Implementation of mmWave-energy Module and Power Saving Schemes in ns-3

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ABSTRACT

Next-generation 5G New Radio (NR) cellular networks operating at mmWave frequencies are targeted to support diverse use cases, such as enhanced Mobile Broadband (eMBB), massive machine-type communications (mMTC), ultra-reliable and low latency communications (URLLC), etc. Energy-Efficiency is one of the key performance indicators for NR technology. User Equipment (UE) battery life significantly impacts the Quality of Experience (QoE) of the UE. Thus 5G NR standard is designed to have great flexibility on network operation modes to adapt to different requirements and trade-offs. 3GPP, in its 5G technical specification release, has proposed various power-saving schemes such as connected mode Discontinuous Reception (cDRX), RRC INACTIVE state, etc. In this work, we discuss the implementation and analysis of UE RRC state-based energy consumption module, including different power saving schemes in ns-3. We have thoroughly evaluated the module with the simulation study and validated the implementation with the 3GPP standards. The implementation source code is publicly available as open-source.

CCS CONCEPTS

• **Networks → Network simulations**; *Network performance analysis.*

KEYWORDS

Millimeter Wave, RRC, 5G NR, ns-3, cDRX

ACM Reference Format:
Argha Sen, Sashank Bonda, Jay Jayatheerthan, and Sandip Chakraborty. 2022. Implementation of mmWave-energy Module and Power Saving Schemes in ns-3. In *Proceedings of the WNS3 2022 (WNS3 2022), June 22–23, 2022, Virtual Event, USA.* ACM, New York, NY, USA, 8 pages. https://doi.org/10.1145/3532577.3532598

WNS3 2022, June 22–23, 2022, Virtual Event, USA

ACM ISBN 978-1-4503-9651-6/22/06…$15.00
https://doi.org/10.1145/3532577.3532598

1 INTRODUCTION

UE battery life is an essential aspect of the user's experience, influencing the adoption of 5G NR handsets and services. It is critical to study UE power consumption to ensure power efficiency for 5G NR UEs can be better than Long Term Evolution (LTE). However, mmWave communication entails higher device energy consumption leading to faster battery drainage [16]. Longer battery life is, nevertheless, essential for uninterrupted connectivity. To reduce energy consumption across the end-user devices, 3GPP has incorporated several energy-efficient features in 5G. At the same time, efficient algorithms for multiple applications are needed to improve energy consumption further. Since the NR framework supports high-speed data transport, the network would serve the bursty client data in short durations. One efficient UE power-saving mechanism is to trigger UE for network access from power-efficient mode. UE would stay power-efficient unless it is informed of network access through the UE power-saving framework. Then again, the network can help the UE switch from the "network access" mode to the "power-efficient" mode when there's no traffic to deliver.

Third Generation Partnership Project (3GPP), in its technical specifications 38.840 [4] on 5G incorporated such power-saving schemes. cDRX and Radio Resource Control (RRC) INACTIVE states are defined in this release. This mechanism keeps the UE in "power-efficient" INACTIVE mode until data reception notification from the network. Suppose the UE receives a data reception notification from a Physical Downlink Control Channel (PDCCH) message. In that case, it switches its state from low power INACTIVE state to high power RRC CONNECTED state. The cDRX timers keep track of these RRC state changes. If there is no active data transmission happening in the RRC INACTIVE state and the cDRX timer expires, UE enters into deep sleep mode. In deep sleep mode, UE keeps all its receiving antenna turned off and stays IDLE until the Deep Sleep timer expiry. In this way, the network can efficiently manage the UE's power consumption.

Now to study these power-saving schemes in 5G NR, we used the network simulator ns-3. 5G technology remains within the development phase, primarily in the middle and low-economy countries because of which it is still not accessible to many users across the globe. ns-3 plays a key role by allowing researchers to validate the performance of their solutions without the need for a real prototype, thus saving time and money. In particular we have used the ns3-mmWave module [11]. This module provides an end-to-end 5G

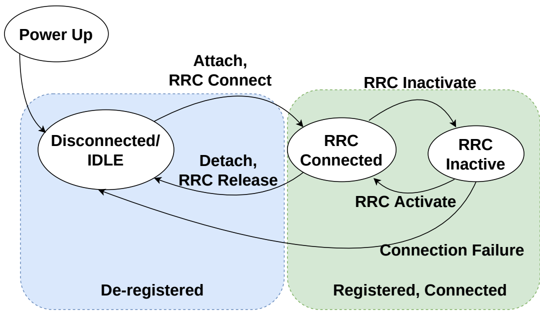


Figure 1: RRC Procedures in 5G NR UE [6]

protocol stack for NR simulations in ns-3 and used in various recent research works [19–22]. However, this module needs to be modified to explore the aforementioned power-saving schemes. The current version doesn't include the RRC Connection Release method; thus, the UE stays in the high power RRC CONNECTED state no matter what application is running. Also this module lacks a UE energy consumption model. In our previous work we have developed a PHY state-based approximate UE energy consumption model [14], which also lacks the RRC state-based energy modelling and thus gives only an approximated estimation of the energy consumption rather than the actual measurements.

