aware scenario. If the NR-U gNB has the cognizance of the suitable beam pair, this information can be shared with the UE through Physical Downlink Control Channel (PDCCH), eliminating the need for exhaustive beam searching mechanism. A DRX mechanism where gNB is knowledgeable of the beam pair between the gNB and UE can make the entire process 'Beam-Aware' [9]. To the best of our knowledge there is no work which explores the DRX mechanism in NR-U. DRX mechanism facilitates power saving but at the cost of delay. Therefore, in this study we investigate the power saving and delay tradeoff. A small part of this work, containing the DRX model of only NSA deployment mode, is published as a magazine article in [8]. We have made significant new contributions and enhancements. Section 3.1, Section 4, and Section 5.1 are completely new while Section 3.2 and Section 5.2 are significantly enhanced. Precisely, our major contributions are:

- We introduce DRX in NR-U for both SA and NSA deployment modes and compare the performance using two beamforming methods: Beam-Search, and Beam-Aware. The four proposed NR-U DRX mechanisms setting are: DRX with (i) Beam-Search (SBS-DRX) and (ii) Beam-Aware (SBA-DRX) in SA deployment mode and DRX with (iii) Beam-Search (NBS-DRX), and (iv) Beam-Aware (NBA-DRX) in NSA deployment mode.
- The DRX mechanism is modeled and analyzed by using a semi-Markov process for both Beam-Search and Beam-Aware scenarios. Performance of the DRX for two beamforming methods are evaluated and compared in terms of Power-Saving Factor (PSF), average delay, and average resource utilization.

The rest of the paper is organised as follows: Section 2 explains the evolution of NR-U. Additionally, we discuss the background of DRX in 5G NR followed by the wireless data traffic model and channel access mechanism. Next, we discuss our proposed DRX models for NR-U in Section 3 followed by their mathematical analysis in Section 4. Section 5 demonstrates the numerical analysis and the simulation study carried out using real traffic trace. Section 6 provides the related work done in NR-U, and finally Section 7 concludes the article.

2 Technology Review

In this section we describe the evolution of NR in the unlicensed spectrum. We present the discussion on DRX mechanism in 5G NR, followed by the concept of channel access mechanism.

2.1 Evolution Towards NR-U

The perpetual increase in data rate has motivated the wireless vendors to think beyond 5G by exploring the unlicensed band known as NR-U. The design of NR-U started in 3GPP Release-16 Study Item in 2018 [5]. Unlike LAA and LTE-Unlicensed (LTE-U), there are several deployment modes in NR-U. Table 1 explains the taxonomy of LAA and NR-U in unlicensed band. There are five deployment scenarios discussed in [5] are: (i) Carrier aggregation between NR and NR-U; (ii) Dual connectivity between LTE and NR-U; (iii) Standalone NR-U; (iv) NR cell with DL in unlicensed band, and UL in licensed band; and (v) Dual connectivity between NR and NR-U.

The operation of cellular network in the unlicensed band is challenging because it is crucial to maintain graceful coexistence between the licensed network and the unlicensed networks such as Wi-Fi and Wi-Gig. To ensure fair coexistence with inter-Radio Access Technology (RAT) services several regulatory requirements should be satisfied. 3GPP aims to define enhancements to NR, which are necessary to determine a single global solution for NR-U [10]. The primary objective behind these enhancements is to ensure...
the regulatory requirements, like Listen Before Talk (LBT), MCOT, Occupied Channel Bandwidth (OCB), power limits, dynamic frequency selection, and frequency reuse [11]. Certain implementation level challenges, including redesign of standard procedures, channels and signals are imposed in order to meet above requirements. An extensive survey on NR-U describing the design challenges and their respective solutions can be found in [11]. Overall, the deployment of NR in unlicensed band will be an integral part of NR for supporting eMBB-based applications. However, the support of NR-U for URLLC-based applications is still an open research area [11], [12]. This is mainly because of the delay involved in the LBT procedure, making NR-U unsuitable for latency intolerant use cases. Therefore, we mainly focus on the eMBB-based applications in our work.

NR-U can be used both with and without the assistance of a licensed carrier [10], i.e., SA deployment mode and NSA deployment mode, respectively, as shown in Fig. 1. The UE in SA deployment mode is connected to the NR-U gNB, without the assistance of any licensed carrier [11]. It is designed to fairly co-exist with the other unlicensed technologies. LBT needs to be performed by both the UE and the gNB individually before transmitting signaling messages as there is no licensed channel over which gNB can inform the UE about the availability of channel. After successful LBT, the device can access the channel for MCOT duration and the data is allowed to be transmitted in the unlicensed spectrum. 3GPP considered two options for defining the structure of COT, i.e., COT with single UL/DL switching and COT with multiple UL/DL switching [11], [12]. For UE-initiated COT, switching is allowed only from UL to DL [12]. Thus, in SA deployment mode, the control signals are transmitted over unlicensed band, requiring re-design of the initial access and scheduling procedures [13]. This further increases the power consumption of UEs. Thus, the study of DRX mechanism becomes inevitable in SA NR-U.

On the other hand, NR-U in NSA deployment mode consists of dual connectivity between licensed band and unlicensed band NR-U, where the data traffic is supported in unlicensed band while the control traffic is supported over the licensed band. The UE is always connected to the licensed channel and gNB is aware of the UE’s current state. The gNB senses the unlicensed channel using LBT and communicates it to the UE over the licensed channel. The occupancy of the unlicensed channel is limited to MCOT. In case the unlicensed channel is unavailable, the UE has to

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**TABLE 1: Technologies used in Unlicensed Band**

<table>
<thead>
<tr>
<th>Features</th>
<th>LAA</th>
<th>NR-U</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standardization</td>
<td>3GPP Rel-13, 3GPP Rel-17</td>
<td></td>
</tr>
<tr>
<td>Operational bands</td>
<td>sub 7GHz, above 7GHz</td>
<td></td>
</tr>
<tr>
<td>Deployment</td>
<td>CA, CA, DC, standalone</td>
<td></td>
</tr>
<tr>
<td>RAT</td>
<td>LTE, NR</td>
<td></td>
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<tr>
<td>Unlicensed bands</td>
<td>5GHz, 2.4, 3, 5, 6, 37, 60GHz</td>
<td></td>
</tr>
<tr>
<td>Aggregated BW</td>
<td>800 MHz</td>
<td></td>
</tr>
<tr>
<td>MIMO: MU-MIMO:</td>
<td>up to 8 streams, up to 8 streams</td>
<td></td>
</tr>
<tr>
<td>Modulation</td>
<td>up to 256-QAM, up to 1024-QAM</td>
<td></td>
</tr>
<tr>
<td>HARQ</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>Channel access</td>
<td>LBT, LBT</td>
<td></td>
</tr>
</tbody>
</table>

CA: Carrier Aggregation, DC: Dual Connectivity, BW: Bandwidth

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**Fig. 2: DRX Mechanism in 5G NR**

wait for the unlicensed channel, increasing the UE’s energy expense. Thus, it becomes imperative to improve the energy efficiency of the UE.

### 2.2 DRX in 5G NR

Efficient techniques for UE power consumption have always drawn the attention of the research community. DRX plays a vital role in saving UE’s power by temporarily disabling the radio frequency front-end based on traffic activity in both 4G [7], [14] and 5G networks [15]. DRX is a MAC layer procedure and can be implemented in RRC_Idle, RRC_Connected or RRC_Inactive modes [15]. DRX mechanism in 5G NR typically consists of ON duration, inactivity timer, active time, and off duration [16]–[18], as shown in Fig 2. The DRX mechanism is essential for 5G-enabled UEs which perform advanced computations, leading to depletion of energy. However, implementation of DRX poses several challenges due to the directional nature of mmWaves [15].

