A Survey on DRX Mechanism: Device Power Saving from LTE and 5G New Radio to 6G Communication Systems

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***Abstract*—The Discontinuous Reception (DRX) is the most effective timer-based mechanism for User Equipment (UE) power saving. In Long Term Evolution (LTE) systems, the development of the DRX mechanism enormously extends the UE battery life. With the DRX mechanism, a UE is allowed to enter a dormant state. Given a DRX cycle, the UE needs to wake up periodically during the dormancy to check whether it receives new downlink packets or not. The UE can achieve a high sleeping ratio by skipping most channel monitoring occasions. As the mobile network evolved to 5G, the battery life requirement increased to support various new services. 3rd Generation Partnership Project (3GPP) also enhances the DRX mechanism and adds new DRX-related features in the New Radio (NR) Release 16 standard. In addition to the time-based design, 3GPP proposed two signaling-based mechanisms: power saving signal and UE assistance information. This survey paper introduces the latest DRX mechanism in the 3GPP NR standard and summarizes the state-of-the-art research.**

Researchers have investigated the DRX mechanism in various use cases, such as web browsing services and heterogeneous networks. They focus on the UE sleep ratio and packet delay and propose corresponding analytical models. New DRX architectures are also discussed to conquer the power-saving problem in specific schemes, especially in the 5G NR networks. This paper categorizes and presents the papers according to the target services and the network scenarios in detail. We also survey the work focusing on the new challenges (such as beamforming and thermal issue) in the NR network and introduce the future research directions in the 6G era.

***Index Terms*—Discontinuous Reception (DRX), New Radio (NR), power saving.**

I. INTRODUCTION

Power-saving in the wireless mobile network has been crucial because of the limitation of the battery capacity. However, the power consumption of mobile devices overgrows as the services provided by the communication network become more and more complicated. Although the battery is still evolving, it is hard to satisfy mobile devices' growing power consumption. Therefore, developing other techniques to reduce power consumption is another way to extend mobile devices' battery life. Fig. 1 summarizes the main directions to reduce the User Equipment (UE) power consumption and prolong the battery life. We can categorize the power-saving mechanisms into four groups: timer-based, signaling-based, data domain, and UE Radio Frequency (RF) domain mechanisms. The first two groups are the mechanisms studying the Discontinuous Reception (DRX)-related procedures for the UE and the base station with or without exchanging control messages. As for the data domain mechanisms, the base station helps the UE save power by scheduling and shaping the data traffic flow. Finally, the UE RF domain solutions improve the UE's configurations and settings for the transmission-related modules, such as antenna module, Multi-input Multi-output (MIMO), and Bandwidth Part (BWP) settings. Many researchers have devoted themselves to developing these power-saving mechanisms. Among these techniques, DRX is the most famed mechanism enabling mobile devices to save power without much signaling overhead between UEs and base stations. Therefore, it is also the primary power-saving mechanism in the Media Access Control (MAC) layer of the 3rd Generation Partnership Project (3GPP) systems.

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TABLE I
ACRONYMS

Acronym	Description
3GPP	3rd Generation Partnership Project
ABS	Almost Blank Subframe
AP	Access Point
BWP	Bandwidth Part
CA	Carrier Aggregation
CC	Component Carrier
C-DRX	Connected mode Discontinuous Reception
CQI	Channel Quality Indicator
C-RAN	Cloud-based Radio Access Network
D2D	Device-to-device communication
DASH	Dynamic Adaptive Streaming over HTTP
DC	Dual Connectivity
DCP	Downlink Control information of Power saving
DDA	Diverse Data Applications
DRX	Discontinuous Reception
DTIM	Delivery Traffic Indication Map
eMBB	Enhanced Mobile Broadband
eNB	Evolved Node B
ETSI	European Telecommunications Standards Institute
FTP	File Transfer Protocol
GBR	Guaranteed-Bit-Rate
gNB	New Radio Node B
GTS	Go-to-sleep Signal
HetNet	Heterogeneous Network
HSDPA	High Speed Downlink Packet Access
HTC	Human Type Communication
HTTP	Hypertext Transfer Protocol
I-DRX	Idle mode Discontinuous Reception
IEEE	Institute of Electrical and Electronics Engineers
IoT	Internet of Things
ITU	International Telecommunication Union

Acronym	Description
JT	Joint Transmission
LAA	License-Assisted Access
LBT	Listen-Before-Talk mechanism
LSTM	Long Short-Term Memory
LTE	Long Term Evolution
MAC	Media Access Control
MC	Multi-connectivity
MIMO	Multi-input Multi-output
mMTC	Massive Machine Type Communication
MOS	Mean Opinion Score
MSMS	Multi-SIM Multi-Standby
MTC	Machine Type Communication
NB-IoT	Narrow-Band Internet-of-Things
NFV	Network Function Virtualization
NR	New Radio
NR-U	NR-Unlicensed
PDCCH	Physical Downlink Control Channel
PDSCH	Physical Downlink Shared Channel
PPI	Power Preference Indicator
PSF	Power Saving Factor
PSM	Power Saving Mode
PS-RNTI	Power Saving Radio Network Temporary Identity
QoE	Quality of Experience
QoS	Quality of Service
RAT	Radio Access Technology
RF	Radio Frequency
RMSE	Root Mean Square Error
RRC	Radio Resource Control protocol
RRH	Remote Radio Head
SCS	Sub-Carrier Spacing
SDN	Software Defined Networking
SIM	Subscriber Identity Module
SON	Self-Organizing Network
SPS	Semi-Persistent Scheduling
TIM	Traffic Indication Map
TSN	Time Sensitive Network
TTI	Transmission Time Interval
UAV	Unmanned Aerial Vehicle
UE	User Equipment
UMTS	Universal Mobile Telecommunications System
uRLLC	Ultra Reliable Low Latency Communication
VoIP	Voice over Internet Protocol
WUR	Wake-up Radio

In the Long Term Evolution (LTE) system, 3GPP redesigned the Connected mode Discontinuous Reception (C-DRX) mechanism in Universal Mobile Telecommunications System (UMTS) [1]–[3] and modified the mechanism into a timer-based power-saving solution [4]. The central concept of the C-DRX mechanism is to allow UEs to temporarily stop monitoring the wireless channel when there is no downlink traffic during Connected mode. However, the UE's connection with the network is not released to prevent unacceptable latency [5]. If the UE needs more dormancy for power saving, it may enter Idle mode and follow the paging mechanism for power-saving, also known as the Idle mode Discontinuous Reception (I-DRX). Since a UE in Idle mode mostly stays in the deep sleep state and has no data transmissions, researchers focus on the design of the paging mechanism to improve the latency to find and wake up UEs in Idle mode. Therefore, the studies on the paging mechanism for Idle mode UEs are out of this paper's scope because we focus on the performance of data transmission and UE power consumption in this survey paper.

In [5], Bontu *et al.* briefly introduced the DRX mechanism applied in the LTE network. They clearly described the difference between ACTIVE, C-DRX, and I-DRX. This article is a milestone since the authors provided the fundamental perspectives to study and evaluate the DRX mechanisms in the LTE network. The authors provided not only an introduction but also a basic analytical model for the DRX mechanism.

The DRX mechanism proposed in the LTE network significantly decreases the UE power consumption. However, it still becomes inadequate as the new generation network starts to support various new services. International Telecommunication Union (ITU) also proposed considering Enhanced Mobile Broadband (eMBB), Massive Machine Type Communication (mMTC), and Ultra Reliable Low Latency Communication (uRLLC) as the main direction of the new generation network. However, a trade-off between the Quality of Service (QoS) and the power saving is inevitable. Researchers have started investigating the DRX mechanisms for various types of services. Hoque *et al.* surveyed the power efficiency of multimedia streaming in [6]. Although the authors carefully categorize some related work, they did not cover the power-saving studies for other applications. We found that there is no existing survey paper concentrating on other services under different network topologies. Therefore, we focus on the work dealing with various types of services.

More methods are proposed for the 5G New Radio (NR) network to solve the new challenges. In [7], Li *et al.* outlined the main power-saving mechanisms in the 5G NR network, including the NR C-DRX mechanism. Esswie [8] also summarized the power-saving techniques applied in the NR network. In [9], Rostami *et al.* provided a more detailed introduction to Wake-up Radio (WUR). The WUR is standardized by the Institute of Electrical and Electronics Engineers (IEEE) 802.11ba working group. It allows a device with a low-power companion connectivity radio to turn off its primary connectivity radio. When the companion connectivity radio detects the wake-up signal, the device turns on its primary radio to receive data. 3GPP utilized this concept to design the power saving signal in the 3GPP Release 16 standard, described in Sec. III-A. Although the papers gave the readers an insight into the power saving of the NR network, the authors did not survey the existing research. Therefore, we also target the state-of-the-art C-DRX-related designs in the 5G NR network.

Although the DRX has been widely studied for more than ten years, there is still no survey paper summarizing the research related to the DRX mechanism. In this paper, we survey the researchers that optimize various services with DRX configured. The DRX procedure in the 5G NR is also studied because of the directionality of the wireless links. The beamforming technology is applied in NR to enhance the transmission rate but makes the communication link unstable. We also include the DRX research related to beamforming in this survey paper.

The main contributions of this paper are summarized below:

1) To the authors' best knowledge, this is the first survey paper focusing on the DRX mechanism.
2) We introduce the latest DRX-related mechanism in the 3GPP NR standard.
3) We present the work focusing on primary services usually configured with DRX. Besides, we also summarize the

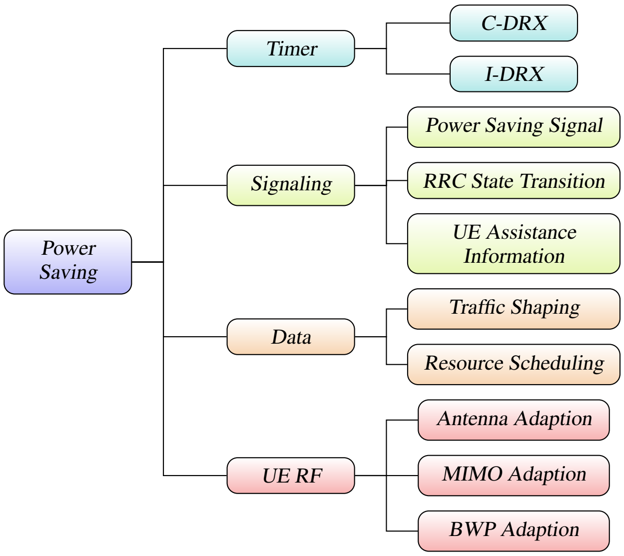


Fig. 1. Major power saving mechanisms for UEs in wireless mobile networks. In this paper, we focus on the timer-based C-DRX mechanism.

TABLE II
BASIC PARAMETERS IN DRX MECHANISM

Parameter	Meaning
Long DRX cycle	A device is required to wake up at the beginning of each cycle.
On duration timer	The minimal holding time after a device wakes up.
Inactivity timer	The minimal holding time after a packet is successfully received. Devices could go to sleep after the timer is expired.
Short DRX cycle	Optional. After a device go dormancy, it first applies short cycle for a while and changes back to long cycle if it keeps receiving no new packets.

work related to the new issues in NR with DRX configured.

4) We introduce the possible future directions for the DRX mechanisms in the 6G networks.

Fig. 2 shows the overview of our survey paper. First, we introduce the 3GPP standard related to the DRX mechanism in Sec. II and III. Sec. IV provides the basic analysis methodology and important performance metrics of the DRX mechanism. Second, the research on the DRX for different services are presented in Sec. V. Third, we summarize the studies that optimize the DRX performance in various scenarios in Sec. VI. Next, we summarize the studies with the implementation of experiment testbed in Sec. VII. Sec. VIII surveys state-of-the-art machine learning based DRX designs. Next, we provide the discussion of new challenges for the DRX in the NR network in Sec. IX. Finally, we introduce the possible future directions for 6G DRX mechanisms in Sec. X.

II. UE POWER SAVING MECHANISMS IN STANDARDS

This section will introduce the main power-saving mechanisms specified in the wireless communication standard, such as NR and WiFi. Most researchers take the design in the standards as starting points and propose their designs to improve

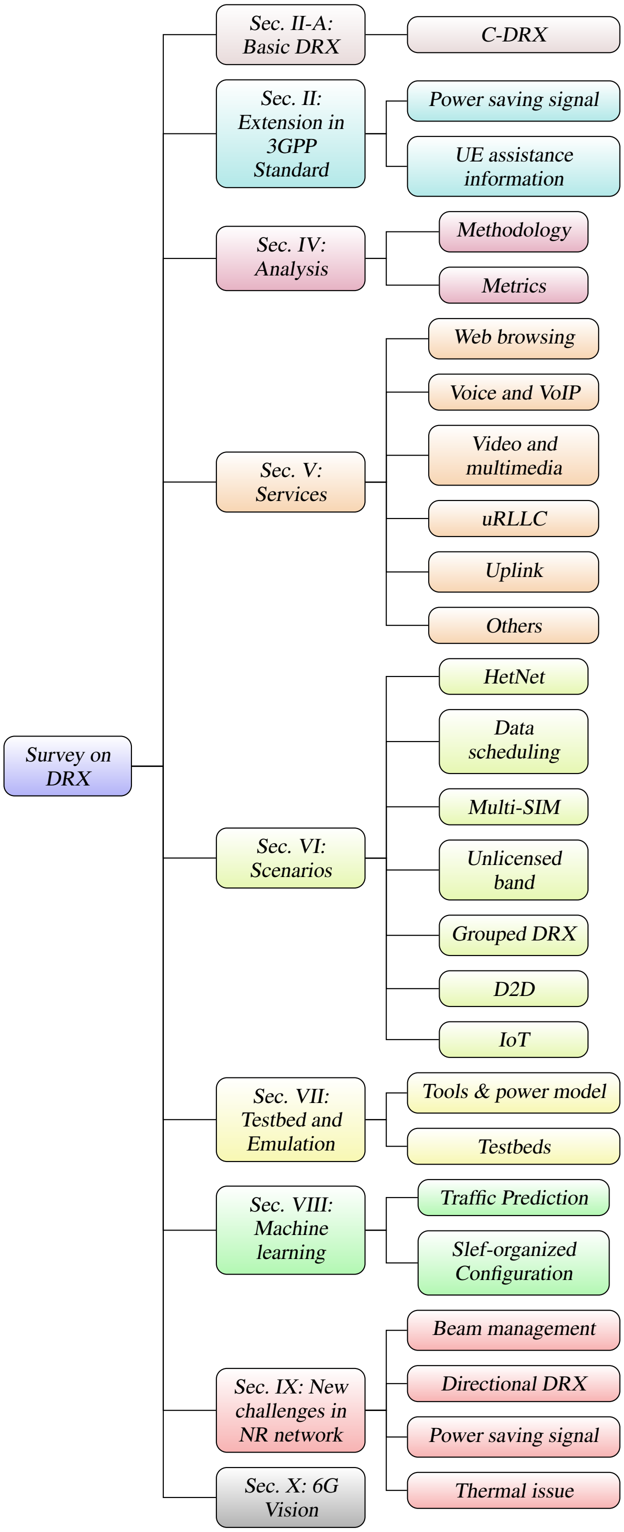


Fig. 2. Structure of this survey paper.

