Performance analysis of user power consumption in NR-unlicensed DRX

Performance Analysis of User Power Consumption in NR-Unlicensed DRX

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Abstract

The 3rd Generation Partnership Project (3GPP) in Release 16 introduced New Radio in unlicensed spectrum (NR-U) to further enhance the capacity of licensed spectrum. The User Equipment's (UE) power consumption is an important metric identified by researchers in Long Term Evolution (LTE) and NR, and now in NR-U. In Long Term Evolution (LTE) and NR, 3GPP has introduced Discontinuous Reception (DRX) to save the UE's power consumption and it can also be used in NR-U. In the DRX procedure, UE sleeps when there is no data packet to serve and wakes up at regular periodic intervals to check if there are any data packets in the downlink. The UE can sleep longer and skip most channel monitoring occasions, which helps to save the power of the UE. In this article, we analyze the power consumption of the UE in the DRX mechanism over NR-U networks. We model the DRX using semi-Markov-based modeling to analyze the power consumption of the UE and the average delay experienced by the UE in the NR-U DRX mechanism. Analytical analysis indicates that power consumption increases with increasing DRX-ON duration and decreases with increasing sleep duration. The power consumption reduces at the cost of delay, i.e. delay increases with an increase in sleep duration.

Keywords: New Radio (NR), NR-Unlicensed, Discontinuous Reception, Beamforming, semi-Markov, Power Consumption.

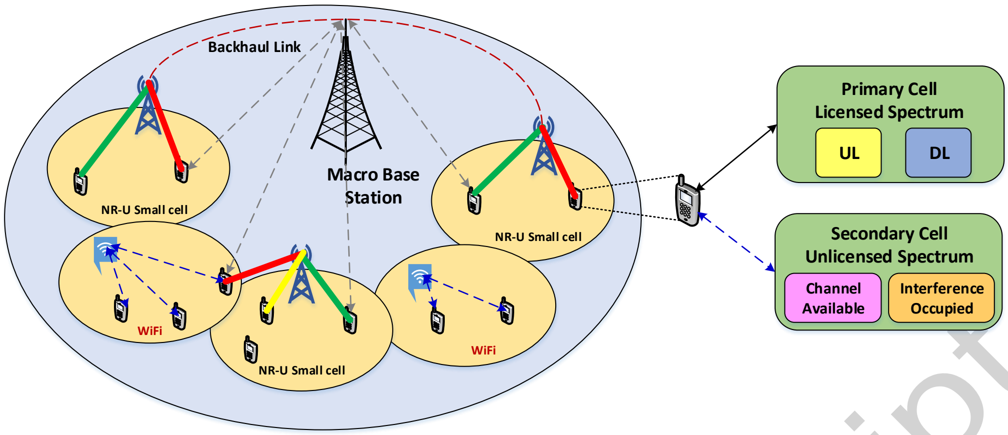


Fig. 1: Deployment of NR in the unlicensed band together with WiFi users

1 Introduction

We have witnessed a massive growth in data traffic demand over the last few years. The introduction of a 5G New Radio (NR) network is expected to efficiently cater to the growing data demand by supporting different applications such as Ultra-Reliable Low Latency Communication (URLLC), enhanced Mobile Broadband (eMBB), massive Machine-Type Communication (mMTC), and enhanced Vehicle to Everything (eV2X) [1, 2]. However, wireless service providers and operators doubt that even 5G NR will meet the UEs' demands [3]. Additionally, cost constraints and the scarcity issue involved in the licensed spectrum persuade the vendors to look into unlicensed bands as one of several complementary technologies [3]. A multi-Gbps data rate can be attained for a large number of devices using this underutilized unlicensed spectrum [4]. Consequently, 3rd Generation Partnership Project (3GPP) Rel. 16 introduced the applicability of NR in unlicensed spectrum (NR-U) [5, 6]. In a dense network scenario, the NR network coupled with an unlicensed spectrum can enhance spectral efficiency, improve UEs' experience, and support higher UE mobility as well as diverse Quality of Service (QoS). For instance, offloading the cellular traffic to the unlicensed spectrum will boost the throughput considerably and at the same time, alleviate the issue of limited radio resources in the licensed spectrum.

Although the integration of unlicensed spectrum complements the licensed spectrum, there are also many challenges associated that need to be meticulously addressed. When Wi-Fi and other cellular technologies share the unlicensed spectrum, it becomes imperative to maintain a fair and harmonious coexistence between them. Fairness for cellular UE in the unlicensed bands implicitly means that the cellular UEs do not affect the performance of existing Wi-Fi devices [7, 8]. For fair coexistence, each Radio Access Technology (RAT) has to abide by the regulatory requirements of the corresponding spectrum bands. Therefore, the gNB and the UE need to sense the availability of the unlicensed channel using Listen Before Talk (LBT) mechanism. LBT is a spectrum sharing mechanism by which a device senses the channel using a Clear Channel Assessment (CCA) check before accessing it. After getting access to an unlicensed channel it can only be occupied for only Maximum Channel Occupancy Time (MCOT), adhering to fairness co-existence. Being shared with WiFi, the availability of the unlicensed channel is restricted and is not always available for the cellular UE. Consequently, the UE has to wait until the unlicensed channel is available again, which causes additional power consumption of the UE. Discontinuous Reception (DRX) is an important Medium Access Control (MAC) layer procedure introduced by 3GPP to reduce power consumption by momentarily switching off the radio circuitry based on the arrival of data traffic in both 4G [9] and 5G networks [10–12].

Directional transmission in NR-U is more complex than omni-directional transmission/reception in Wi-Fi and LTE in unlicensed spectrum [3]. The directional communication in NR comes with several impairments due to severe path loss, blocking, and propagation losses. To overcome these losses in directional communication, an additional step, called beamforming, is required, which makes directional communication mandatory for both transmitters and receivers. Beamforming includes a beam-searching process, where the UE has to find a beam pair that can align the UE with the gNB. In this process, UE has to spend more energy in searching the optimal beam. Sometimes the beam search time is comparable to or even greater than the sleep time. This motivates the introduction of a new concept where the network has the information about the optimal beam pair, which can be referred to as the Beam-Aware scenario [13]. This eliminates the need for an exhaustive beam-search process and considerably saves the power of the UE. The UE power consumption is an important matrix to assess the performance of the DRX mechanism [14]. In our previous work in [11], we explore the semi-Markov analysis of the DRX model in different deployment modes with different beam-forming techniques, i.e. beam search and beam aware scenarios. We evaluate the proposed model in terms of power saving factor, average delay, and average resource utilization. This work is the extension of our previous work [11]. In this article, we leverage the DRX model proposed in [11] to further analyze the UE power consumption in different DRX states. To the best of our knowledge, this work is the first attempt to explore the UE power consumption in different NR-U DRX states. We explore the UE power consumption and the average delay associated with different states of the DRX cycle for both standalone (SA) and non-standalone (NSA) deployment modes. Also, we numerically analyze the power consumed by the UE in different DRX states.