The beamforming based directional communication is essential to resolve challenges, like high path loss, associated with the mmWave frequencies. Therefore, an additional step, called Beam-Search, is required to search the beam pair which aligns the UE and gNB, before the transition from Sleep to Active state. Beam-search mechanism is intended to estimate the best beam pair between the transmitter, $T_x$ and receiver, $R_x$. The complete $T_x \times R_x$ beam sweeping will take a considerable amount of time ($B_{r_{\text{max}}}$), adding significant overhead to the DRX mechanism and reducing the overall sleep time of the UE. However, it is not mandatory to estimate and maintain the best beam pair between the $T_x$ and the $R_x$ [15]. If the signal strength of a beam pair is above a certain defined threshold, it can be considered as optimal beam [19]. Unfortunately, beam searching decreases the Sleep state duration, leading to a significant drop in power-saving. Packets that arrive while the UE is in Sleep state are buffered until the UE goes to an Active state, thereby increasing the packet service delay. Moreover, before serving the buffered packets, UE hunts for the best beam pair, which further adds to the delay.

### 2.3 Channel Access Mechanism and Wireless Data Traffic Model

LBT process is adopted by NR-U for channel access in unlicensed spectrum. The spectrum occupancy model for Dynamic Spectrum Access (DSA)/Cognitive Radio (CR) and WLAN has already been explored. The probability of channel idle time $\omega(t_{\text{idle}})$ follows generalized Pareto distribution and is given by [20].
In this section, we present the modeling of DRX mechanism in 5G. The conventional DRX in 5G does not consider channel access mechanism and MCOT making it not suitable for NR-U. This motivates us to explore: (i) re-design DRX in NR-U for both SA and NSA deployment modes; (ii) analyze performance in terms of PSF and average delay; and (iii) resource utilization in NR-UDRX.

3 MODELING OF NR-U DRX

In this section, we present the modeling of DRX mechanism for NR-U in SA and NSA deployment mode, considering both Beam-Search and Beam-Aware scenario.

3.1 Standalone Deployment mode

In SA deployment mode the UE is connected to the gNB using unlicensed carrier and gNB is connected to the 5G core network. The state diagrams for DRX with Beam-Search (SBS-DRX) and Beam-Aware (SBA-DRX) for SA deployment mode are depicted in Fig. 3a and Fig. 3b, respectively.

3.1.1 DRX with Beam-Search: SBS-DRX

We model the SBS-DRX mechanism as a semi-Markov model, where the current state is used to predict the future state. The time differences between state transitions and the holding times of states of semi-Markov model are random. Moreover, if the holding times are exponentially distributed, semi-Markov process model possesses the memory-less property [23], [24]. We propose a five-state semi-Markov model for SBS-DRX, as shown in Fig. 3a. The SBS-DRX states are: (i) Active state (Sα1), (ii) Sleep state (Sα2), (iii) DRX-ON state (Sα3), (iv) Beam-Search state (Sα4), and (v) Random Backoff (RBF) Sleep state (Sα5). The state transition probabilities from state i to state j are given by $P_{ij}^\alpha$ for $i, j \in \{1, 2, 3, 4, 5\}$.

When the UE is in $S\alpha_1$, a large amount of power is spent while transmitting/receiving the packets and monitoring the PDCCCH channel. In state $S\alpha_2$, the packets are served for service timer $t_{serv}$ and UE waits for inactivity timer $t_i$ to expire. In case no packet arrives before the expiry of $t_i$, the UE transits from $S\alpha_2$ to $S\alpha_3$ with a probability $P_{12}^\alpha$. If the packet arrives before the $t_i$ expires, inactivity timer re-starts and the UE remains in state $S\alpha_2$ with a probability $P_{22}^\alpha$. The value of $t_{serv}$ can be increased by $t_i$, which can repeat for $n_i$ times. In other words, in $S\alpha_2$, the inactivity timer $t_i$ repeats $n_i$ times such that $t_{serv} + n_i t_i = MCO$. After occupying the unlicensed channel for MCO, if there remains some data in the buffer, the UE switches to state $S\alpha_3$ with probability $P_{32}^\alpha$ to get access to unlicensed channel again.

In $S\alpha_3$, the UE does not monitor PDCCCH or transmit/receive data. Rather, it saves power by remaining in the $S\alpha_2$ for the sleep timer $t_i$. Conventional DRX consists of short and long sleep cycles with small ON durations. In NR-U, since unlicensed channel is shared with WiFi and the channel occupancy time is limited, the length of the sleep timer $t_i$ can be adjusted based on delay requirements. Depending on the length of the $t_i$ both long and short DRX cycles are taken care of. However, if the duration of sleep state is excessively long, there is a high possibility that the UE will miss the unlicensed channel as it is shared with WiFi. The $t_i$ is made up of single sleep duration $t_{sc}$. The $t_{sc}$ is repeated $N_{sc}$ number of times, where the $N_{sc}$ varies uniformly between the minimum and maximum value. After the sleep timer $t_i$ expires, the UE transits to DRX-ON state $S\alpha_4$ with probability $P_{43}^\alpha$.

In $S\alpha_4$, if the unlicensed channel is available and there is data for the UE, the UE transits to $S\alpha_5$ with probability $P_{45}^\alpha$. In case the unlicensed channel is unavailable, the UE switches to $S\alpha_5$ with probability $P_{45}^\beta$, for some random time. After the expiry of the random backoff timer $t_{rbf}$, the UE moves...
to $S^4_5$ with probability $P^4_{32}$. Once in $S^4_5$, the UE searches the optimal beam pair between the UE and the gNB. After finding the suitable beam pair in Beam-Search time $t_{bs}$, the UE moves to $S^4_1$ with probability $P^4_{11}$ and serves the packet.

3.1.2 DRX with Beam-Aware: SBA-DRX
The beam searching between $T_a$ and $R_s$ is done in $B_{T_{max}}$ time. This $B_{T_{max}}$ time adds extra delay while accessing the unlicensed channel, which is available for a limited time. The additional time involved in beam searching results in higher probability of missing the access of unlicensed channel by the UE. To overcome the challenges involved with beam searching, we leverage the concept of beam awareness in NR-U. Thus, in SBA-DRX the Beam-Search state is not considered, and the UE gets the information of an optimal beam pair from the gNB along with the information of unlicensed channel availability during DRX-ON state.

We model SBA-DRX as a four-state semi-Markov model as shown in Fig. 4(a). The SBA-DRX states are: (i) Active state ($S^3_1$), (ii) Sleep state ($S^3_2$), (iii) DRX-ON state ($S^3_3$), and (iv) Random Backoff (RBF) Sleep state ($S^3_4$). The state transition probabilities from state $i$ to state $j$ are given by $P^i_{ij}, i,j \in \{1,2,3,4\}$. The behavior of the UE in $S^3_3$, $S^3_2$, and $S^3_1$ is same as $S^3_1$, $S^3_2$, and $S^3_3$, respectively, in SBS-DRX. In $S^3_4$, if the unlicensed channel is available and there is data for the UE, the UE switches to $S^3_1$ state with probability $P^3_{31}$. In case, if the unlicensed channel is not available, the UE transits to $S^3_4$ with probability $P^3_{43}$ for $t_{bsf}$ time. After the expiry of $t_{bsf}$, the UE moves to $S^3_4$ with probability $P^3_{43}$.