TABLE III
SUPPORTED VALUES FOR DRX PARAMETERS IN 3GPP TECHNICAL STANDARD TS38.331 [10]

Parameter	Values (ms)
Long DRX cycle	10, 20, 32, 40, 60, 64, 70, 80, 128, 160, 256, 320, 512, 640, 1024, 1280, 2048, 2560, 5120, 10240
On duration timer	$\frac{1}{32}..\frac{31}{32}$, 1, 2, 3, 4, 5, 6, 8, 10, 20, 30, 40, 50, 60, 80, 100, 200, 300, 400, 500, 600, 800, 1000, 1200, 1600
Inactivity timer	0, 1, 2, 3, 4, 5, 6, 8, 10, 20, 30, 40, 50, 60, 80, 100, 200, 300, 500, 750, 1280, 1920, 2560
Short DRX cycle	2, 3, 4, 5, 6, 7, 8, 10, 14, 16, 20, 30, 32, 35, 40, 64, 80, 128, 160, 256, 320, 512, 640

the performance of UE power saving. Thus, we provide the following background knowledge for ease of reading.

A. *Basic connected mode DRX in 3GPP standard*

In the 3GPP standard, the DRX mechanism could be applied to UEs in Connected, Inactive, and Idle states. For Inactive and Idle states, the DRX procedure is also known as paging. However, this paper focuses on the DRX mechanism in Connected mode. This section will introduce the current status of the 3GPP standard, including a) C-DRX, b) power saving signal, and c) UE Assistance Information.

The DRX mechanism has already been adopted in traditional LTE networks for UE power saving. It enables a UE to turn off most RF circuits when there is no data traffic to the UE. The UE enters dormancy during the period without packets to receive. However, the UE stays Connected so that it can recover from dormancy faster. If the UE keeps idle for longer, it will enter Inactive or Idle to release more network resources for other UEs.

Physical Downlink Control Channel (PDCCH) monitoring and data receiving are two power-consuming downlink-related processes for UEs. When a UE is active, it is required to monitor the control channel and check whether a new downlink packet is sent. The PDCCH monitoring process involves the search space blind decoding procedure that consumes much power. If a new packet is sent, the UE decodes the corresponding wireless resources indicated in the PDCCH; otherwise, the UE keeps monitoring PDCCH. Thus, the central concept of the DRX mechanism is to skip the PDCCH monitoring without downlink packet indications.

In 3GPP technical specification TS38.300 [11], the C-DRX is mainly characterized by 1) DRX cycle, 2) on duration timer, and 3) inactivity timer. As shown in Fig. 3, when a UE is configured with DRX, it periodically turns on and starts its on duration timer according to the DRX cycle. Before the on duration timer expires, the UE must monitor the PDCCH to check whether any downlink traffic exists. After the on duration timer expires, the UE has the opportunity for DRX before the end of the DRX cycle. It could skip decoding PDCCH and turn off its RF module to save energy. Suppose the UE receives any downlink packet before the expiry of the on duration timer. In that case, the UE starts the inactivity timer and extends the active time to receive the consecutive packets. Fig. 4 illustrates the example of the inactivity timer. From 3GPP technical specification TS38.321 [12], each successful reception resets the inactivity timer, so the UE does not have the opportunity for DRX until the expiry of the inactivity timer. Table II summarizes the key parameters above, and Table III shows the supported values in 3GPP technical specification TS38.331 [10].

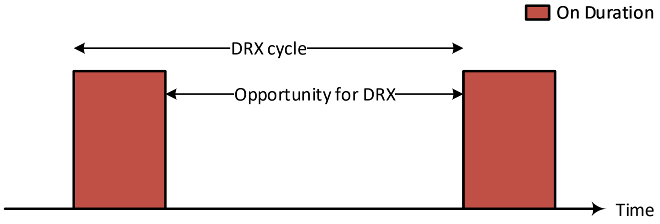


Fig. 3. Basic operation of the DRX mechanism. When the UE has no downlink traffic, it has the opportunity for DRX after the on duration.

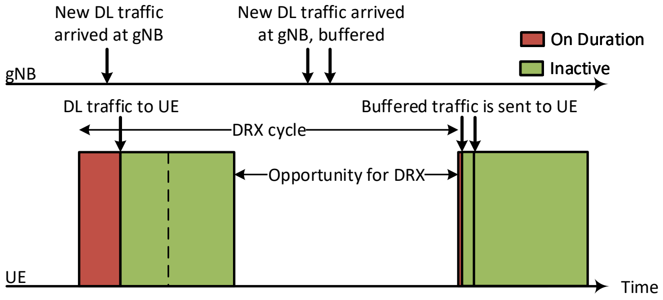


Fig. 4. Operation of the inactivity timer. When the gNB sends a new downlink packet to the UE, it resets the inactivity timer and extends its active time. The UE could have the opportunity for DRX after the timer expires. It is also possible that the extended active time covers the whole DRX cycle.

If the traffic fluctuates, the gNB could further configure a short DRX cycle for the UE. When the inactivity timer expires, the UE first applies the short DRX cycle and starts a timer. If there is no new downlink traffic until the timer expires, the UE changes to the long DRX cycle. Fig. 5 depicts an example of the short DRX cycle. When the UE's inactivity timer expires, the UE performs DRX according to the short DRX cycle. After two short cycles, the UE changes to the long DRX cycle if receiving no new downlink traffic.

With the design of the DRX cycle, the DRX mechanism is suitable for periodic traffic. With the inactivity timer and the short cycle, the DRX mechanism is also ideal for bursty

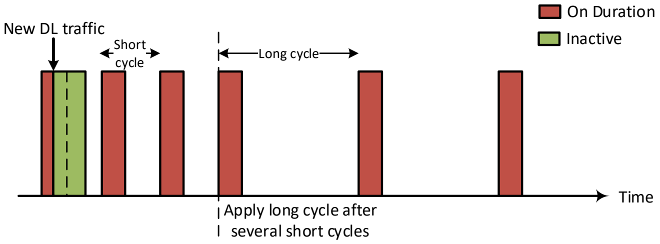


Fig. 5. Example of the short DRX cycle. The UE applies the long DRX cycle after several short cycles when there is no downlink traffics.

traffic. However, the requirements of various services in the 5G network are higher and more diverse, so the study and evolution of DRX are still inevitable.

B. Uplink operations in 3GPP connected mode DRX

The DRX mechanism is proposed for the UE power saving during the downlink traffics reception. However, it also influences the behavior of UE's uplink transmissions. A UE is not forbidden to send an uplink scheduling request to its serving gNB during its dormancy period if the UE receives some packets to send from the application layer. In other words, a UE can always send the uplink scheduling requests if needed, but note that each uplink transmission would reset the inactivity timer and prevent the UE from dormancy after its uplink transmissions according to the 3GPP standard. This reset would increase the UE's power consumption.

To avoid this kind of power wasting, manufactures may prefer to defer the uplink transmissions until the UE's next DRX cycle while implementing the chip-set. The UE could save more power by aligning the uplink transmissions with the DRX cycle. This phenomenon is also studied in [13].

C. Power Saving Mode in 802.11 systems

Other than the 3GPP DRX mechanism, other Radio Access Technology (RAT) also specifies power-saving mechanisms for mobile devices. Power Saving Mode (PSM) is a duty-cycle beacon-based power saving mechanism in 802.11 systems. In PSM, an Access Point (AP) pre-configures a Delivery Traffic Indication Map (DTIM) period to the client. The AP stores the arriving packet in its buffer if the packet arrives when the client is dormant. Fig. 6 illustrates the procedure of the PSM mechanism. Upon the beginning of a DTIM period, the AP transmits a beacon with Traffic Indication Map (TIM) to indicate whether the client should receive data during this DTIM period. If there are buffered data, the TIM indicates that the client should wake up; otherwise, the client would stay dormant. Meanwhile, the client wakes up, receives the beacon with TIM, and follows the indication in TIM.

If the TIM indicates no data for reception, the client keeps dormant until the beginning of the next DTIM period; otherwise, the client gets active and starts receiving data. When the client is active, the client requests data through a polling-based mechanism. Meanwhile, the AP transmits the data along with a tag in the MAC header, called "more data," to indicate whether there is remaining buffered data. A client goes dormant after it receives the data with DATA_more = 0.

If we compare the PSM mechanism in the 802.11 systems with the DRX mechanism in the 3GPP systems, we can find that the main difference is the behavior of random back-off in the 802.11 systems. Since most 802.11 systems operate in the unlicensed band, the devices must compete for the channel resources before transmitting data. Thus, when there is more than one client under the 802.11 AP trying to poll for downlink data, the channel contention will likely extend each client's active time. Such a situation would happen less in the 3GPP gNB-centric communication network.

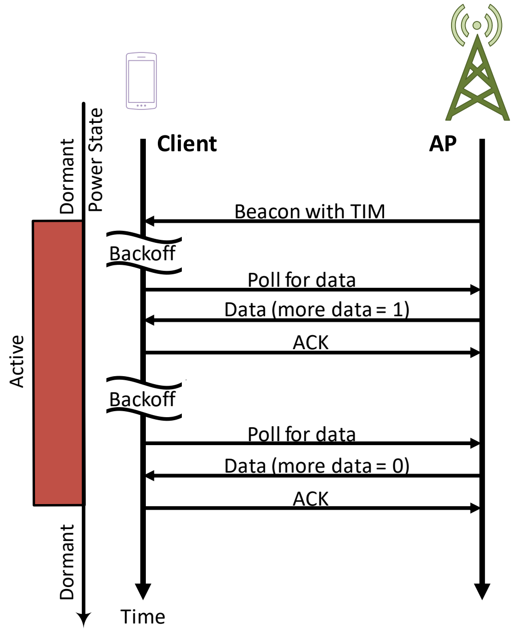


Fig. 6. PSM in 802.11 systems.

III. DRX EXTENSION IN 3GPP STANDARD RELEASE 16

The DRX mechanism has been essential in the 3GPP communication systems for more than ten years. Researchers keep contributing proposals to 3GPP standard meetings to improve power-saving performance. Consequently, some new functions are included in the latest DRX mechanism. In the following paragraphs, we will briefly introduce these functions.

A. Power saving signal

Though the DRX mechanism has been introduced to the wireless mobile network, further enhancement for the DRX mechanism and power saving is still vital. 3GPP technical report TR38.840 [14] indicated that reducing the monitoring and decoding of PDCCH is effective for UE power saving; therefore, 3GPP decided to adopt the power saving signal in the Release 16 of the NR system. The central concept is close to the design of WUR specified by IEEE 802.11ba. WUR specified a low-power receiver to monitor a wake-up signal. Typically, a UE with the WUR receiver turns off its main radio by default. If a wake-up signal is detected, the UE turns on its main radio to receive data.

Unlike the WUR design, 3GPP proposed using a low power-consuming indication, called power saving signal in the NR standard. It allows the UEs with DRX configured to monitor Downlink Control information of Power saving (DCP), a newly designed control message, and skip the coming PDCCH monitoring. The DCP is still transmitted over the PDCCH but is scrambled with a specific Power Saving Radio Network Temporary Identity (PS-RNTI), so the UE does not need to perform blind decoding while receiving the DCP. The DCP would indicate whether the UE could skip the PDCCH monitoring with complete blind decoding in the coming DRX cycle. Note that the blind decoding procedure consumes UEs much

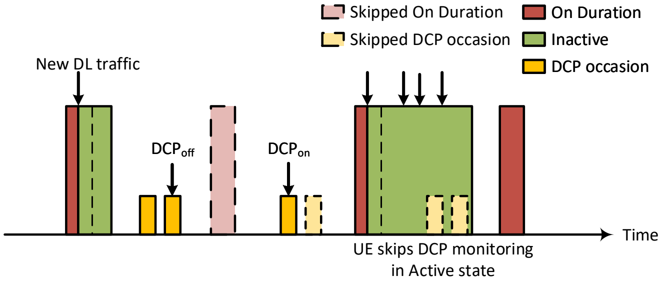


Fig. 7. The power saving signal enables the gNB to inform the UE whether there is new downlink traffic or not. If there is no traffic in the next on duration, the UE could skip the PDCCH monitoring, which is more power-consuming than the DCP monitoring.

power. Therefore, the power saving signal indeed improves the power efficiency. Besides, the DCP is transmitted in the same format as the physical control signals, so the UE does not need another receiver to detect the power-saving signal.

Based on the 3GPP technical standard TS38.213 and TS38.321 [12], [15], Fig. 7 illustrates an example of the DRX mechanism with the power saving signal configured. The UE is provided another search space to monitor DCP. The timing of monitoring is called DCP occasion. The dormant UE should monitor the DCP to determine whether to enter the on duration in the next DRX cycle. If the DCP indicates *off*, the UE will stay dormant in the next DRX cycle. If the UE receives an *on* indication, it will enter the active state in the next DRX cycle. Note that the UE does not monitor the DCP during the active state. If all DCPs are skipped, the UE still wakes up in the next DRX cycle.

The power saving signal enables the gNB to explicitly inform the UE whether it would be scheduled for downlink transmission in the next on duration. Although the UE is required to monitor additional search space, the power consumption of DCP monitoring is much lower than that of PDCCH monitoring during the on duration. Nevertheless, the delivery of DCP is crucial, especially for millimeter-wave communications. Further studies for the DCP occasion pattern and the integration of beam management are needed to optimize the overall system performance.

