DRX in New Radio Unlicensed: A Step Beyond 5G Wireless

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The authors introduce two different aspects of discontinuous reception (DRX) for energy and resource savings in 5G NR unlicensed networks. As 5G NR is based on directional beams, the proposed solutions are based on beam searching and beam awareness. Beam-aware DRX explores next generation NodeB's assistance in alleviating mobile user equipment's (UE's) beam searching burden and results in more power-saving.

Abstract

5G wireless has ushered in new promises of improved performance and ubiquitous connectivity. However, a continuous increase in connected devices and the proliferation of the Internet of Things have already created skepticism about the capacity of 5G wireless to satisfy the huge data requirements across a myriad of devices. This has made wireless researchers, vendors, and standards bodies look beyond 5G wireless by extending 5G New Radio (NR) in unlicensed bands. Operation in unlicensed bands requires additional channel sensing and fairness across different types of networks. This makes power consumption in battery-constrained mobile devices more challenging. In this article, we introduce two different aspects of discontinuous reception (DRX) for energy and resource savings in 5G NR unlicensed networks. As 5G NR is based on directional beams, the proposed solutions are based on beam searching and beam awareness. Beam-aware DRX explores next generation NodeB's assistance to alleviate mobile user equipment's (UE's) beam searching burden and results in more power saving. Simulation experiments using real wireless traces demonstrate that our NR-U DRX solutions significantly improve UE's power saving and network resource utilization over existing 5G NR DRX.

Introduction

Recent years have witnessed a phenomenal growth in wireless connectivity. Penetration of smartphones, introduction of Internet of Things (IoT) devices, and emerging new multimedia applications have significantly contributed toward this growth. While these smart devices and applications have improved our quality of life and unveiled new industrial opportunities, the resulting growth in traffic and users is burdening the resource-constrained cellular networks. Naturally, wireless operators are looking for more spectrum to cater for this increase in demand. As the scarce licensed spectrum imposes several cost constraints, unlicensed bands are recently being considered as one of the key future technologies [1, 2]. However, allowing cellular networks to operate in the unlicensed spectrum, while maintaining graceful coexistence with other unlicensed technologies like WiFi, is a major challenge. This has led to the evolution of different variants of 4G wireless, like License Assisted Access (LAA) [3] and enhanced LAA (eLAA) in Third Generation Partnership Project (3GPP) Releases 13 and 14, respectively. While LAA introduces an additional unlicensed carrier, assisted by the licensed carrier in the downlink (DL), eLAA extends LAA even in the uplink (UL). Unfortunately, even with the inclusion of unlicensed spectrum, commercial 4G wireless systems cannot satisfy the almost exponential increase in connectivity (IoT devices, smartphones, machine type communications [MTC], etc.).

The emergence of 5G wireless raised a flicker of hope to resolve most of the existing challenges of 4G wireless by providing magnitudes of improvement in data rate, latency, and user capacity. According to Ericsson's mobility report [4], by the middle of this decade, 5G New Radio (NR) will penetrate 65 percent of the global population and generate almost half of all global mobile traffic. 5G NR offers flexible network design for supporting different applications, like ultra-reliable low-latency communication (URLLC), enhanced mobile broadband (eMBB), massive MTC (mMTC), and enhanced vehicle-to-everything (eV2X). However, usage of millimeter-wave (mmWave) frequencies, directional air interface, and network densification raise the challenge of higher power dissipation at the power-constrained mobile user equipment (UE). Major research and standardization efforts in this direction have pointed out the necessity to support discontinuous reception (DRX) for UE powercsaving in 5G NR [5, 6].

Unfortunately, wireless vendors and operators are skeptical that even the introduction of 5G NR is likely to fall short of satisfying the exponential increase in user demands. This has recently paved the way for 5G NR to enter its next phase of evolution — exploring 5G over "unlicensed bands." Ratification of major wireless standards, under the aegis of 3GPP, is now introducing such applicability of NR over unlicensed spectrum (NR-U) [7]. Figure 1 shows a typical NR-U deployment scenario. Unlike LTE-LAA, where the access of unlicensed spectrum is always assisted by the licensed carrier, NR-U can be deployed with or even without any assistance from the licensed carrier. This introduction of unlicensed bands makes NR-U an interesting platform for many organizations including private networks, industrial networks, retail networks, and cable operators. One major concern for NR-U deployment is to address regulatory requirements, like Listen-Before-Talk (LBT), to ensure fairness in coexistence with other technologies (e.g,. WiGig and WiFi)

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operating in the same frequency bands. Figure 1 shows NR-U non-standalone access (NSA) with the coexistence of licensed and unlicensed bands in NR-U, where the unlicensed band is assisted by a licensed band. Unfortunately, as the unlicensed bands are used by WiFi and other network technologies, there could be significant or even complete coverage overlap between WiFi and NR-U deployments [8, 9]. This results in reduced probability of channel availability for data transmission. Hence, the user has to wait for the channel's availability, which naturally imposes additional power consumption. Thus, the necessity of power saving in unlicensed spectrum is not only more important, but also involves significant challenges.