3.2 Non-Standalone Deployment mode
In NR-U NSA deployment mode, the data traffic is supported in unlicensed band while the control traffic is supported over the licensed band. The state diagrams for DRX with Beam-Search (NBS-DRX) and Beam-Aware (NBA-DRX) in NSA deployment mode are depicted in Fig. 4(a) and Fig. 4(b) respectively.

3.2.1 DRX with Beam-Search: NBS-DRX
We model the NBS-DRX as a semi-Markov model having four states: (i) Active state ($S^2_1$), (ii) Sleep state ($S^2_2$), (iii) DRX-ON state ($S^2_3$), and (iv) Beam-Search state ($S^2_4$). The behavior of the UE in $S^2_1$, $S^2_2$, and $S^2_3$ is similar to SBS-DRX states $S^3_1$, $S^3_2$, and $S^3_3$, respectively. In $S^2_4$, the UE is informed by the gNB about the availability of the unlicensed channel over the licensed carrier. In case the unlicensed channel is idle or busy, and updates the UE periodically.

3.2.2 DRX with Beam-Aware: NBA-DRX
NBA-DRX mechanism is modeled as a semi-Markov model having three states: (i) Active state ($S^3_1$), (ii) Sleep state ($S^3_2$), and (iii) DRX-ON state ($S^3_3$). The behavior of the UE in $S^3_1$ and $S^3_2$ is similar to SBS-DRX states $S^3_1$ and $S^3_2$, respectively. In $S^3_3$, gNB informs the UE about the status of the unlicensed channel and the data packets over the licensed carrier. If the unlicensed channel is available, the UE switches to $S^3_1$ with probability $P^3_{31}$ and serves the packet. Note that, in NBS-DRX scenario, the UE transits to Beam-Search state to search a suitable beam pair for $t_{bs}$ whereas in NBA-DRX scenario, $t_{bs}$ time is zero as the network has cognizance of the suitable beam pair. In NBA-DRX, we assume that the gNB informs the UE about the optimal beam pair in $S^3_4$, reducing the significant burden associated with beam searching. If the unlicensed channel is unavailable, the UE switched to $S^3_2$ for $t_s$ time. After the expiry of $t_s$, the UE again transits to $S^3_3$ to get the access of unlicensed channel.
4 Analysis of Power-Saving Factor and Average Delay

In this section, we analyze the proposed DRX models in terms of PSF and average delay. Table 2 summarizes the performance metrics of the proposed DRX mechanisms based on the beamforming techniques used while modeling the DRX.

4.1 Analysis of SBS-DRX

Fig. 3a shows the proposed semi-Markov based DRX model for analyzing SBS-DRX. The state transition dynamics of the model are explained in Section 3.1.1. The state transition probabilities $P_{11}^\alpha$, $P_{12}^\alpha$, and $P_{35}^\alpha$ are given by [2]

$$P_{11}^\alpha = (1 - \frac{1}{\mu_{pc}}) Pr(t_{pc} < t_{t_s}) Pr(t_{ipc} < n_t) + \frac{1}{\mu_{pc}} Pr(t_{is} < t_{t_s}) Pr(t_{is} < n_t)$$

$$P_{12}^\alpha = (1 - \frac{1}{\mu_{pc}})(1 - e^{-\lambda_{pc}t_{t_s}})(1 - e^{-\lambda_{pc}n_t}) + \frac{1}{\mu_{pc}}(e^{-\lambda_{is}t_{t_s}})(1 - e^{-\lambda_{is}n_t})$$

$$P_{35}^\alpha = (1 - \frac{1}{\mu_{pc}})(1 - e^{-\lambda_{pc}t_{t_s}})(1 - \omega) + \frac{1}{\mu_{pc}}(1 - e^{-\lambda_{is}t_{t_s}})(1 - \omega)$$

where $\omega$ is the probability of channel being idle and is obtained using Equation [1]. From Fig. 3a, it is seen that $P_{35}^\alpha = 1, P_{34}^\alpha = 1, P_{31}^\alpha = 1, P_{35}^\alpha = 1 - P_{34}^\alpha$, and $P_{35}^\alpha = 1 - P_{34}^\alpha$. The steady state probability $\varphi_k^\alpha$ of any state $S_k^\alpha \in \{1, 2, 3, 4, 5\}$ can be calculated by using $\sum_k \varphi_k^\alpha = 1$, and the balance equation $\varphi_k^\alpha = \sum_{k=1}^{5} \varphi_k^\alpha P_{kk}^\alpha$. It is given as

$$\varphi_k^\alpha = \frac{P_{34}^\alpha P_{44}^\alpha P_{41}^\alpha P_{11}^\alpha + P_{35}^\alpha P_{55}^\alpha P_{51}^\alpha P_{11}^\alpha + P_{34}^\alpha P_{44}^\alpha P_{45}^\alpha P_{55}^\alpha}{P_{34}^\alpha P_{44}^\alpha P_{41}^\alpha P_{11}^\alpha + P_{35}^\alpha P_{55}^\alpha P_{51}^\alpha P_{11}^\alpha + P_{34}^\alpha P_{44}^\alpha P_{45}^\alpha P_{55}^\alpha}$$

Let $\gamma_k^\alpha \in \{1, 2, 3, 4, 5\}$ represent the holding time of any state $S_k^\alpha$. Using the steady state probability, we estimate the holding time, $E[\gamma_k^\alpha]$ for different states. When the UE is in $S_k^\alpha$, it serves the buffered packets and waits for $t_{iw}$ to expire. If no packet arrives before $t_{iw}$ expires, the UE leaves $S_k^\alpha$. The value of $t_{t_s}$ should be kept small owing to the limitation of MCOT. If the packets are remaining in the buffer, after the expiry of $t_{t_s}$, the value of $t_{t_s}$ can be increased by $t_{iw}$, which can repeat for $n_t$ times. The values of $t_{t_s}$, $t_{iw}$, and $n_t$ should be carefully selected and should be within the limit of MCOT. The holding time of $S_k^\alpha$ is calculated as $E[\gamma_k^\alpha] = t_{t_s} + \overline{T}_t$, where $\overline{T}_t$ is given by [2]

$$\overline{T}_t = \frac{1 - \frac{1}{\mu_{pc}}}{\lambda_{pc}} + \frac{1}{\mu_{pc}}(1 - e^{-\lambda_{is}t_{t_s}})$$

The UE remains in $S_k^\alpha$ for the sleep timer $t_s$ and saves power. In case the packets arrive, they are buffered until the next active period. The holding time of $S_k^\alpha$ can be estimated as $E[\gamma_k^\alpha] = t_s + \overline{T}_t$. The UE stays in DRX-ON state $S_3^\alpha$, Beam-Search state $S_4^\alpha$, and RBF Sleep state $S_5^\alpha$ for $t_{on}$, $t_{bs}$, and $t_{bf}$, respectively. The holding time of states $S_3^\alpha$, $S_4^\alpha$, and $S_5^\alpha$ are estimated as

$$E[\gamma_3^\alpha] = \frac{1 - \frac{1}{\mu_{pc}}}{\lambda_{pc}} + \frac{1}{\mu_{pc}}(1 - e^{-\lambda_{is}t_{bf}})$$

$$E[\gamma_4^\alpha] = \frac{1 - \frac{1}{\mu_{pc}}}{\lambda_{pc}} + \frac{1}{\mu_{pc}}(1 - e^{-\lambda_{is}t_{bf}})$$

$$E[\gamma_5^\alpha] = \frac{1 - \frac{1}{\mu_{pc}}}{\lambda_{pc}} + \frac{1}{\mu_{pc}}(1 - e^{-\lambda_{is}t_{bf}})$$