The remaining part of the article is organized in the following manner: Section 2 describes the preliminary study, giving the details of the regulatory requirements and DRX mechanism followed by the related work done in the energy efficiency of NR-U UEs. In Section 3 and Section 4, we describe the NR-U DRX models and the mathematical analysis of UE power consumption as well as average delay experienced by the UEs, respectively. Section 5 delineates the numerical analysis of the proposed UE power consumption model and average delay for varying data rates and is followed by the conclusion in Section 6.

Table 1: Cellular technologies operating in unlicensed band

Features	LTE-U	LAA	NR-U
Standard	3GPP Rel-12	3GPP Rel-13	3GPP Rel-17
Operational bands	sub-6 GHz 0	sub-6 GHz	sub-6 GHz, above 6 GHz
Deployment	CA	CA	CA, DC, SA
RAT	LTE	LTE	NR
Unlicensed bands	5 GHz	5 GHz	2.4, 3.5, 5, 6, 37, 60 GHz
Aggregated BW	60 MHz	80 MHz	800 MHz
Modulation	up to 256 QAM	up to 256 QAM	up to 1024 QAM
HARQ	yes	yes	yes
Channel access	LBT	LBT	LBT

2 Preliminary study

This section consists of a brief description of Wi-Fi/Wi-Gig, followed by details of NR-U. This includes the regulatory requirements, initial access procedures, and DRX in NR-U for both NSA and SA deployment modes. A summary of the various cellular technologies that operate in the unlicensed band is given in Table 1.

2.1 Wi-Fi and Wi-Gig Technology

Wi-Fi is based on the specifications of IEEE 802.11 for its physical and Medium Access Control (MAC) layer. IEEE 802.11b standard operating in 2.4 GHz band supported a data rate of 11 Mbps while the most recent IEEE 802.11ad standard operates at 60 GHz frequency providing a data rate upto 7 Gbps. Presently, new protocols, such as IEEE 802.11n and IEEE 802.11ac, aim to increase the throughput per unit area by several folds in dense deployment scenarios. The current Wi-Fi standards use Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) as the MAC protocol for both channel access and collision avoidance [15]. Devices using CSMA/CA must transmit one frame at a time over the entire channel bandwidth. In the dense deployment scenario, CSMA/CA delivers poor performance. Therefore, Wi-Fi (IEEE 802.11ax) standards provide new protocols, similar to cellular standards, to schedule Wi-Fi transmission and improve network performance [15].

Wi-Gig, also called 60 GHz Wi-Fi, allows devices to communicate at multi-Gbps speeds [16, 17]. It includes the current IEEE 802.11ad and upcoming IEEE 802.11ay standard. IEEE 802.11ay aims to support a data rate of 7 Gbps, which is much higher than the current data rates supported by Wi-Fi standards. The MAC layer is expected to be backward compatible with the other IEEE 802.11 standards. Since the 60 GHz millimeter-waves are prone to propagation losses, IEEE 802.11ay also supports efficient beamforming to enable robust communication [18]. Its multi-Gbps wireless connectivity is likely to support emerging use cases such as VR/AR applications and uncompressed video transmission.

2.2 NR-Unlicensed

A glance into the recent wireless traffic statistics shows the growing trends of mobile data traffic [19]. The current 5G wireless system is likely to fall short of supporting

Table 2: Unlicensed spectrum band in 3GPP

Countries	**Available Band**	**Under Study**
USA	5.2-5.8 GHz, 5.9-7.1 GHz	57-71 GHz
Canada	5.2-5.8 GHz	57-71 GHz
European Union	5.2-5.9 GHz	5.9-6.4 GHz, 57-71 GHz
United Kingdom	5.2-5.9 GHz	57-71 GHz
Germany	5.2-5.7 GHz	57-71 GHz
France	5.2-5.7 GHz	57-71 GHz
Italy	5.2-5.7 GHz	57-71 GHz
China	5.2-5.3 GHz, 5.7-5.8 GHz	59-64 GHz
South Korea	5.2-5.8 GHz	5.9-7.1 GHz, 57-64 GHz
Japan	5.2-5.7 GHz	57-66 GHz
India	5.2-5.5 GHz, 5.7-5.9 GHz	—
Australia	5.2-5.8 GHz	57-66 GHz

the escalating trends of wireless data traffic demand. This exponential increase in UE demands drives the focus of the wireless industry towards the use of unlicensed spectrum bands and enhances the capacity of future cellular systems. The capacity of the wireless networks depends on spectral efficiency and bandwidth. The large amount of unlicensed spectrum that is available may open up new possibilities for applications that call for a high data rate of several Gbps for a large number of UEs. The unlicensed frequency bands for NR-U are classified as (i) sub-6 GHz bands which include 2.4 GHz, 3.5 GHz, 5 GHz, and 6 GHz bands, and (ii) mmWave bands include 37 GHz and 60 GHz bands. Table 2 describes the unlicensed spectrum allocation by different countries for 5 GHz band and 60 GHz band, respectively [5].

3GPP Rel-17 [20] supports the NR operation in unlicensed spectrum in sub-6 GHz band as well as in mmWave band. The mmWave band intends to offer a much larger spectrum than the congested sub-6 GHz band. To maintain low cost and complexity as well as to ensure easy integration between NR and NR-U, the radio stack of NR-U is built upon the NR radio stack, with a few modifications [21]. NR-U has a great ability to work well with other unlicensed technologies. Due to beam transmission, it is less susceptible to interference than LTE in unlicensed spectrum (LTE-U). Also, due to better scheduling of radio resources and reduced processing time in NR, transmission latency in NR-U is lower than in LTE-U. NR-U deployment is introduced in both SA and NSA modes. Figure 1 shows the NR-U deployment scenario and coexistence with other unlicensed technologies. In SA NR-U, the deployment of 5G private networks becomes easier while NSA NR-U boosts the existing deployment by providing a better UE experience.

As mentioned above, the addition of unlicensed spectrum boosts the capacity of licensed spectrum. It seems to be a promising solution for emerging eMBB-based applications. In contrast, unlicensed use of spectrum for URLLC-based applications needs further investigation and is an open research problem [22]. URLLC-based applications have a strict delay budget. So, the latency associated with the channel access mechanism and LBT makes NR-U unsuitable for URLLC applications in its current state [21]. In 3GPP Rel-17, researchers explore solutions by which NR-U can expand its horizon beyond eMBB services, by improving the latency and reliability requirements [23]. This will open up the support to emerging applications like the Industrial