In this article, we explore new avenues of power saving by using DRX over next-generation 5G NR unlicensed networks. Our major contributions in introducing novel DRX mechanisms in NR-U are:

- We first model the DRX in NR-U by introducing a new beam searching state. Of course, for NR-U NSA, the UE can align with the beam only after receiving an intimation about data and unlicensed channel availability over the licensed channel.
- Subsequently, we introduce new beam awareness in NR-U. We argue that if 5G next generation NodeB (gNB) is cognizant enough to maintain the knowledge of best beam pairs, it can alleviate the UE's burden of beam searching, thereby making the system "beam-aware" [10]. Beam awareness endows the UE with an increased sleep duration, as the UE does not need to search for the beam anymore.
- Furthermore, the DRX mechanism is analyzed by using a semi-Markov process, as the associated state transitions and holding times are arbitrarily distributed.
- Finally, results of extensive system-level simulation, carried out over actual wireless traces [11], demonstrate significant gains achieved by beam-aware and beam-searching NR-U DRX compared to regular 5G NR DRX.

After taking a look into existing 5G NR DRX, in the remainder of this article, we first highlight the emerging NR-U and introduce new DRX mechanisms for power savings in NR-U.

Background of Beamforming and DRX in 5G

5G wireless heralds new horizons of wireless communication by exploiting mmWave frequencies to ensure the availability of the huge bandwidths required for supporting unprecedented data rates. However, mmWave frequencies also raise new challenges, like high susceptibility to channel variation, severe path loss, fading, and atmospheric absorption. This calls for precise beam alignment between transmitter and receiver to reap the benefits of mmWave frequencies. The presence of multiple beams at gNB and UEs makes a beam selection procedure inevitable for establishing directional communication. Subsequently, searching for the best beam pair is crucial to prevent misalignment during actual communication. Unfortunately, the introduction of directional communication, involving a large number of beams, further aggravates power dissipation in the already power-constrained mobile UEs.

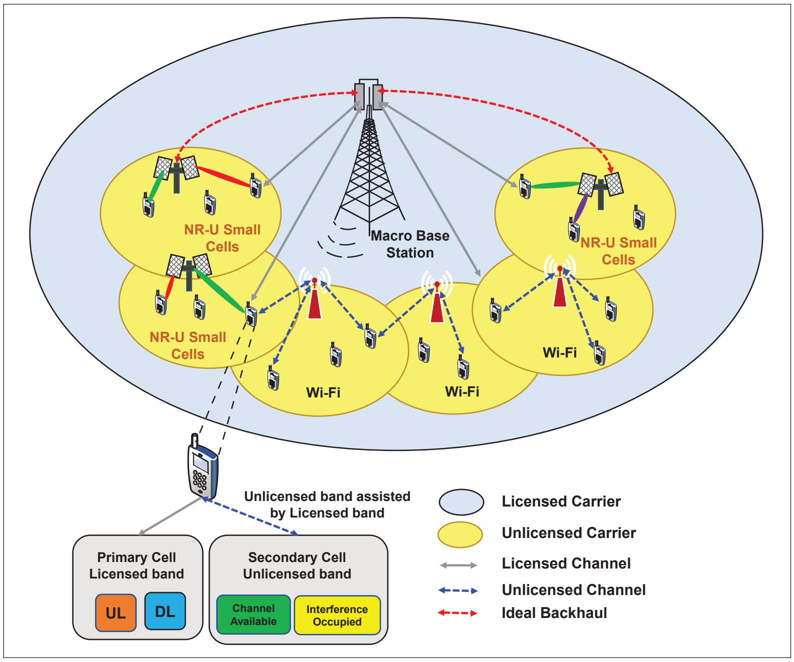

FIGURE 1. NR-U deployment with coexistence of licensed and unlicensed bands.