Using the value of $\varphi_k^\alpha$ calculated in Equation (5) and $E[\gamma_k^\alpha]$ calculated in Equation (7), we calculate the PSF $\rho_k^\alpha$. The PSF is defined as the ratio of the time spent by the UE in Sleep state to the total time spent across all the states. In SBS-DRX UE sleeps during the $S_2^\alpha$ and $S_3^\alpha$. The PSF $\rho_k^\alpha$ for SBS-DRX is given by

$$\rho_k^\alpha = \frac{\varphi_k^2 E[\gamma_k^2] + \varphi_k^3 E[\gamma_k^3]}{Q^\alpha}$$

where $Q^\alpha = \sum_k \varphi_k^\alpha E[\gamma_k^\alpha]$. DRX mechanism facilitates power saving but at the expense of delay. The packets which arrive during $S_2^\alpha$, $S_3^\alpha$, $S_4^\alpha$, and $S_5^\alpha$ have to wait for the next active period. The delay is defined as the time from packet arrival during Sleep, DRX-ON, and Beam-Search states to the end of that DRX cycle [25]. Since packet arrival events are random observers to the sleep and Beam-Search duration, the delays associated with $S_2^\alpha$, $S_3^\alpha$, $S_4^\alpha$, and $S_5^\alpha$ are given by

$$\delta_2^\alpha = \frac{\varphi_2^\alpha E[\gamma_2^\alpha]}{Q^\alpha} \sum_{\tau=1}^{t_{on}} (t_{on} - \tau)$$

$$\delta_3^\alpha = \frac{\varphi_3^\alpha E[\gamma_3^\alpha]}{Q^\alpha} \sum_{\tau=1}^{t_{on}} (t_{on} - \tau)$$

$$\delta_4^\alpha = \frac{\varphi_4^\alpha E[\gamma_4^\alpha]}{Q^\alpha} \sum_{\tau=1}^{t_{on}} (t_{on} - \tau)$$

$$\delta_5^\alpha = \frac{\varphi_5^\alpha E[\gamma_5^\alpha]}{Q^\alpha} \sum_{\tau=1}^{t_{on}} (t_{on} - \tau)$$

The overall delay $\delta^\alpha$ in SBS-DRX is computed as

$$\delta^\alpha = \delta_2^\alpha + \delta_3^\alpha + \delta_4^\alpha + \delta_5^\alpha$$

4.2 Analysis of SBA-DRX

Fig. 3b shows the proposed semi-Markov based DRX model for analyzing SBA-DRX. The state transition dynamics of the model are explained in Section 3.1.2. The state transition probabilities $P_{31}^\beta$, $P_{32}^\beta$, and $P_{34}^\beta$ are given by the Right-Hand Side (RHS) of Equation (3), (4), and (4), respectively. From Fig. 3b, it is seen that $P_{32}^\beta = 1, P_{32}^\beta = 1, P_{35}^\beta = 1 - P_{34}^\beta$, and $P_{35}^\beta = 1 - P_{34}^\beta$.
Similar to $\varphi^s$, the steady state probability $\varphi^b_k$ of the state $S^b_k \forall k \in \{1, 2, 3, 4\}$ is given as

$$\varphi^b_k = \begin{cases} 
\varphi^b_1 = & \frac{p^b_1}{p^b_1 + (1 - p^b_1)(1 + p^b_{34})} \\
\varphi^b_2 = & \frac{p^b_2}{p^b_2 + (1 - p^b_1)(1 + p^b_{34})} \\
\varphi^b_3 = & \frac{p^b_3}{p^b_3 + (1 - p^b_1)(1 + p^b_{34})} \\
\varphi^b_4 = & \frac{p^b_4}{p^b_4 + (1 - p^b_1)(1 + p^b_{34})} 
\end{cases} \quad (11)$$

Now, we calculate the holding time for the different states shown in Fig. 3b. Let $\vartheta^b_k \forall k \in \{1, 2, 3, 4\}$ denote the holding time of any state $S^b_k$. The estimation of expected holding time $E[\vartheta^b_k]$ of all the states is described as follows.

The holding times $E[\vartheta^b_1]$ and $E[\vartheta^b_2]$ of states $S^b_1$ and $S^b_2$, respectively, are the same as $E[\vartheta^s_1]$ and $E[\vartheta^s_2]$, respectively, as described in Section 4.1. If there is a packet for transmission but the channel is unavailable, the UE moves from $S^b_3$ to $S^b_4$ for random backoff time $trbf$. After the expiry of $trbf$, the UE again tries to access the channel, and moves to state $S^b_3$. Thus, the holding times $E[\vartheta^b_1]$ and $E[\vartheta^b_2]$ of state $S^b_1$ and $S^b_2$ are estimated with the help of the RHS of Equation (7a) and (7c), respectively. After calculating the holding time for different states, the PSF $\rho^b_s$ for SBA-DRX is computed as

$$\rho^b_s = \varphi^b_2 E[\vartheta^b_2] + E[\vartheta^b_4], \quad (12)$$

where $Q^b = \sum_{k=1}^{4} \vartheta^b_k E[\vartheta^b_k]$. Next, the delay associated with $S^b_2$, $S^b_3$, and $S^b_4$ are given by

$$\delta_{S^b_2} = \frac{\vartheta^b_2 E[\vartheta^b_2]}{Q^b} \sum_{t=1}^{trbf} (t_s - \tau)$$

$$\delta_{S^b_3} = \frac{\vartheta^b_3 E[\vartheta^b_3]}{Q^b} \sum_{t=1}^{t_{on}-1} (t_{on} - \tau)$$

$$\delta_{S^b_4} = \frac{\vartheta^b_4 E[\vartheta^b_4]}{Q^b} \sum_{t=1}^{t_{bf}-1} (t_{bf} - \tau). \quad (13c)$$

Hence, the overall delay $\delta^b$ is given as

$$\delta^b = \delta_{S^b_2} + \delta_{S^b_3} + \delta_{S^b_4}. \quad (14)$$

4.3 Analysis of NBS-DRX

Fig. 4a shows the proposed semi-Markov based DRX model for analyzing NBS-DRX. The state transition dynamics of the model are explained in Section 3.2.1. The state transition probabilities $P^y_11$ and $I^y_1$ are given by the RHS of Equation (2) and (3), respectively. The state transition probabilities $P^y_{34}$ and $P^y_{33}$ can be estimated as

$$P^y_{34} = (1 - \frac{1}{\mu_{pc}}) Pr(t_{ipc} < t_{on}) + \frac{1}{\mu_{pc}} Pr(t_{is} < t_{on}) \omega$$

$$= (1 - \frac{1}{\mu_{pc}}) (1 - e^{-\lambda_{pc}t_{on}}) + \frac{1}{\mu_{pc}} (1 - e^{-\lambda_{is}t_{on}}) \omega \quad (15)$$

$$P^y_{33} = (1 - \frac{1}{\mu_{pc}}) (1 - e^{-\lambda_{pc}t_{on}}) (1 - \omega) + \frac{1}{\mu_{pc}} (1 - e^{-\lambda_{is}t_{on}}) (1 - \omega) \quad (16)$$

From Fig. 4a, it is seen that $P^y_11 = 1$, $P^y_{13} = 1 - P^y_{31} - P^y_{12}$, and $P^y_{32} = 1 - P^y_{34} - P^y_{33}$. The steady state probability $\varphi^y_k$ of a state $S^y_k \forall k \in \{1, 2, 3, 4\}$ can be calculated using $\sum_{k=1}^{4} \varphi^y_k = 1$ and the balance equation $\varphi^y_k = \frac{P^y_{34} \varphi^y_1 + P^y_{33} \varphi^y_2 + P^y_{31} \varphi^y_3 + P^y_{32} \varphi^y_4}{P^y_{34} + P^y_{33} + P^y_{31} + P^y_{32}}$. The steady state probability $\varphi^y_1$ of state $S^y_1$ can be calculated using $\varphi^y_1 = \frac{P^y_{34} \varphi^y_1 + P^y_{33} \varphi^y_2 + P^y_{31} \varphi^y_3 + P^y_{32} \varphi^y_4}{P^y_{34} + P^y_{33} + P^y_{31} + P^y_{32}}$.