In this work, we have implemented an RRC state-based UE energy model, based on the 3GPP specifications defined in TR 38.840 [4]. To implement the power-saving features as proposed in [4], we have added some new functionalities so that the UE can switch from the RRC CONNECTED state to RRC IDLE state or the sleep state. This RRC Connection Release method enables the UE to save energy by entering into a sleep mode when there is no active data transmission happening between the base station and the user equipment. To monitor the sleep modes, we use cDRX timers. The simulation is thoroughly analyzed under different scenarios, different applications, different Inter Arrival Timers (IATs), Inactivity Timers (ITs), and cDRX cycles. We also validate our results with the calibrations done in TR 38.840 [4] on real-world devices. The entire implementation code with newly added features is publicly available as open source[1].

The rest of this work is structured as follows. Section 2 provides a description of the power saving schemes as proposed in 3GPP TR 38.840 [4]. In Section 3 we discuss the limitations of previously proposed UE energy model. Section 4 describes the implementation of power saving schemes and RRC state-based energy model in ns-3, followed by validation result in Section 5. Finally, in Section 6 we draw the conclusions with some future possible directions.

2 BACKGROUND AND RELATED WORK

In this section, we discuss the current power saving schemes proposed in 3GPP release 38.840 [4]. Then we also explore the limitations of the previous work on the UE energy consumption model [14].

[1]https://github.com/arghasen10/ns3-mmwave/tree/rrcenergy

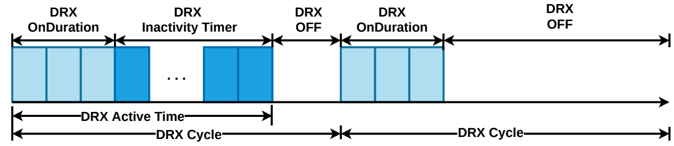


Figure 2: cDRX Mechanism [8]

2.1 Newly Proposed RRC INACTIVE State

In LTE, RRC state machine governs the energy management of the UE. It consists of RRC connected state and RRC IDLE state. The IDLE state is defined so that UE can operate under lower energy consumption mode when there is no active data transfer happening between the base station and the UE. When there is data activity, UE switches to RRC connected state by completing the state switching procedure, which requires extensive signalling [5] between the UE and the base station. The RRC state machine uses RRC Inactivity Timer to trigger a state change from CONNECTED to IDLE when there is no data activity within the time slot. This inactivity timer leads to a trade-off between power consumption and data communication efficiency. A longer inactivity timer will keep the UE in a CONNECTED state for a longer duration leading to higher energy consumption but better data transmission efficiency, low latency, and low signaling overhead. With a smaller inactivity timer setting, the UE will stay in the IDLE state longer time, leading to low energy consumption at the cost of latency and higher signaling overhead. A state switch from CONNECTED to IDLE will delete the registered UE context from the base station.

This challenge is addressed in 5G NR by incorporating a new state RRC INACTIVE [4] as shown in Figure 1. This newly proposed state helps in reducing the control plane latency, signaling overhead, and the energy requirement for RRC IDLE to RRC CONNECTED state transition. In the RRC INACTIVE state, the UE identity, context, mobility information is maintained both by the network and the UE. Stored information permits the UE to switch back to RRC CONNECTED state from the INACTIVE state during data activity. Thus the overall state transition becomes more efficient than IDLE to CONNECTED state switching.

However with small data packets, repeated switching from INACTIVE to CONNECTED state will require energy cost, latency, signalling overhead, RRC Connection Establishment procedures which consume more traffic in comparison to the actual data payload [1]. Thus, only adding this new state wont help in designing a power saving scheme for 5G NR.

2.2 cDRX Mechanism

To prolong the battery life of UE, cDRX is proposed in the early stage of LTE and inherited by NR [3]. cDRX is controlled by the RRC protocol. RRC signaling sets a cycle where the receiver of the UE is operational for a certain period, usually when the scheduling and paging information is transmitted. The serving base station has knowledge of this timing window when the UE's receiver is turned ON/OFF. In cDRX, the UE's receiver gets activated to monitor a PDCCH to identify downlink (DL) data arrival or uplink (UL) grant. If there is no data scheduled, the UE can turn off its receiver antenna and enter into a power-saving state. If UE detects a PDCCH indicating a new DL or UL transmission, Discontinuous Reception (DRX) RRC framework would start inactivity Timer. Until the DRX Inactivity Timer expires, the UE needs to keep monitoring PDCCH for the potential subsequent data scheduling.

