A Narrowband Internet-of-Things Communications Scheme over Non-Terrestrial Networks

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***Abstract*—Non-Terrestrial Networks (NTNs) based on emerging 5G New Radio (NR) technology stand as an effective solution to complement terrestrial networks in service provisioning, owing to their ability to satisfy requests for anywhere and anytime connection. This work concentrates on the power saving and battery lifetime of a User Equipment (UE) communicating with NTN. We consider NTN to support Narrowband Internet-of-Things (NB-IoT) applications in 5G networks. We model an NTN UE's Discontinuous Reception (DRX) as a Semi-Markov-based model. We assess the model's performance in terms of UE power consumption and average delay. We validate the proposed model through extensive simulations. The reduction of the number of signaling steps can also reduce the power consumption of the UE. In this line, we also compare the random access performance obtained with 3GPP compliant configuration and satellite configuration with the aim of studying the power consumption of the UE.**

***Index Terms*—NB-IoT, LEO Satellite, 3GPP NTN, DRX, Energy Efficiency.**

I. Introduction

The Beyond 5G (B5G) or emerging Sixth-Generation (6G) standard for wireless communications is expected to support ubiquitous coverage for exponentially increasing Internet-of-Things (IoT) devices in a reliable and cost-effective manner [1]. The current Terrestrial Network (TN) lacks enough coverage in the remote area and also cannot provide connectivity to such a massive number of devices. Therefore, to alleviate this issue, the wireless vendors focus on the integration of non-terrestrial components into the existing TN elements. It is believed that the use of Non-Terrestrial Networks (NTN) will complement and enhance the existing TN by providing extreme coverage anywhere and anytime. Towards this end, both the industries and academics have been very hard pushing forward the integration of TN and NTN. Currently, the development of NTN is explored by standards bodies. Especially, Third Generation Partnership Project (3GPP) in Release 15 (Rel-15) [2], started working on using satellites and aerial networks to provide network connectivity to ground users. 3GPP is also continuously working towards extending the existing 5G and B5G networks to support NTN in the subsequent 3GPP releases [3]. In 3GPP Rel-17 and 18, the study of the integration of NTN and 5G-NR (or B5G) is currently underway.

The low-earth-orbit (LEO) satellites are the major part of NTN to provide seamless coverage globally. The LEO satellites allow considerably lower transmission latency and improve radio link budget. LEO satellite-based IoT applications emerge as one of the most promising technologies to support enhanced Machine Type Communication (eMTC) and Narrowband Internet-of-Things (NB-IoT) applications [4]. Moreover, the 3GPP also released study items covering the applicability of NB-IoT over NTN [3], [5]. Of course, this integration comes with several challenges like long proportion delay, large path losses, and Doppler shift that need to be carefully addressed.

Considering the energy limitation of the satellite and the UE, less complex and energy efficient methods are needed to save the power of the devices. There is the need of a reliable design of Random Access (RA) preamble detection to deal with the highly dynamic satellite communication environment. The reduction of the amount of signaling overhead can also reduce the power consumption of the UE. Along with these modifications, it is imperative to consider an energy saving mechanism where the UE can sleep when there is no data for that UE. This motivates us to propose a Discontinuous Reception (DRX) mechanism for an NB-IoT UE over NTN, considering an overhead due to the RA procedure. Hence, the primary contribution of this paper is a novel DRX framework for NB-IoT UEs connected to NTN. Fig. 1 shows an architecture of NTN-based communications. The contributions of this paper are as follows:

1) The modeling of a DRX procedure for the NB-IoT based NTN communication system.
2) The analysis of the RA procedure overhead, considering the DRX mechanism.
3) The performance analysis of the DRX procedure in power saving, average delay, and the RA procedure overhead.

The rest of the paper is organized as follows. We first present the preliminary study in Section II and then related work in Section III. Section IV then presents the proposed NTN DRX model. Section V describes a semi-Markov process model of NTN DRX. The performance evaluation is described in Section VI. Finally, Section VII concludes this paper along with future work.

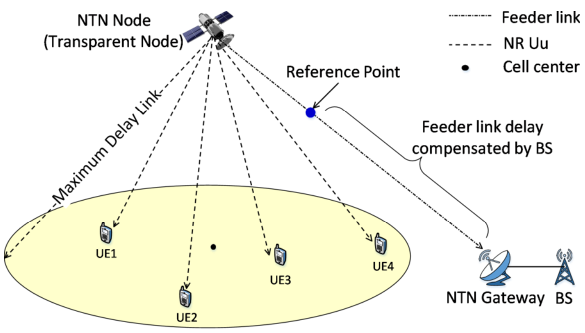


Fig. 1. An architecture of NTN-based communications

II. Preliminary Study

In this section, we include the discussion on NTN and NB-IoT and its integration.

A. Discussion on NTN

Both 3GPP NR NTN and IoT NTN standards are designed and built on the TNs and IoT specifications, leveraging the existing 5G network to enable new user opportunities. Satellite-based communication plays a vital role in coverage extension in isolated areas and provides edge content delivery services for the terrestrial nodes. In Release-15, 16, 17, and 18, 3GPP has discussed several activities to extend the 5G network by enabling the NR operation in NTN [2], [3], [6]. A tight integration between the satellite and the terrestrial mobile technology will improve the existing communication system. However, several modifications are required to support NTN-enabled communication with LEO and GEO satellites.

The major motivation behind integrating NTN with NR and IoT is to to cater enhanced Mobile Broadband (eMBB), massive Machine Type Communications (mMTC), and remotely located devices, where providing terrestrial network coverage is cost-intensive. Providing NTN applications to ultra Reliable and Low Latency Communications (uRLLC), applications can be challenging due to its stringent latency requirement [1]. NB-IoT NTN and NR NTN are attractive technologies for the cellular industry to serve the massive increase in the number of UE applications by improving the limited performance of TNs. Precisely, the satellite access use cases in NR can be divided into three major categories: continuity and reliability of service, ubiquitous service, and service scalability [6]. These applications are mostly deployed in remote locations where the coverage of TN becomes limited.

Unlike the conventional architecture of terrestrial cellular network consisting of a UE, Base Station (BS), core network, and data network, many different architectures exist depending on non-terrestrial (NT) platform placement. These include the NT platform such as UE [7], relay, BS, and a mixed architecture [1], [8].