Let $\vartheta^y_1 \forall k \in \{1, 2, 3, 4\}$ represent the holding time of any state $S^y_k$. Using the steady state probability, we estimate the holding time, $E[\vartheta^y_k]$ for different states. In case of NBS-DRX, the holding times of $S^y_1$ and $S^y_2$ are $E[\vartheta^y_1]$ and $E[\vartheta^y_2]$, respectively, which are the same as $E[\vartheta^s_1]$ and $E[\vartheta^s_2]$, described in Section 4.1. The UE waits in $S^y_3$ for $t_{on}$ duration. After the expiry of $t_{on}$, UE might move to $S^y_2$ or $S^y_4$ depending upon the availability of channel and intimation of packet arrival. The UE remains in state $S^y_3$ for $t_{bf}$ period and searches for the optimal beam pair. The holding time of states $S^y_3$ and $S^y_4$ can be calculated as

$$E[\vartheta^y_3] = \frac{1 - \frac{1}{\mu_{pc}}}{\lambda_{pc}} \frac{1}{\lambda_{is}} \left( 1 - e^{-\lambda_{pc}t_{on}} \right) \frac{1}{\lambda_{is}} \left( 1 - e^{-\lambda_{is}t_{on}} \right) \quad (18a)$$

$$E[\vartheta^y_4] = \frac{1 - \frac{1}{\mu_{pc}}}{\lambda_{pc}} \frac{1}{\lambda_{is}} \left( 1 - e^{-\lambda_{pc}t_{on}} \right) \frac{1}{\lambda_{is}} \left( 1 - e^{-\lambda_{is}t_{on}} \right) \quad (18b)$$

Using the value of $\varphi^y_1$ calculated in Equation (17) and $E[\vartheta^y_1]$, we analyze the PSF $\rho^y_s$, which is given as

$$\rho^y_s = \frac{\varphi^y_1 E[\vartheta^y_1]}{Q^y}, \quad (19)$$

where $Q^y = \sum_{k=1}^{4} \vartheta^y_k E[\vartheta^y_k]$. The delays associated with $S^y_1$, $S^y_2$, $S^y_3$, and $S^y_4$ are given by

$$\delta_{S^y_1} = \frac{\vartheta^y_1 E[\vartheta^y_1]}{Q^y} \sum_{t=1}^{t_{on}} (t_{on} - \tau)$$

$$\delta_{S^y_2} = \frac{\vartheta^y_2 E[\vartheta^y_2]}{Q^y} \sum_{t=1}^{t_{bf}} (t_{bf} - \tau)$$

$$\delta_{S^y_3} = \frac{\vartheta^y_3 E[\vartheta^y_3]}{Q^y} \sum_{t=1}^{t_{bf}} (t_{bf} - \tau)$$

The overall delay $\delta^y$ is given as

$$\delta^y = \delta_{S^y_2} + \delta_{S^y_3} + \delta_{S^y_4}. \quad (21)$$

4.4 Analysis of NBA-DRX

Fig. 4b shows the proposed semi-Markov based DRX model for analyzing NBA-DRX. The state transition dynamics of the model are explained in Section 3.2.2. The state transition probabilities $P^s_11$, $P^s_13$, $P^s_3$, and $P^s_33$ are also given by the RHS of Equation (2), (3), (13), and (16), respectively. From Fig. 4b, it is seen that $P^s_3 = 1$, $P^s_1 = 1 - P^s_11 - P^s_12$, and $P^s_33 = 1 - P^s_31 - P^s_33$. The steady state probability $\varphi^s_k$ of a state $S^s_k \forall k \in \{1, 2, 3, 4\}$ can
be calculated using $\sum_{k=1}^{3} \varphi_k^\xi = 1$ and the balance equation $\varphi_k^\xi = \sum_{j=1}^{3} \varphi_j^\xi p_{ik}^\xi$. The $\varphi_k^\xi$ is given by Equation (22).

$$\varphi_k^\xi = \begin{cases} \varphi_1^\xi = \frac{P_S^k}{P_S^k + P_P^k + (1 + P_{PB}^k)(1 - P_{PB}^k)} & \text{if } k = 1 \\ \varphi_2^\xi = \frac{P_S^k}{P_S^k + P_P^k + (1 + P_{PB}^k)(1 - P_{PB}^k)} & \text{if } k = 2 \\ \varphi_3^\xi = \frac{P_S^k}{P_S^k + P_P^k + (1 - P_{PB}^k)} & \text{if } k = 3 \end{cases}$$

(22)

We use the steady state probability to calculate the holding time associated with different states. Let $\theta_k^\xi$ for $k \in \{1, 2, 3\}$ represent the holding time of any state $S_k^\xi$. The expected holding times of $S_1^\xi$ and $S_2^\xi$ are given by $E[\theta_1^\xi]$ and $E[\theta_2^\xi]$, respectively and are the same as $E[\theta_1^\xi]$ and $E[\theta_2^\xi]$, respectively, described in Section 3.4. The expected holding time $E[\theta_3^\xi]$ is given by the RHS of Equation (18). It should be noted that in case of NBA-DRX, the gNB is knowledgeable of the suitable beam pair and transits from $S_3^\xi$ to either $S_1^\xi$ or $S_2^\xi$ depending on the intimation of packet arrival and the availability of unlicensed channel. After calculating $\varphi_k^\xi$ and $E[\theta_k^\xi]$, we analyze the PSF $\rho_k^\xi$ which is the fraction of time the UE spends in Sleep state $S_k^\xi$ and is given as

$$\rho_k^\xi = \frac{\varphi_k^\xi E[\theta_k^\xi]}{Q_k^\xi},$$

(23)

where $Q_k^\xi = \sum_{k=1}^{3} \varphi_k^\xi E[\theta_k^\xi]$. The delays $\delta_{S_k^\xi}$ and $\delta_{S_k^\xi}$ associated with states $S_1^\xi$ and $S_3^\xi$ are given by

$$\delta_{S_1^\xi} = \frac{\varphi_1^\xi E[\theta_1^\xi]}{Q_1^\xi} \sum_{t=1}^{N_{sc}} (t_s - t)$$

(24a)

$$\delta_{S_3^\xi} = \frac{\varphi_3^\xi E[\theta_3^\xi]}{Q_3^\xi} \sum_{t=1}^{N_{sc}} (t_{on} - t)$$

(24b)

The overall delay can be estimated as

$$\delta^\xi = \delta_{S_1^\xi} + \delta_{S_3^\xi}.$$  

(25)