The DRX mechanism consists of cycles with OnDuration and OffDuration as shown in Figure 2. When the UE is in RRC INACTIVE state, within the OnDuration of the DRX cycle, UE needs to detect paging occasion and system information updates coming from the network. If it receives any PDCCH message, it switches to RRC CONNECTED state and keeps the Inactivity timer turned on. On the expiry of the inactivity timer, it then switches back to lower power IDLE state.

In NR, we use the term DRX or cDRX interchangeably as with the newly proposed RRC INACTIVE state, UE is still connected or registered to the serving base station. Thus, the cDRX mechanism allows the UE to enter power saving mode periodically and finally helps in lowering the net energy consumption of the UE. Nonetheless, the inactivity timer in cDRX is a crucial component that leads to a trade-off between energy efficiency and communication latency. Recent works have leveraged DRX mechanism for NR multi-beam millimeter-wave communication for enhanced beam-based DRX measurements [15] or directional DRX [9], deep learning-based DRX tuning [10], etc.

2.3 Energy Consumption Model

For evaluation of different power saving schemes, an energy consumption model is required. Thus 3GPP adopts energy consumption model in its several technical specification release [2, 4, 7]. The key power states and corresponding power consumption values as proposed in 3GPP specification [4] is shown in Table 1. It consists of three sleep states depending upon the transition time of the sleep state as shown in Table 2. Other than these sleep states we have control channel data reception state (PDCCH-only) and DL reception (PDCCH+PDSCH). Based on these Power states and corresponding power consumption values the energy consumption model can be developed.

Previous works such as [13, 17, 18] implemented energy consumption model for Wifi, Narrow-Band Internet of Things (IoT) and LTE devices in ns-3. In our previous work [14] we have developed UE energy consumption model for mmWave Networks in ns-3 using the aforementioned specifications taken from 3GPP TR 38.840 [4]. However, the power states considered in [14] are dependent upon the UE Physical layer states (PHY states). Although it gives an excellent approximation of energy consumption, it doesn't leverage the UE RRC state machine to quantify the energy. Thus this module cannot be used with RRC power-saving schemes such as RRC INACTIVE, cDRX mechanism, etc. In this work, we have developed an end-to-end RRC energy module and UE's power-saving strategies keeping the ns3-mmwave module [11] as the base of the simulation tool.

[2] **Note:** In this work we have considered the scaling factor as 1. Meaning if the deep sleep power is 1mW, the light sleep and micro sleep will be 20mW and 40mW. The scaling factor can be computed with a real 5G UE prototype. Users can configure these power attributes in the simulation setup as per the requirements.

Table 1: Power Consumption Model [4]

Power State	Relative Power (mW)[2]
Deep Sleep	1
Light Sleep	20
Micro Sleep	40
PDCCH-only	100
PDCCH+PDSCH	300

Table 2: UE Sleep States With Transition Time [4]

Sleep Type	Transition Time
Deep Sleep	20ms
Light Sleep	6ms
Micro Sleep	0ms

3 PILOT EXPERIMENTS

For simulation of 5G cellular networks operating at mmWave frequencies, ns3-mmWave module is developed [11]. This module is interfaced with the core network of the ns-3 LTE module for full-stack simulations of end-to-end connectivity, and advanced architectural features, such as dual-connectivity, are also available.

In our previous work in [14], using the ns3-mmWave module, we have developed a UE energy consumption model based on the PHY states of the UE. Since this module is dependent upon the PHY states and doesn't consider UE RRC states, we cannot perform RRC power-saving schemes with this module. To validate this, we perform a simulation study with this module. We have taken the *mc-two-enbs* simulation file a sample simulation script for multi-connectivity (MC) device. The simulation instantiates a LTE and two mmWave evolved NodeB (eNB), attaches one MC UE to both LTE and mmWave eNB, and starts a network traffic flow for the UE to and from a remote host. The energy module [14] is installed over the UE node. First, we trace the minimum and the maximum time taken in the four PHY states (IDLE, RX_CTRL, RX_DATA, TX). Here we observe the PHY states change rapidly in the range of a few nanoseconds to 1 millisecond. So clearly, the transition time in the IDLE state corresponds to only Micro Sleep. Other sleep modes as mentioned in Table 2 cannot be explored with this module. Even if we remove the application installed on the UE, the results remain the same (see Table 3) as the PHY state change doesn't follow the RRC state machine. Thus we can conclude this module doesn't fit well with the 3GPP specifications [4] to have the other sleep states, such as, deep sleep or light sleep.

To develop RRC state-based energy module, we started with tracing the RRC state changes in the simulation. When the simulation begins, we observe that the UE first stays in the RRC `IDLE_START` state. It completes the RRC connection establishment in this phase and then finally switches to RRC `CONNECTED_NORMALLY` state. We find the RRC implementation in [11] doesn't include the RRC Connection Release method. Thus for the rest of the simulation, the UE stays in the `CONNECTED_NORMALLY` state and never switches to the IDLE state. We have done the pilot study under three different scenarios. First, with the application installed on the UE, second, with the application removed from the UE, and finally, when UE

Table 3: Time Traces in each PHY States; with and without (w/o) Applications (app.)