B. UE assistance information

The power-saving requirement for a UE might change based on its status. For example, if the UE's battery is low, it might require a longer DRX cycle for power saving. However, there are only limited methods in traditional networks to report UE's preference of power-saving configuration to the gNB. Although 3GPP proposed a design called power preference indication in Release 11, it does not satisfy the requirements of the new network systems. Recently, 3GPP has standardized the signaling of UE assistance information in 3GPP technical specifications TS38.300 and TS38.331 [10], [11] so that the gNB could gather more information from UEs. Fig. 8 shows the signaling flow of the UE assistance information. First, the gNB could enable the UE to report UE assistance information. When the UE prefers another DRX configuration, it could inform the gNB of its new preference. After that, the gNB could determine a better configuration based on the feedback. Finally, the gNB might reconfigure the UE with new DRX parameters.

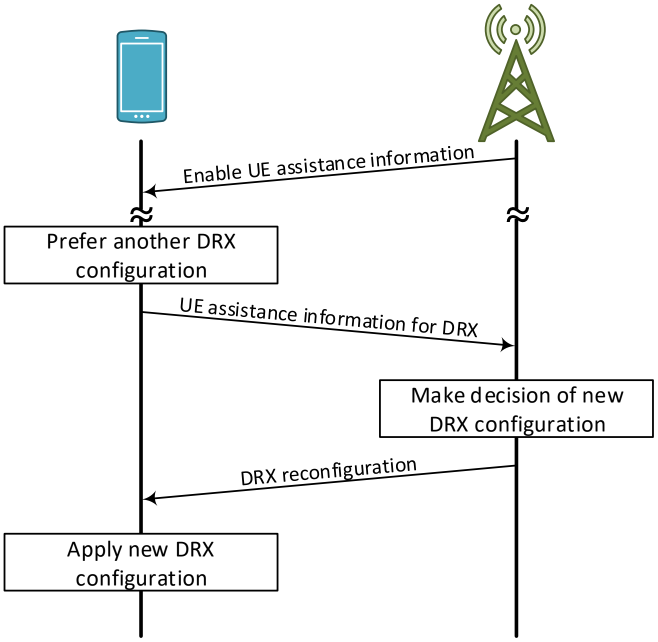


Fig. 8. The gNB could gather UE's preference of DRX configuration. When the UE changes its preference, it could report to the gNB. After that, the gNB might configure more suitable DRX parameters for the UE.

Although the UE assistance information makes the gNB aware of UE's power-saving preference, the gNB might decide not to follow the UE's feedback. The gNB should consider the resource utilization of the entire cell. For example, it is less beneficial for a power-consuming UE to shorten its DRX cycle when other UEs use most wireless resources in its on duration. On the other hand, the gNB might not want to extend the DRX cycle for a UE with a heavy traffic load, even if it prefers a long dormancy. However, the standardization of UE assistance information still enables the system to better support the dynamic DRX configuration schemes.

IV. ANALYSIS OF DRX MECHANISM

As introduced in the previous sections, the DRX mechanism is designed for the UE's power-saving and is characterized by several timers. Based on the operations of the timers, researchers typically define several DRX states to model the overall performance. By applying Markov models or Semi-Markov Models, we could find the system's stationary state after determining the state transition probability. The authors of [16] provided more details on comparing the two models while analyzing the DRX mechanism. After finding the stationary state probability distribution, we can also get the vital system performance metrics. In the following paragraphs, we present the main system performance metrics along with the simulation results to ease understanding of the DRX mechanism's properties.

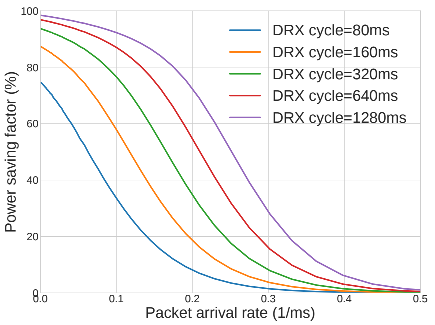


Fig. 9. Power saving factor of the basic DRX procedure, where the inactivity timer is 20 ms.

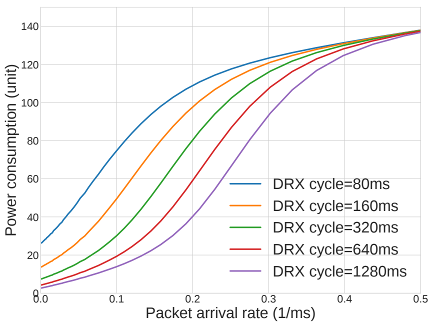


Fig. 10. Power consumption of the basic DRX procedure, where the inactivity timer is 20 ms. The power consumption model is from 3GPP technical report TR38.840 [14], and the unit is define as 0.01 times the power of PDCCH-only slot.

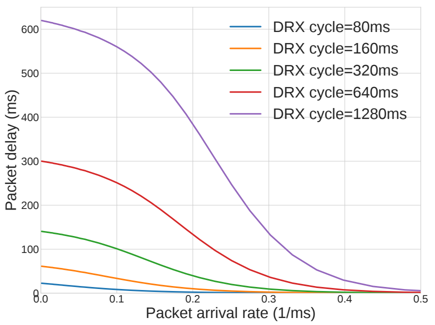


Fig. 11. Packet delay of the basic DRX procedure, where the inactivity timer is 20 ms.

A. *Power saving factor*

Power Saving Factor (PSF) is commonly used in DRX research to quantify performance. It is also known as the ratio of sleeping (sleep ratio) and is defined as the average percentage of time a UE stays in the dormancy state. A UE could save more power when it can remain in the dormant state longer. Therefore, a DRX design or configuration with higher PSF can help the UEs extend their dormant time and save more power.

Fig. 9 illustrates the PSF performance of the basic DRX procedure. We can see that the longer DRX cycle leads to higher PSF because the UE could sleep longer. However, when the packet arrival rate increases, the UE fails to go dormant because the probability of the inactivity timer reset is also higher.

B. *Power consumption*

Although PSF is widely used in the analysis of the DRX performance, the definition is so simple that the performance of power-saving can not be effectively observed, especially for complicated system models. Therefore, some researchers proposed directly using the consumed energy as a performance metric. The main challenge is measuring power consumption and constructing a convincing power consumption model for different DRX states. Fortunately, 3GPP proposed their power consumption model in technical report TR38.840 [14] so that the researchers could analyze the UE's power consumption better than before.

Fig. 10 shows the power consumption of the basic DRX procedure. We reference the power consumption model from the 3GPP technical report TR38.840 [14], where the power consumption of a slot with only PDCCH decode is defined as 100 units. The simulation results showed that a longer DRX cycle decreases the overall power consumption.

C. *Packet delay*

Another popular performance metric is the transmission delay. Because the DRX mechanism enables the UE to sleep periodically, it brings extra latency to the packet transmission. Therefore, most researchers tried to optimize the tradeoff between power consumption and packet delay.

Fig. 11 depicts the packet delay of the basic DRX procedure. We can see that the packet delay is longer when the DRX cycle is longer. When the packet arrival rate rises, the UE will go to sleep less so that the packet delay decreases.

D. *Effect of the Inactivity timer*

The design of the inactivity timer in the DRX procedure enables the UE to receive the successive downlink packets. Unlike the traffic in the 3G network, most traffic in the LTE is packet calls, such as web browsing. The traffic pattern is much different from the cellular phone calls. Therefore, applying the inactivity timer decreases the transmission delay for an LTE UE with the DRX mechanism.

Fig. 12 and 13 show the performance of the DRX mechanism when the inactivity timer is configured to different values. We can see that the power consumption is higher, and the packet delay is lower when the inactivity timer is longer. The reason is that the inactivity timer would prevent the UE from going to dormancy after the reception of the downlink packets and increase the power consumption.

E. *Overhead of DRX mechanism*

The main reason that the DRX mechanism is designed to be a timer-triggered mechanism is to reduce the signaling overhead between the UE and its serving gNB. After the gNB configures the timer value, the UE could operate the DRX mechanism individually. However, the shortcoming is the low adaptability. When the UE's traffic fluctuates more, the gNB might need to reconfigure the DRX parameters for the UE to achieve better power-saving performance. Such reconfiguration is an Radio Resource Control protocol (RRC) level signaling, which often causes a delay of several milliseconds and consumes extra power to handle the signaling messages.

For the newly introduced power saving signal, 3GPP reused the control signal format in the 5G NR network. The DCP is still transmitted over PDCCH but with a specific PS-RNTI. The benefit is that the UE could directly decode the DCP with its NR RF module instead of adding another low-power

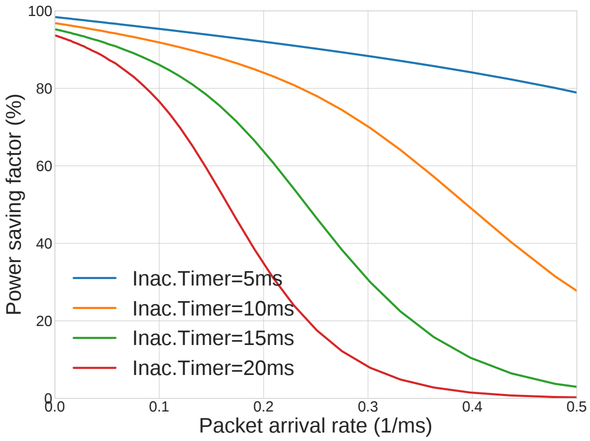


Fig. 12. Power saving factor of the basic DRX procedure, where the DRX cycle is 320 ms.

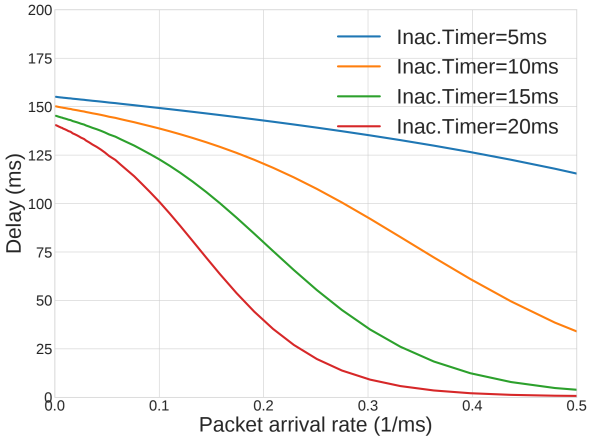


Fig. 13. Packet delay of the basic DRX procedure, where the DRX cycle is 320 ms.

RF module to avoid the extra cost of the UE. Regarding the signaling overhead, the UE needs to decode at least one DCP every DRX cycle. If the system operates at a higher frequency band, such as the millimeter-wave band, the number of DCPs will increase to prevent the UE from missing the control signalings.

V. DRX OPTIMIZATION DRIVEN BY SERVICES

The DRX mechanism is widely adopted in various services because of the tremendous enhancement of the UE power efficiency. We summarize state-of-the-art research in the following subsections and Table IV based on the classification of the main traffic types.

A. DRX for web browsing

Web browsing is one of the primary network services, and the DRX is also suitable for it. Since the web browsing traffic is similar to bursty traffic, most early work in DRX widely adopted the European Telecommunications Standards Institute (ETSI) packet data traffic model in analysis and simulation. With the ETSI traffic model, a classic three-state semi-Markov chain to model the DRX mechanism was constructed and served as a precise and simple formula to analyze the PSF and delay for LTE DRX research [17]. Regarding the analysis of the adjustable DRX mechanisms, if the short DRX cycle increases exponentially when the UE receives no new downlink traffic, the system could select better DRX parameters to improve the PSF and the delay [18].

To improve the analytical model's accuracy and derive more realistic results, we must not make too many assumptions to simplify the derivation of mathematical formulas [19], [20]. For example, we should carefully handle each DRX state and compare the DRX variations under an identical scenario. If so, we could discover that LTE DRX attained higher PSF with a reasonable cost wake-up delay than the UMTS DRX [3]. Similarly, a simulation analysis of legacy DRX was under the ETSI traffic model [21].

Based on the basic adjustable DRX analytical model, researchers can optimize the parameters to fulfill application requirements. For instance, considering two scaling factors, one for the short DRX cycle and the other for the long DRX cycle, we can balance the trade-off between delay and power consumption by setting the scaling factors [22]. The analytical results show that smaller scaling factors are more suitable for delay-sensitive applications since the short DRX cycle increases exponentially. Moreover, we can limit the UE's delay to a tolerable level by constantly increasing the short DRX cycle after a given threshold. Besides, if setting a longer on duration timer in the long DRX cycle than in the short DRX cycle, we can prevent the UE from entering the next long DRX cycle and get shorter delays [23]. Furthermore, if we make all DRX parameters adjustable, including the inactivity and on duration timer, the base station can reconfigure the DRX based on the Channel Quality Indicator (CQI) reporting [24], [25]. The results show that both power consumption and delay are lowered compared with the static DRX.

Instead of optimizing the DRX parameters, we can improve the performance by modifying the mechanism. For example, a six-state DRX was proposed to prevent the UE from immediately switching from the short DRX cycle to the long DRX cycle under bursty web traffic [26]. A UE can also maintain two DRX settings for multiple traffic flows, such as active and background traffic, and dynamically switches between them [27]. The switch condition could be the UE's Power Preference Indicator (PPI). If so, we can minimize the delay for active traffic and reduce the UE's active time for background traffic. We can also design a DRX-aware power and delay optimized resource scheduler [28]. According to the estimated transmission delay, the scheduler can prioritize the UE with the most prolonged delay.

Suppose the characteristic of the arriving data pattern is known. In that case, the configuration of the DRX cycle should dynamically fit the arriving data period so that the trade-offs between user throughput and power savings could be optimized [29], [30]. Such traffic-based DRX mechanisms can also enhance power savings while fulfilling the delay constrain simultaneously [31], [32]. The system can select the best energy-saving DRX parameters by conjecturing the UE's traffic status.

Another way to contribute to academia is to improve the mathematical modeling of the DRX mechanisms. Most researchers make assumptions about the system to derive formulas in closed form effectively. However, the premises lead to errors in the final analytical results, so it is imperative to improve the model accuracy without conducting sophisticated mathematical techniques [33]. The exact analytical models for power consumption and packet delay should also be validated by accurate simulations [34]–[37]. After deriving the accurate analytical models, the network operators can optimize the DRX performance by jointly considering packet delay and power-saving based on the results.