B. NB-IoT Technology

NB-IoT is a cellular based technology, standardized by 3GPP in Rel-13 [9] to support a tremendous increase in IoT devices, spanning from smart homes to smart vehicles and smart hospitals. The primarily design objective is to support high connectivity, ubiquitous coverage, lower design complexity, and a long battery life, usually more than 10 years. The NB-IoT technology is envisaged to accommodate most of the IoT applications with static or limited mobility devices. Intelligent Transportation Systems (ITS), sensors, smart metering, wearables, and e-health are some of the prospective applications supported by NB-IoT. The support of NB-IoT and mMTC services needs several requirements that need to be fulfilled by the 5G networks to support the aforementioned use cases.

An NB-IoT architecture is derived from the architecture of the legacy LTE. In both Uplink (UL) and Downlink (DL), NB-IoT supports Frequency Division Duplexing (FDD) mode with channel and full carrier bandwidths of 200 kHz and 180 kHz, respectively [9]. It supports a single antenna in the UE and multiple antennas in the BS. NB-IoT defines three Coverage Enhancement (CE) levels in a cell, CE-0, CE-1, and CE-2, having a Maximum Coupling Loss (MCL) of 144 dB, 154 dB, and 164 dB, respectively. NB-IoT is designed for devices having a long battery lifetime of at least 10 years. Therefore, it becomes imperative to discuss saving the battery of the UE. In this regard, 3GPP proposes Power Saving Mode (PSM) in Rel-12 while extended Discontinuous Reception (eDRX) is proposed in Rel-13 [9], [10]. Using these techniques, the UE can enter a sleep mode when there is no data transmission or reception, similar to the DRX in LTE [11].

C. Integration of NB-IoT and NTN

The integration of NB-IoT and NTN can provide continuous global coverage everywhere on Earth. Being remotely located, NB-IoT devices require energy-efficient communications such as data transmission and accessing a network. Needless to add, the integration of a satellite network (i.e., NTN) and an NB-IoT network (i.e., TN) comes with several challenges and are are discussed in the later part of this paper.

The primary challenge in the integration of NTN and TN is the distance and velocity of a satellite. The altitude of the satellite causes an extra delay in the communication. In TN, the maximum Round Trip Time (RTT) is in the order of milliseconds (ms) for a maximum cell radius of 100 km [3]. However, the RTT for a satellite can vary from several ms to 100 ms, resulting in the misalignment of downlink and uplink timings. This long propagation delay also impacts the protocol layers in terms of a random access procedure, synchronizations, and retransmission. In addition, NTN transmissions are also subjected to extra Doppler shift due to the movement of the satellite, which is approximately 10 times higher than TNs [1]. The constant handovers are required to maintain continuous communications with a ground UE. Interruptions in communications often lead to reliability and latency issues. Authors in [12] highlight several issues in NB-IoT NTN integration along with the potential solutions.

Some modifications are required in NB-IoT protocol stack to support satellite channel impairments which is more complicated than the TN. The protocol stack in NB-IoT consists of a user plane (UP), which handles data transmission, and a control plane (CP), which manages the necessary signaling. The long RTT in NTN impacts the UP functionalities. Procedures like random access, DRX, scheduling request, and Hybrid Automatic Repeat reQuest (HARQ) need to be reconsidered to tackle the impairments caused by the long RTT [13]. The timers defined in Media Access Control (MAC) and Radio Link Control (RLC) layers are considered generously to support extended coverage which requires long Transmission Time Intervals (TTI). Also, for the NB-IoT devices, power efficient operation in Radio Resource Control (RRC) idle mode is important. Note that the enhancements on the other layers in 5G Radio Access Networks (RAN) are out of scope of this work. Overall, despite the issues due to long propagation delay and moving cells, NTN can support NB-IoT devices with some enhancements [5].

III. Related Work

Considering the focus of this paper, it is relevant to discuss the preliminary work done in NTN. A significant amount of work has been done in NB-IoT communications over satellite [12], [14]–[18]. Authors in [12] discuss the modifications required to support NB-IoT over NTN. The work explores several aspects including architectural modifications and physical layer & higher layer enhancements. For instance, supporting fixed beam architecture to avoid frequent beam switching and performing autonomous timing advance and frequency adjustments are required to overcome high delay and Doppler variation. Authors in [14], [15] describe the NB-IoT's coverage extension using NTN. Sciddurlo *et al.* [16] design and evaluate a service-oriented solution to support NB-IoT over LEO satellite. Here authors extensively investigate the link-level features like antenna design and elevation angle and also evaluate the system-level performance by justifying the design choice taken to satisfy NB-IoT specifications. Work in [17] discusses the necessary mechanisms for adapting NB-IoT over a Geostationary Earth Orbit (GEO) satellite. Most existing work on NTN also includes evaluation of link budget [19]–[21].

Random access as an important MAC procedure is extensively studied by researchers [18], [22]–[24].

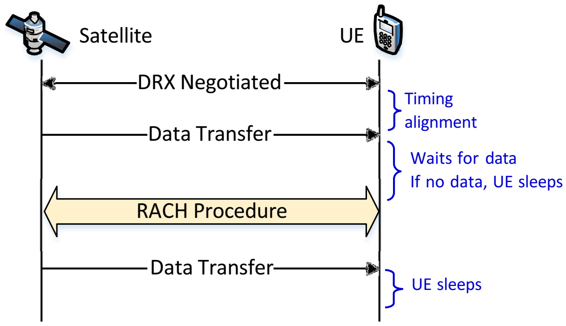


Fig. 2. A message flow between Satellite and UE

Authors in [4] provide a system-level performance evaluation of NB-IoT via NTN defined by 3GPP in terms of access delay and access success probability. Work in [22] presents a Physical Random Access Channel (PRACH) preamble design for 5G NR NTN based on concatenating two existing NR PRACH preambles to achieve uplink timing and frequency synchronization. Authors in [23] propose a reliable design and detection of RA preamble to effectively enhance the access efficiency in the LEO scenario. The proposed method shows a significant performance enhancement in terms of timing estimation accuracy, the success probability of the first access, and mean normalized access energy, which is compared with the existing RA methods. Chougrani *et al.* propose an RA technique which is robust to typical satellite channel impairments, including long delays, significant Doppler effects, and wide beams, without requiring any modification to the current NB-IoT RA waveform. Authors in [24] propose a method leveraging a joint clustering algorithm to accurately capture the timing position corresponding to the first arrival path without noise variance estimation. The performance is evaluated in terms of error detection probability and the timing mean square error.