4.5 Resource Utilization in NR-U DRX

The basic unit of resource assigned in 5G NR is Resource Block (RB). The RBs allocated to the UE while transmission/reception are known as resource batches. DRX mechanism intends to conserve the power of the UE by temporarily shutting off its radio circuitry. Having the knowledge of DRX parameters for each UE, the gNB allocates the resources to the UE only when it is in the wake-up state. This implies that with DRX mechanism, the resources are used by UE during the active time for monitoring PDCCH and transmitting data. While the UE is in Sleep state, the available resources can be assigned to other UEs. Let $X$ be the total number of connected UEs. If only some number of UEs, say $X_B$, are monitoring PDCCH and involved in transmitting data, the remaining resources of $(X - X_B)$ UEs are free, and could be assigned to other UEs. This enhances the resource utilization, resulting in the overall increase in system’s capacity. In case of NR-U DRX with beam-search mechanism, the resources are utilized during Active, DRX-ON, and Beam-Search states, but not in the Sleep state. However, resources are required for only Active and DRX-ON states in case of NR-U DRX with beam-aware mechanism. Naturally, extra resources utilized in Beam-Search state are saved if the gNB has knowledge of the optimal beam pair. The resource batches allocated to NR-U are shared with Wi-Fi and other unlicensed wireless nodes. This sharing of resources leads to interference which depends on the data traffic from Wi-Fi, channel conditions, and deployment scenario of Wi-Fi and NR-U. Resource utilization in NR-U DRX can be obtained by taking the product of UE’s sojourn probability and resource utilized during wake-up states in the presence of channel interference [26].

5 Performance Evaluation and Simulation Results

In this section, we discuss the performance of DRX mechanism for NR-U in both SA and NSA deployment modes. The performance is studied by analyzing the PSF, average delay, and resource utilization. The simulation of NR-U DRX is performed using MATLAB-based discrete event simulation, which includes the real wireless traces obtained from UMass Repository [27] and Crawdad DataSet Repository [28].

5.1 Numerical Analysis

This section presents the numerical results derived from the proposed semi-Markov based DRX model explained in Section 3.4. Here, we consider three sectors, having 16 beams each on the transmitter side of NR-U gNB. Each beam is of width 7.5° [19], [29]. On the receiver side, we consider 8 beams per UE with a sub-frame length (TTI) of 125 μs. The UE has to align 128 (16 x 8) beams to get the optimal beam pair between the UE and the gNB. The power-saving and delay is calculated using $t_{on} = 1$ ms, $t_i = 2$ ms, and $t_{off} = 1 \sim 10$ ms. MCOT is considered to be 6 ms and the initial value of service time of the packet is 2 ms [7]. The inactivity timer $t_i$ can be repeated twice in order to increase the packet service time. The other performance parameters required for analytical evaluation are explained in Table 3 and are in accordance with recent works [15], [30], [31]–[34]. The UE’s minimum data rate (min-Rate) and maximum data rate (max-Rate) are considered as 2 Mbps and 4 Mbps, respectively, where min-Rate and max-Rate are derived from traffic models [31]–[34].

Table 2: Performance metrics of the proposed DRX mechanisms based on beamforming techniques

<table>
<thead>
<tr>
<th>Models</th>
<th>Standalone Mode</th>
<th>Non-standalone Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam-Search</td>
<td>• SBS-DRX</td>
<td>• NBS-DRX</td>
</tr>
<tr>
<td></td>
<td>$\rho_1^\xi = \frac{\varphi_1^\xi E[\theta_1^\xi]}{Q_1^\xi}$</td>
<td>$\rho_2^\xi = \frac{\varphi_2^\xi E[\theta_2^\xi]}{Q_2^\xi}$</td>
</tr>
<tr>
<td>Beam-Aware</td>
<td>• SBA-DRX</td>
<td>• NBA-DRX</td>
</tr>
<tr>
<td></td>
<td>$\rho_3^\xi = \frac{\varphi_3^\xi E[\theta_3^\xi]}{Q_3^\xi}$</td>
<td>$\rho_4^\xi = \frac{\varphi_4^\xi E[\theta_4^\xi]}{Q_4^\xi}$</td>
</tr>
</tbody>
</table>

Fig. 5 depicts the PSF with varying sleep timer values for max-Rate. We considered $t_{sc} = 120$ ms, $t_{on} = 1$ ms, $t_i = 2$ ms, and $N_{sc} = 1 \sim 8$. Due to variable $N_{sc}$, the sleep timer $t_s$ varies between 120 ~ 960 ms. The PSF improves as the sleep timer increases because a longer value of sleep timer postpone the transition to DRX-ON and Active states. Fig. 5 shows that NBS-DRX and NBA-DRX achieve higher
power-saving as compared to SBS-DRX and SBA-DRX. The reason lies in the fact that in NBS-DRX and NBA-DRX, the UE receives channel information from the gNB whereas, in SBS-DRX and SBA-DRX, the UE has to sense the channel in order to access the unlicensed band. In case the unlicensed channel is not available, UE sleeps for the random backoff time. After the expiry of $t_{db}$, UE transits to DRX-ON state and again senses the channel, thereby increasing the UE’s energy expenses. The $PSF$ achieved with SBA-DRX is 7.8% higher than SBS-DRX because in SBA-DRX the UE is aware of the optimal beam pair.

Fig. 5b shows average delay for varying sleep timer values. The delay varies from 0 ~ 450 ms when sleep timer varies from 120 ~ 960 ms. SBS-DRX experiences higher average delay compared to SBA-DRX as the UE has to search for the optimal beam pair before accessing the unlicensed channel. The delay observed by SBS-DRX for the short value of sleep cycle is higher since Beam-Search time is higher for a small value of sleep cycle and random backoff time. As observed from Fig. 5b, the delay achieved with NBS-DRX and NBA-DRX is higher than SBA-DRX. This arises from the fact that if UE does not receive an intimation of unlicensed channel and gNB has no knowledge of the channel, the UE sleeps for $t_{db}$ in case of SBA-DRX, whereas it sleeps for the same sleep duration in case of SBS-DRX and NBA-DRX.

Fig. 5c and Fig. 5d show the $PSF$ and the average delay, respectively, with varying DRX-ON duration for max-Rate. We consider single sleep duration $t_{sc} = 120$ ms, average number of sleeps $N_{sc} = 4$, which makes the sleep timer $t_s = 480$ ms. Both the $PSF$ and average delay are inversely proportional to the DRX-ON duration. Longer DRX-ON duration provides more time to the UE to get intimation of the unlicensed channel. The power-saving achieved with SBS-DRX is more than SBS-DRX as UE does not have to align the beam and hence, sleeps for a longer duration. It is observed from Fig. 5c that the power-saving achieved with SBS-DRX is 5.9% lower than NBS-DRX. This is because in SBS-DRX, if the unlicensed channel is not available for the UE, it sleeps for $t_{db}$ whereas it sleeps for the same sleep time $t_s$ in case of NBS-DRX. Fig. 5b presents the delay with varying DRX-ON duration. From Fig. 5a, for SBS-DRX, the delay varies from 113.2 ms to 117.6 ms and is 6.7 ms higher than SBA-DRX. The delay for NBA-DRX varies from 108.4 ~ 114 ms and is lower than NBS-DRX.