Moreover, we could model other parts of the network more accurately. First, the web traffic consists of one main object with several embedded objects. We can improve the power-saving performance at the cost of tolerable delay by handling the web traffic characteristic well [38]. Second, considering RRC state transition in the PSF and actual power consumption modeling also helps the UE enter Idle and save more power under a lower packet arrival rate [39]. Third, examining batch packet servers instead of a single packet server benefits the DRX mechanism's optimization [40]. The batch packet server buffers the received packets proactively until the number of packets in the server attains the buffer threshold. The results showed that the batch packet server saved more power under a high packet arrival rate.

B. DRX for voice and VoIP services

Voice traffic is bursty with a low data rate compared to other traffic. Speech traffic models, such as the Brady model [41], are used in Voice over Internet Protocol (VoIP) research. Because users experience a series of short silences while talking, DRX is suitable for VoIP applications. The impact of DRX on QoS and the power-saving performance under VoIP were studied in [42]–[45].

The influence of packet scheduling and resource allocation for power-saving in VoIP is critical [42]–[44]. Dynamic and semi-persistent packet scheduling strategies help solve the scheduling problems for VoIP. A UE is recommended using only the long DRX cycle in VoIP, according to [42]. The additional short DRX cycle causes more downlink packet loss and delay. In addition, setting appropriate Transmission Time Interval (TTI) sizes according to the instant UE DRX states also improves the power saving of VoIP [43]. Besides, the opportunistic scheduling approach considering the Quality of Experience (QoE), UEs' fairness, and DRX status proposed in [44], [46] reduces packet delay and packet loss. The mechanism improves fairness and UE power saving with high user satisfaction. We can compute more accurate energy consumption and packet delay if we further consider the DRX light and deep sleep [47].

It is also helpful to switch the DRX parameters dynamically for the VoIP services as in web browsing services [48]. An algorithm can determine the optimized DRX parameters depending on the application's delay or power-saving constraints. Similarly, adaptively reconfiguring DRX parameters based on average packet delay and CQI information reduces the UE's power consumption and packet delay [49]. Comparing to static DRX, the dynamic DRX algorithms reduced 60%, 60% and 75% packet delay and 75%, 43% and 90% power consumption for video streaming, VoIP, and bursty data applications, respectively.

Another solution is to design the voice traffic generator and DRX mechanism jointly. For example, in [45], suppose the traffic model generates one voice packet every 20 ms during talking and no packets during the silence period. Then we can set the inactivity timer to zero and add a random number of short DRX cycles before entering the long DRX cycle. Consequently, the UE can enter dormancy after receiving the packet. The results show that the modified DRX saves more power than the conventional DRX.

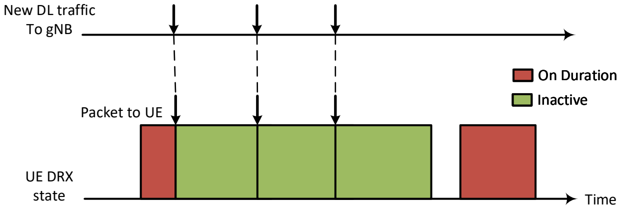
Some researchers focus on multiple types of traffic. If a UE has both VoIP and best-effort traffic, the impact of the DRX mechanism on throughput is worth studying [50], [51]. In this case, VoIP users with buffered data are scheduled preferentially over best-effort users. According to the results, a long DRX cycle and short inactivity timer lead to higher cell throughput. If we further study the DRX power consumption ratio and cell capacity, we would find that deploying a short DRX cycle with a short inactivity timer reduced the UE power consumption without degrading cell capacity. Another issue is the CQI measurement. The on duration may expire before the CQI information is available in the scheduler on the base station side. In this case, a CQI preamble for the measurements before the on duration could solve the outdated CQI information [52].

C. DRX for video and multimedia services

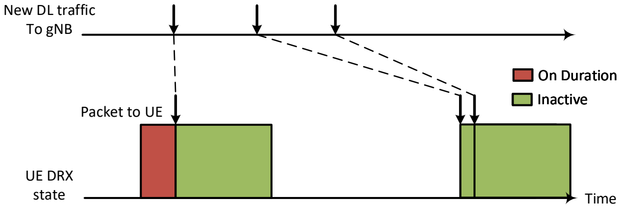
Video traffic occupies the most considerable portion of all data traffic in the wireless network. The video streaming applications, including YouTube, Netflix, and Facebook, have grown exponentially in recent years and create massive video data. We also consider video streaming as an intensive power-draining application. Therefore, researchers are dedicated to applying the DRX mechanism to save power without harming video streaming QoE [53]–[58].

There are several video streaming services, such as on-demand streaming, live streaming, and video calls. The most important factors related to the QoE are the video quality and the buffering delay. Nowadays, most servers usually cut the video into small segments while streaming video data. For example, a one-minute-long video may be divided into 30 two-second-long clips. These clips would then be encoded into different qualities and be streamed to the users. This upper layer behavior would result in a periodic bursty traffic pattern and is suitable for the UE to save power with the DRX mechanism.

For the video services that encode and transmit the video data on-the-fly, such as video conference calls, the DRX mechanism is still effective. Consider a high-quality video with 30 fps 1080p, whose video bitrate is usually in the scale of 10,000s kbps. The frame period is around 30 ms, and the frame size is about 300 Kbits on average. Such a traffic pattern is still helpful for the DRX mechanism. The UE can save much



(a) DRX without traffic regulation.



(b) DRX with traffic regulation.

Fig. 14. As shown in Fig. (a) and (b), DRX with traffic regulation can increase the UEs' opportunities for DRX and improve the power efficiency.

RF power while video streaming by configuring an appropriate parameter set (e.g., a suitable DRX cycle and a short inactivity timer).

Transmission scheduling, resource allocation, traffic regulation, and packet bundling can be applied for DRX operation to achieve better power-saving while maintaining the required QoE. From the aspect of transmission scheduling, a scheduler could consider the video buffer level to avoid draining, which is one factor harming the QoE [53]. A scheduler can also prioritize the UEs according to their DRX status. For example, the Evolved Node B (eNB) assigns higher priority to a UE if its remaining active time is lower [59]. If the streaming resolution is known to the radio access network, the network can further switch the DRX parameters based on the streaming resolution [60]. From the resource allocation perspective, we can consider joint optimization of power consumption and QoE [54]. We can use a generally known traffic pattern to analyze the video QoE under DRX operation. For example, the truncated-Pareto distribution is suitable for self-similar traffic, such as web browsing and video streaming [61]. When the traffic pattern or channel status is distributed in an unknown manner, we can also leverage prediction methods to dynamically adjust the optimized parameters [57], [58].

We can also predict video frame sizes to estimate the necessary radio resource in advance, allowing the gNB to adjust the DRX cycle length for power consumption reduction dynamically. The concept of traffic regulation is shown in Fig. 14. With traffic regulation, UEs could keep dormant longer and shorten the data reception period [55], [56]. Packet bundling is a potential solution for uplink video transmission. The packets generated at the UE are not transmitted immediately. Instead, they are bundled together and transmitted once the bundle size exceeds a threshold [62]. Through packet bundling, the UE can reduce signaling overhead and power consumption at the cost of longer latency and the possible inflexibility of the uplink grant schedule.

D. DRX for uRLLC services

Critical applications and services, such as disaster alerts and healthcare sensors require the system to support uRLLC. Traditionally, the optimization of reliability and delay is more important than the power consumption of devices, but the battery life is also vital; thus, some researchers also focus on enabling DRX for uRLLC services. Although the DRX mechanism saves the power, it also increases the packet delay and interrupts the uRLLC services. Researchers work on the feasibility of maintaining the low latency requirement for UEs with DRX configured.

Suppose we conduct a measurement of one-way end-to-end latency. In that case, we can control the over-the-air traffic and the air interface configuration and reduce the delay by shortening the DRX cycle or increasing the on duration timer [63]. The UE can also increase the scheduling request opportunities to reset its inactivity timer and prevent itself from entering dormancy. However, the adjustments to meet the latency requirement substantially raise the power consumption.

To exploit the DRX mechanism in the tradeoff between latency and power consumption in uRLLC applications, we can group neighboring UEs to notify each other of the downlink packets via Device-to-device communication (D2D) links [64]. Another way is to equip the UE with a secondary WUR. The WUR consumes little power in active mode, and the primary radio can stay in DRX more. The gNB transmits a narrowband signal over the WUR to wake up the UE's primary radio [64].

E. DRX for uplink transmissions

As introduced in Sec. II-B, although the DRX mechanism is mainly designed for downlink traffic, the power-saving performance is also influenced by the uplink data traffic. Therefore, researchers also tried to examine and improve the power efficiency for UEs with both downlink and uplink traffic flows.

In [65], Baek *et al.* were the first team to establish a Markov-based analytical model for the LTE DRX mechanism for a UE with both downlink and uplink traffic flows. They considered the schemes that the UE would directly send the uplink packets even if it is in the sleep state. They justified that the power consumption grows with the uplink traffic arrival rate if the UE directly wakes up to send the uplink packets during the dormancy. Polignano *et al.* investigated the uplink behavior of the VoIP applications for the UEs with DRX configured [42]. They studied the effects of the downlink/uplink scheduling methods, including dynamic scheduling and Semi-Persistent Scheduling (SPS), on power consumption. In [66], Ergul *et al.* studied the DRX performance for UEs with both downlink and uplink traffic. Different from the model in [65], Ergul *et al.* enabled the eNB to postpone a UE's uplink scheduling requests until the next DRX on duration with the consideration of its QoS and power consumption. Ramazanali and Vinel solved the scheme with a special military service traffic model, including downlink and uplink traffic [67]. They thoroughly investigated the DRX performance for such particular service.

In [68], Afrin *et al.* researched the SPS for the uplink Machine Type Communication (MTC). They considered multi-services and tried to optimize the resource allocation for SPS. Besides, the DRX cycle is synchronized to the SPS scheduling cycle to obtain the maximum power efficiency. In [69], Tirronen *et al.* investigated the DRX mechanism for MTC devices with a detailed power consumption model where both the downlink and uplink traffic are considered. Based on their analysis results, they conclude that the DRX cycle for MTC devices could be longer to get better power-saving performance.

Based on the analysis of state-of-the-art uplink-related DRX mechanisms, we can conclude that optimizing the power consumption with joint consideration of the downlink and uplink traffic's QoS improved the performance of power saving remarkably.

F. Others

For specific applications other than those mentioned in the previous subsections, we can still enhance the DRX operation. For example, for always-on type applications, the power consumption analysis in terms of RRC signaling load and DRX mechanism is important [70]. Diverse data application (DDA) traffic features small data packets generated every few seconds even if the application itself is not active. As one of the most recently prevailing human-type services, DDA traffic is hence worth analyzing [71]. Assuming general Poisson arrival, the authors in [72] discussed the effect of short DRX cycle, long DRX cycle, on duration timer, and the mean packet arrival rate on PSF and delay.

For general use cases, the traffic pattern is usually unknown, putting more difficulty on the analysis and enhancements of the DRX operation. A model of real traffic patterns is provided in [73]. We can find that the inactivity timer has less influence on power saving than the DRX cycle and the on duration timer. The authors of [74] also researched the DRX operation on real traffic patterns. They reduced UEs' active time by introducing a pointer determining which radio subframe contains data. The UE goes to sleep if the subframe has no data, yielding a higher sleep ratio.

As for unknown channel status or traffic patterns, an operator can adopt adaptive DRX methods to reduce the power consumption by adapting the DRX parameter according to the traffic condition without a prediction procedure. For example, the DRX cycle length could gradually increase or decrease according to the packet arrival [75], [76]. If no packet arrives in a given threshold period, the DRX cycle length increases, and vice versa. The inactivity timer and the on duration timer could also be adapted based on the traffic load and system load [77], [78].

It is also practical that the network predicts or estimates the channel quality or traffic pattern before adjusting the DRX configurations. Such methods usually yield better optimization results with higher estimation accuracy at the cost of additional computational resources and latency for the prediction and estimation. We can consider a two-stage procedure for an online power-saving optimization in real-time [79]–[81]. In the first stage, the network estimates the real-time traffic pattern or channel status, whereas it conducts optimization algorithms in the second stage.

However, the adaptive DRX mechanisms require frequent reconfiguration of DRX settings. To improve the signaling overhead caused by frequent reconfiguration, we could enable an eNB to delay new downlink traffic before their corresponding downstream queues reach a predefined adjustable threshold [82].

G. Summary

From the evolution of the wireless mobile network, we can find that communication systems are required to serve more and more kinds of services. These services have different traffic patterns and properties, including batch downloading, periodic traffic, etc. To enhance the power efficiency without harming the service quality, we should jointly optimize the traffic patterns and the DRX configurations. In most cases, long DRX cycles could improve the power efficiency, but the packet delay also increased. A long inactivity timer would result in a short packet delay, but the power consumption would be considerable.

On the other hand, most research proposed adaptive solutions to change the DRX cycle dynamically. Some work proposed the gNB to make traffic regulations for mobile devices. Although this increases the average packet delay, the UEs obtain more opportunities for power-saving.

VI. DRX DESIGN IN SPECIFIC SCENARIOS

To satisfy various requirements of the applications, researchers have developed many solutions and schemes for the wireless mobile network. However, the newly designed technologies bring difficulties to the DRX mechanism. There are also existing difficulties in the traditional networks, such as the DRX optimization for UEs with ongoing unicast and multicast traffic flows. Therefore, researchers also pay attention to the DRX issues. In the following subsections, we will introduce the challenges in different scenarios, such as Heterogeneous Network (HetNet) and D2D, and summarize state-of-the-art DRX in specific scenarios. Table V also provides a detailed list.

A. DRX for heterogeneous network

The network operators often prefer HetNet architecture because it could provide better coverage and system capacity. Besides, Multi-connectivity (MC) and CA have been introduced into LTE and NR to enhance the system throughput further. As shown in Fig. 15, MC enables UEs to establish connections to multiple APs simultaneously. An AP can be either an eNB or a gNB, depending on the surrounding RATs. With the coordination among the APs, a UE can receive data from all connected APs.