A significant amount of work has been done in the energy efficiency of the NB-IoT UE [25]–[29]. It is crucial to maintain the energy efficiency of the NB-IoT devices. To the best of our knowledge, there are limited studies on the energy efficiency of the ground UE with NTN communications. Methods for reducing the power consumption of the energy constrained NB-IoT UE communicating with NTN are needed. Power saving in a UE is crucial to discuss because NTN is used in an environment where power is usually a scarce resource. IoT is considered a major use case of NTN and also requires low power consumption. We focus on the adaptation of NB-IoT in the context of satellite communications, as it can benefit from a good link budget due to narrowband technology which can compensate for the large path losses in NTN.

IV. A Proposed NTN Scheme for NB-IoT

We consider a LEO satellite for providing connectivity to power-constrained NB-IoT enabled ground UEs. The air interface in the access and feeder link is the same as the TN. Fig. 2 shows a message flow between a Satellite and a UE.

NB-IoT applications can serve the IoT traffic in 5G network. Since the satellite is moving, we consider a moving cell where the UEs are entering and leaving its coverage. To avoid frequent beam switching, we consider an Earth-fixed beam architecture, which is also prioritized by the 3GPP [12]. It is also worth noticing that no modification is required on the UE's hardware if Doppler pre-compensation is done at the satellite [30].

We propose a five-state semi-Markov process model of DRX for NB-IoT over NTN, as shown in Fig. 3. Also, Fig. 4 shows a timing diagram showing state transitions in the DRX model. The semi-Markov process model is used, as the time of a state transition and the holding time of a state are random variables [31]. Moreover, this semi-Markov process model does not possess memoryless property, if the sojourn time is not exponentially distributed [32], [33]. The states of NTN-DRX are (i) Connected Active state (S_1), (ii) Connected Sleep state (S_2), (iii) eDRX state with Paging Occasions (S_3), (iv) PSM state with Paging Occasions (S_4), and (v) Random Access Channel (RACH) state (S_5). Based on the state model in Fig. 3, a UE could be in one of the following five states, where state transitions are explained below. Note that our proposed model is aligned with the conventional eDRX model for IoT with a state set such as Connected Active, Connected Sleep, and RACH states.

In the state S_1, the UE spends a large amount of power in transmitting and receiving data packets and monitoring the Physical Downlink Control Channel (PDCCH). The transition from S_1 depends on the inactivity timer, T_{inact}, and the arrival of data packets. In the Connected Sleep state (S_2), the UE saves the power by avoiding the monitoring of the PDCCH channel when no data packet can be received. During this state, the device is in a low-power state while remaining connected to the network, allowing for quick wake-up and data transmission. From S_2, the UE has to perform RACH before transmitting and receiving the data packets. Expiry of a DRX inactivity timer shifts the UE to S_3, where the UE receives regular Paging Occasions (POs) indicating the arrival of the downlink data. Also, due to the discontinuous coverage, it becomes important to shift the UE to the eDRX state and save its power. Because of NTN cell mobility, the UE needs to trigger cell reselection and pre-synchronization for downlink monitoring for every eDRX PO, which also consumes additional power. Timing advance adjustment mechanisms are needed to deal with long RTTs. The arrival of data shifts the UE to S_5 and no arrival of data until the eDRX timer expires shifts the UE to S_4. Unlike S_3, in S_4, the UE is connected to the network but not reachable. A minimum amount of energy is consumed in S_4 as the UE wakes up only for uplink data transmission.

In S_5, the UE initiates the RA procedure to perform transmission. Now, with the knowledge of a UE's location, the RTT difference between the UE and the satellite can be determined based on the satellite ephemeris. So, the offset can be adjusted to postpone the subsequent RA procedure window for IoT NTN. Consequently, the delay compensation is performed by the network before UE initiates the RA procedure. The existing preamble format defined in NR can be reused [24]. The RA procedure is leveraged from the existing work and its design is out of scope of this paper.

To perform uplink data transmission, an IoT device needs to initiate an RA procedure to connect to a BS. When a device attempts to access the BS, it randomly selects one of the available preambles from the given preamble set to transmit a data packet on an RA time slot. However, different from the TN scenarios, a massive number of devices exist in the satellite coverage. Consequently, severe preamble collision and congestion will unavoidably occur, leading to frequent access retries and extra time spent on the RA procedure for the collided devices, which causes additional energy consumption to their already limited energy supplies. Therefore, it becomes imperative to improve the access efficiency of the IoT devices to minimize the energy consumption in NTN. To accommodate the massive RA requests, we consider the UE to transmit the messages only during the RACH state and Connected Active state. Thus, the number of messages with the DRX decreases, which means lower power consumption of the UE.

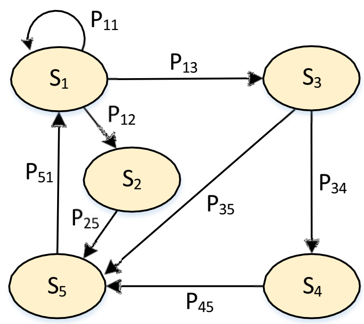


Fig. 3. A semi-Markov process model of DRX for NB-IoT over NTN

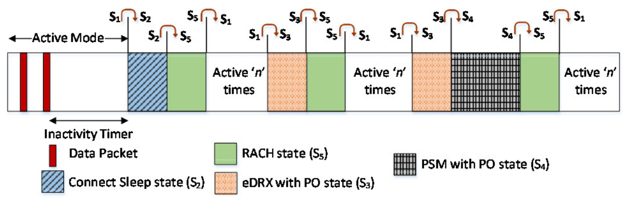


Fig. 4. A timing diagram showing state transitions in the DRX model

V. Discontinuous Reception for NTN

In this section, we take into account the trade-off between power saving and delay and also the estimation of battery lifetime of the NB-IoT UE as a primary objective of NB-IoT. The DRX procedure is modeled as a semi-Markov model, where a possible future state depends on the current state. The semi-Markov model is used as state holding time, and transition time is a random variable. Moreover, this model

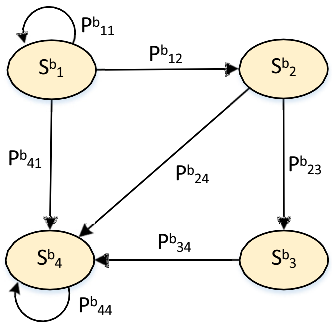


Fig. 5. A DRX model for NB-IoT UE [34]