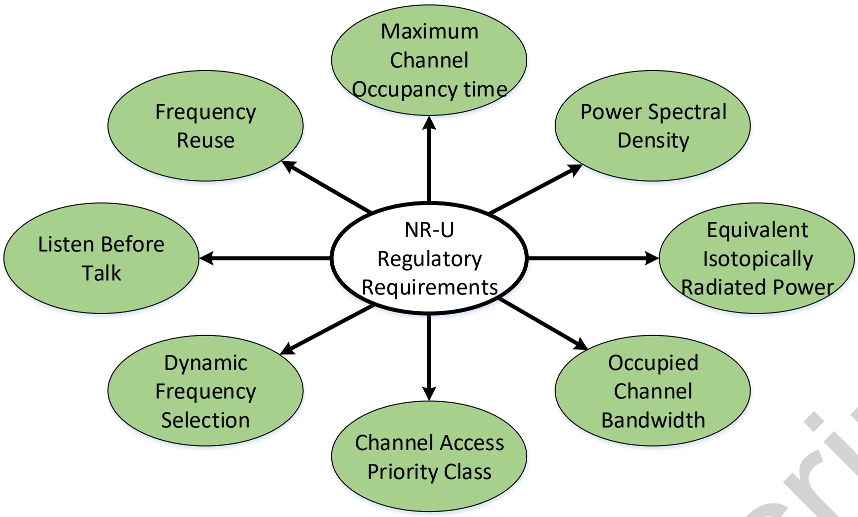


Fig. 2: Regulatory requirements of cellular networks operating in unlicensed spectrum

IoT (IIoT) [24]. The discussion of the prominent NR-U use cases includes Industry 4.0, unmanned aerial vehicles and drones, augmented reality, mixed reality, robotic surgery, and vehicular communications [25].

2.3 Regulatory Requirements

The graceful coexistence of cellular networks in the unlicensed band is subject to several regulatory requirements. There are several challenges related to fair coexistence between licensed and unlicensed networks. In this section, we describe certain limitations and regulatory requirements for the operation of NR in unlicensed bands [3, 10]. Fig. 2 depicts the regulatory requirements of cellular networks to be fulfilled while operating in an unlicensed spectrum.

1. **Listen Before Talk (LBT)** is a procedure where the UE senses the spectrum for the CCA period before using the channel. CCA uses the concept of Energy Detection (ED) threshold to detect the availability of the channel, i.e. whether the channel is free (available) or busy (not available). If the energy detected during the CCA period is lower than the ED threshold, the UE is allowed to use the channel for MCOT. If the detected energy during the CCA period is higher, the channel is perceived as unavailable. At this point, the extended CCA period starts, where the detected energy is again compared with the given ED threshold. This process repeats until the channel is allocated to the UE. The ED threshold should be carefully decided depending on the deployment environment to avoid unnecessary collisions. 3GPP has specified 4 categories of LBT which are as follows [5]: (i) Category 1 (Cat-1) LBT; (ii) Category 2 (Cat-2) LBT; (iii) Category 3 (Cat-3) LBT; and (iv) Category 4 (Cat-4) LBT. The Cat-4 LBT is considered the default

Table 3: Channel Access Parameters of NR-U with Different CAPC

Priority Class	Defer Period	CW_{min}	CW_{max}	MCOT
1	25 μs	4	8	2 ms
2	25 μs	8	16	3 ms
3	43 μs	16	64	8 ms or 10 ms
4	79 μs	16	1024	8 ms or 10 ms

LBT mechanism used by gNB for downlink transmission to initiate COT for data transmission [26] while the Cat-2 LBT is used by the UE for transmission of specific signaling. In the case of NR-U, researchers have agreed to also support Cat-1 LBT, which is called 'no-LBT' [26]. More precisely, after the gNB initiates COT, the responding device will transmit without checking CCA, if the gap between the downlink and uplink transmission is less than 16 μs. So, the UE will perform uplink transmission after the gNB occupies the downlink channel.

2. **Maximum Channel Occupancy Time (MCOT)** imposes limit on the maximum time the channel can be occupied by a cellular network. To maintain fair co-existence, the device is refrained from continuous transmission and is only allowed for MCOT, which can vary from 2 ms to 6 ms in 5 GHz band based on the Channel Access Priority Class (CAPC) and can extend up to 8 – 10 ms in some cases [27]. Higher priority CAPC implies faster channel access but for lower MCOT. NR-U identifies 4 CAPC for different traffic classes with maximum and minimum contention window, CW_{max} and CW_{min}, respectively, which is explained in Table 3. For URLLC transmission, priority class 1 with the smallest MCOT is considered to ensure low latency.
3. **Other Requirements:** considered in the deployment of NR in the unlicensed spectrum, besides LBT and MCOT are CAPC, Equivalent Isotropically Radiated Power (EIRP), Power Spectral Density (PSD), Occupied Channel Bandwidth (OCB), Frequency Reuse (FR), Dynamic Frequency Selection (DFS). Interested readers can refer to the work in [3, 10] for detailed information.

2.4 Initial Access and Discovery Design

The initial access procedure in NR is similar to LTE. A pair of downlink signals, Primary Synchronization Signals (PSS), and Secondary Synchronization Signals (SSS), are used by the UE to find, identify, and synchronize to the network. The downlink Physical Broadcast Channel (PBCH) is used to transmit system information together with PSS and SSS. PSS/SSS and PBCH are known as Synchronization Signal (SS) blocks, which are sent together with the same periodicity [28–30]. In NR-U operations, SS block is transmitted by the gNB in all the deployment scenarios. The details of the SS block can be found in [31]. However, there are several issues involved in the SS block design and transmission principle of NR-U. First, the periodical transmission of SS block is not possible as it is interrupted by channel occupancy [32]. The design of SS block patterns needs to be reconsidered, leaving sufficient space for LBT and

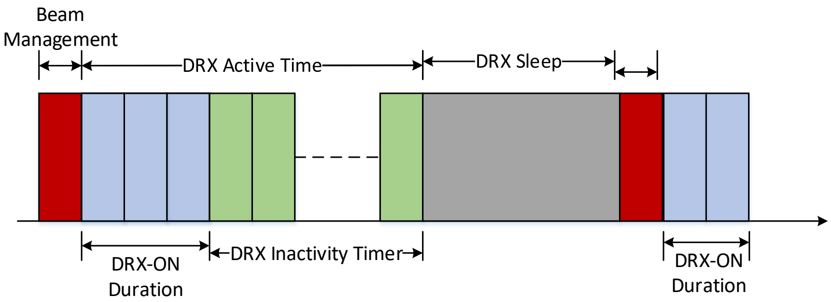


Fig. 3: DRX Mechanism in 5G NR consisting of Active state, DRX-ON state, DRX Sleep state, and Beam Management [11]

beam management procedures. Second, due to OCB requirements and large channel bandwidth, the current SS block design is not suitable for 60 GHz band [3].

Random Access Channel (RACH) procedure in 5G has four steps [33] (i) the device transmits a RACH preamble to the gNB, (ii) the gNB transmits Random Access Response (RAR) with Physical Uplink Shared Channel (PUSCH) resource allocation information to the device, (iii) the device transmits Message 3 over the allocated PUSCH resource, and (iv) the gNB transmits Message 4 for contention resolution. In NR-U, RACH procedure needs improvement for dual connectivity and SA deployment scenarios. At each step of the RACH process, carrier detection is required, which can slow down the process if the unlicensed channel is busy. So, the Cat-2 LBT, without random backoff, is recommended for RACH. The two-step RACH considered in 3GPP helps in reducing the delay incurred by initial access as it requires fewer LBTs [32, 34]. The increase in the transmission opportunities for each SSB transmission can also reduce the initial access delay [35].