On the other hand, CA enables UEs to receive data on different carriers at the same time. It can also be integrated with MC to enhance the throughput further. Fig. 16 depicts the concept of the CA technique. For example, one gNB has

TABLE IV
DRX OPTIMIZATION DRIVEN BY SERVICES

Paper	Target traffic	Problems or challenges	Approach	Metrics
[17]	ETSI bursty model	Derive analytical model for LTE DRX	Semi-Markov model design	PSF, delay
[18]	ETSI bursty model	Maximize PSF without extra delay	Semi-Markov model design	PSF, delay
[19]	ETSI bursty model	Derive analytical model for LTE DRX	Semi-Markov model design	real-PSF, delay
[20]	Diverse Data Applications (DDA)	Derive accurate analytical model for LTE DRX	Semi-Markov model design	PSF, delay
[22]	ETSI bursty model	Attain a better trade-offs between power saving and delay	Semi-Markov model design	PSF, delay
[23]	ETSI bursty model	Improve power saving	Semi-Markov model design	PSF, delay
[24]	Random bursty model	Improve power saving	Adjusting DRX parameters based on CQI	Remaining energy, delay
[26]	Bursty web traffic model	Improve power saving	Semi-Markov model design	PSF, sleep energy
[27]	Bursty model	Attain a better trade-offs between power saving and delay	Semi-Markov model design	Delay, PSF
[28]	File Transfer Protocol (FTP)	Attain a better trade-offs between power saving and delay	DRX-aware and optimized scheduler	FTP end-to-end delay, power consumption, throughput fairness index
[42]	VoIP	Improve power saving	Measure the power costs	power consumption
[43]	VoIP	Improve power saving	Measure the power usage	Power usage
[46], [44]	VoIP	Improve power saving, decrease packet delay and losses	Opportunistic scheduling approach	Mean Opinion Score (MOS), throughput fairness index, delay, packet loss ratio
[45]	VoIP	Improve power saving	Semi-Markov model design	PSF
[53]	Hypertext Transfer Protocol (HTTP) video streaming	Shorten the interruption duration during streaming	Scheduling method (PBDAS)	Power consumption, initial delay, interruption delay
[54]	Dynamic Adaptive Streaming over HTTP (DASH)	Decrease power consumption, maintain video quality	Optimization	Power consumption, MOS
[55]	On-demand video services	Improve power saving	Probabilistic model	PSF
[56]	M/G/1 busy period	Improve power saving	Probabilistic model	PSF, video frame delay
[57]	Video streaming	Improve power saving	Optimization	Energy usage, number of empty slots
[58]	Video streaming	Improve power saving, prevent buffer underflow	Optimization	Energy usage, number of buffer underflows
[83], [84]	Real data, burst traffic, video streaming	Reduce packet delay	LSTM model for traffic prediction	Root Mean Square Error (RMSE), PSF, delay
[63]	uRLLC	Satisfy the uRLLC requirements for DRX configured UEs	Experiments, shortening DRX cycle, increase scheduling requests	One-way delay
[64]	uRLLC	Trade-off between energy efficiency and the packet delay	Grouping, WUR	–
[71]	Poisson model	Investigate the DRX analytical model	Semi-Markov model design	PSF, delay
[75]	Poisson model	Increase the flexibility deployment in DRX	Semi-Markov model design	Delay, power consumption, sleep ratio
[76]	Poisson model	Increase the flexibility deployment in DRX	Heuristic algorithm	Delay, power consumption, PSF
[82]	Poisson model	Reduce DRX reconfiguration in adjustable DRX	Heuristic algorithm	PSF, queuing delay
[81]	Erlang model	Improve energy efficiency	Two-phase data driven approach	Energy reduction, delay
[72]	Poisson model	Analyze the DRX effect	Semi-Markov model design	Energy consumption, delay, PSF
[73]	Two-type traffic	Investigate DRX effect	Probabilistic model	Delay, PSF
[74]	Live mobile network	Reduce power consumption	Intra-subframe micro sleep, pointer of the radio subframe with data	Delay, active time reduction, active time in bursty hour

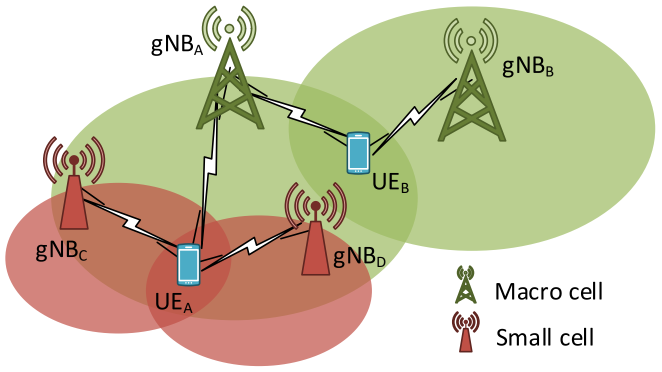


Fig. 15. HetNet typically consists of macro cells and small cells. If a UE has multi-connectivity, it can simultaneously connect to multiple cells. All linked gNBs should jointly optimize the corresponding DRX configuration.

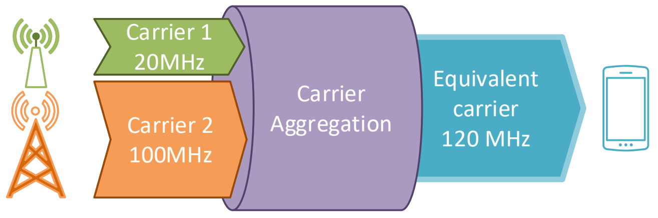


Fig. 16. With the CA technique, the gNB to collects bandwidth fragments and aggregate them into a single carrier for the serving UEs.

a 20 MHz channel, and the other has 100 MHz. With CA, the UE would have a 120 MHz equivalent carrier.

However, if the UE requires power saving, the DRX configuration becomes much more complicated than the configuration for a single connection. For the example in Fig. 15, the DRX for UE$_A$ should be cooperatively optimized by gNB$_A$, gNB$_C$, and gNB$_D$. The UE$_B$ also faces a similar situation. Without the negotiation between the APs, the UEs might lose all opportunities for DRX even if the UEs apply the DRX mechanism.

Maintaining the DRX configurations for different connections or carriers is one of the essential issues in this scenario. If the carriers operate on the same RF module, the UE is active if at least one of the carrier operations is active. In such cases, applying a common DRX configuration to all connections can be considered [85], [86]. With the common configuration, the active periods of different carrier operations overlap with each other as much as possible, leading to a reduced active ratio. In contrast, if the carriers operate on different RF modules, carrier-specific DRX configurations save more power than a single DRX configuration [87]. Classification of traffic characteristics further enhances the independent operation mode since the gNB can properly adjust each DRX configuration according to a specific traffic profile.

A UE is also connected to two network entities in the relay hotspot scenarios. It is a receiver through a cellular interface; meanwhile, it serves as a transmitter on the relay link through the WiFi interface. In such scenarios, power mitigation is beneficial to align the DRX cycle of the relay UE with the WiFi sleep cycle of the remote UE [88].

As shown in Fig. 17, an Multi-SIM Multi-Standby (MSMS) scenario can be regarded as a multi-connectivity case with the difference that MSMS operation treats each Subscriber Identity Module (SIM) as an independent entity. In contrast, multi-connectivity operation controls all of the UE's connections. Like multi-connectivity, MSMS UEs consume more power than single SIM UE. Since the SIMs control the same RF module, the UE would consume more power if there is no coordination for the DRX between its two Internet service providers [89].

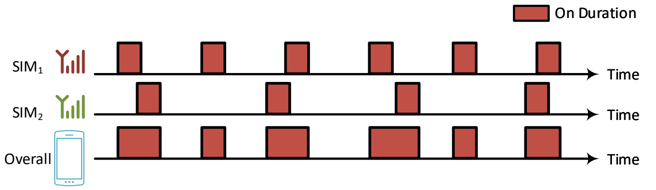


Fig. 17. Example of an MSMS UE with DRX configured. The UE has to turn on its RF module when any of its SIM card is configured to be on duration.

In addition to the mechanism design, optimization is also of great importance in the HetNet DRX operation. The major objective is the minimization of power consumption or the maximization of sleep ratio. We can group the decision variables into three types: the DRX-intrinsic [90]–[92], the MC-related [90]–[92], and the CA-related parameters [93]. The DRX-intrinsic parameters are the most fundamental parameters affecting the DRX operation, such as the DRX cycle length, the inactivity timer, and the on-duration. The MC-related parameters include the pairing relation between the UEs and their surrounding APs. As for the CA-related parameters, given multiple available carriers, the main decision variable is the selection of carriers for the UEs.

Besides power consumption, we can leverage the DRX mechanism for inter-cell interference mitigation in HetNet. By combining DRX and Almost Blank Subframe (ABS), if most UEs are dormant in one cell, then the subframe is almost blank to avoid interfering with the neighboring cells, and the neighboring cells could share the same frequency resources [94], [95].

Last, some other network topologies similar to HetNet are worthy of analysis for their specific features. Cloud-based Radio Access Network (C-RAN) is composed of numerous baseband units and remote radio units. Baseband units are responsible for computational tasks and the upper layer of wireless communications, whereas remote radio units are in charge of the transmission and reception of the physical signals. A detailed analytical power consumption model for C-RAN is provided in [96]. Another similar scenario is the multi-RAT connection, where a device is connected to multiple access points via different radio interfaces. For different wireless communication technologies, different power-saving mechanisms are applied; as a result, it is worth researching how the power-saving protocols interact with each other. A power estimation model is proposed in [97], and experiments are conducted in [98], which are strong bases for future research on the interaction between multi-RAT power-saving mechanisms.

B. DRX for unlicensed bands

A method to increase system throughput is to utilize unlicensed bands. In LTE, License-Assisted Access (LAA) is the technology that allows the transmission over unlicensed bands; likewise, 3GPP is also progressing on NR-Unlicensed (NR-U) for the NR network. For fairness to all RATs operating on the unlicensed band, all devices should perform Listen-Before-Talk mechanism (LBT) while accessing the unlicensed channel. Afterward, a device should randomly assess the channel to transmit data on the unlicensed channel. It transmits data if the channel is idle; otherwise, it waits for another random period.

Under LAA operations, UEs should remain active during the LBT procedure and suffer from extra power consumption, so applying DRX to LAA is favorable and beneficial. However, the main challenge is the randomness of the transmission over shared unlicensed bands. A feasible method is that eNB commands the UE to turn its RF module on or off according to the unlicensed channel status [99]. On the other hand, the transmission of unlicensed access is limited for the sake of fairness requirements, i.e., a UE must interrupt its data transmission at the transmission period limit [100]. Thus, the PSF can be enhanced by synchronizing the licensed and the unlicensed channel [101].

C. Grouped DRX

Grouping UEs is a robust solution to support massive devices in the wireless mobile network. If UEs send enormous uplink requests to the AP at once, they would use up the control resources and crash the system. In this case, the wireless network operator can group the UEs with similar traffic patterns to reduce signaling overhead; thus, the network could avoid the radio congestion caused by traffic bursts. The DRX mechanism could be applied to the separation of groups. Using various DRX cycles and timing offsets, the UEs in different groups could take turns to wake up. Thus, the main challenges are grouping UEs with similar traffic and optimizing DRX parameters for each group. For downlink cases, the multicast and broadcast services for different UE groups suffer from the same problem. Fig. 18 shows that two UEs with personal DRX settings receive the same multicast flow. The gNB could send the multicast packets only when the UEs are both in the active state; otherwise, the gNB should send the packet via unicasting, which costs more wireless resources. The problem would be more complicated when there are more multicast flows and UEs with different DRX configurations.

For uplink grouping-based DRX, an operator can separate the report timings by assigning different DRX configurations for different UE groups to avoid instantaneous intensive reports [102], [103]. In downlink multicast scenarios, the base station delivers a single data packet to multiple UEs through the same radio resources. In such scenarios, it is challenging to apply DRX operation since the UEs may not be active concurrently without the alignment of their DRX configurations. In such cases, a compromised solution is that gNB duplicates the transmission on different time slots and delivers the multicast service separately to a sub-group of UEs that are simultaneously active [104], [105]. Another solution is to optimize the DRX configurations of the UEs with joint consideration of resource efficiency and power consumption. In LTE, the physical channel for multicast services is periodic, so the eNB has a holistic view of the status of each UE. As a result, the optimization of transmission order scheduling for different multicast groups is essential [106], [107]. As for NR, PDCCH, and Physical Downlink Shared Channel (PDSCH), which are dynamically configured, serve as the physical channels for multicast service. With a more dynamic framework in NR, it is more important to research the impact of the grouping method and the parameter configuration under uncertain packet arrivals.

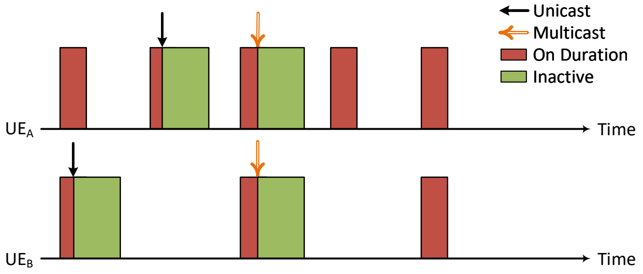


Fig. 18. If two UEs apply different DRX configurations, the gNB could use multicast only when they are both in the active state; otherwise, the gNB should distribute the packet via multiple unicast transmissions.

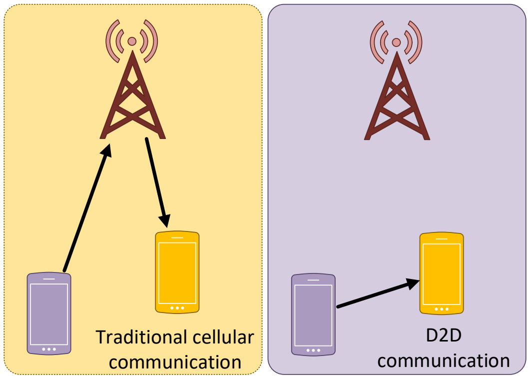


Fig. 19. With the D2D mechanism, the UEs within the same cells could directly communicate with each other.

D. DRX for Device-to-Device communications

D2D technology enables devices to communicate with each other over sidelink directly. Fig. 19 shows the comparison between traditional cellular communication and D2D communication. With the advantage of shorter distances, data rate and reliability are enhanced. There are also challenges in applying the DRX mechanism to D2D communications.

The first challenge is the DRX operation of a UE, which relays data from an eNB to multiple remote UEs. The power consumption of the relaying UE is more critical since it maintains multiple connections. In such scenarios, it is beneficial that the remote UEs follow the schedule of relaying UE to mitigate the power consumption on both sides [108].