TABLE I
MODEL PARAMETERS

Parameter	Description
S_i	State of DRX model, where $i \in \{1, 2, 3, 4, 5\}$
T_{inact}	Period of inactivity timer
T_{sl}	Period of sleep timer
T_{RA}	Duration of synchronization and random access
T_{eDRX}	Period of eDRX timer
T_{PSM}	Period of Power Saving Mode (PSM) timer
T_{PO}	Period of Paging Occasion (PO) monitoring
$E[h_i]$	Expected holding time in each state S_i
P_{idle}	Power consumption during DRX Idle state
P_{RA}	Power consumption during synchronization and random access
P_{PSM}	Power consumption during PSM
P_{Tx}	Power consumption during uplink transmission
P_{Rx}	Power consumption during downlink transmission
P_{act}	Power consumption during active state
ρ	Power saving factor
δ	Average delay experienced by UE
EC_{tot}	Total power consumption per DRX cycle
θ	Battery life of UE

possesses a memoryless property if the sojourn time is exponentially distributed [32], [33]. In our model, for each static UE, the packet arrival follows a Poisson process with an exponentially distributed inter-arrival time (IAT) [31], [35]. All the model parameters are described in Table I.

A. *Modeling of NB-IoT DRX over NTN*

The probability of transiting from one state to another state, i.e., the state transition probabilities, defined in Fig. 3 are given as follows:

$$P_{11} = 1 - e^{-\lambda_p T_{inact}}, \tag{1}$$

$$P_{12} = e^{-\lambda_p (T_{inact}+NT_{sl})}, \tag{2}$$

$$P_{35} = 1 - e^{-\lambda_p N(T_{PO}+T_{eDRX})}. \tag{3}$$

After transiting from the sleep state, the UE intends to perform random access in S_5 to acquire the channel and eventually moves to S_1 with the probability of $P_{51} = 1$, to serve the incoming data.

The state transition probabilities of P_{13} and P_{34} are $P_{13} = 1 - P_{11} - P_{12}$ and $P_{34} = 1 - P_{35}$, respectively. The steady-state probabilities, $\pi_i \forall i \in \{1, 2, 3, 4, 5\}$, for staying in state S_i can be obtained using the equation $\sum_{j=1}^{5} \pi_i = 1$ and the balance equation is given as $\sum_{j=1}^{5} \pi_j P_{j,i} = \pi_i, \forall i$.

Since the power saving of the UE is governed by the time it spends in each state, therefore it becomes imperative to derive the holding time in different states. So, after estimating the steady-state probabilities and the transition probabilities, we evaluate the state holding times. The state holding time, $E[h_i]$, $\forall i \in \{1, 2, 3, 4, 5\}$ for the 5-state DRX, denotes a period of time the UE remains in a particular state S_i before transiting to another state of the DRX model. $E[h_i]$ for different DRX states are given as follows:

$$E[h_1] = \frac{1 - e^{-\lambda_p T_{inact}}}{(1 - e^{-\lambda_p})e^{-\lambda_p T_{inact}}}, \tag{4}$$

$$E[h_2] = \frac{1 - e^{-\lambda_p T_{sl}}}{\lambda_p}, \tag{5}$$

$$E[h_3] = \frac{1 - e^{-\lambda_p N(T_{PO}+T_{eDRX})}}{\lambda_p}, \tag{6}$$

$$E[h_4] = \frac{1 - e^{-\lambda_p T_{PSM}}}{\lambda_p}, \tag{7}$$

$$E[h_5] = \frac{1 - e^{-\lambda_p T_{RA}}}{\lambda_p}. \tag{8}$$

1) Power and Delay Estimation: A core objective of the NB-IoT device is to reduce power consumption. After computing the steady state probabilities and the holding times using the equations mentioned above, we can estimate the Power Saving Factor (ρ). The ρ of the UE is defined as the ratio of the time spent by the UE in the sleep states to the total time spent across all the states as follows:

$$\rho = \frac{\pi_2 E[h_2] + \pi_3 E[h_3] + \pi_4 E[h_4]}{\sum_{i=1}^{5} \pi_i E[h_i]}. \tag{9}$$

NB-IoT has been designed for delay-tolerant applications. The power saving of the user during the eDRX and PSM is accompanied by an increase in the delay. The data packets arriving during the S_2, S_3, and S_4 are buffered and are served only when the UE transits to S_1. Using the concepts given in [31], the average delay (δ) is given as:

$$\delta = \frac{\pi_2 E[h_2]\frac{nT_{sl}}{2} + \pi_3 E[h_3]\frac{T_{eDRX}}{2} + \pi_4 E[h_4]\frac{T_{PSM}+T_{PO}}{2}}{\sum_{i=1}^{5} \pi_i E[h_i]}. \tag{10}$$

2) Battery Lifetime Estimation: The power consumption of the UE affects its battery life. Therefore, estimating UE's power consumption is an unavoidable parameter when considering the design of an IoT system. The power consumption during the active state is given by the following equation:

$$P_{act} = \pi_1 [P_{Tx}(E[h_1] - T_a) + P_{Rx} T_a]. \tag{11}$$

The total power consumption per DRX cycle is given as follows:

$$EC_{tot} = \frac{P_{act} + \pi_2 E[h_2] P_{idle} + \pi_3 E[h_3] P_{PSM} + \pi_4 E[h_4] P_{PSM} + \pi_5 E[h_5] P_{RA}}{\sum_{i=1}^{5} \pi_i E[h_i]}. \tag{12}$$

The battery lifetime is evaluated using Peukert's law [36], which is related to the non-linear relationship between the battery capacity and the rate of discharge. Using the work in [36], the battery lifetime (θ) of the UE can be estimated as follows:

$$\theta = \frac{a}{I^b}, \tag{13}$$

where I is the discharge current, and a and b are constants. The a has a value close to the capacity of the battery and b lies between 1.2 and 1.7 for most batteries [36]. The model is considerably good for predicting the battery lifetime for constant loads. However, for variable, non-constant loads, Rakhmatov and Vrudhula proposed an extended version of Peukert's law [36], which can be used for evaluation of battery lifetime. This battery lifetime is given as follows:

$$\theta = \frac{a}{\left[\frac{\sum_{i=1}^{j} I_i(t_i - t_{i-1})}{\theta}\right]^b}, \tag{14}$$

for $j = 1$, Eq. (14) is reduced to Eq. (13) [36].