PHY State	minimum time(s)		maximum time(s)		total time(s)	
	with App.	w/o app	with app	w/o app	with app	w/o app
IDLE	0.000000001	0.0002148	0.000232144	0.000232144	2.842615897	10.3912
RX_CTRL	0.000017856	0.000017856	0.000017856	0.000017856	0.000017856	0.000017856
RX_DATA	0.000032143	NA	0.000214282	NA	8.12283384	NA
TX	0.000017856	0.000017856	0.000054291	0.000341875	0.095544781	0.6598149

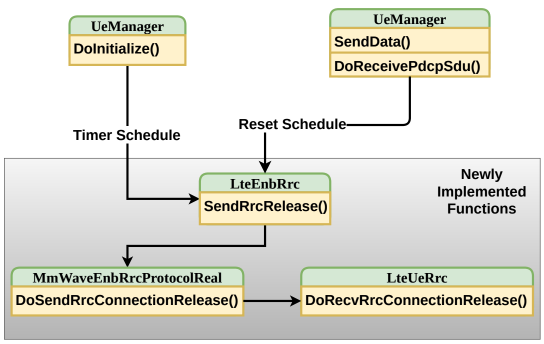


Figure 3: Implementation of RRC Connection Release

starts moving far away (5000m away) from the connected eNB. We observe in all the scenarios till the end of the simulation UE stays in the RRC `CONNECTED_NORMALLY` state because the RRC Connection Release method is missing in the RRC state machine.

Thus, from the pilot studies, we conclude that the previous energy module [14] cannot be used for RRC power saving schemes, and we need to develop a new energy module that works under the RRC state machine. Also, the current implementation of ns3-mmWave [11] lacks an RRC Connection Release method, which needs to be developed.

4 SYSTEM DESIGN

Our contributions to the current ns3-mmWave module [11] include (1) development of the RRC Connection Release method, (2) paging notifications, (3) addition of the newly proposed RRC INACTIVE state, (4) implementation of cDRX to incorporate UE's RRC layer state change according to the configured cDRX timers, and finally (5) UE RRC energy module to evaluate UE's energy consumption across different RRC states.

4.1 Implementation of RRC Connection Release Method

As we discussed in Section 3, the current implementation of the RRC state machine lacks `RrcConnectionRelease` method. We implement that by modifying the `LTE_ENB_RRC` and `LTE_UE_RRC` files. The `LTE_ENB_RRC` method sends RRC Release message using the method `SendRrcRelease` at a fixed interval timer set by the user script. Once the `SendRrcRelease()` is triggered by the LTE eNB, UE switches to low power state RRC INACTIVE. In Figure 3 we show the newly added functions required for sending RRC Connection Release from the eNB to the UE.

4.2 Implementation of Power Saving Schemes

3GPP proposes several power saving schemes such as a newly proposed RRC INACTIVE state (see Section 2.1) and cDRX timers (see Section 2.2) for performing RRC state change.

4.2.1 Implementation of RRC INACTIVE State. In the newly proposed RRC INACTIVE state the UE enters in the listening mode periodically, to receive PDCCH DL data notification or the UL data grant from the eNB. This listening mode can also be referred to as paging. In the RRC_INACTIVE state, we periodically enter the RRC paging mode for listening and turn off the UE receiver. The paging direct message is sent to the UE from the eNB using `LTE_ENB_RRC`. The `LTE_RRC_SAP` receives the paging information to check for PDCCH reception at the UE.

4.2.2 cDRX Implementation. The UE state switching from RRC `CONNECTED_NORMALLY` to RRC IDLE or INACTIVE is implemented using `RrcConnectionRelease()`. This function is called using the preset cDRX timers. cDRX timers consists of RRC Inactivity Timer (`rrc_release_timer`) and connected-mode Discontinuous Reception(cDRX) Inactivity Timer (`inactivity_timer`). After completing the RRC connection establishment, when UE enters in the RRC `CONNECTED_NORMALLY` state, the RRC Inactivity Timer starts. If the RRC Inactivity Timer expires and within that time window there is no active data transfer, UE switches its state to `CONNECTION_CDRX` which is the RRC INACTIVITY state by calling the method `RrcConnectionRelease`. It instantiates the cDRX Inactivity timer after every cDRX cycle. In this state, UE performs paging periodically in the `OnDuration` of the cDRX cycle. If any PDCCH reception happens at the UE during the paging, the UE switches its state from `CONNECTION_CDRX` to `CONNECTED_NORMALLY`, and the RRC Inactivity Timer gets reset. If there is no reception of PDCCH, the UE switches its state to `CONNECTION_DS` or Deep Sleep state. The UE is completely disconnected from the base station in this deep sleep state until the deep sleep timer expires. Once it expires, the UE again enters the `CONNECTED_NORMALLY` state.