The second challenge is the problem of the discovery procedure. Before transmitting and receiving on the D2D interface, a UE should perform the discovery procedure to establish D2D connections with other UEs; meanwhile, the data reception from eNB is still ongoing. Hence, a model for the discovery behavior is necessary for further enhancements [109]. Possible directions include mechanism modification and parameter optimization. When a UE has no D2D connections, the duration of the discovery procedure can be conditioned on the DRX parameters so that the discovery procedure is finished within the active period.

The third challenge is beam tracking with DRX operations under high-mobility D2D transmission scenarios, especially in the NR network. Since the beamforming technique is widely used to solve the high pathloss in high-frequency bands and improve the transmission rate, the transmission link becomes directional in the new generation mobile network. UEs need to keep maintaining the best beam configuration via beam tracking. The possibly frequent beam misalignment resulting from DRX dormant period and device mobility cause longer latency for connection reconstruction. As a result, the device mobility and the beam tracking mechanism should be incorporated into the DRX mechanism in such scenarios.

E. DRX for Internet of Things network

Internet of Things (IoT) devices often have limited energy; hence, the power-saving method is incredibly crucial. To capture the IoT features, the derivation of the analytical model for different IoT requirements and traffic profiles is important. It is a cornerstone for recent and more advanced research. An accurate model for DRX in IoT scenarios is provided in [110]. The authors used one state for DRX active, $2N$ states for N short DRX cycles, and $2L$ states for L long DRX cycles. Considering an IoT scenario as well as a multimedia scenario where a military train is applied, the authors in [67] proposed a discrete-time Markov model for the DRX mechanism instead of the semi-Markov model. An IoT scenario with transmission characteristics similar to conventional cellular transmissions is considered in [111]. For power charging and energy harvesting devices with DRX operation, the power consumption models differ from the previous ones with the feature of energy gain [112], [113]

The objective of the optimization of DRX mechanisms is power consumption, while the decision variables include the DRX-intrinsic and the IoT-related parameters. For optimization on DRX-intrinsic decision variables, DRX cycle length, inactivity timer, and on-duration are determined with joint consideration of IoT constraints [114]–[119]. As for the IoT-related parameters, the packet transmission order [116], the bundling interval sequence [120],

The constraints in IoT scenarios include the QoS requirements such as latency, bit rate, and packet loss ratio [114], [115], [117]–[121]. Signaling overhead can also be taken into account in uplink report cases [116].

We should note that in addition to heuristic methods for optimization solutions, we can also leverage a machine-learning-based method to predict the traffic pattern [114], [117], [121]. For example, the authors of [114], [117] used online learning to predict the traffic pattern. Fig. 20 shows their proposed actor-critic framework. They adopt symmetric sampling to accelerate learning. The eNB can adjust the DRX configuration based on the predicted traffic pattern.

Besides the optimization, modifying the DRX mechanism is another way to improve the PSF under given scenarios. As an example, the authors in [122] suggested that an IoT UE is allowed to conditionally switch from the on state to the long sleep state directly, which increases the possible dormant period and improves the PSF. Another feasible modification is to add a threshold on the arrival packets. If a UE receives more than a given threshold number of packets in a DRX cycle, it directly gets dormant until the next cycle [123]. The design increases the sleep ratio by conditionally shifting the dormancy instant to an earlier timestamp. However, we should note that the design may be infeasible under a high packet arrival rate since the scheduling may fail to keep up with packet arrivals. An operator can further lower the operational expenditure by reducing the network's power consumption while pursuing the UEs' low power consumption. Considering the UEs and the network jointly, we can merge the DRX operation with a polling-based power-saving mechanism operated on the network side [124]. As for Narrow-Band Internet-of-Things (NB-IoT) systems, we can add an auxiliary state to the DRX operation for the small data transmission [125]

F. Summary

Researchers have investigated the solutions to enable power-saving in most advanced technologies. Although mobile wireless networks have become more complicated, the DRX mechanism still plays a vital role. However, the DRX mechanism needs modifications in most of these cases to satisfy specific requirements. Most researchers solve this problem by modifying the trigger and procedure of the DRX mechanism or adding new signaling messages to help the UEs and gNB coordinate better.

VII. EMULATION AND TESTBED FOR DRX ANALYSIS

Though many studies are done and evaluated by numerical analysis and computer simulation, it is still essential to investigate the performance of the DRX mechanisms on testbeds consisting of real devices. These researches provide the foundations for academia to connect the numerical analysis results to practical systems.

A. Tools and power models

To evaluate the system performance in practice, developing tools and models for testbeds is essential. Many researchers were devoted to measuring power consumption and proposed power models for the in-device components. These power models help many other researchers to estimate their DRX design. First, the most important is constructing a power model for UEs. The constructed power model can help us analyze power consumption for UEs based on real traces [127]. In addition to the RF module, we may consider other device

TABLE V
RELATED WORK ON DRX IN SPECIFIC SCENARIOS

Target	Paper	Proposed solution	Approach	Metrics
HetNet, CA, MC	[97]	Estimate the power consumption.	Experiment and math derivation	Energy consumption
	[98]	Power saving analysis.	Experiment	Energy consumption, throughput
	[89]	UE determines its DRX configuration	Semi-Markov	Delay, sleep ratio
	[94]	Downlink interference control through DRX.	Heuristic algorithm design	SINR, throughput
	[88]	Keep WiFi and LTE sleep cycle consistent.	N/A	N/A
	[96]	Analytical power consumption modeling.	Semi-Markov	Power consumption, PSF, Delay
	[85]	Align the active duration.	N/A	N/A
	[86]	UE may shift directly to long-sleep.	Semi-Markov	PSF, delay
	[87]	Apply different DRX parameters to distinct Component Carrier (CC).	Mechanism design	Power saving gain
	[90]	Optimize power consumption for DRX parameters and Remote Radio Head (RRH) Joint Transmission (JT) pairing.	Heuristic algorithm design	Throughput, resource utilization rate, power consumption, fairness, complexity
	[93]	Minimize wake-up time via resources allocation for UEs with CA DRX.	Integer programming	Resource utilization rate, power consumption, wake-up time
	[91]	Reduce UE power consumption via resource allocation and transmitting node selection.	Heuristic algorithm design	Throughput, PSF, power consumption
	[92]	Reduce UE power consumption via Resource allocation, data offloading and transmitting node selection for C-RAN schemes.	Heuristic algorithm design	Throughput, resource efficiency, power consumption
	[95]	Apply DRX and ABS to solve the inter-cell interference.	Heuristic algorithm design	Power efficiency, throughput, dropping ratio of Guaranteed-Bit-Rate (GBR) flows
LAA	[101]	Add beam-searching state to DRX state model.	Semi-Markov	PSF, delay
	[99]	Reduce power consumption of LBT procedure.	Semi-Markov	PSF, delay, resource utilization rate
Grouped DRX	[106]	Arrange multicast data reception orders.	Heuristic algorithm design	Wake-up ratio
	[105]	Power saving through group sleeping.	Heuristic algorithm design	Throughput, energy efficiency
	[102]	Avoid the signaling storm.	Semi-Markov	PSF, delay
	[103]	Improve power consumption via grouped DRX.	Semi-Markov	PSF, delay
	[104]	Improve resource utilization rate and power consumption with standard compliance.	Heuristic algorithm and mechanism design	Wake-up time, number of multicast transmissions
	[107]	Improve the utility of periodic multicast services	Heuristic algorithm design	Conserved power, PSF, failed-to-sleep probability, complexity
D2D	[108]	Take Tx/Rx states of the relay node into consideration.	Discrete-time Markov	Energy efficiency, packet delay, packet loss rate, power consumption
	[109]	Consider the discovery state in the DRX model.	Semi-Markov	PSF, delay
	[126]	Only perform beam training when data arrive.	Semi-Markov	PSF, delay
IoT	[121]	Predict the traffic arrival and adjust DRX configuration dynamically.	Machine learning (bank-of-experts algorithm) for traffic prediction, heuristic algorithm design	Power consumption, PSF, delay
	[67]	Accurate Markov model for DRX mechanism.	Discrete-time Markov	PSF, wake-up delay
	[113]	DRX in energy harvesting devices.	Discrete-time Markov	Energy consumption
	[112]	Model wireless power charging devices.	N/A	Battery lifetime
	[115]	Optimization of DRX configuration.	Heuristic algorithm design	Packet loss rate, jitter, sleep ratio, power consumption
	[116]	Optimization of DRX configuration.	Discrete-time Markov, heuristic algorithm design	Signaling overhead, power consumption, delay
	[124]	DRX for wireless interface and polling-based power saving mechanism in wired network.	Semi-Markov	PSF, delay, battery lifetime, backhaul power saving
	[110]	Quantitative modeling.	Semi-Markov	PSF, wake-up delay
	[123]	Directly go to sleep when number of accumulated packets arrive in a single cycle.	Semi-Markov	PSF, wake-up delay
	[119]	Dynamic programming.	Markov decision process	N/A
	[117], [114]	Traffic adaption for Human Type Communication (HTC) and MTC.	Online learning, Markov decision process	Energy efficiency, delay
	[118]	The UE finds optimal WUR cycle value for energy efficiency.	Semi-Markov model design, non-linear integer programming	Power consumption, delay
	[120]	Improve eDRX for IoT devices.	Online algorithm design, random process	Energy efficiency, delay
	[122]	Design DRX mechanism enabling MTC UEs to directly enter long DRX cycle.	Semi-Markov model design	Power saving gain, delay

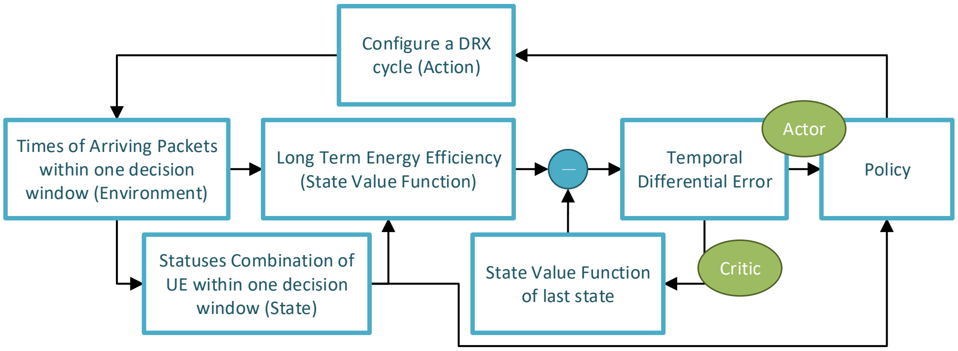


Fig. 20. Actor critic framework for DRX configuration [114].

components [128]. Afterward, we can use functions to fit the measured power consumption numerically.

It is also helpful to develop an Android application to collect devices' traces effectively and construct power models for CPU, GPU, cellular links (3G and LTE), and WiFi links based on their testbed measurements [129]. A powerful application called MobileInsight [130] enables the status monitoring of the UEs. It helps researchers acquire detailed logs from the mobile phone, such as RRC DRX state. Furthermore, we could improve the accuracy of the power model more by investigating the modem power model for all RRC states and radio events [131].

Besides, some researchers strove to build applications and tools to enable the UEs to record detailed lower-layer signaling. A measurement study of the 5G NR system could be found in [132]. They investigated the performance of the NR non-standalone system, including coverage, handover, end-to-end throughput, and packet delay. The tested services are web browsing and ultra high definition video phone call. They also presented the power consumption profiling in the 5G system and found that the dynamic switching of the EN-DC link has better power-saving performance.

B. Testbeds for DRX evaluation

Some researchers focus on the power consumption of real applications. They first observed the application's performance and implemented their proposed solutions on their testbeds. Baghel *et al.* [133] provided their observation of traffic patterns for Facebook, Skype, and TCP-based services on an Android platform. With the traffic traces, we can investigate the power-saving performance of the DRX mechanism. The operators should carefully configure the DRX parameters for different services to maintain performance. Regarding the optimization of web browsing, some researchers found that the cloud's assistance reduced the page loading time and power consumption and established cellular-friendly connections [134].

The impact of the RRC state transitions on the packet delay and packet loss can also be investigated on the testbeds. Some researchers build their testbed on Android devices by using QxDM, a tool that logs the low-layer control and data plane messages. They also measured the performance of web browsing and Facebook application [135]. Another tool for packet generating called MoonGen is also valuable for the performance measurements of the DRX mechanism [136].

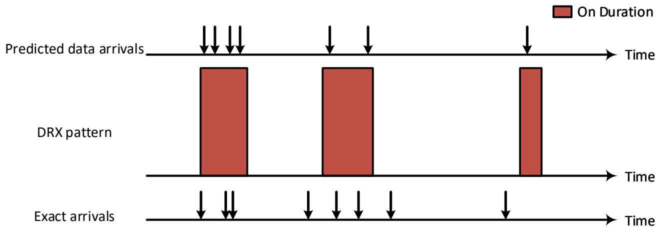


Fig. 21. UEs have more opportunities for DRX if the traffic patterns are correctly predicted in advanced. However, the wrong prediction might lead to large packet delay.

Some researchers target studying video streaming services. Based on the measurements of the YouTube streaming services over 3G and LTE systems, we can conclude that the base stations could apply a traffic shaping mechanism for the DRX mechanism on smartphones [137]. We might further improve the power consumption for TCP video streaming by using traffic shaping and building a buffer-aware application to optimize the burst size and burst interval [138], or even for video stream under bandwidth fluctuation [139]. Some researchers found that for on-demand video streaming services, including YouTube and Vimeo, prefetching video frames wastes power according to the experiment results on 3G, LTE, and WiFi testbeds. Thus, an algorithm scheduling the downloads of video clips based on the collected statistics benefits the overall system performance [140], [141].

The signaling messages and procedures of NB-IoT and LTE-M, the main 3GPP standard systems supporting the MTC, are worth investigating. Some researchers established a testbed with N211 (NB-IoT) and R410M (LTE-M) modules and measured the power consumption of different UE states and the delay of the UE state transition [142]. Based on the measured data, they constructed a Battery Lifetime model for the devices.

VIII. MACHINE LEARNING IN DRX MECHANISM

Recently, machine learning has been extensively applied to optimization problems and plays a vital role in developing the Self-Organizing Network (SON). It enables the network components to automatically and dynamically decide their configurations and parameters to optimize the performance in a highly changeable network. Researchers also investigate and optimize the DRX operations by machine learning.