B. Modeling of NB-IoT DRX: Baseline

For the baseline, we consider the conventional DRX model specified in 3GPP for NB-IoT over LTE and further extended for NR [34]. The DRX model consists of four states: (i) Active state, (ii) eDRX state, (iii) PSM state, and (iv) RACH state. We model the conventional DRX using semi-Markov. The state transitions properties, defined in Fig. 5 are given as follows:

$$P_{11}^b = 1 - e^{-\lambda_p T_{inact}}, \tag{15}$$

$$P_{24}^b = 1 - e^{-\lambda_p T_{eDRX}}, \tag{16}$$

$$P_{41}^b = 1 - e^{-\lambda_p T_{RA}}. \tag{17}$$

The state transition probabilities of $P_{12}^b = 1 - P_{11}^b$, $P_{23}^b = 1 - P_{24}^b$, $P_{44}^b = 1 - P_{41}^b$, $P_{41}^b = 1$ can be easily deduced. The steady-state probabilities, $\pi_i^b \forall i \in \{1, 2, 3, 4\}$, for staying in state S_i^b can be obtained by using the equation $\sum_{i=1}^{4} \pi_i^b = 1$ and the balance equation is $\sum_{j=1}^{4} \pi_j^b P_{j,i}^b = \pi_i \forall i$.

As mentioned above, the power saving of the UE is governed by the time it spends in each state, therefore we derive the holding time in different states. The state holding time, $E^b[h_i]\ \forall i \in \{1, 2, 3, 4, 5\}$ for the 4-state DRX are given by the following equations:

$$E^b[h_1] = \frac{1 - e^{-\lambda_p T_{inact}}}{(1 - e^{-\lambda_p})e^{-\lambda_p T_{inact}}}, \tag{18}$$

$$E^b[h_2] = \frac{1 - e^{-\lambda_p N T_{eDRX}}}{\lambda_p}, \tag{19}$$

$$E^b[h_3] = \frac{1 - e^{-\lambda_p T_{PSM}}}{\lambda_p}, \tag{20}$$

$$E^b[h_4] = \frac{1 - e^{-\lambda_p T_{RA}}}{\lambda_p}. \tag{21}$$

Using the equations mentioned above, we can estimate the Power Saving Factor (ρ^b), average delay (δ^b), and power consumption per DRX cycle (EC_{tot}^b) as follows:

$$\rho^b = \frac{\pi_2^b E^b[h_2] + \pi_3^b E^b[h_3]}{\sum_{i=1}^{4} \pi_i^b E^b[h_i]}, \tag{22}$$

$$\delta^b = \frac{\pi_2^b E^b[h_2] \frac{T_{eDRX}}{2} + \pi_3^b E^b[h_3] \frac{T_{PSM}}{2}}{\sum_{i=1}^{4} \pi_i^b E^b[h_i]}, \tag{23}$$

$$EC_{tot}^b = \frac{P_{act} + (\pi_2^b E^b[h_2] + \pi_3^b E^b[h_3]) P_{PSM} + \pi_4^b E^b[h_4] P_{RA}}{\sum_{i=1}^{4} \pi_i^b E^b[h_i]}. \tag{24}$$

TABLE II
PERFORMANCE PARAMETERS

Parameter	Values
Min/Max Data Rate	2 Mbps / 4 Mbps [31]
T_{inact}	$2 \sim 20\ ms$
T_{sl}	$80 \sim 480\ ms$
T_{RA}	$640\ ms$
T_{eDRX}	$160 \sim 5,120\ ms$
T_{PSM}	$1,280 \sim 20,480\ ms$
T_{PO}	$320\ ms$
P_{idle}	$21\ mW$ [28]
P_{RA}	$664\ mW$ [28]
P_{PSM}	$15\ \mu W$ [28]
P_{Tx}	$716\ mW$ [28]
P_{Rx}	$213\ \mu W$ [28]

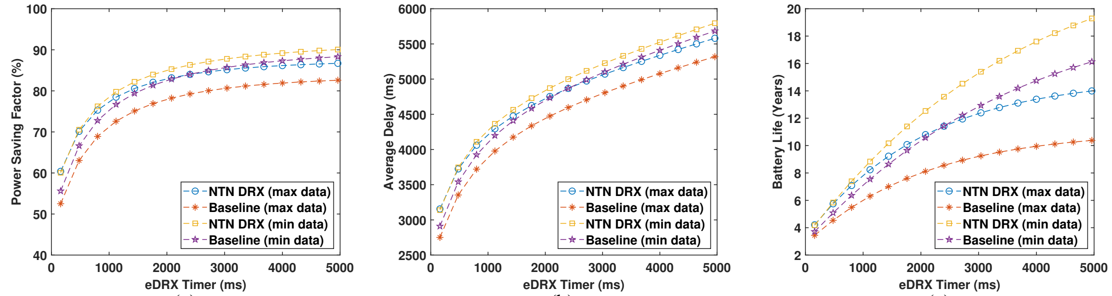
VI. PERFORMANCE EVALUATION

In this section, we discuss the simulation setup followed by the results obtained from both the analytical modeling and simulation using real traffic trace.

A. Analytical Results

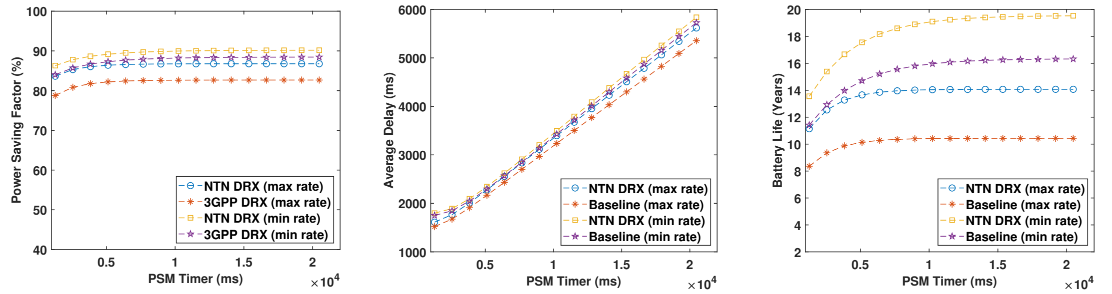
We first present the analytical results based on the semi-Markov model. Table II outlines the list of parameters used in the analytical modeling. The traffic model considered in the work is in line with the one defined by 3GPP for IoT applications [37]. There are no major modifications in timers are needed to support IoT NTN. However, the system model should support an RTT constraint in NTN systems [3].