2.5 DRX in NR-U

UE power consumption has always been a topic of interest to the research community. 3GPP introduced the DRX mechanism to save the power of the UE in both 4G [9, 36] and 5G networks [37]. Here, the UE temporarily goes to a sleep state and saves its power when there is no traffic activity. Whenever there is traffic activity, the UE again transits to the active state to serve the data. DRX mechanism is a MAC layer procedure that primarily consists of ON duration, inactivity timer, active time, sleep duration, and beam management [38–40], as shown in Fig. 3. RRC connections are important to establish a connection between the UE and the network and can be operated in three different modes: (i) RRC_CONNECTED; (ii) RRC_IDLE; and (ii) RRC_INACTIVE modes [38]. RRC_CONNECTED mode involves active communication and data scheduling procedures between the UE and the network. The maximum amount of UEs' energy is consumed in this state. In RRC_IDLE mode, there is no active communication between the UE and the network. The maximum amount of UEs' energy is saved in this state. RRC_INACTIVE state is similar to the

RRC_IDLE state but here the UE context is saved in the network which reduces the delay involved in transiting from RRC_INACTIVE to the RRC_CONNECTED state. In both RRC_INACTIVE state and RRC_IDLE state, UE has to periodically monitor the paging occasions within each DRX cycle. The periodic monitoring of paging occasions contributes to the power consumption of the UE in the RRC_INACTIVE state and RRC_IDLE state.

The energy efficiency of both UE and gNB is among the major performance indicators in wireless networks [39]. The DRX in NR is not suitable for NR-U. Indeed, it does not take into account the channel access mechanism and MCOT, which are the key requirements for maintaining fair coexistence. In the case of unlicensed spectrum, it is important to ensure smooth coexistence between NR-U and Wi-Fi. Therefore, the channel is granted to an NR-U UE for MCOT time only, depending on priority classes. After the expiry of MCOT time, the NR-U UE has to wait for an unlicensed channel again, which tends to increase the energy consumption of the UE. To tackle this issue, we propose a DRX mechanism for NR-U [10]. DRX is modeled using a semi-Markov model and the performance is analyzed using two beamforming scenarios: beam search and beam awareness. A trade-off between the power-saving factor and average delay was established. The work was further extended in [11], where we analyze the NR-U DRX in both SA and NSA modes using two beamforming techniques. Here, we provide an extensive mathematical analysis of the energy-saving model of NR-U. The authors also consider the resource pool sharing between the NR-U and Wi-Fi and conclude that with DRX, the resource utilization by the cellular network decreases significantly when a UE is in a sleep state. However, the work did not take into account the power consumption of the UE, which is also an important metric to study the performance of DRX mechanism. Further, in [41] we proposed ML-based DRX for NR-U in NSA deployment mode. In this work, the unlicensed channel availability was predicted by using a non-parametric approach, i.e. ML based channel access mechanism. Work in [42] jointly adopt the Duty Cycle Muting (DCM) and Orthogonal Frequency-Division Multiplexing (OFDM) technologies to allocate the spectrum and power resources. Using a power and spectrum optimization model, the authors minimize the URLLC device power consumption.

3 Modeling of DRX for NR in Unlicensed Spectrum

This section describes the semi-Markov-based modeling of the DRX mechanism for NR-U in NSA and SA deployment modes, considering the two beamforming techniques. We leverage the system model from our previous work introduced in [11]. The model is briefly explained in the following sections.

3.1 DRX in NSA Deployment Mode

In NSA deployment mode, the control traffic is supported over the licensed band. This means the control plane functions operate on legacy LTE or NR. On the other hand, the data traffic is supported in an unlicensed band. Despite the easy and cost-effective deployment and faster roll-out, there are some drawbacks in NSA deployment mode.

First, it is currently not capable of supporting low-latency applications [21]. Second, the power consumption of the network increases by using two different RATs.

3.1.1 DRX with Beam-Search (NSA-BS DRX)

We present the modeling of four-state NSA-BS DRX using a semi-Markov model. The four states are (i) Active state (S_1), (ii) Sleep state (S_2), (iii) DRX-ON state (S_3), and (iv) Beam-Search state (S_4), as shown in Fig. 4a [11]. The semi-Markov model is used because the current state is used to predict the future state and the state transitions as well as the state holding times are random [43]. The states are explained as follows:

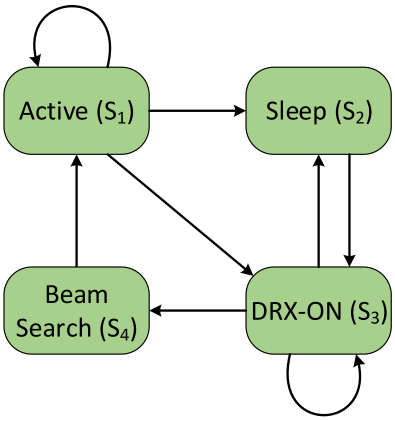
- **Active state (S_1)**: UE is involved in transmitting and receiving the data packets as well as monitoring the PDCCH channel for the service timer duration. UE resides in this state until the inactivity timer expires. The transitions from this state depend on the arrival of the data packets or the data packets remaining in the buffer. The maximum amount of UE power is consumed in S_1, as the UE is involved in the monitoring of the PDCCH channel and data transmission.
- **Sleep state (S_2)**: UE does not monitor the PDCCH channel and sleeps in this state for the sleep timer. The transition from this state happens after the expiry of the sleep timer. Minimum UE power is consumed in sleep state.
- **DRX-ON state (S_3)**: gNB notifies the UE when the unlicensed channel is available over the licensed carrier. The transitions from this state depend on the data packets remaining in the buffer and the availability of the unlicensed channel. UE's power is utilized in searching for the unlicensed channel.
- **Beam-Search state (S_4)**: UE hunts for the optimal beam pair that aligns the UE with the gNB, after which it transits to the S_1 to serve the packet. The power of the UE is used in the search for the optimal beam pair to align the UE and gNB. The power spent by the UE is saved in the case of the beam-aware state, where the UE is cognizant of the optimal beam pair between the UE and the gNB.

3.1.2 DRX with Beam-Aware (NSA-BA DRX)

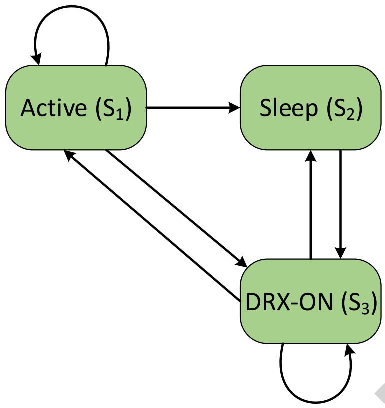
We present the modeling of three-state NSA-BA DRX using semi-Markov. The three states are (i) Active state (S_1), (ii) Sleep state (S_2), and (iii) DRX-ON state (S_3), as shown in Fig. 4b [11]. The behavior of the UE remains similar to NSA-BS DRX except for no beam search state in this case. In the NSA-BA DRX scenario, the network has cognizance of the optimal beam pair that aligns UE and the gNB. This reduces the beam searching time, t_{bs}, to zero.