Fig. 5c shows the $PSF$ with a varying sleep cycle considering min-Rate. Here, the power-saving factor for SBS-DRX and SBA-DRX varies from 76.46% ~ 96.28% and from 90.15% ~ 98.65%, respectively. The power-saving obtained with SBA-DRX is 5.7% higher than SBS-DRX. Fig. 5d also shows that the $PSF$ achieved with min-Rate is higher than max-Rate (Fig. 5c) due to lower data rate. The average delay with varying sleep cycle for min-Rate is depicted in Fig. 5d. The average delay observed by the UE increases with increase in sleep cycle as the UE intends to sleep for a longer time and postpones the DRX-ON duration. The delay obtained in Fig. 5a follows similar trends as in Fig. 5b.

Fig. 6a and Fig. 6b show the $PSF$ and average delay, respectively for different values of DRX-ON duration. As expected, both the $PSF$ and average delay decreases with an increase in DRX-ON duration as it postpones the sleep cycle. The power-saving achieved with min-Rate is higher than max-Rate as UE easily transits to sleep state to save power in case of min-Rate. It is noticed from Fig. 6a that the power-saving achieved with NBA-DRX is higher than NBS-DRX and SBS-DRX as the UE does not have to align the beam. The power-saving achieved with NBA-DRX is higher than SBA-DRX for DRX-ON duration less than 8 ms. However, for DRX-ON duration greater than 8 ms, power-saving achieved with NBA is less than SBA-DRX. This is because in NBA-DRX, the DRX-ON duration repeats for $n_{on}$ times which increases the UE’s active time. The delay observed by the UE with varying DRX-ON duration is demonstrated in Fig. 6b. The average delay observed with...
5.2 Simulation Results

To validate our proposed DRX mechanism, we perform simulation in MATLAB. We first explain our simulation setup by providing major simulation parameters and assumptions. Subsequently, we elaborate on the simulation results for power-saving and average delay. Finally, we extend our results to show resource utilization using DRX. The simulation setup is described as follows:

1) We considered a macro-cell, 50 NR-U small-cells, 50 Wi-Fi transceivers, and 120 UEs are randomly and uniformly deployed in an area of 1000 × 1000 m². NR-U small-cells have a bandwidth of 1 GHz each and a transmit power and CCA threshold of 10 dBm and ~62 dBm, respectively. On the other hand, the transmit powers in unlicensed bands and Wi-Fi are considered to be 10 dBm and 15 dBm, respectively. AWGN noise power is ~174 dBm/Hz and noise figure is considered to be 7dBi [8], [11], [26], respectively. We use the path loss models described in [35] and a resource batch bandwidth of 1 GHz [11]. Table 3 provides the list of other major simulation parameters.

2) The simulation is fed with two real traffic traces obtained from UMass Trace Repository (Trace 1) [27] and Crawdad Dataset Repository (Trace 2) [28], respectively.

- The trace 1 consists of real wireless network for both HTTP and peer-to-peer video streaming applications [36]. Its measurement is carried out in three different settings. The first measurement captures mobility, where a cellular device is in the bus riding with the maximum speed of 50 km/h for a stretch of 3.6 kms. The other two measurements are carried out in the stationary setting, with 3G and WiFi network. The trace measurement consists of three devices, each including two measurement runs. The trace consists of the following fields: time in seconds (packet receiving time), source and destination address, protocol, length (in bytes), and Info (source and destination port number and data in bytes).

- The trace 2 is 4G and 5G monitoring data, collected using the ElasticMon 5G monitoring framework over FlexRAN. This data set consists of 4G/5G MAC, RRC, PDCP statistics and monitoring data. It is grouped into two versions of 5 datasets each: raw statistics and processed monitoring data. The data set was collected using single eNB and UE pair in five different mobility scenarios (moving away, moving closer, stable long distance, stable mid distance and stable short distance). It consists of date, time, and MAC Status (eNBid, UE MAC status, pktTxBytes, pktRxBytes etc.).

We extract the time stamp, TX data, and RX data from both the traces and feed them to the discrete time simulator built in MATLAB to analyse the energy efficiency and delay of our proposed scheme.

3) A discrete event simulator is developed to analyze the performance of DRX in NR-U. Five types of events, i.e., Active, Sleep, Beam-Search, DRX-ON, and packet arrival are considered. During the Active event, the UE serves the packets and remains active for $t_i$ time. It switches to Sleep event if an unlicensed channel is not available or the packets have been served before the $t_i$ timer expires. It transits to DRX-ON event after every sleep event in order to get information about the data and the unlicensed channel availability. If there is data packet for the UE and the unlicensed channel is available, it intends to find the optimal beam by moving to Beam-Search. In Beam-Aware NR-U DRX scenario, the Beam-Search event is eliminated, as the gNB informs the UE about the optimal beam pair. The packet arrival event reads the time of packet generation and data size from the trace and moves the packets to buffer.

4) The PSF and the average delay are calculated using packet arrivals in a simulation run, total waiting period of a served packet, total wakeup time, total sleep time, and simulation clock. Every simulation is run for 50 minutes, is repeated ten times with different random seeds, and the average results are recorded.

Overall, the simulation is divided into two parts:

1) We calculate the power saving factor and average delay. The DRX mechanism is UE specific, due to which we consider a single UE for DRX simulations. The UE reads the length and time field of the trace, and if the current timer matched with the time field the data is added to the buffer. The process continues until the timer stops.

2) We calculated the resource utilization of NR-U DRX by considering 120 UEs in the simulation settings. The 120 UEs do not read the trace. We considered the concept described in [26] to calculate resource utilization.

### TABLE 3: NR-U DRX Performance Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>DRX-ON Duration ($t_{on}$)</td>
<td>1~10 ms</td>
</tr>
<tr>
<td>Inactivity Timer ($t_i$)</td>
<td>2 ms</td>
</tr>
<tr>
<td>Maximum No. of Inactivity Timer ($n_i$)</td>
<td>2</td>
</tr>
<tr>
<td>Single Sleep Duration ($t_{ss}$)</td>
<td>120 ms</td>
</tr>
<tr>
<td>Number of Sleeps ($N_{sc}$)</td>
<td>1~8</td>
</tr>
<tr>
<td>Sleep Timer ($t_s = t_{sc} × N_{sc}$)</td>
<td>120 ~960 ms</td>
</tr>
<tr>
<td>Random Backoff Sleep duration</td>
<td>1~10 ms</td>
</tr>
<tr>
<td>Maximum Channel Occupancy Time (MCOT) [5]</td>
<td>6 ms</td>
</tr>
<tr>
<td>3dB beamwidth ($\theta$)</td>
<td>7.5°</td>
</tr>
<tr>
<td>No. of Beam on Tx per sector</td>
<td>16</td>
</tr>
<tr>
<td>min-Rate &amp; max-Rate [13]</td>
<td>16</td>
</tr>
<tr>
<td>Transmit power on unlicensed band [11]</td>
<td>10 dBm</td>
</tr>
<tr>
<td>Transmit power of Wi-Fi station</td>
<td>15 dBm</td>
</tr>
<tr>
<td>CCA energy detection threshold</td>
<td>15 dBm</td>
</tr>
<tr>
<td>Path loss model [35]</td>
<td>$15.3 + a × 10\log_{10}(d)$</td>
</tr>
<tr>
<td>Licensed, Unlicensed</td>
<td>$a = 3.75, a = 5$</td>
</tr>
<tr>
<td>AWGN Noise Power, Noise Figure</td>
<td>$-174$ dBm/Hz</td>
</tr>
</tbody>
</table>