Fig. 6 delineates the power saving, average delay, and battery lifetime of the NB-IoT UE with varying eDRX timer for different Max and Min data rates. The T_{eDRX} varies from $160 \sim 5120$ ms. The increase in power saving comes at the cost of increased delay. For max data rate, the power saving increases from 60% to 85%, with a delay varying from approximately $3,000$ to $5,600$ ms. To serve max data rate, the UE remains active for a longer duration of time which reduces the power saving of the UE and also the average delay when compared to the min data rate. Figs. 7 and 8 and also show similar trends for power saving and average delay experienced by the UE and also the expected battery lifetime of the UE. Similarly, Fig. 9 shows the power saving and average delay for connected sleep timer T_{sl}. The T_{sl} varies from $80 \sim 480$ ms. As



(a) (b) (c)

Fig. 6. Analytical Results of (a) Power Saving Factor, (b) Average Delay, and (c) Battery Life with varying eDRX Timer



(a) (b) (c)

Fig. 7. Analytical Results of (a) Power Saving Factor, (b) Average Delay, and (c) Battery Life with varying PSM Timer

expected, the power saving for min data rate is more than max data rate.

Figs. 6(c), 7(c), 8(c), and 9(c) show the battery lifetime of the NB-IoT UEs for different data rates. As expected, the battery lifetime of the UE becomes longer when it has less data to serve. This is due to the fact that the UE remains active for a shorter duration which increases the battery lifetime of the UE. The increase in the connected sleep timer does not significantly impact the battery lifetime. However, there is a considerable increase in battery lifetime by increasing the eDRX and PSM timers.

B. Simulation Setup and Results

We develop a discrete event simulator in MATLAB to analyze the performance of DRX in the NTN network. We consider the five states in the modeling along with the packet arrival event. During the Active state, the UE serves the packets and remains active until the inactivity timer expires. In the sleep state, the UE sleeps for a shorter sleep time. After the sleep timer expires, the UE has to perform RACH to access the channel. The UE transits from S_2 for n times. If there is no packet arrives after n transitions from S_1 to S_2, the UE transits to S_3. The UE sleeps for eDRX timers and after its expiry, the UE checks the packets and transits to either S_4 or S_5 depending on the data packets. Similarly, in S_4, the UE sleeps for the PSM timer and after the end of the PSM timer, UE transits to S_5. The RACH state deals with three consequences: (i) the UE selects a preamble and transmits packets; (ii) if another UE selects the same preamble, this will result in a collision. To avoid this, the UE waits for a random time and again attempts to select the preamble; (iii) On the contrary, when there is no collision, the UE waits for the random access response message. After that, the conventional RACH procedure is followed.

During the packet arrival event, packets are stored in the buffer and transferred to the UE only when the UE is in S_1. The events are processed in a non-decreasing timestamp order. The user power saving and delay are calculated using packet arrivals in a simulation run, a waiting period until the packet is served, wake-up time, sleep time, and simulation clock. The simulation is repeated for 10 times for each sleep duration with different random seeds to compute the average results. In our simulation, we consider a 4G and 5G RAN monitoring data, which was collected using the ElasticMon 5G monitoring framework over FlexRAN [38].

Fig. 10 shows MATLAB simulation results. Our simulation considers a satellite moving over a specific geographical area of interest. Each beam of the satellite corresponds to the NB-IoT cell. The UEs are uniformly distributed over the geographical area. Based on the UEs' deterministic locations, every UE will have a certain coverage time by the satellite.

C. Impact of RACH Preambles

DRX saves the power at the cost of delay. The packets arrived during the sleep state and had to wait for the next ON period. In NTN, if a UE continuously remains active, it has to perform handover as satellites are moving. In that case, the number of the messages transmitted/received by the UE may be great. By configuring the DRX, the UE will transmit/receive messages only during Active and RACH states. The UE only monitors the paging occasion (called PO) during PSM and eDRX states. Thus, by configuring the DRX, the number of messages transmitted by UE

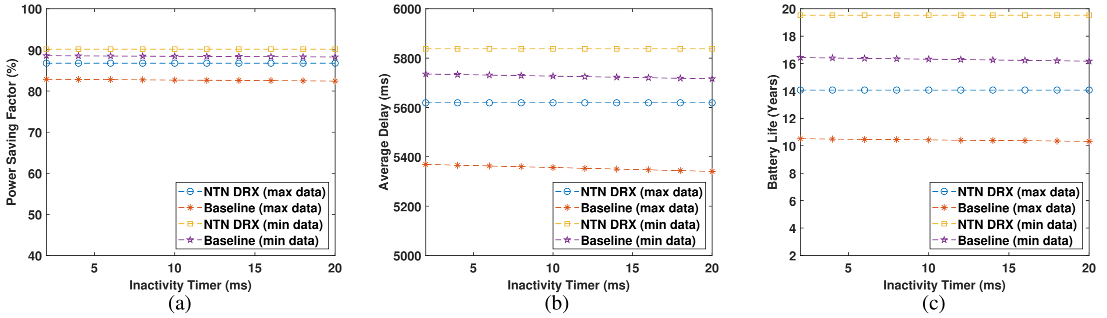


Fig. 8. Analytical Results of (a) Power Saving Factor, (b) Average Delay, and (c) Battery Life with varying Inactivity Timer

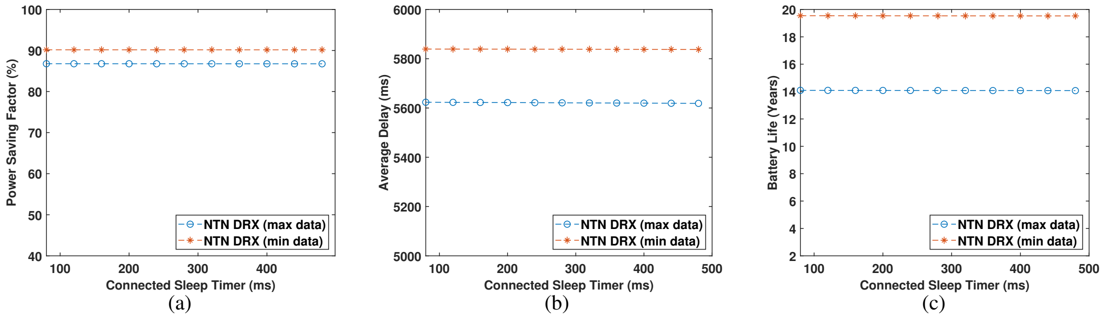


Fig. 9. Analytical Results of (a) Power Saving Factor, (b) Average Delay, and (c) Battery Life with varying Connected Sleep Timer