A. Traffic-based machine learning

Fig. 21 shows the advantages of correctly predicting data patterns, but the wrong-predicted packets may suffer from considerable delay. By learning data patterns and predicting the outcome precisely, the machine learning methods help the network automatically configure the UEs. We already summarized some in the previous sections. Long Short-Term Memory (LSTM) model could be used to predict the packet arrival time in the real world. If the DRX cycle is configured according to the predictions from the LSTM model, a UE turns its RF module on only when the predicted new downlink packet arrives [83].

Furthermore, deploying the LSTM model in NR could capture the beam misalignment problem [84]. Another online learning algorithm trained with the data from eNB is useful to predict the next packet arrival time as well. The packet size and arrival time at eNB, as training data of the learning algorithm, help the eNB predict the packet arrival time and indicate the sleep time of UE [121].

Other than the traffic prediction, applying machine learning to the silence prediction in the VoIP services also enhances the energy efficiency of the DRX mechanism [143]. Based on the precise prediction, the voice data volume decreases by skipping the silent parts of the transmission. The overall power consumption is improved up to 30%.

B. Protocol-based machine learning

Another research category conducting machine learning in the DRX mechanism is enabling the eNB to select the DRX parameters intelligently. The DRX parameter selection problem for the NR UEs could be formulated into a contextual bandit problem and solved with Vowpal Wabbit [144]. Vowpal Wabbit is a fast and flexible open-source machine learning library developed by Microsoft Research teams and could be used to optimize the mentioned selection problem. In most cases, Vowpal Wabbit could optimize the DRX parameters with around 1,000 learning steps according to the results. Another machine learning based framework proposed by [145] also enables the UE to select the DRX parameters dynamically. The LSTM model is adopted to predict the UE's packet arrival interval and decide the proper parameters accordingly.

Instead of focusing on the general transmission scenarios, the DRX operations in the NR-U network are also suitable for machine learning-based solutions [146]. Since the access of the unlicensed wireless channel is random, it is difficult for a UE to operate the timer-based DRX mechanism with high power-saving performance. Thus, applying a machine learning-based solution when accessing the unlicensed channel helps the gNB simultaneously optimize the packet delay and power consumption.

C. Summary

This section surveyed the state-of-the-art DRX research based on ML techniques. We could identify two research directions to apply the ML methods to the DRX: traffic-based and protocol-based designs. However, both designs handle time series data such as traffic arrivals or devices' actions. In these cases, recurrent neural networks (RNN), such as the LSTM model, are helpful for the prediction. Better prediction enables the gNB to instruct the UEs to take better DRX-related actions. Although the ML-based mechanisms could improve the performance of DRX, the power consumption for training and applying the ML models should be carefully investigated. A power-consuming ML model is not acceptable for a UE with DRX configured.

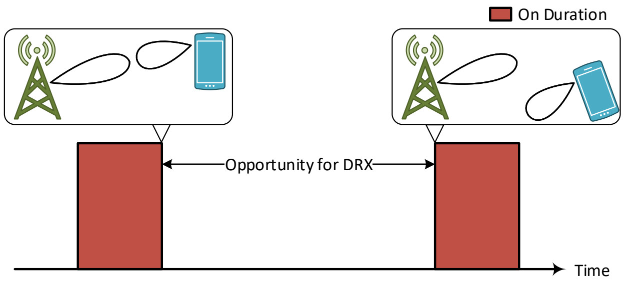
IX. NEW CHALLENGES IN NR NETWORK

In the previous sections, we investigated the issues in general mobile networks. However, when the wireless mobile network evolved from LTE to NR, we also encountered new challenges in designing the DRX mechanism. The NR system applies beamforming technology to improve the system throughput and capacity. Moreover, the beamforming technique also enables the wireless mobile network to operate on the millimeter-wave band. In 4G LTE systems, digital beamforming techniques are only applied to the transmissions of user plane data. The eNB directly broadcasts the control messages to all UEs within its coverage area. Nevertheless, the control messages in 5G NR systems are also transmitted via beamformed links. Consequently, the control messages are more likely to be blocked or dropped because of the link's directionality. Researchers must review most procedures between the gNB and UEs, including the DRX mechanism. Thus, most studies of NR DRX are related to beam operations.

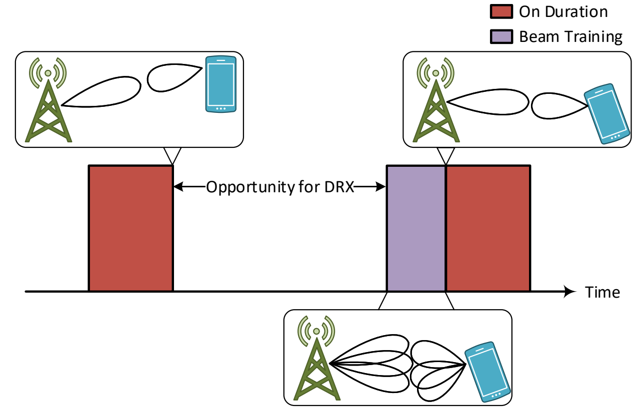
In addition to the issues of beamforming, the WUR-based design called power saving signal in the NR network is another new technique in the NR network. It helps the gNB manage the UEs' dormancy flexibly, so many researchers also investigated the performance based on the WUR. We will summarize the main aspects in the following subsections.

A. Beam management for DRX

The main problem of DRX with beamforming is that the UE might lose the connection after the dormancy period since it does not perform the beam tracking during the dormancy period. Fig. 22(a) shows an example of the beam mismatch. Although the UE has found the best beam pair between the gNB and itself, its movement and rotation break the link after the dormancy. Moreover, the directional links are more likely to be blocked by blockages in the millimeter-wave band. Fig. 22(b) presents the central concept of the solution proposed in [147]–[149]. The UE and the gNB perform beam training before the on duration. In the beam training procedure, the gNB transmit reference signals in every beam direction, and the UE tries to receive the reference signals on any of its receiving beam. After the procedure, the UE can know the best beam pair and fixes its communication. In the DRX scheme, advance beam training recovers the beam pair for



(a) Beam mismatch might happen after the short dormancy.



(b) Beam training at the beginning of the active time could ensure the link accessibility.

Fig. 22. As shown in Fig. (a) and (b), the beam training enables the DRX mechanism when the system applies directional links. However, it consumes additional power and reduces the opportunities for DRX.

the communication in the next on duration. Therefore, the NR UEs can execute the DRX procedure successfully.

The beam training also increases power consumption overhead to the system, although it solves the beam mismatch problem. Typically, the gNB and the UE must test all beam combinations to find the best pair. The process consumes not only extra UE power but also several timeslots. Therefore, many feasible solutions could address this kind of problem in DRX operations from different perspectives [126], [150]–[155]. The overhead imposed by the beam training procedure is eliminated by using an algorithm to monitor only a portion of the cells and beams in the DRX mechanisms [150], [151]. In [152], the D2D devices perform the beam training and share the training results cooperatively. Moreover, if the UE operates in the MC mode, the gNB could send the beam training indication via the more reliable link [154]. For power conservation, beam tracking strategies using various types of bandit algorithms are adopted to track only a fraction of the available beams [151]. The simulation results concluded that even a sub-optimal link achieves considerable power conservation at the cost of relatively little degradation on link performance. Table VI summarizes the solution of these papers.

B. *Configuration optimization for directional DRX*

In addition to the beam matching problem discussed in the previous subsection, the researchers identified another opportunity for power saving in the NR network. The gNB cannot cover every UE at once with beamforming, so the UEs temporarily out of beam coverage have the opportunity for DRX. As shown in Fig. 24, the traditional gNB has high flexibility in scheduling, but the UE might be out of beam coverage during most of its active time if the gNB is required to serve UEs on different beams. Fig. 25 shows this beam matching problem from the perspective of the system. The UEs on the inactive beams have the opportunity for DRX.

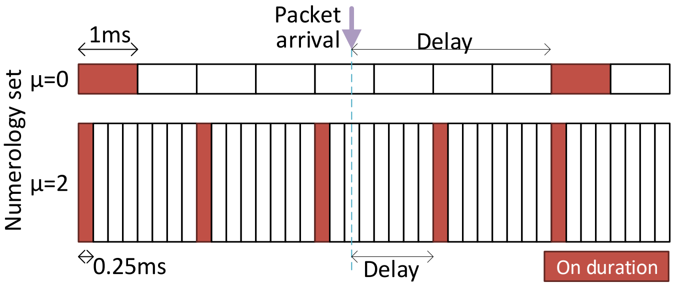


Fig. 23. Packet delay is different when the DRX mechanism is configured to give the same PSF under different numerology settings.

Therefore, if a UE knows the beam directions used by its serving gNB, then the UE can enter light dormancy while the gNB is serving the UEs on other beams. Although this brings some limitations and overhead of scheduling to the gNB, some studies have shown the profits in [156]–[158]. Other ways focusing on integration in the NR network frame structure improve the performance of DRX in addition to the solutions described [159]. The NR system supports a more flexible frame structure, also known as flexible multi-numerology, to satisfy various kinds of services. When a larger subcarrier spacing is selected, the length of a timeslot is shorter. Therefore, the larger subcarrier spacing is more suitable for a strict delay-aware service, whose delay requirement is smaller than a traditional subframe duration 1 ms. The evaluation results showed that the DRX performance depends on the selected numerology. Fig. 23 shows an example for the DRX under different numerology settings. In both cases, if we set the PSF equal to 0.125, we can see that when $\mu = 2$, the DRX cycle could be shorter because of the short timeslot duration. Hence, the delay of the arrived packet is shorter. To sum up, the NR system has many new properties compared to the traditional LTE network, so many open issues are still worthy of further study. Table VI provides a detailed comparison between these papers.

C. *DRX with power saving signal*

IEEE 802.11ba [160] proposes the WUR to solve the power consumption of green IoT applications in wireless local area networks. A device supporting WUR is equipped with a low-power receiver to monitor the wake-up signal. If an indication for packet reception is detected, the device turns on its primary receiver and receives the data. 3GPP adopted the concept of WUR and proposed the power saving signal to further improve the DRX mechanism in Release 16. The discussions of WUR in 3GPP standardization meetings also encouraged researchers

TABLE VI
RELATED WORK ON DRX IN NR NETWORK

Target	Paper	Proposed solution	Approach	Metrics
Beam training for NR DRX Basic design	[147]	Trigger beam training before the UE wakes up.	Semi-Markov model design	Beam mismatch probability, power consumption, delay
	[148]	Consider beam training for UEs in connected state.	Semi-Markov model design	PSF, delay
	[149]	Consider beam training for UEs in both idle state and connected state.	Semi-Markov model design	PSF, power consumption, delay
Improve power consumption	[150], [151]	UE monitors only parts of the beams and cells.	Heuristic algorithm design	PSF
	[126]	Unmanned Aerial Vehicle (UAV) only performs beam training when data arrive. UAV movement is considered during beam training.	Semi-Markov model design	PSF, delay
	[152]	D2D devices cooperatively perform beam training.	Semi-Markov model design	PSF, delay
	[153]	Beam failure triggers beam training.	Semi-Markov model design	PSF, delay
	[154]	UE in MC mode receives beam training indication via the more reliable link.	Semi-Markov model design	PSF, delay
	[155]	UE skips beam training during the light traffic state.	Semi-Markov model design	PSF, delay
	[151]	UE only tracks a fraction of available beams.	Bandit algorithms	PSF, throughput
Beam-aware Directional DRX	[156]	The gNB uses dynamic beam frame for traffic adaption	Semi-Markov model design	PSF, delay
	[157]	UAV only performs beam training when data arrive. UAV movement is considered during beam training.	Semi-Markov model design	PSF, delay
	[158]	D2D devices cooperatively perform beam training.	Semi-Markov model design	PSF, delay
	[159]	Beam failure triggers beam training.	Semi-Markov model design	PSF, delay

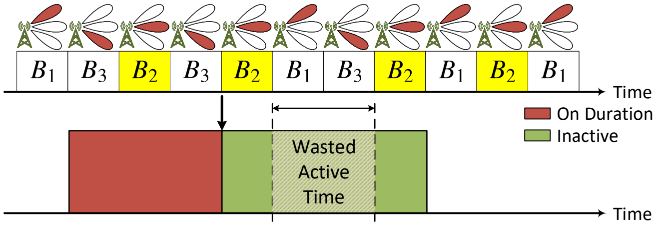


Fig. 24. In the NR system, the gNB serves its coverage area with directional beams. For example, if a UE is on the beam B_2 with DRX configured, we can see that the UE could save more energy while the gNB is serving the UEs on other beams.

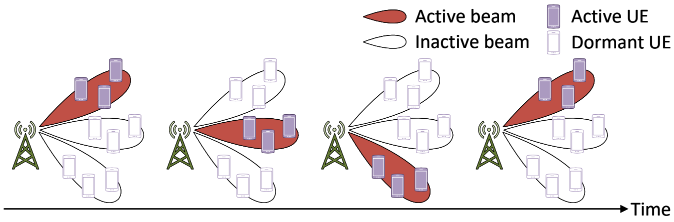


Fig. 25. Since the beamformed transmission links of the gNB cover only partial serving UEs, the UEs on the inactive beams could have the opportunity for DRX.

to study the impact of the power saving signal on DRX. Power consumption models and performance metrics except for PSF are essential for accurate analysis because the power consumption for monitoring the power saving signal is lower than monitoring regular data.

Most research on the MAC protocols with WUR for wireless sensor networks is included in [161]. Although covering most WUR-related research, the survey paper lacks the studies on DRX mechanism with WUR. Thus, we provide some related work, summarized in Table VII, in the following. The fundamental WUR mechanism for DRX is presented in [162], [163]. The papers showed that we can use the UE power consumption models in different states from 3GPP technical report TR38.840 [14] to calculate the UEs' power consumption. The UEs' power consumption and battery life with WUR are compared with existing power-saving methods, such as microsleep, cross-slot scheduling, and Go-to-sleep Signal (GTS). The evaluated results showed that WUR is adaptive to aperiodic traffic type because the UE turns off its primary receiver while its low-power wake-up receiver monitors the channels for wake-up signals. Once any incoming wake-up signals are detected, the wake-up receiver would trigger the primary receiver to turn on the radio and receive data. The experiment results showed that the WUR improves power consumption. Besides, combining different power-saving schemes is worth exploring to improve energy

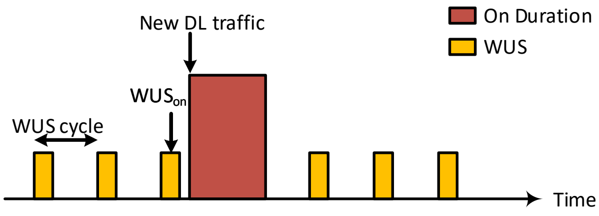


Fig. 26. UE with WUR presented in [9] monitors periodic wake-up signal (WUS). If a WUS is detected, the UE immediately enters the on state for data reception.

efficiency.