In Figure 4 RRC state switching is shown. All the necessary changes are implemented in the `LTE_UE_RRC` and `LTE_ENB_RRC` file. Figure 5 shows the RRC state changes over time according to the cDRX timers.

In the `CONNECTION_CDRX` state eNB maintains UE's state information so that when UE enters RRC INACTIVE or Deep Sleep state, eNB saves all the downlink data in a packet buffer `m_packetsaved`. Once the UE reenters `CONNECTED_NORMALLY` state, eNB sends all the buffered packets to the UE. This implementation is handled by the `SendData()` method of `LTE_ENB_RRC`.

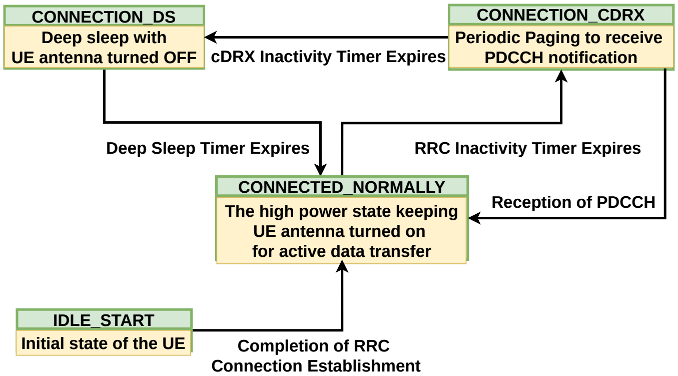


Figure 4: State Diagram of cDRX based UE RRC State Switching

All the cDRX timers can be configured using the simulation script commandline arguments and for that some modifications have also been done in the `LTE_HELPER` file.

4.3 Implementation of RRC Energy Module

To calculate the energy consumption of the UE under different RRC states, we have developed the RRC state energy module. The energy framework in ns-3 consists of the Energy Source and the Device Energy Model as shown in Figure 6. The energy source represents the total energy reserved at the node. This energy source is installed on the UE node. Multiple device energy models can exist on a single node, representing different network devices. mmWave UE netdevice has an object named `LteUeRrc` which provides a trace source for the RRC state change. Our device energy model uses the corresponding trace sink that triggers `stateChange` function and accordingly updates the total energy consumption based on the RRC state power consumption as mentioned in Table 1. It then notifies the energy source about the consumed energy. The energy source checks the remaining energy, and when energy is completely drained, it reports all the connected device energy models.

Based on the time taken in each IDLE state we quantify the power value following the specifications shown in Tables 1 and 2. If the UE stays in the `CONNECTED_NORMALLY` state, we quantify that power value to the PDCCH and PDSCH reception power(300mW) as in this state UE receives/transmits data. If there is any PDCCH reception while paging in the `CONNECTION_CDRX` state, we assign a power of 100mW. Based on these RRC state powers and the corresponding time taken in each state, we calculate the total energy consumption of the UE.

5 EVALUATION

This section evaluates the UE RRC state energy module and the power saving schemes. The evaluation is performed under different cDRX timer settings, different traffic loads based on three user applications. We mainly focus on the UE energy consumption and the average latency in packet delivery. Finally, we validate the energy module performance with the 3GPP specifications [4].

Table 4: Simulation Parameters

Parameter Description	Value
Bandwidth of mmwave gNBs	1 GHz
Bandwidth of LTE eNB	20 MHZ
Carrier frequency mmwave	28 GHz
Carrier frequency LTE	2.1GHz
Bandwidth of the LTE eNB	20 MHz
LTE carrier frequency	2.1 GHz
MIMO array size gNB	8×8
MIMO array size UE	4×4
Number of mmWave gNB	2
Number of LTE eNB	1
Number of UE	1
UE speed	5 m/s
Simulation Time	12s

5.1 Evaluation Setup

To simulate the energy consumption behavior under different scenarios, we take hep of the `LTE_HELPER` file, using which we can set the attributes of the cDRX timers, such as the cDRX cycle length, cDRX inactivity timer, on duration in the cDRX, etc. We installed the energy source and the developed energy module on the UE node. `mc-two-enbs` simulation file[3] is used to develop the simulation topology. In Figure 7 the simulation topology is shown. The simulation parameters are also shown in Table. 4. We have used three different user applications; (1) File Transfer Protocol (FTP) application, (2) Instant Messaging application, and (3) Video streaming application. The FTP application is developed using ns-3 `OnOffHelper` as packet source and `PacketSinkHelper` as the sink. Instant messaging application is developed using the `UDPEchoClient` and `UDPEchoServer` applications. And for the video streaming application, we have used the DASH-NS3 module [12]. Packet size and packet inter-arrival time are set as shown in Table 5.