3.2 DRX in SA Deployment Mode

In SA deployment mode, the UE and the gNB are connected to each other using an unlicensed carrier and gNB is connected to the 5G core network. Since there is no licensed channel available, both the UE and the gNB must separately perform LBT before sending any signaling messages or data. The SA operation in unlicensed bands could give rise to a new class of wireless private networks, e.g., for Industry 4.0 scenarios [44]. However, it comes with additional challenges of initial access and



(a) DRX model where UE has to search for optimal beam pair to align with gNB and is defined as NSA-BS DRX



(b) DRX model where network is aware of optimal beam pair and is defined as NSA-BA DRX

Fig. 4: Semi-Markov-based modeling of DRX in NR-U for NSA deployment mode

scheduling when operating without any support from licensed carriers. In contrast with the NSA deployment mode, the power consumption of the network is less as SA uses a single RAT for cellular connectivity.

3.2.1 DRX with Beam-Search (SA-BS DRX)

We present the modeling of five-state SA-BS DRX using semi-Markov. The five states are (i) Active state (S_1), (ii) Sleep state (S_2), (iii) DRX-ON state (S_3), (iv) Beam-Search state (S_4), and (v) Random Backoff (RBF) Sleep state (S_5), as shown in Fig. 5a [11]. The behavior of the UE remains the same as NSA-BS DRX except for the addition of RBF-sleep state in this case. Unlike NSA-BS DRX, the RBF-sleep state is taken into account in SA-BS DRX. This is because in SA deployment mode, the UE is not connected to the 5G network with NR anchor, and the control signaling is also supported using the unlicensed carrier. The RBF-sleep is introduced in the DRX model to allow the UE to sleep for random time, if the unlicensed channel is unavailable and gNB has information about the availability of an unlicensed channel. In NR-U, the gNB performs a mandatory LBT during DRX-ON period to check if the unlicensed channel is available or not and updates the UE accordingly. If UE gets the indication of an unlicensed channel during DRX-ON state, it transits to the Active state and serves the packets. On the other hand, if gNB does not get access to the unlicensed channels, then the UE transits to sleep state. Since the unlicensed channel occupancy time is limited to Maximum Channel Occupancy Time (MCOT), gNB might have some knowledge about when and which UE will release the unlicensed channel after its the MCOT expires. If a UE requests for an unlicensed channel but the unlicensed channels are occupied, so based on the channel availability information, the gNB requests the UE to wait for random backoff time by transiting to the RBF-Sleep state. After the expiry of random backoff time, the UE transits to the DRX-ON state. The gNB senses the channel during the DRX-ON state, and the DRX process continues.

3.2.2 DRX with Beam-Aware (SA-BA DRX)

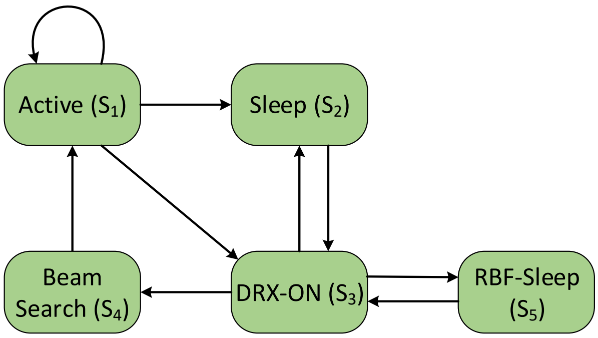
We present the modeling of four-state SA-BA DRX using semi-Markov. The four states are (i) Active state (S_1), (ii) Sleep state (S_2), (iii) DRX-ON state (S_3), and (iv) Random Backoff (RBF) Sleep state (S_5), as shown in Fig. 5b [11]. The behavior of the UE remains similar to SA-BS DRX except for no beam search state in this case. In the SA-BA DRX scenario, there is no beam searching, so the beam search time, t_{bs} becomes zero. This means that the network is aware of the optimal beam pair between the gNB and the UE.

4 Analysis of Power Consumption of UE and Delay due to NR-U DRX

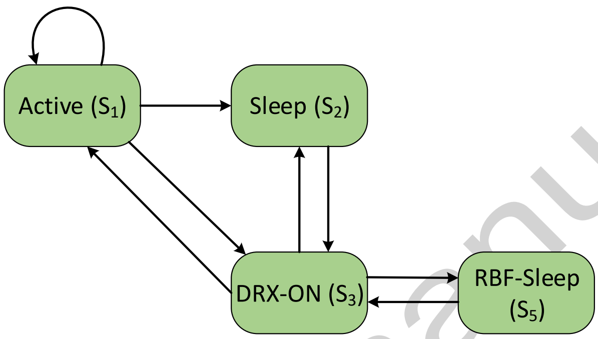
The analysis of DRX performance widely includes the usage of the power consumption of the UE as an important metric. The semi-Markov model of DRX is used for analyzing the power consumption of the UE. The state transition dynamics of the DRX model majorly depends on various factors like the availability of unlicensed channel, data traffic, data in the buffer, beam searching, etc. A detailed description of the state transitions, steady state probability, and the calculation holding time in each state are discussed in [11]. The power consumed by UE is different in all the states. There is a significant difference in the power consumption during an effective data transfer, during the period in which the inactivity timer runs while looking for data, during ON duration, during sleep mode, and during beam searching [14]. The UE consumes minimum power when it is in the sleep state. The target UE is unable to transit from a sleep state to an active state in the case of NR-U. It has to change to DRX-ON state and beams search state first, and then to active state. Note that the beam search state is eliminated in case of beam aware scenario, where the UE is aware of the best beam pair between the UE and the gNB.

UE power consumption reduction comes at the cost of increased delay. During the sleep state, DRX-ON state, Beam search state, and RBF-sleep state, the data packets are required to remain in the buffer until the next active state, where the data can be served. So the average delay in the system can be defined as the amount of time the UE spends in each state except for the active state to the end of the DRX cycle [45]. Since the arrival of the data packets is seen as a random variable in different DRX states, the delay for DRX state S_i is calculated as

$$\Delta_i = \frac{\theta_i \ E[H_i]}{\sum_{x=1}^{j} \ \theta_x \ E[H_x]} \sum_{\tau=1}^{t_x-1} (t_x - \tau), \tag{1}$$



(a) DRX model where UE has to search for optimal beam pair to align with gNB and is defined as SA-BS DRX



(b) DRX model where network is aware of optimal beam pair and is defined as SA-BA DRX

Fig. 5: Semi-Markov-based modeling of DRX in NR-U for SA deployment mode

where θ_x is the steady state probability of DRX state S_x, t_x is the timer of DRX state S_x, $E[H_x]$ is the expected holding time in DRX state S_x, and S_x is one of the DRX states in $\{$Active state (S_1), Sleep state (S_2), DRX-ON state (S_3), Beam-Search state (S_4), and Random Backoff (RBF) Sleep state (S_5)$\}$ and j is a number of states and it depends on the DRX model i.e. $j \epsilon \{3,\ 4,\ 5\}$.