The connected mode DRX mechanism [5] is introduced to resolve this problem by allowing mobile UE to periodically enter into the power-saving (sleep) mode, where UE turns off the major circuits when there is no intimation of packet arrival. However, the UE also wakes up periodically to check for packet arrival. In order to prevent any loss of data, UE and the network need to have a predefined agreement about the UE's periodic transition between sleep and wake-up states. Typically, UE receives the required DRX configuration parameters in a DL radio resource control (RRC) reconfiguration message sent by the network (gNB).

Directional communications in 5G imposes an additional step, called beam searching [6], before UE's transition to active state in the DRX cycle. For beam searching, UE measures the reference signal of various transmit beams against each of the receiver beams. The entire beam sweeping operation requires a substantial amount of time. This incurs additional delay overhead and reduces the effective sleep time of the mobile UE [6], leading to a considerable increase in UE's power dissipation. Moreover, DRX also increases packet delay, as the packets arriving during UE's sleep state need to be buffered until the UE returns to active state, after searching and obtaining the best transmit-receive beam pair.

NR-Unlicensed: Evolution Beyond 5G

The ever increasing data demand, spawning of new mobile applications, and proliferation of IoT have compelled wireless vendors, operators, and researchers to look beyond 5G NR by exploring unlicensed bands [1]. Broadly, the unlicensed frequency bands for NR-U are classified into two categories: (a) sub-7 GHz bands (including 2.4, 3.5, 5, and 6 GHz) and (b) mmWave bands (comprising 37 GHz and 60 GHz). Among these unlicensed bands, 60 GHz band is less crowded and possesses a relatively large bandwidth [12]. However, the use of directional antennas will form a

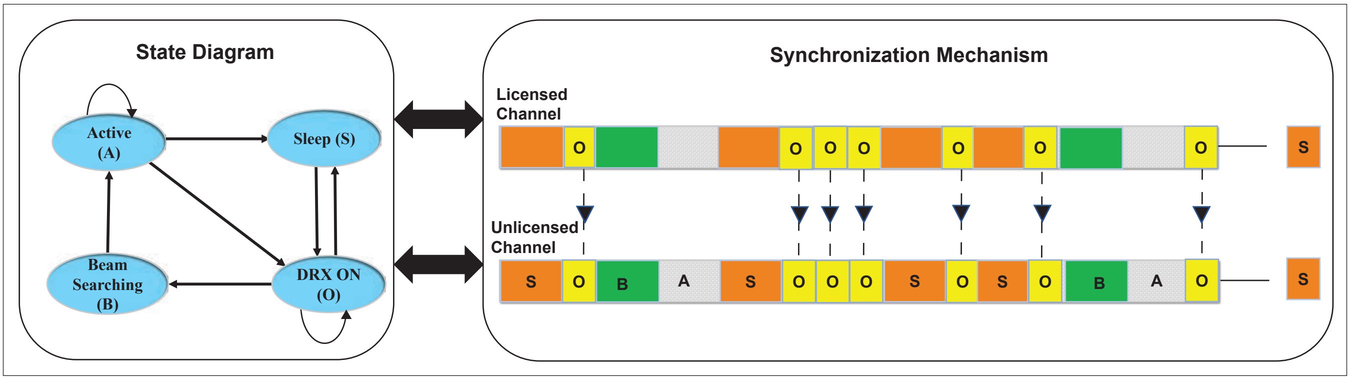

FIGURE 2. NR-U DRX modeling and synchronization mechanism between licensed and unlicensed channels.

large number of beams, which will complicate the interference and power management [1], thereby making NR-U coexistence significantly different and more challenging. This motivates us to look one step beyond beam searching and introduce new solutions based on beam awareness, where the gNB will use its knowledge of best beam pairs and alleviate the UE's burden of beam searching.

Deployment scenarios of NR-U involve:

- Carrier aggregation between licensed NR and NR-U
- Dual connectivity between licensed LTE and NR-U
- Dual connectivity between licensed NR and NR-U
- Såtandalone NR-U
- NR cell with DL in the unlicensed band and UL in the licensed band

The first major challenge in allowing cellular access in unlicensed bands is ensuring fairness in coexistence with other unlicensed networks like WiGig and WiFi. For enabling graceful coexistence with WiFi and other unlicensed network nodes, NR-U nodes need to follow a set of requirements [1]:

- LBT is the mechanism by which an unlicensed network node can sense the spectrum for a clear channel assessment (CCA) period, before actually acquiring the channel, for a specific channel occupancy time (COT). Four categories of LBT are mentioned, where
  –Category 1 is "No LBT."
  –Category 2 is "LBT without any backoff."
  –Category 3 is "LBT with fixed backoff."
  –Category 4 (default) is "LBT with random backoff."
- Category 4 LBT mandates assignment of channel access priority class (CAPC). A lower value of CAPC corresponds to higher priority. Typically, signaling radio bearers (SRBs) are assigned the highest priority. In order to maintain fair coexistence with WiFi, it is mandated to assign the lowest priority CAPC to a packet data unit (PDU) formed by multiplexing of data across multiple logical channels, each having a different CAPC.
- Maximum channel occupancy time (MCOT) imposes a limit on COT and refrains an unlicensed network node from continuous spectrum usage. MCOT can vary from 2 ms to 10 ms in 5 GHz band, and is almost 9 ms in 60 GHz. Typically, higher-priority CAPC corresponds with faster channel access and lower MCOT.
- Equivalent isotropically radiated power (EIRP) and power spectral density (PSD) impose a certain limit on the transmission power in the available spectrum for controlling the inter-radio access technology (RAT) and intra-RAT interference. As per the European Telecommunications Standards Institute (ETSI) regulation, the maximum mean EIRP and PSD are different for different transmission bands. For instance, the maximum mean EIRP and PSD in 5 GHz band is limited to 23 dBm and 10 dBm/MHz, respectively. Similarly, for 60 GHz band, these are limited to 40 dBm and 13 dBm/MHz.
- Occupied channel bandwidth (OCB) is the bandwidth containing 99 percent of signal power, assisting the unlicensed technology to use the major part of the channel bandwidth during channel access. According to ETSI, the OCB should be between 70–100 percent for 5 GHz band and 80–100 percent for 60 GHz band, respectively.
- Frequency reuse (FR) allows different devices of the same radio access network to reuse the same channel at a particular time instance. This increases the FR factor and improves the spectral efficiency. The number of times a frequency can be reused depends on the tolerance capacity of the radio channel from the nearby transmitter, which is using the same frequencies.
- Dynamic frequency selection (DFS) is used to avoid interference and achieve uniform spread of traffic load across the different channels in each band. It is designed to prevent electromagnetic interference with other uses of the important other frequency bands, such as military radar, satellite communication, and weather radar. The actual mechanism, radar pulse pattern, power level, and frequency band on which it is enforced vary by country and jurisdiction.

LBT process was first adopted by 4G LTE cellular networks for LAA. Interestingly, NR-U offers significantly more challenges over LAA, as NR-U can operate in standalone mode, without any licensed carriers. Thus, even important signaling (radio resource control, mobility, paging, network attach, idle-to-active transition, etc.) and medium access control (MAC) management and control (e.g., scheduling request, random access) messag-

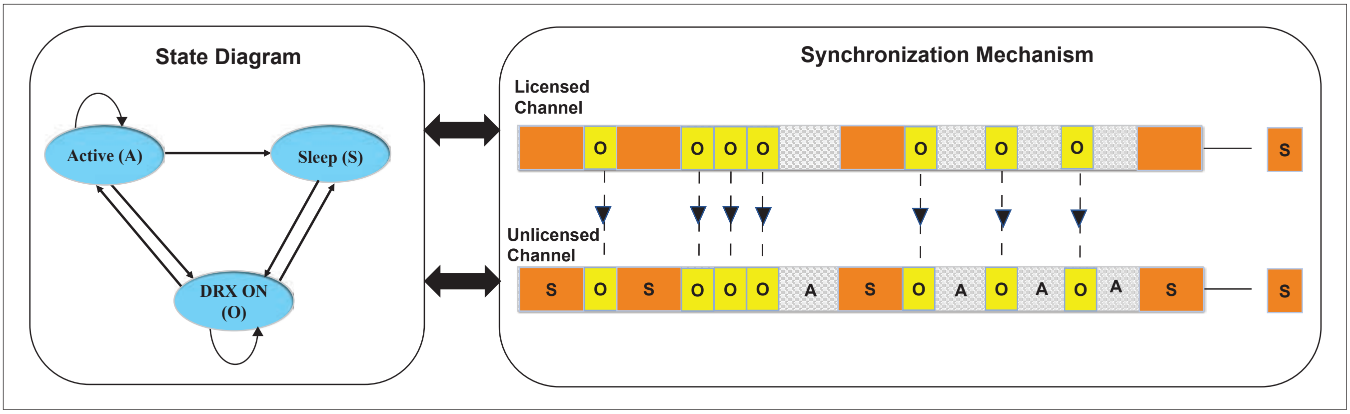

FIGURE 3. Beam-aware NR-U DRX model with licensed and unlicensed operation synchronization.