5.2 Energy Consumption

Based on the three user applications, we trace the total energy consumption and the average per-packet latency by taking different cDRX timer settings (cDRX cycle length, cDRX Inactivity Timer, and cDRX on duration).

5.2.1 FTP Application. In Figure 8 we show the variation of energy consumption and latency under different cDRX timer settings for FTP application. Here we observe longer cDRX cycles (320ms) results in higher energy consumption as the UE stays in an INACTIVE state for a longer duration resulting in a higher latency which increases the net simulation time. Thus the total energy consumption is higher. Although a smaller cDRX cycle (40ms) results in low latency, it keeps the UE in the CONNECTED state for a longer period, and thus the net energy consumption is also high in this case. The minimum energy consumption and low latency both are observed at cDRX cycle length of 160ms with cDRX Inactivity timer

[3]https://github.com/nyuwireless-unipd/ns3-mmwave/blob/new-handover/src/mmwave/examples/mc-twoenbs.cc

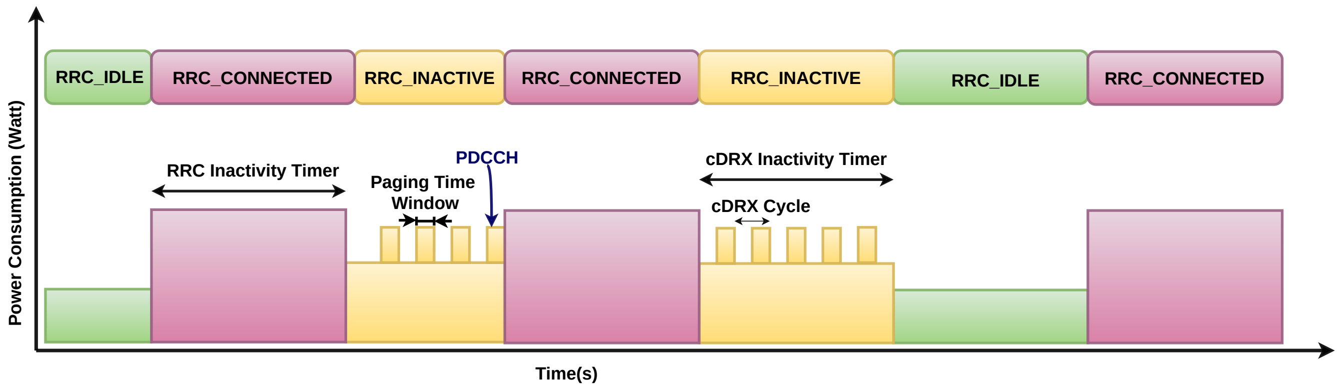


Figure 5: Overview of mmWave UE RRC Duty Cycle States

Table 5: Evaluation Setup

Parameters	Applications		
	FTP Traffic	Instant messaging	Video Streaming
Packet Size	0.5 Mbytes	0.1Mbytes	-
Inter Arrival Time	200ms	2sec	-
{cDRX cycle, cDRX Inactivity Timer, OnDuration}	{320,200,5}, {320, 80, 5}, {160, 100, 4}, {160, 40, 4}, {40, 25, 2}, {40, 10, 2}		

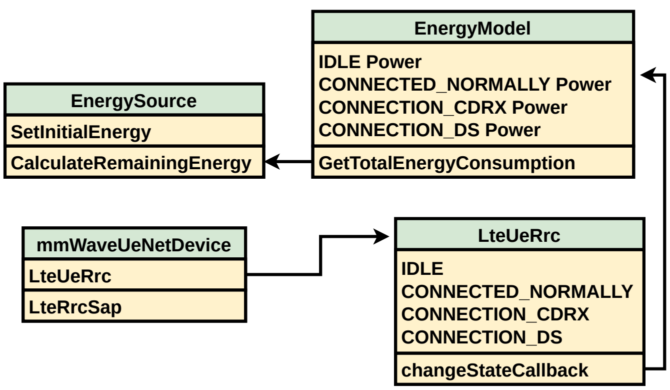


Figure 6: Energy Model Implementation Flow Diagram

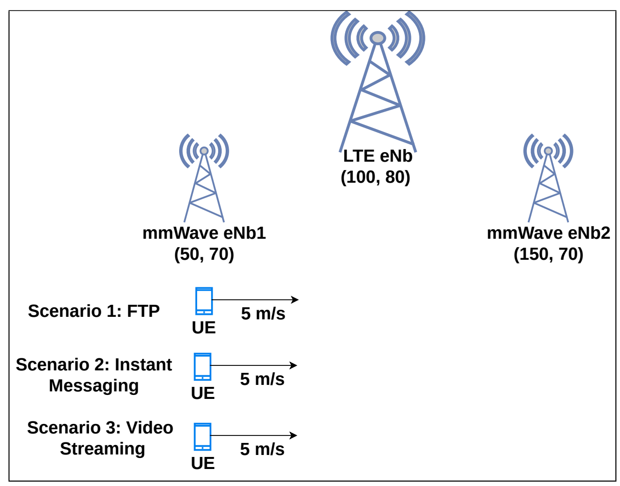


Figure 7: Simulation Topology: Taken from `mc-two-enbs` Simulation Example File

of 40 ms or 100 ms and the on duration timer at 4ms. The time taken in `CONNECTION_CDRX`, `CONNECTION_DS` and `CONNECTED_NORMALLY` RRC states are mostly uniform (see Figure 11(a)).