Since the reception of the wake-up signal might fail, which impairs power efficiency or extends packet delay, the false alarm rate, and the misdetection rate are representative metrics to evaluate the performance of WUR [164], [165]. A quantitative analytical model is developed to estimate the performance of WUR, which is useful for extensive investigations in related power-saving techniques [166]. The performance analysis of the WUR under various scenarios aids the development of optimized WUR mechanisms that could select the best parameter value to reduce power consumption [118], [167]. According to real-time traffic patterns, dynamic scheduling methods for the wake-up signal are presented to decrease power consumption [168]. The machine learning model could enhance the scheduling methods used in WUR mechanisms by predicting packet arrivals under various traffic types. With the prediction model, the scheduling method could reduce power consumption under realistic traffic scenarios. An enhanced WUR mechanism is proposed to make a UE monitor a power saving signal called PoSS with minimal power usage in [169]. A PoSS carries two types of information: indication of 1) wake-up and 2) power level in the active state. The DRX cycle length is also adjustable according to the number of consecutive cycles without data arrival. By merging channel and mobility measurements into the WUR DRX mechanism, a UE detects the wake-up signal, measures the channel quality, and receives data, as depicted in the six-state semi-Markov model [170]. If the wake-up signal is positive, the measurement in the next WUR cycle and the data reception in the current WUR cycle is activated.

Although much work investigated WUR for the DRX mechanism, it is notable that most papers do not follow the design of power saving signal proposed in the 3GPP standard because most research is done before the finalization of the standard. Fig. 26 shows the WUR model in [9], a magazine article introducing the WUR in 5G networks. The UE monitors the periodic wake-up signal for a short period in each WUR cycle. If the UE receives the wake-up indicator, it immediately wakes up the primary receiver to receive the data. We can see the difference between the considered model and the power saving signal introduced in Sec. III-A. The former replaces DRX cycles with short WUR cycles, and the latter uses power saving signal to enhance the basic DRX mechanisms. To better capture the standardized Release 16 DCP DRX operation, a two-state discrete Markov model is proposed in [171]. According to the analytical model and the observations, the Release 16 DCP DRX mechanism effectively reduces the power consumption at the cost of slightly increased latency.

In addition to the WUR, researchers also investigate the GTS, which indicates the target UE to start dormancy immediately if no packets arrive at gNB. Although GTS is less discussed in the standardization meeting, it is still worthy of further study. We discovered that the fundamental GTS designs might reduce the on duration to ease power consumption based on the simulation estimations [163]. Power Saving Indication, embedded in the beam training procedure, is a comparable concept to GTS and works similarly to improve power efficiency [149]. If a UE receives the indication, it applies a longer DRX cycle and goes to sleep. Instead of explicit signaling for UE to go to sleep, another go-to-sleep signaling design reduces power consumption when the UE is not scheduled during on duration [172]. If the UE does not receive any signals to schedule it after the fast control channel decoding, it can skip the decoding of the data channel and go to sleep immediately [173].

D. Thermal issue in NR network

The support of millimeter-wave bands is an essential feature in the NR network to enhance the network capacity. The maximum carrier bandwidth of the NR system is also larger than the one of the LTE system. Therefore, the NR UEs encounter overheating problems when transmitting at a high data rate. Despite the heat dissipation design, the UEs still require more advanced techniques to handle the thermal issues. The overheating issue is also recognized as a critical problem by the UE manufacturers [174], [175]. According to the 3GPP NR standard TS38.331 [10], the gNB could require the UE to report assistance information when it suffers from overheating. The UE could provide its preferred number of component carriers, bandwidth, and MIMO settings to mitigate its internal overheating.

It is also notable that the DRX mechanism might ease the overheating issues [174]. Fig. 27 shows an example of the temperature change. When the UE is in the active state, it turns on its RF module to receive data, so the internal temperature increases accordingly. After the inactivity timer expires, the UE could turn off its RF module and start dormancy. During the dormancy, the internal temperature decreases. To provide a more comprehensive investigation for the UE temperature variation during DRX operations, the thermal model based on Newton's Law is included into the analytical model for the DRX mechanism [176]. The results showed that the steady temperature varies when the UE applies different DRX configurations.

X. FUTURE DIRECTION FOR POWER SAVING TOWARD 6G

As for the 6G communication systems, power-saving and green communication networks are the keys to the communication industry's sustainable development. We could separate the power-saving issue into two parts: power saving for core network entities and mobile devices [177]. For the front end of the network, enterprises target developing devices with

TABLE VII
RELATED WORK ON WUR BASED DRX

Target	Paper	Proposed solution	Approach	Metrics
Investigation of basic WUR	[161]	A comprehensive survey for different wake-up MAC protocol	–	–
	[162]	WUR is compared with microsleep and DRX&DTX.	–	Battery life
	[163]	With DRX, WUR is compared with cross-slot scheduling, reduced PDCCH decoding candidate set, and GTS.	–	Power consumption, delay
	[164]	The UE uses low-power receiver to monitor power saving signal	–	Power consumption, false alarm rate, misdetection rate
	[165]	The UE decodes PGM instead of PDCCH	–	Power consumption, false alarm rate, misdetection rate
	[166]	WUR is comprehensively analyzed with mathematical model	Semi-Markov model design	Power consumption, delay, false alarm rate, misdetection rate, synchronization failure rate
Adaptive WUR	[118]	The UE finds optimal WUR cycle value for energy efficiency.	Semi-Markov model design, non-linear integer programming	Power consumption, delay
	[167]	With the awareness of service time, the UE finds optimal WUR cycle value for energy efficiency.	Semi-Markov model design, mixed-integer non-linear programming	Power consumption, delay
	[168]	The gNB adjusts power saving signal dynamically based on actual traffic.	LSTM model	Power consumption, delay
	[169]	Power saving signal carries the indication of wake-up and the power level of the active cycle with dynamic DRX cycle length.	Semi-Markov model design	PSF, delay
	[170]	Merge the channel quality measurement procedure with WUR DRX.	Semi-Markov model design	Power consumption, delay

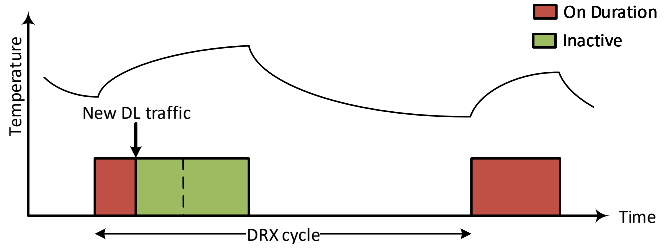


Fig. 27. The internal temperature increases when the UE is active. After that, the internal temperature drops during the dormancy.

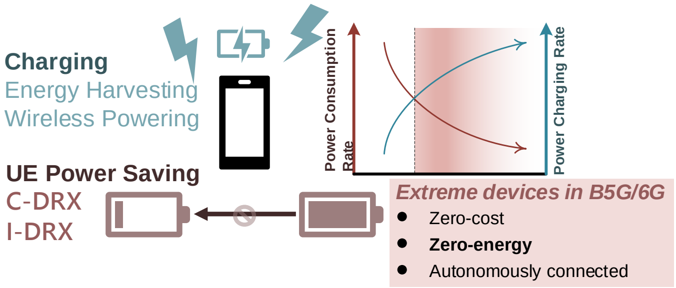


Fig. 28. Concept of Zero-energy devices in the vision of the 6G network.

extreme capabilities to support revolutionary applications. Ericsson presented their vision for the 6G network in [178]. They summarized three goals in different aspects for the extreme devices in the new generation: 1) zero-cost, 2) zero-energy, and 3) autonomously connected. These extreme devices often operate in a tough environment, so they must keep working for tens of years with battery charging. DOCOMO and Nokia also showed similar viewpoints in their white paper [179], [180]. In 6G, the requests for wireless charging or free-from-charging for mobile devices will excite the evolution of the DRX mechanism.

Fig. 28 illustrates the basic concept of Zero-energy devices in the vision of the 6G network. There are two components to enable mobile devices to be zero-energy. One is the evolution of the charging, and the other is the improvement of the power-saving mechanisms. As for the improvement of the DRX mechanism, the goal is to reduce the power consumption rate to be lower than the power charging rate provided by wireless powering or energy harvesting.

A. DRX evolution to meet the power-saving requirements in 6G

There are also worth studying directions to reduce the UE's power consumption rate to be lower than the power charging rate. In the white paper [181], the authors presented the potential of predictive power management. As the machine learning and self-organized network techniques mature, the network services providers can set better configurations, including DRX settings, for the UEs by predicting the UEs' profiles, such as traffic patterns and wireless charging behavior. If the UE's profile can be precisely predicted, the UE could wake up at exactly the timeslots with its downlink traffic to prevent wasting power and stay dormant when it predicts no wireless charging opportunities in the near future.

Second, WUR is another promising way to achieve zero-energy communications [182]. Although some solutions have already been implemented in the 5G network, such as the power saving signal in the 3GPP NR standard, the techniques still need further investigation and enhancement. For example, how to determine the DRX cycle for the WUR and how to further lower the cost and power consumption of the WUR for IoT MTC devices are waiting for further studies. In addition, researchers might try to integrate the WUR module with the wireless powering modules. In such cases, the signaling flow of the wireless powering and WUR mechanisms between the gNB and the UE need further joint optimization to improve the power management performance.

Third, D2D could increase the energy efficiency of wireless communications because of the short transmission range. In D2D communications, the UEs could use less energy to transmit the same volume of data. One may set the vision for energy efficiency is to meet 1 Tb per Joule [183]. Thus, researchers have already studied the application of the DRX mechanism for D2D devices, which will remain important in the 6G communication networks. Considering wireless powering in the 6G network, the power management for the UEs would become more challenging. The gNB should schedule the wireless charging and configure the DRX jointly for the devices. The D2D technique is worth studying in such scenarios to enable the collaboration between UEs to extend the battery life. Finding better ways to coordinate the DRX configurations and the wireless powering settings for the D2D pairs or groups is important.

B. *Joint power saving among network and devices*

Mobile edge computing and cloud platforms for mobile devices recently attracted people's attention. In the 6G network, more and more services will be published on these platforms. Peltonen *et al.* [184] pointed out that we should combine the energy consumption evaluation of network nodes and devices. In most cases, mobile devices could offload their computation tasks to the edge or cloud server to save power and improve the service quality. However, task offloading would increase the power consumption on the network side, so it is essential to balance the power consumption and service quality by the joint optimization of the DRX configuration and task offloading policies. In addition to mobile edge computing, many other new schemes, such as non-terrestrial communications or UAV applications, are proposed in the 6G network. The DRX mechanism is always essential to extend the battery life of mobile devices.

Other related promising techniques in the next-generation communication network are Software Defined Networking (SDN) and Network Function Virtualization (NFV). These techniques enable the network service providers to centrally orchestrate their network resources according to the service requirements [185]. From the power efficiency perspective, the systems should be well configured to save the power of the network infrastructure and user devices without sacrificing the quality of content delivery.

C. *DRX for enhanced ultra-reliable network*

5G NR has already put the uRLLC into the design scope, and 3GPP proposed the new NR frame structure to support various numerology sets and shorten the transmission delay. Increasing the Sub-Carrier Spacing (SCS) could extremely shorten the length of a timeslot. To dynamically configure the UE's numerology, 3GPP proposed the concept of BWP in NR [186]. By specifying different SCS for the BWPs, the UE could switch its numerology according to its active BWP. However, the bandwidth size of the BWP would influence the power consumption while performing PDCCH monitoring. Therefore, the interaction between the DRX mechanism and the BWP switching mechanism will be a worth-study problem.

Another crucial related scenario is the Time Sensitive Network (TSN) [187]. 3GPP also spent much time discussing supporting TSN in the latest version of the standard. For a TSN, the timing of the packet reception is a strict requirement. We should carefully handle both packet delay and jitter in the TSN. To conclude, the optimization goal is to minimize the variance of the inter-packet delay in the TSN scenarios. As for the DRX mechanisms, the gNB might have to regulate the traffic pattern for the UEs and set the proper DRX parameters for the UE to receive the packets on time. However, the fluctuation of the network condition is still an open issue. In such a network scenario, designs rapidly adapting the DRX configuration to the network conditions are essential.

D. *Summary*

We have introduced three possible directions to enhance the C-DRX mechanisms in the 6G communication network. First, we must integrate wireless powering technologies with the DRX mechanisms. Jointly optimized power management frameworks are essential in the 6G network to realize zero-energy devices. Second, power-saving for the network infrastructure must be solved in the 6G network. With the UE DRX mechanism, the gNBs with low traffic loading also have the opportunity for power-saving. Third, the power-saving mechanisms for ultra-reliable networks are worth investigating. The possible designs of UEs' dormancy behaviors are still open issues considering different requirements of service reliabilities. In addition to the listed problems, we believe there exist other issues related to the DRX mechanisms to be solved in the 6G network.

XI. CONCLUSIONS

The DRX mechanism is indispensable to the power saving in wireless mobile networks. It significantly enhanced the battery life of LTE devices and will continuously get attention in the 5G era. In this paper, we summarized the status of DRX-related techniques in the 3GPP NR standard. Besides, researchers have also focused on the DRX mechanism for more than ten years. Therefore, we presented a comprehensive survey on the state-of-the-art DRX mechanism. With the requirements of different network schemes, we discussed the main challenges and corresponding enhanced DRX designs. However, many new 5G network schemes are still not studied as the network evolves from LTE to NR; thus, we also introduced some future directions in the NR network.

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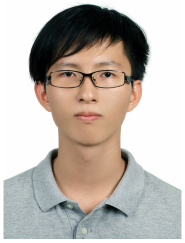

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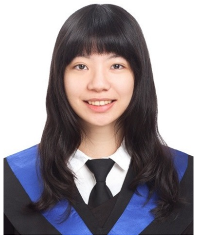

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