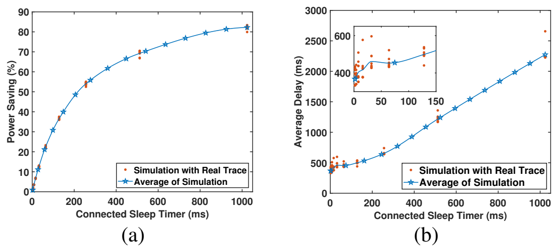


Fig. 10. Simulation Results of (a) Power Saving Factor and (b) Average Delay with varying Connected Sleep Timer

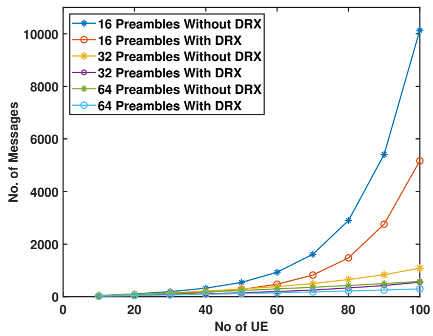


Fig. 11. Impact of RACH preambles with and without the DRX mechanism

will be small as compared to that of a UE remaining active all the time.

To analyze the effect of the DRX mechanism on the number of messages, we considered a cell diameter of 50 km, satellite speed of 7.56 km/s, time to handover for a UE of 6.61 s [39] and the uniform distribution of UEs in the cell. Every time for handover UE performs the random access process. For random access, the UEs select the preamble for transmission. The selected preamble is checked whether or not two or more UEs selected the same preamble during the same time slot, leading to a collision. Those UEs whose preambles are different can successfully perform the random access. The collided UEs perform the random access during the next time slot. Fig. 11 depicts that the number of messages exponentially increases with the increase of the number of UEs. With the increase of the number of UEs, the chance of selecting the same preamble will get higher. This adds a significant overhead to the system. With the inclusion of the DRX mechanism, the decrease of the number of messages is observed, which also reduces the overhead in the system. As shown in Fig. 11, as the number of the preambles increases, the number of messages transmitted by UEs decreases due to the reduction of message collisions.

VII. Conclusion

This paper concentrates on the power consumption of the NB-IoT UE communicating with NTN for ubiquitous connectivity. It proposes a Semi-Markov-based DRX model for NTN. It assesses the performance of the proposed model in terms of UE power saving, average delay, and UE's battery life. By varying the different sleep timers and inactivity timer, we can save the power at the cost of average delay. The reduction of the number of signaling steps, i.e., the signaling overhead can also reduce the power consumption of the UE. As future work, the modeling of random access and timing advance will be considered and evaluated.

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REFERENCES

[1] M. M. Azari, S. Solanki, S. Chatzinotas, O. Kodheli, H. Sallouha, A. Colpaert, J. F. M. Montoya, S. Pollin, A. Haqiqatnejad, A. Mostaani, *et al.*, "Evolution of non-terrestrial networks from 5G to 6G: A survey," *IEEE communications surveys & tutorials*, 2022.

[2] 3GPP, "Technical Specification Group Radio Access Network, Study on New Radio (NR) to Support Non-Terrestrial Networks (NTN)," Technical Report TR 38.811, 2020.

[3] 3GPP, "Solutions for NR to Support NTN," Technical Report TR 38.821, 2021.

[4] C. Amatetti, M. Conti, A. Guidotti, and A. Vanelli-Coralli, "NB-IoT random access procedure via NTN: system level performances," in *ICC 2022-IEEE International Conference on Communications*, pp. 2381–2386, IEEE, 2022.

[5] 3rd Generation Partnership Project, "Study on NB-IoT/eMTC support for non-terrestrial network, 3GPP RP-193235," Accessed Dec, 2024. Rev.

[6] T. Darwish, G. K. Kurt, H. Yanikomeroglu, M. Bellemare, and G. Lamontagne, "LEO satellites in 5G and beyond networks: A review from a standardization perspective," *IEEE Access*, vol. 10, pp. 35040–35060, 2022.

[7] M. M. Azari, F. Rosas, and S. Pollin, "Reshaping cellular networks for the sky: Major factors and feasibility," in *2018 IEEE International Conference on Communications (ICC)*, pp. 1–7, IEEE, 2018.

[8] X. Zhang, L. Zhu, T. Li, Y. Xia, and W. Zhuang, "Multiple-user transmission in space information networks: Architecture and key techniques," *IEEE Wireless Communications*, vol. 26, no. 2, pp. 17–23, 2019.

[9] 3GPP, "3rd Generation Partnership Project; Evolved Universal Terrestrial Radio Access (E-UTRA) and Evolved Universal Terrestrial Radio Access Network (E-UTRAN); Overall description," Technical Specification TS 36.300, 2018.

[10] E. Rastogi, N. Saxena, A. Roy, and D. R. Shin, "Narrowband Internet of Things: A Comprehensive Study," *Computer Networks*, vol. 173, p. 107209, 2020.

[11] M. K. Maheshwari, A. Roy, and N. Saxena, "DRX over LAA-LTE-a new design and analysis based on semi-Markov model," *IEEE Transactions on Mobile Computing*, vol. 18, no. 2, pp. 276–289, 2018.

[12] O. Liberg, S. E. Löwenmark, S. Euler, B. Hofström, T. Khan, X. Lin, and J. Sedin, "Narrowband Internet of Things for non-terrestrial networks," *IEEE Communications Standards Magazine*, vol. 4, no. 4, pp. 49–55, 2020.

[13] X. Lin, S. Rommer, S. Euler, E. A. Yavuz, and R. S. Karlsson, "5G from space: An overview of 3GPP non-terrestrial networks," *IEEE Communications Standards Magazine*, vol. 5, no. 4, pp. 147–153, 2021.

[14] S. Cluzel, L. Franck, J. Radzik, S. Cazalens, M. Dervin, C. Baudoin, and D. Dragomirescu, "3GPP NB-IoT coverage extension using LEO satellites," in *2018 IEEE 87th Vehicular Technology Conference (VTC Spring)*, pp. 1–5, IEEE, 2018.