5.2.2 Instant Messaging Application. In Figure 9 the variation of energy consumption and average per-packet latency is shown for the Instant Messaging application. In the instant messaging application, the inter-arrival time is 2s. Thus the UE stays mostly in IDLE or `CONNECTION_DS` state in this case (see Figure 11(b)). We observe a longer cDRX cycle (320ms) in this case gives the minimum energy consumption and minimum latency as shown in Figure 9. The reason behind this is longer cDRX cycle keeps the UE in IDLE mode for a longer duration. And since, in this case, the frequency of active data transfer is very low compared to the other two applications thus, keeping the UE in deep sleep mode saves a lot of energy.

5.2.3 Video Streaming Application. Compared to the other two applications, in the video streaming application, we observe the UE stays in the CONNECTED mode for most of the simulation period as shown in Figure 11(c). The packet transfer, in this case, is very frequent. Thus shorter cDRX cycles (40ms) perform the best (see Figure 10) as it keeps the UE in a CONNECTED state for most of the simulation and doesn't compromise on latency. Selecting longer cDRX will result in more IDLE time for the UE, which will increase the net latency of the application, and thus the total time taken in completing the simulation increases, which further increases the energy consumption of the UE.

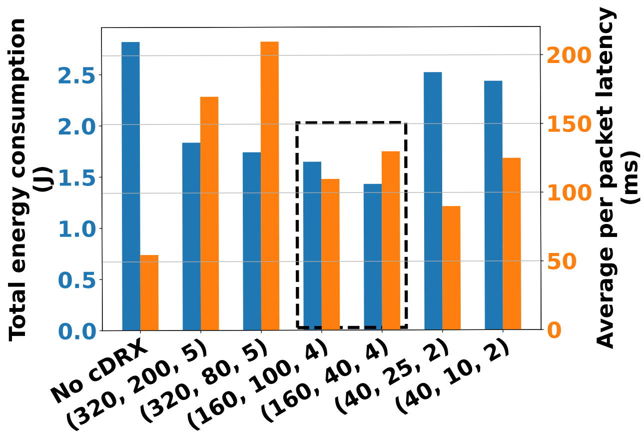


Figure 8: Energy Consumption and Latency of FTP Application under Different cDRX Settings

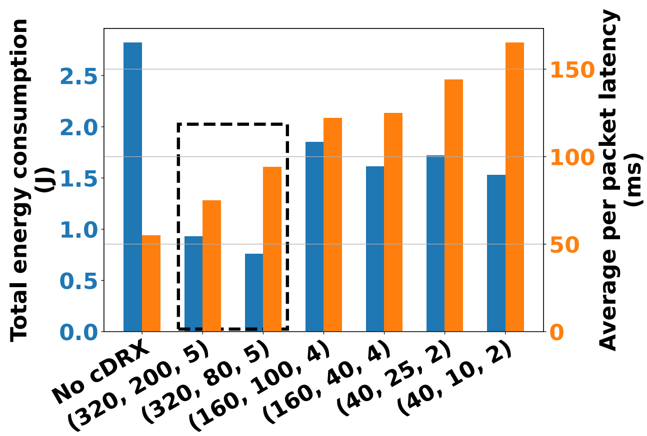


Figure 9: Energy Consumption and Latency of Instant Messaging Application under Different cDRX Settings

Based on our study we find the perfect cDRX timer settings under the three different user applications. We notice this observation is also matching with the proposition of 3GPP TR 38.840 [4] where they have done calibration study of the cDRX timers under the similar three applications. This validates our implementation of energy module and power saving schemes.

Now to understand the performance of the RRC state-based energy model including the power saving schemes over the previously implemented PHY state-based energy model [14], we have taken the same simulation setup with FTP application running on the UE. We have used three different scenarios with three different energy models installed on the UE. In the first scenario we have installed the RRC energy model without any power saving scheme (w/o RRC energy [10]). In the second scenario we have taken the PHY state-based energy model [14] (with PHY energy) installed over the UE. And finally we have taken our implemented RRC state-based energy model under the implemented power saving schemes (with RRC energy). The energy consumption over time is shown