SBS-DRX is higher than NBS-DRX because in SBS-DRX, if the channel is not available the UE transits to RBF sleep state whereas in NBS-DRX, if a channel is not available the UE may extend the DRX-ON duration. It is observed from Fig. 5 that the delay observed by the UE decreases with an increase in DRX-ON duration as longer DRX-ON duration allows the UE to transit to Active state easily.
Utilization of Resource Batches

Average Delay/byte (ms)

Utilization of Each Resource Batch

Fig. 7: (a) Power-Saving Factor (PSF) and (b) Average Delay with Varying Sleep Timer for SBS-DRX & SBA-DRX, (Simulation Results)

Fig. 8: SA (a) Utilization of resource batches as X NR-U UEs sharing a pool of five resource batches and (b) Utilization of resource batches for varying $\Gamma$

(a) SA DRX Power-Saving Factor (PSF)

(b) SA DRX Delay

Fig. 9: (a) Power-Saving Factor (PSF) and (b) Average Delay with Varying Sleep Timer for NBS-DRX & NBA-DRX, (Simulation Results)

Fig. 10: NSA (a) Utilization of resource batches as X NR-U UEs sharing a pool of five resource batches and (b) Utilization of resource batches for varying $\Gamma$

Level of interference for the same assigned resource batch. As seen from Fig. 8, for $\Gamma = 0.8$, with the pool of 5 resource batches shared by 10 UEs, maximum utilization of 36.6% is achieved with 5G NR DRX, followed by 15.48% with SBS-DRX and 14.89% with SBA-DRX.

Fig. 9 shows the utilization of 2, 5, & 10 resource batches for both with and without DRX for varying $\Gamma$. The utilization of resources is high for a lower value of interference. The resource utilization reduces with an increase in interference as higher interference prevents the use of unlicensed channel. For instance, we can notice from Fig. 9 that the utilization of 2 resource batches is higher than 5 & 10 resource batches as the NR-U UEs suffer from different levels of interference for the same assigned resource batch. The resource utilization without DRX mechanism is the highest because the UE does not go to a sleep state and thus always needs resources. The resources utilized with SBA-DRX are 57.79% less when compared to those used without DRX. The UE needs the resources during Active state $S_1$ and DRX-ON state $S_2$ in SBA-DRX. But, during Sleep state $S_3$ and RBF-Sleep state $S_4$, there is no data transmission and the resources can be assigned to other UEs. The resources used with SBA-DRX are 3.81% less than SBS-DRX.
beam pair during the DRX-ON period and it transits to Active state only when there is data to be served and unlicensed channel is available. Otherwise, it continues to be in Sleep state. The power-saving achieved with NBS-DRX is 11.07% and 14.96% higher than 5G NR DRX for trace 1 and trace 2, respectively. Fig. 9b depicts the average delay/byte for varying sleep timers from 120 to 960 ms. The average delay/byte achieved with NBA-DRX is 15.18% less than NBS-DRX for trace 1 as the UE does not have to align the beams before receiving the data. For trace 2 the average delay/byte achieved with NBA-DRX is 19.16% less than NBS-DRX. It can be observed from both Fig. 9a and Fig. 9b that the analytical and simulation results are comparable for all the cases, thus validating our proposed scheme.

Fig. 10a compares the utilization of resource batches versus the number of NR-U UEs sharing the pool of resource batches for NSA mode with and without DRX. For 8, the maximum utilization of resource batch with NBA-DRX and NBS-DRX is 16.5% and 24.5%, respectively. However, the resource utilization without including DRX mechanism is 40.9%. This implies that fewer resources are utilized when DRX mechanism is incorporated as UEs need resources only during the Active state and DRX-ON state. It is noticed from Fig. 10b, the increase in Wi-Fi interference results in an increase in the number of UEs sharing the resource pool, because each UE observes a different level of interference for the same assigned resource batch. Also, for 8, with a pool of 5 resource batches shared by 10 UEs, maximum resource utilization of 36.6% is achieved without DRX. However, when the DRX mechanism is employed, the resource utilization decreases to 21.5% and 14.8% for NBS-DRX and NBA-DRX, respectively. The utilization of resource batches with varying Wi-Fi interference for NSA mode with and without DRX are shown in Fig. 10b. The resource used with NBA-DRX are 18% less as compared to those used for NBS-DRX which, in turn, are 41% less as compared to those used without DRX.

6 RELATED WORK

The unlicensed spectrum in NR is being widely explored by both industries and academicians. Authors in [12] provided an overview of design elements and research challenges associated with NR-U and evaluate the performance of co-existence of NR-U and Wi-Fi network. Research work in [13] proposed NR-U and IEEE 802.11 co-existence model and evaluated how well it adheres and fulfills the regulatory requirements like LBT, MCOT, OCB, and maximum power limit. Patriciello et al. [10] discussed the co-existence performance of NR-U with IEEE 802.11ad Wireless Gigabit (WiGig) with different channel access mechanism in indoor scenario. The simulation results are analyzed in terms of throughput and latency, and exhibit the fair co-existence between NR-U and WiGig. Authors in [37] proposed LBT with Collision Resolution (CR-LBT) with an objective of greatly reducing the resource wastage due to collision and improving the resource sharing fairness. The authors attempt to simultaneously increase the throughput of both NR-U and WiFi network.

NR-U operating in mmWave spectrum requires beam-related procedures to overcome impairments related to propagation losses [35]. The existing channel access mechanism may not work because of directional transmission in higher frequencies. The directional transmission involves multiple-beam related procedures including beam sweeping for beam measurements, determination, and reporting. While directional beams can improve network performance and reduce interference, they may also create hidden node or exposed node problems [39], [40]. LBT might not work due to both hidden node and exposed node problems. To overcome this issue, Lagen and group in [40] proposed a dynamic LBT switching procedure for access to unlicensed spectrum. Here, the criteria for switching between the directional LBT (dirLBT) to Omni-directional LBT (omniLBT), and vice versa, is investigated to achieve fairer access to the unlicensed channel.

Hirzallah et al. [12] provided an overview of NR-U with primary emphasis on coexistence in 5 GHz and 6 GHz bands. The authors performed an extensive simulation to explore the coexistence between NR-U and Wi-Fi, and evaluate the performance in terms of throughput, latency, buffer occupancy, and channel utilization. The improvement offered by NR-U over LAA is also discussed. The above mentioned research works demonstrate the co-existence of NR in unlicensed spectrum and IEEE 802.11 but none of them discuss about the energy consumed by the UE while waiting to access the unlicensed channel. In our previous work in [8], we modeled the DRX in NR-U in NSA mode. However, in this article we propose and mathematically analyze DRX in NR-U for both SA and NSA deployment modes.

7 CONCLUSION

In this work, we present DRX mechanisms in NR-U for SA and NSA deployment modes, with two flavours i.e., Beam-Search and Beam-Aware. We propose four NR-U DRX mechanisms: (i) SBS-DRX, (ii) SBA-DRX, (iii) NBS-DRX, and (iv) NBA-DRX. The proposed NR-U DRX mechanisms are analyzed using semi-Markov model. The performance of NR-U DRX is evaluated using PSF, overall delay, and resource utilization. Numerical analysis and simulation results using real wireless trace validate the NR-U DRX models. The power-saving achieved with SBA-DRX is 21.13% and 24.84% higher than 5G NR DRX for both trace 1 and trace 2, respectively. The power-saving achieved with NBA-DRX is 11.73% and 12.55% higher than NBS-DRX, for trace 1 and trace 2, respectively. Re-design of channel access mechanism and scheduling procedure while modeling NR-U DRX can be the part of our future work.

REFERENCES


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