es need to perform mandatory LBT prior to actual transmission. As these messages are subject to LBT failure, it is recommended that the NR-U gNB provides more paging and transmission opportunities. Unfortunately, increased transmission opportunity demands further power consumption from the mobile UE. This makes DRX even more necessary for power saving in NR-U. Interestingly, conventional 5G NR DRX is neither compatible nor directly applicable over NR-U, as legacy 5G NR DRX does not take into account channel access mechanism and MCOT. Based on this basic knowledge of NR-U, in the remainder of this article, we illustrate our new DRX methods in NR-U, with modeling, analysis, and, performance results.

DRX in NR-U: New Concepts and Discussion

We now discuss two different variants of our proposed DRX over NR-U. As mentioned before, beam searching is inevitable in current mmWave-based 5G wireless networks. Thus, introducing DRX over 5G NR-U should typically involve "Beam-Searching (B)" periods, besides the regular "Active (A)," "Sleep (S)," and "DRX ON (O)" periods.

NR-U DRX with BeamvSearching

Figure 2 demonstrates our proposed four-state DRX model in NR-U. Details of the mobile UE's behavior during these individual states are mentioned below:

- In Active state, the mobile UE consumes maximum power for data transmission, reception, and monitoring of the physical downlink control channel (PDCCH). The duration of the state is controlled by an inactivity timer. This timer is initialized to a specific value. Any packet arrival before the expiry of the inactivity timer resets the timer to its initial value, and the mobile UE continues to remain in the same state.
- Upon expiry of the inactivity timer (i.e., no packet arrival), the UE undergoes a transition to the Sleep state. Dynamics of sleep duration in this state are pre-determined by the gNB based on unlicensed channel availability.
- As mentioned before, in order to ensure fair coexistence of NR-U and WiFi, the maximum serving time of the packets cannot exceed MCOT. Naturally, there is a non-zero probability that the mobile UE's transmission remains incomplete during the expiry of MCOT. At this point, UE makes a transition to DRX ON state.
- While residing in DRX ON state, if the UE receives an intimation of packet arrival and the unlicensed channel is also available, it moves to the "Beam-Searching" state to search and find the best beam pair between the transmitter and the receiver. After the beam alignment is completed, the UE transits to the Active state for packet transmission and reception. On the other hand, if gNB has no information about the unlicensed channel availability, it can extend UE's "DRX ON" period. If UE fails to acquire unlicensed channel during the ON state, it performs backoff with a value randomly selected between 0 and the backoff timer.

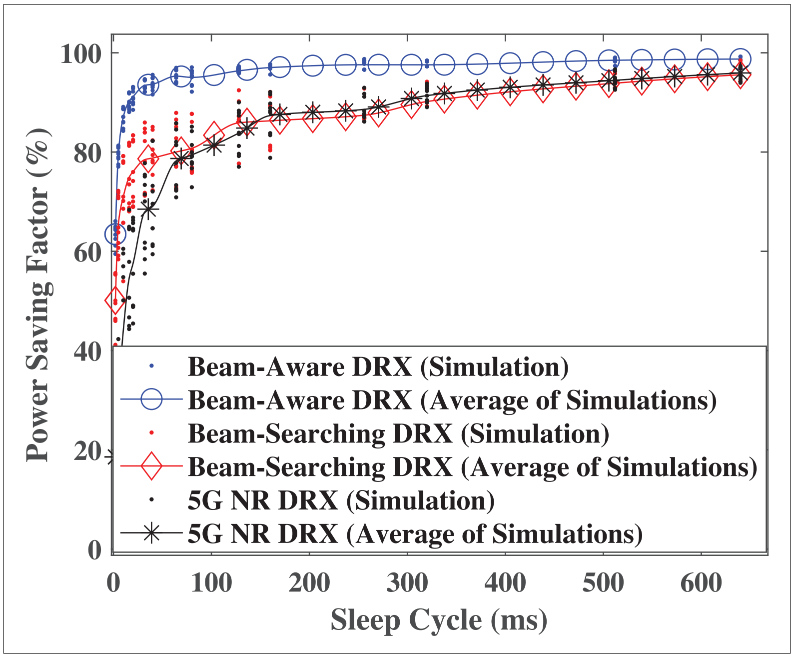

FIGURE 4. Power-saving factor with varying sleep timer.