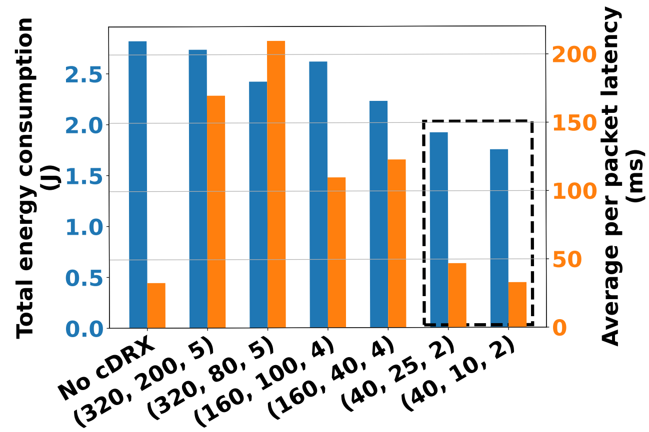
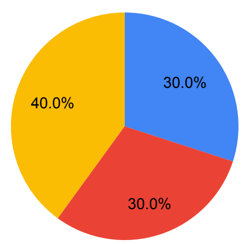
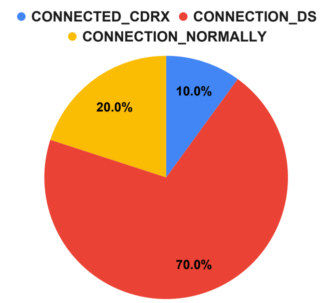


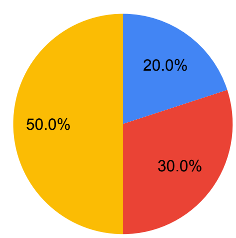
Figure 10: Energy Consumption and Latency of Video Streaming Application under Different cDRX Settings



(a) FTP Application (160,100,4)



(b) Instant Messaging Application (320, 200, 5)



(c) Video Streaming Application (40, 25, 2)

Figure 11: Distribution of Time Taken in each State for the Three Different Applications under the Optimal cDRX Configurations

in Figure 12. It shows the proposed RRC state-based energy model consumes the least energy among the others. Since there is no opportunity of any sleep state in the ns3-mmWave version (w/o RRC energy) it consumes the maximum power. The PHY state-based energy consumption model is more energy-efficient compared to the former as when the PHY states change to IDLE in it's runtime UE consumes lesser energy. However since the IDLE state transition time in this module comes under the micro sleep category as

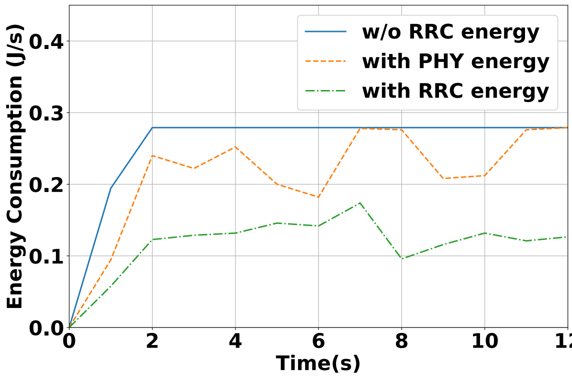


Figure 12: Under FTP Application, Change in UE's Energy Consumption over Time with Different Energy Models

discussed in Section 3, the energy consumption is still higher than the RRC state-based energy model. The RRC state-based energy module leverages the power saving schemes as proposed in 3GPP TR [4], thus it has opportunistic deep sleep when there is no active data transfer. This further reduces the net energy consumption of the UE and provides an energy-efficient design for the UE.

6 CONCLUSION

In this work, we have developed UE RRC state-based energy module that also incorporates the 3GPP TR 38.840 [4] for power saving schemes such as cDRX, RRC INACTIVE state, etc. The newly developed energy module is implemented over the ns3-mmWave module. With extensive simulation study, we show one can validate this module with the latest 3GPP specifications. The main goal of the developed module is to enable system-level simulation of 3GPP TR 38.840 [4] UE energy consumption in mmWave networks. With the change in the RRC layer states the energy consumption of the UE is captured. It provides a framework for tracing UE energy consumption under diverse user applications, inter arrival times, packet size, etc. We have validated our module with the 3GPP TR 38.840 [4] calibrations on different real world devices while keeping different cDRX timers. Thus, in conclusion, we can use this module to perform energy consumption studies under diverse scenarios.

This module can help in designing energy-aware user applications as well as networks that can provide better User QoE and longer battery life. A simple energy-aware user application can be Dynamic Adaptive Video Streaming (DASH), where based on user's energy performance, application can select the video chunk bitrate. When the UE is under low power, this application can fetch lower video chunk bitrate, and when the UE battery power is high, the application can fetch higher bitrate video chunks. Thus the energy-aware application can help in providing longer battery life for the UE.

In our future work, we want to extend this module to support the base station energy modelling, so that an end-to-end energy consumption of the network can be captured. Overall energy consumption of the network will help experts/researchers to design an energy-aware network or user application, which can provide a better battery life and QoE of the UE.

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