The detailed semi-Markov analysis of the states of NR-U DRX can be found in our previous work [11]. It should be noted that the fraction of time spent by the UE in a state S_x is given by T_x, where T_x is different for different DRX configurations, i.e. NSA-BS DRX, NSA-BA DRX, SA-BS DRX, and SA-BA DRX. Similarly, j, θ_x and $E[H_x]$ are also different for different DRX configurations.

4.1 Analysis of NSA-BS DRX

Using the existing equations mentioned in [11], we calculate the portion of time the UE spends in sleep state T_s, DRX-ON state T_{on}, and beam search state T_{bs} as

$$T_s = \frac{\theta_2 E[H_2]}{\sum_{x=1}^{4} \theta_x \; E[H_x]}, \tag{2}$$

$$T_{on} = \frac{\theta_3 E[H_3]}{\sum_{x=1}^{4} \theta_x \; E[H_x]}, \tag{3}$$

$$T_{bs} = \frac{\theta_4 E[H_4]}{\sum_{x=1}^{4} \theta_x \; E[H_x]}. \tag{4}$$

Let P_{tx}, P_{inact}, P_2, P_3, and P_4 be the power consumption during the data transmission, inactivity timer run, sleep state, DRX-ON states, and beam search state, respectively. t_{inact} is defined as the inactivity timer and $\overline{T}_{t_{inact}}$ is defined as the average time duration of inactivity timer. We leverage the concept used by the authors in [14, 36] to estimate the average power consumption (P_{avg}) due to NSA-BS DRX as

$$P_{avg} = \frac{\theta_1 [P_{tx}(E[H_1] - t_{inact}) + P_{inact}\overline{T}_{t_{inact}}]}{\sum_{x=1}^{4} \theta_x \; E[H_x]} + P_2 T_s + P_3 T_{on} + P_4 T_{bs}. \tag{5}$$

In the case of NSA-BS DRX, the average delay depends on the time UE spends in sleep state T_s, DRX-ON state T_{on}, and beam search state T_{bs}. The individual delay in each state can be calculated using Equation 1 (considering $j = 4$)and the average delay is estimated as

$$\Delta_{avg} = \Delta_2 + \Delta_3 + \Delta_4. \tag{6}$$

4.2 Analysis of NSA-BA DRX

Using the existing equations mentioned in [11], we calculate the portion of time the UE spends in sleep state T_s and DRX-ON state T_{on} as

$$T_s = \frac{\theta_2 E[H_2]}{\sum_{x=1}^{3} \theta_x \; E[H_x]}, \tag{7}$$

$$T_{on} = \frac{\theta_3 E[H_3]}{\sum_{x=1}^{3} \theta_x \; E[H_x]}. \tag{8}$$

We leverage the concept used by the authors in [14, 36] to estimate the average power consumption (P_{avg}) due to NSA-BA DRX as

$$P_{avg} = \frac{\theta_1 [P_{tx}(E[H_1] - t_{inact}) + P_{inact} \overline{T}_{t_{inact}}]}{\sum_{x=1}^{3} \theta_x \; E[H_x]} + P_2 T_s + P_3 T_{on}. \tag{9}$$

In the case of NSA-BA DRX, the average delay depends on the time UE spends in sleep state T_s and DRX-ON state T_{on}. The individual delay in each state can be calculated using Equation 1 (considering $j = 3$) and the average delay is estimated as

$$\Delta_{avg} = \Delta_2 + \Delta_3. \tag{10}$$

4.3 Analysis of SA-BS DRX

Using the existing equations mentioned in [11], we calculate the portion of time the UE spends in sleep state T_s, DRX-ON state T_{on}, beam search state T_{bs}, and RBF-sleep state T_{rbf} as

$$T_i = \frac{\theta_i E[H_i]}{\sum_{x=1}^{5} \theta_x \; E[H_x]}. \tag{11}$$

where T_i is the portion of time UE spends in DRX states S_x, θ_i is the steady state probability of DRX state S_x, $E[H_i]$, is the expected holding time in DRX state S_x, and S_x is one of the DRX states in {Active state (S_1), Sleep state (S_2), DRX-ON state (S_3), Beam-Search state (S_4), and Random Backoff (RBF) Sleep state (S_5)}.

We leverage the concept used by the authors in [14, 36] to estimate the average power consumption (P_{avg}) due to SA-BS DRX as

$$P_{avg} = \frac{\theta_1 [P_{tx}(E[H_1] - t_{inact}) + P_{inact} \overline{T}_{t_{inact}}]}{\sum_{x=1}^{5} \theta_x \; E[H_x]} + P_2 T_s + P_3 T_{on} + P_4 T_{bs} + P_2 T_{rbf}. \tag{12}$$

In the case of SA-BS DRX, the average delay depends on the time UE spends in sleep state T_s, DRX-ON state T_{on}, beam search state T_{bs}, and RBF-sleep state T_{rbf}. The power consumed in the RBF-sleep state S_5 is the same as that in the sleep state S_2. The individual delay in each state can be calculated using Equation 1 (considering $j = 5$) and the average delay is estimated as

$$\Delta_{avg} = \Delta_2 + \Delta_3 + \Delta_4 + \Delta_5. \tag{13}$$

4.4 Analysis of SA-BA DRX

Using the existing equations mentioned in [11], we calculate the portion of time the UE spends in sleep state T_s, DRX-ON state T_{on}, and RBF-sleep state T_{rbf} as

$$T_s = \frac{\theta_2 E[H_2]}{\sum_{\substack{x=1 \\ x \neq 4}}^{5} \theta_x \ E[H_x]}, \tag{14}$$

$$T_{on} = \frac{\theta_3 E[H_3]}{\sum_{\substack{x=1 \\ x \neq 4}}^{5} \theta_x \ E[H_x]}, \tag{15}$$

$$T_{rbf} = \frac{\theta_5 E[H_5]}{\sum_{\substack{x=1 \\ x \neq 4}}^{5} \theta_x \ E[H_x]}. \tag{16}$$

We leverage the concept used by the authors in [14, 36] to estimate the average power consumption (P_{avg}) due to SA-BA DRX as

$$P_{avg} = \frac{\theta_1 [P_{tx}(E[H_1] - t_{inact}) + P_{inact}\overline{T}_{t_{inact}}]}{\sum_{\substack{x=1 \\ x \neq 4}}^{5} \theta_x \ E[H_x]} + P_2 T_s + P_3 T_{on} + P_2 T_{rbf}. \tag{17}$$

In the case of SA-BA DRX, the average delay depends on the time UE spends in sleep state T_s, DRX-ON state T_{on}, and RBF-sleep state T_{rbf}. The individual delay in each state can be calculated using Equation 1 (considering $j = 5$ and $x \neq 4$)and the average delay is estimated as

$$\Delta_{avg} = \Delta_2 + \Delta_3 + \Delta_5. \tag{18}$$

5 Numerical Results and Discussion

In this section, we demonstrate the analytical results to verify the efficacy of the proposed DRX models. Here, we thoroughly examine the efficiency of DRX for NR-U in both SA and NSA deployment modes for varying sleep timers and DRX-ON duration for different data rates. Intuitively, the power consumption incurred in SA mode is higher than in NSA mode, as the control signaling is handled over unlicensed carriers. The metrics used for assessing the performance of the proposed DRX models are listed below:

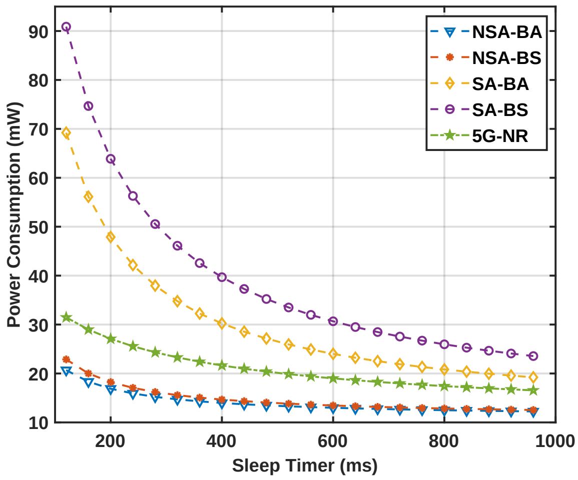


Fig. 6: Impact of Sleep Timer on the Power Consumption of the UE for max-Rate (= 4 Mbps)

- **Power Consumption of UE** (P_{avg}) is defined by the power consumed by the UE in different DRX states. Intuitively, the power consumed by the UE is maximum in an active state and minimum in the sleep state.
- **Average Delay** (Δ_{avg}) is defined as the waiting time experienced by the data packets in the buffer. The average delay depends on the time UE spends in all states, except for the active state.

We considered the European Telecommunication Standards Institute (ETSI) traffic model, where the packet transmission time and packet size follow truncated Pareto distribution. The packet data transmission consists of a packet service session, each comprising of one or more packet calls depending on the applications. According to ETSI model, the inter-packet arrival time between two packets and inter-session idle time follows the exponential distributions. The number of packet calls per session and the number of packet calls per packet call follows the Geometric distribution [36] [46]. We also considered max-Rate (= 4 Mbps) and min rate (= 2 Mbps), where max-Rate and min-Rate represent the UE's perceived data rate driven from the traffic model [47], [48]. The power consumption and delay are calculated using ON duration t_{on} of 1 ms, inactivity timer t_i of 2 ms, random back-off timer t_{rbf} $1 \sim 10$ ms, MCOT of 6 ms and initial serving time is set to 2 ms [3], [36]. The inactivity timer ti can be repeated twice in order to increase the packet service time. We considered three sectors on the transmitter side of NR-U gNB with each sector having 16 beams with a beam width of 7.5° per beam [37], [49], and 8 beams per UE on the receiver side, with a TTI of 200 µs. The UE has to align $16 \times 8 = 128$ beams to get a suitable beam pair. During the active state the UE consumes 500 mW for transmission/reception of data and 255.5 mW, while the inactivity timer runs, not transmitting/receiving any data [50, 51]. The power consumed by UE during the seep state is 11 mW. During the ON

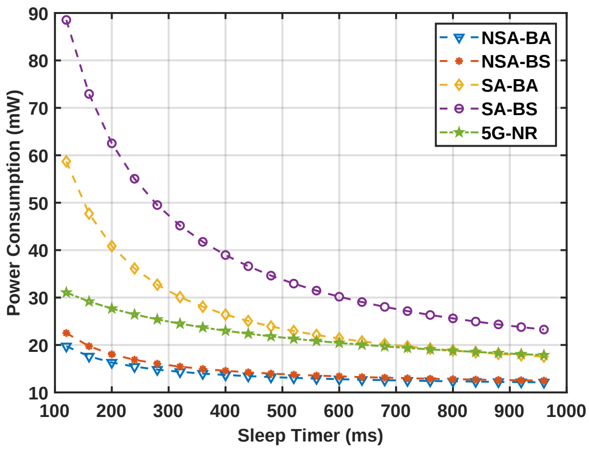


Fig. 7: Impact of Sleep Timer on the Power Consumption of the UE for min-Rate (= 2 Mbps)

state and beam search state the UE consumed 255.5 mW of power. The results are obtained with varying sleep and ON duration timers, with each execution repeated 10 times and the average is calculated to plot the results.

Fig. 6 depicts the power consumed by the UE with varying sleep timers from 100 ms to 1000 ms with a max-Rate (= 4 Mbps). The max-Rate represents the UE's maximum data rate driven from traffic models [47, 48]. As the sleep timer duration increases, the amount of power used by the UE decreases because the UE consumes the least amount of power when it is in the sleep state. The power consumed by the UE in SA deployment mode is more than that in NSA deployment mode. This is because, in the SA mode, the data transfer and control signaling takes place over the unlicensed carrier. Power consumption of the UE in SA-BS DRX increases when the UE has to search for the optimal beam pair to align with the gNB after every sleep cycle, which is eliminated in the SA-BA DRX scenario. The power consumption is less when the UE is cognizant of the optimal beam pair and gets aligned with the gNB. Moreover, Fig. 6 presents the comparison of NR-U DRX with 5G-NR DRX [37, 52]. It can be observed that the power consumed by SA deployment mode is higher than 5G DRX. This is due to the fact that in NR-U, the availability of the unlicensed channel is not guaranteed all the time. Consequently, the UE has to wait for the unlicensed channel information from the gNB, resulting in higher power consumption. Fig. 7 depicts the power consumed by the UE with varying sleep timers with a min-Rate (= 2 Mbps). The minimum data rate of the UE is indicated by the min-Rate, which is determined based on various traffic models [47, 48]. It is observed from Fig. 7 that the power consumed in NSA deployed mode is lower compared to existing 5G-NR DRX. This is because in NSA mode, the UE gets the information of the channel in the control signal which is over the licensed carrier.

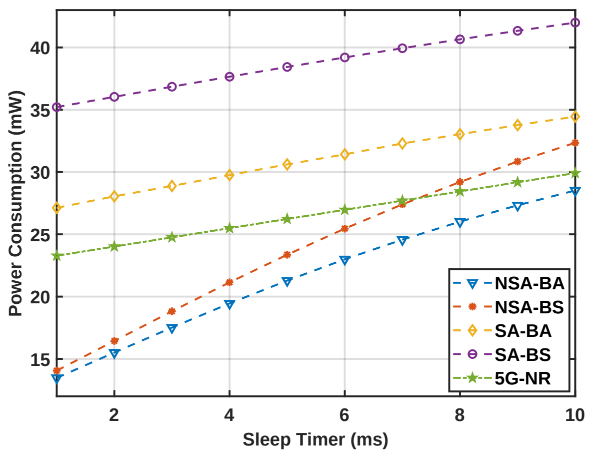


Fig. 8: Impact of DRX-ON Duration on the Power Consumption of the UE for max-Rate (= 4 Mbps)

Fig. 8 delineates the power consumed by the UE with varying DRX-ON Duration from 1 ms to 10 ms with a max-Rate (= 4 Mbps). The increase of the DRX-ON duration increases the amount of power used by the UE. This is because, for a longer DRX-ON duration, the UE is awake for a longer time to get intimation of the unlicensed channel. The power utilized by the UE in SA-BA DRX is lower compared to SA-BS DRX because the UE is not required to align the beam, thus allowing it to conserve power. The power utilized by the UE in SA deployment mode is more than that in NSA deployment mode. It is noticed from Fig. 8 that in case of 5G-NR DRX the power consumed by the UE increases with an increase in DRX-ON duration. This is because with longer DRX-ON duration the user active time increases resulting in higher power consumption. Fig. 9 describes the power consumed by the UE with varying DRX-ON Duration with a min-Rate (= 2 Mbps).