Looking at Fig. 2, we can infer that the time between state transitions and holding time (sojourn time) instances are random variables, and it is possible to estimate the future states based on the current state. This observation leads us to model the DRX using a semi-Markov process [13]. Interestingly, if the sojourn time is not

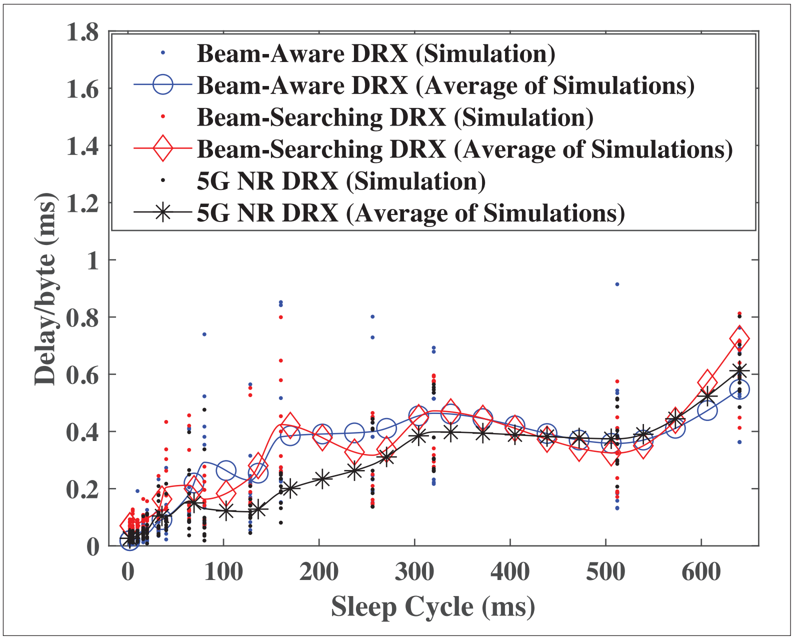

FIGURE 5. Celay with varying sleep timer.

exponentially distributed, the semi-Markov process model does not possess memoryless property. Thus, observing Fig. 2 during state transitions, we can obtain an embedded Markov chain. Using the state transition probability matrix, the steady state probabilities can be estimated. These steady state probabilities and holding times across different states are used to calculate the corresponding power consumption. Figure 2 also explains the synchronization mechanism between the licensed and the unlicensed channels. For NR-U NSA, with both licensed and unlicensed carriers, the licensed and unlicensed channels work separately. Hence, the ON period of the unlicensed channel must be aligned with the ON period of the licensed channel.

Interestingly, there are several practical challenges associated with beam searching in NR-U. The standard MCOT value, required to limit the transmission duration for ensuring graceful coexistence between WiFi and gNB, is merely 6 ms [7]. It can be extended up to a maximum 10 ms depending on CAPC. Hence, in the worst case, if the beam-searching time gets longer than the associated MCOT duration, UE is likely to miss the invaluable unlicensed channel transmission period. This incurs additional latency overhead, as the UE now needs to again wait to acquire the unlicensed channel. Intuitively, it will be more efficient if the NR-U gNB becomes cognizant enough to identify a suitable, if not the best, beam pair. We now provide an outline of this solution in the remainder of this section.

The Blessing of Beam Awareness

If the NR-U gNB is knowledgable about the best beam pair, it can signal the UE, using PDCCH, about this beam pair. This will relieve the significant burden associated with the UE's beam searching. If it is computationally difficult to estimate and maintain the best beam pair, as a fair compromise, any suitable beam pair with signal strength above a certain threshold could also work. When the UE periodically listens to the DL control channel, it can read the best beam pair. This DRX mode is actually endowed with cognizance of the suitable beam pair, thus making the entire process *beam-aware*.

Figure 3 delineates the operation model of beam-aware NR-U DRX. The transitions for Active state still remain the same. Similar to NR-U DRX with beam searching, in dynamic Sleep state, after the expiry of the sleep state timer, the user goes to the DRX ON state. If the user receives an intimation of packet arrival and the unlicensed channel is idle, it returns to Active state to service the packet. However, as the system is aware of the best beam pair, the beam searching step is no longer needed, and the associated time spent by the UE to search the best beam pair is also reduced to zero.