[15] K. M. O'Hara and G. J. Skidmore, "Providing narrowband IoT coverage with low earth orbit satellites," *Microwave Journal*, vol. 62, no. 12, pp. 74–84, 2019.

[16] G. Sciddurlo, A. Petrosino, M. Quadrini, C. Roseti, D. Striccoli, F. Zampognaro, M. Luglio, S. Perticaroli, A. Mosca, F. Lombardi, *et al.*, "Looking at NB-IoT over LEO satellite systems: Design and evaluation of a service-oriented solution," *IEEE Internet of Things Journal*, vol. 9, no. 16, pp. 14952–14964, 2021.

[17] R. Barbau, V. Deslandes, G. Jakllari, J. Tronc, J.-F. Chouteau, and A.-L. Beylot, "NB-IoT over GEO satellite: Performance analysis," in *2020 10th Advanced Satellite Multimedia Systems Conference and the 16th Signal Processing for Space Communications Workshop (ASMS/SPSC)*, pp. 1–8, IEEE, 2020.

[18] T. T. T. Le, N. U. Hassan, X. Chen, M.-S. Alouini, Z. Han, and C. Yuen, "A Survey on Random Access Protocols in Direct-Access LEO Satellite-Based IoT Communication," *IEEE Communications Surveys & Tutorials*, 2024.

[19] O. Kodheli, N. Maturo, S. Andrenacci, S. Chatzinotas, and F. Zimmer, "Link budget analysis for satellite-based narrowband IoT systems," in *International Conference on Ad-Hoc Networks and Wireless*, pp. 259–271, Springer, 2019.

[20] G. Charbit, D. Lin, K. Medles, L. Li, and I.-K. Fu, "Space-terrestrial radio network integration for IoT," in *2020 2nd 6G Wireless Summit (6G SUMMIT)*, pp. 1–5, IEEE, 2020.

[21] C. Amatetti, J. Bucheli, D. Panaitopol, S. Tong, X. Leturc, M. Caus, M. Shaat, E. Recayte, M. Gurelli, M. A. Vazquez, *et al.*, "6G NTN in C and Q/V Bands: Link Budget Analysis and Waveforms Performance," 2024.

[22] T. A. Khan and X. Lin, "Random Access Preamble Design for 3GPP Non-terrestrial Networks," in *2021 IEEE Globecom Workshops (GC Wkshps)*, pp. 1–5, IEEE, 2021.

[23] Y.-H. Chuang, P.-F. Lee, S.-S. Wang, and S.-T. Sheu, "Enhanced RACH Occasion in LEO-Based Non-Terrestrial Networks," in *ICC 2023-IEEE International Conference on Communications*, pp. 283–289, IEEE, 2023.

[24] L. Zhen, Y. Wang, T. Sun, W. Wang, K. Yu, and R. Kharel, "A Threshold-Free Random Access Preamble Detection Method Based on Joint Clustering for 6G NTN," in *2021 IEEE Globecom Workshops (GC Wkshps)*, pp. 1–6, IEEE, 2021.

[25] A. K. Sultania, P. Zand, C. Blondia, and J. Famaey, "Energy Modeling and Evaluation of NB-IoT with PSM and eDRX," in *2018 IEEE Globecom Workshops (GC Wkshps)*, pp. 1–7, IEEE, 2018.

[26] A. K. Sultania, C. Blondia, and J. Famaey, "Optimizing the energy-latency tradeoff in NB-IoT with PSM and eDRX," *IEEE Internet of Things Journal*, vol. 8, no. 15, pp. 12436–12454, 2021.

[27] P. Andres-Maldonado, M. Lauridsen, P. Ameigeiras, and J. M. Lopez-Soler, "Analytical modeling and experimental validation of NB-IoT device energy consumption," *IEEE Internet of Things Journal*, vol. 6, no. 3, pp. 5691–5701, 2019.

[28] J. P. García-Martín and A. Torralba, "Energy Consumption Analytical Modeling of NB-IoT Devices for Diverse IoT Applications," *Computer Networks*, p. 109855, 2023.

[29] L. Hema and R. S. Raj, "Enhancing energy-efficient sleep scheduling for Narrowband Internet of Things devices in coordinated 5G networks within smart environments," *International Journal of Communication Systems*, vol. 37, no. 9, p. e5773, 2024.

[30] H. Chougrani, S. Kisseleff, W. A. Martins, and S. Chatzinotas, "NB-IoT Random Access for Nonterrestrial Networks: Preamble Detection and Uplink Synchronization," *IEEE Internet of Things Journal*, vol. 9, no. 16, pp. 14913–14927, 2021.

[31] M. K. Maheshwari, E. Rastogi, A. Roy, N. Saxena, and D. R. Shin, "DRX in NR unlicensed for B5G wireless: Modeling and Analysis," *IEEE Transactions on Mobile Computing*, 2022.

[32] J. Janssen and R. Manca, *Applied semi-Markov processes*. Springer Science & Business Media, 2006.

[33] V. S. Barbu and N. Limnios, *Semi-Markov chains and hidden semi-Markov models toward applications: their use in reliability and DNA analysis*, vol. 191. Springer Science & Business Media, 2009.

[34] 3GPP, "Evolved Universal Terrestrial Radio Access (E-UTRA); Medium Access Control (MAC) protocol specification," Technical Specification TS 36.321, 2018.

[35] J. Zhang, D. Qin, C. Kong, F. Zhao, R. Li, J. Wang, and Y. Wang, "System-level evaluation of beam hopping in NR-based LEO satellite communication system," in *2023 IEEE Wireless Communications and Networking Conference (WCNC)*, pp. 1–6, IEEE, 2023.

[36] M. Jongerden and B. Haverkort, "Battery modeling Enschede," 2008.

[37] 3GPP, "Cellular System Support for Ultra-Low Complexity and Low Throughput Internet of Things (CIoT)," Technical Report TR 45.820, 2015.

[38] B. Koksal, R. Schmidt, X. Vasilakos, and N. Nikaien, "Crawdad eurecom/elasticmon5g2019," 2022.

[39] Y. I. Demir, M. S. J. Solaija, and H. Arslan, "On the performance of handover mechanisms for non-terrestrial networks," in *2022 IEEE 95th Vehicular Technology Conference:(VTC2022-Spring)*, pp. 1–5, IEEE, 2022.