Table 4: Impact of Sleep Timer on the Average Delay experienced by the UE for max-Rate (= 4 Mbps) and min-Rate (= 2 Mbps)

Deployment mode	Sleep Timer					
	120 ms		420 ms		960 ms	
	max-Rate	min-Rate	max-Rate	min-Rate	max-Rate	min-Rate
NSA-BS	8.46	9.22	134.41	134.41	458.95	458.58
NSA-BA	6.91	6.93	133.93	134	458.25	458.39
SA-BS	26.7	36.09	132.85	137.34	447.96	448.57
SA-BA	6.2	6.4	92.78	93.67	414.75	416.77
5G-NR	6.74	6.81	85.58	85.68	452.88	452.52

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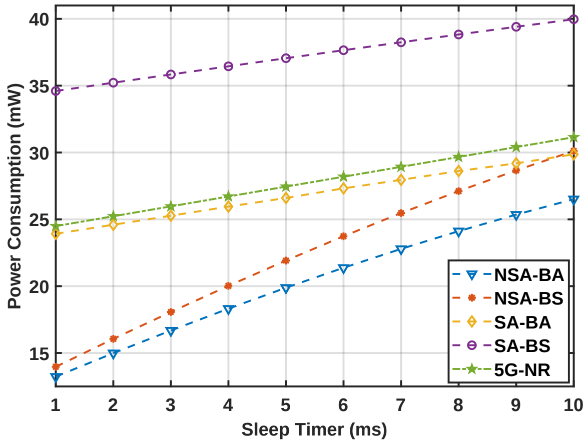

Fig. 9: Impact of DRX-ON Duration on the Power Consumption of the UE for min-Rate (= 2 Mbps)

Table 5: Impact of DRX-ON Duration on the Average Delay experienced by the UE for max-Rate (= 4 Mbps) and min-Rate (= 2 Mbps)

Deployment mode	DRX-ON Duration					
	1 ms		5 ms		10 ms	
	max-Rate	min-Rate	max-Rate	min-Rate	max-Rate	min-Rate
NSA-BS	114.49	114.69	112.77	113.03	111.54	111.5
NSA-BA	114.03	114.1	111	111.31	108.4	108.65
SA-BS	117.6	120.55	115.6	119.75	113.23	117.21
SA-BA	110.79	111.76	108.77	110.09	106.43	108.2
5G-NR	49.24	49.37	49.24	49.37	49.24	49.37

Table 4 shows the average delay with varying sleep timers for maximum and minimum data rates. SA-BS DRX experiences a higher average delay compared to SA-BA DRX, for both max-Rate (=4 Mbps) and min-Rate (=2 Mbps). This is because the UE has to find a beam pair and align with the gNB before acquiring the unlicensed channel. The delay observed by SA-BS DRX (26.7 ms for min-Rate) for a smaller sleep cycle is higher than SA-BA DRX (6.2 ms for min-Rate) since the fraction of time used for beam searching is higher for a smaller sleep cycle. The delay achieved with NSA-BS DRX (9.22 ms for max-Rate) and NSA-BA DRX (6.93 ms for max-Rate) is higher than SA-BA DRX (6.4 ms for max-Rate). This is due to the fact that if UE is not intimated about the availability of the unlicensed channel and gNB is also unaware of the channel, the UE tends to sleep for RBF-sleep in the case of SA-BA DRX, whereas it sleeps for the same sleep duration in the case of NSA-BS DRX and NSA-BA DRX. The delay increases with the increasing sleep timer as the UE gets to sleep for a longer time. The delay increases from 8.46 ms to 458.25 ms (for max-Rate) and 9.22 ms to

458.39 ms (min-Rate) in NSA-BS DRX with the increase in sleep timer. The performance of the proposed models is compared with conventional 5G-NR DRX and is depicted in Table 4. For the sleep timers of 120 ms and 420 ms, the delay observed by NSA-BS and SA-BS is higher than 5G-NR DRX. Whereas, for a sleep timer of 960 ms the delay observed by NSA-BS and SA-BS is almost similar to 5G-NR DRX. This is because in the case of 5G-NR DRX, the UE transits to an Active State more frequently to serves the packet in shorter sleep timers. However, in case of a longer sleep timer, the data packets wait for a longer time resulting in higher delay.

Table 5 shows the average delay with varying DRX-ON duration for maximum and minimum data rates. In the case of SA-BS DRX, the delay varies from 117.62 ms to 113.23 ms and is higher than SA-BA DRX. The delay for NSA-BA DRX varies from 108.4 to 114.03 ms and is lower than NSA-BS DRX for max-Rate. As noticed from Table 5, for NSA-BS deployment mode, for max-Rate the delay observed by UE is 114.49 ms for 1 ms on duration. The delay decreases to 112.77 ms and 111.54 ms for ON duration of 5 ms and 10 ms, respectively. This is due to the fact that when UE remains active longer ON duration, the chances of getting the channel increases which results in less delay observed by UE. The delay observed for both max-Rate and min-Rate is slightly affected by varying the DRX-ON Duration in all four configurations of DRX. It is observed from Table 5 that the delay observed in NSA and SA deployment modes is higher than 5G-NR DRX. This is because for NSA and SA deployment modes, the availability of the unlicensed channel is not guaranteed, and the UE is bound to wait for the channel.

6 Conclusion

In this research work, we introduce the details of NR-U spectrum and its regulatory requirements to maintain fair coexistence with other unlicensed technologies, like Wi-Fi. We propose UE power consumption model in NR-U DRX for SA and NSA deployment modes, with two flavors: Beam-Search and Beam-Aware. Analytical modeling demonstrates the UE power consumption with varying sleep timer values and DRX-ON durations for different data rates. The UE power consumption is higher when operating in the SA mode compared to the NSA mode, considering different sleep timer values and DRX-ON durations. In our study, we also examine the differences in delay encountered by the UE in various DRX states.

DECLARATIONS

Ethical Approval
Not Applicable.

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Conflict of Interest Statement
All authors declare that they have no conflicts of interest.

Availability of data and materials
Data sharing is not available in this article as no external datasets have been taken for this research. Also, no dataset is created in this article except the experimental results.

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