Figure 3 also shows the necessary synchronization between unlicensed and licensed channel operations. UE receives the information of data, unlicensed channel, and, most importantly, the best (or a suitable) beam pair during the ON period. The gNB senses the unlicensed channel during the ON period and allows the UE to transit to Active state if unlicensed channel is available. UE still occupies the Active state for MCOT. If packets in the buffer are served before MCOT expires, UE transits to Sleep state. On the other hand, if packets are remaining in the buffer after MCOT expires, the UE needs to perform LBT again. The NR-U gNB can perform this LBT and share the MCOT with UE for UE's UL transmission. For NR-U NSA [6], UEs are also connected with gNB through the licensed channel, and gNB has knowledge of the UE's current state. The gNB senses the unlicensed channel using LBT only during UE's ON state. If the unlicensed gNB's LBT is successful, the UE gets an indication of unlicensed channel, transits to Active state, monitors PDCCH to get the information about the best beam pair, and serves the packets. On the other hand, if the gNB's LBT fails, UE can still acquire the unlicensed channel if UE's UL-LBT is successful. However, in that case, UE cannot obtain the information about the unlicensed channel. If both the UE's and gNB's LBT fails, the UE transits to sleep state. Since, unlicensed channel occupancy time is limited to MCOT, gNB might have some knowledge about which UE will release the unlicensed channel after its MCOT expires. If a UE requests an unlicensed channel and all available unlicensed channels are currently occupied, the gNB asks the UE to wait for a random backoff time. At expiry of random backoff time, UE transits to ON state, the gNB senses the channel during the ON state, and the process continues.

Interestingly, with DRX, the mobile UE needs resources only during wake up state for data transmission and PDCCH monitoring. The physical wireless resources available during sleep state can be assigned to other UEs. For example, if only N_1 out of total N connected UEs ($N_1 < N$) are transmitting and monitoring PDCCH, the remaining physical resources of ($N - N_1$) UEs are available. These available physical resources could be used for supporting additional users, thereby increasing the overall capacity of the system. Referring to Fig. 2, we can argue that in our proposed NR-U DRX with beam searching, UE needs resources during the Active, DRX ON, and Beam Search states, but not in Sleep state. Similarly, referring to Fig. 3, in beam-aware DRX, physical resources are only consumed during the Active and DRX ON states. The resource batches (i.e., assigned resource blocks) assigned to NR-U UE are also shared by WiFi and other unlicensed wireless nodes. This resource sharing generates interference, which depends on traffic, channel conditions, and deployment scenarios. Thus, the utilization of resource batch depends on interference. Using existing resource usage [14], we can estimate the resource usage by multiplying UE's sojourn probability and resource utilization during the different states in the presence of unlicensed channel interference.

Performance Evaluation and Simulation Results

We have developed a discrete event simulator using MATLAB to validate our proposed DRX framework over NR-U. We consider five types of events:

- Active
- Sleep
- DRX ON
- Beam-Searching
- Packet arrival

There is no Beam-Searching event in the beam-aware DRX scenario, as the user is informed of the best beam pair by the gNB during the ON state. The packet arrival event pushes the packets to buffer (queue) after reading the packet generation time and size of the data. However, before going into the discussion of simulation results, we first highlight the major simulation parameters and assumptions:

- We have used a dense network deployment, involving a macrocell, 50 NR-U small cells, 50 WiFi transceivers, and 120 users randomly deployed in a 1 km^2 area. Each NR-U small cell has a bandwidth of 1 GHz, a transmit power of 10 dBm, and a CCA threshold of –62 dBm [11, 14].
- We have considered three-sector NR-U gNBs, where every sector has 16 beams with a beam-width of 7.5° per beam [6] and 8 beams in mobile UE, with a sub-frame length (TTI) of 200 μs.
- We have also assumed a DRX ON duration of 1 ms, an inactivity timer of 2 ms, and a random backoff time of 1~10 ms. The MCOT is set to 6 ms, and packet service time is set to 2 ms [1, 3]. Details of this timer were explained earlier.
- Transmit power in unlicensed bands and WiFi are assumed to be 10 dBm and 15 dBm [1], respectively. Additive white Gaussian noise (AWGN) power and noise figure values are assumed to be –174 dBm/Hz and 7 dB [1], respectively. We have also used the popular path loss models [15] and a resource batch bandwidth [1] of 1 GHz.
- The simulation is fed with real mobility trace, the "Monitoring Mobile Video Delivery to Android Devices" trace, containing actual peer-to-peer and HTTP applications obtained from the UMass Trace Repository [11].
- The power-saving factor and latency are calculated using packet arrivals in a simulation run, total waiting period of served packet, total wakeup time, total sleep time, and simulation clock. Every simulation is run for 50 minutes, repeated 10 times with different random seeds, and the average results are reported.

Figure 4 demonstrates the dynamics of power-saving factor as the sleep timer varies from 2~640 ms, with a constant ON duration of 1 ms. The power-saving factor increases with an increase in sleep timer as a longer sleep cycle postpones the ON duration state and the Active state. As observed from Fig. 4, the power- aving achieved with NR-U beam-aware DRX is 13 percent higher than NR-U beam-searching DRX. The reason lies in the fact that in NR-U beam-aware DRX, the UE does not have to align the beams, but just get an intimation of the best beam pair during the ON period. Moreover, the user transits to Active state only when there is data to be served and unlicensed channel is available; otherwise, it continues to sleep. Moreover, Fig. 4 also points out that compared to 5G NR DRX, NR-U beam-aware and beam-searching DRX mechanisms achieve 24 and 12.8 percent more power saving, respectively. This is attributed to the fact that in 5G NR DRX, UE aligns the beams after every sleep cycle, which is not needed in NR-U beam-searching DRX.

Note that DRX achieves UE's power saving at the cost of some additional delay. Figure 5 depicts the average delay per byte lies between 0~1 ms for a varying sleep timer. The delay increases with an increase in sleep duration, as the incoming packets are buffered during UE's sleep state. For delay-sensitive traffic, shorter DRX cycle is preferable at the expense of reduced power saving. Note that it is also clear from Fig. 5 that delay achieved with NR-U beam-aware DRX is 11 percent less than beam-searching DRX. Additional time associated with mobile UE's beam searching is primarily responsible for this.

Figure 6 delineates usage of resource batches with number of NR-U users sharing the resource pool for different WiFi interference (Γ). For interference of Γ = 0.2, the maximum resource usage is 16.5 percent for NR-U beam-aware DRX, 24.5 percent for NR-U beam-searching DRX, and 40.9 percent without DRX. The usage of resource batches is lower with NR-U DRX, as the users transit to Active state only when there is data to be served and the unlicensed channel is available. The resources used without DRX are the highest as the UE does not go to sleep state and always needs the resources. Figure 6 also points out that the number of users sharing a resource pool increases with the increase in WiFi interference, as each user observes a different level of interference for the same assigned resource batch. As an example, for Γ = 0.8, with a pool of 5 resource batches shared by 10 users, maximum usage of 36.6 percent is achieved without DRX, followed by 21.5 percent with NR-U beam-searching DRX and 14.8 percent with NR-U beam-aware DRX.

Conclusion

In this article, we introduce two different DRX mechanisms for energy and resource savings in 5G NR unlicensed networks. The two different mechanisms are based on beam searching and beam awareness. Although both mechanisms

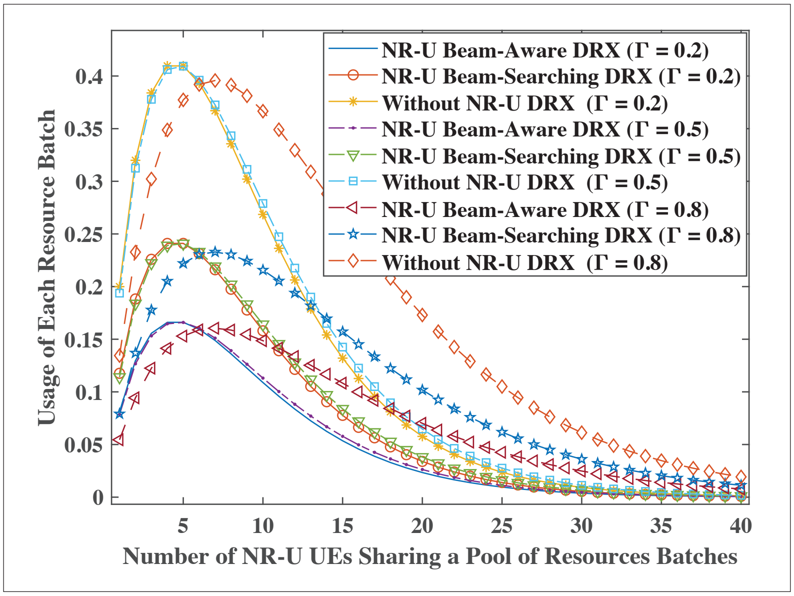

FIGURE 6. Resource batch usage for different interference (Γ).

enable mobile UE to save power, beam-aware DRX uses gNB's assistance to alleviate UE's beam-searching burden and results in more power saving. Semi-Markov models are used for analysis of both DRX mechanisms. The solutions and analysis are verified by simulation results using actual wireless trace.

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