

Direct-to-Satellite NB-IoT: the Contention-Based Early Data Transmission Advantage

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Abstract—Direct-to-satellite narrowband Internet of Things (NB-IoT) is a prominent use case in non-terrestrial network (NTN) communications, rapidly approaching commercialization. The scalability of these systems relies heavily on the access procedures implemented by user equipments. While standardized access protocols perform well in terrestrial networks, their efficiency in NTN environments supporting massive machine-type communications remains uncertain. In this work, we analyze the latest access procedure features introduced in the 3GPP standard for IoT-NTN, specifically contention-based early data transmission (CB-EDT) in Release-19. We compare the solution with legacy procedures to assess its potential for future deployments. The results highlight substantial advantages when implementing CB-EDT in terms of energy savings, access completion time, and spectral efficiency, making it an optimal candidate for future massive IoT satellite deployments.

I. INTRODUCTION

The 3rd generation partnership project (3GPP) has recognized non-terrestrial networks (NTN) as a foundational pillar of 6G, the next-generation mobile systems, positioning them as natively integrated components of the network architecture from day one. The NTN paradigm delivers ubiquitous connectivity from above by leveraging aerial platforms, such as unmanned aerial vehicles and high-altitude balloons, alongside Earth-orbiting satellites.

NTN are essential for providing seamless and complementary connectivity in areas where deploying terrestrial infrastructure is physically or economically unfeasible. A relevant example is provided by Internet of Things (IoT) applications, expected to be a key solution for connecting unserved and underserved environments such as maritime regions, vast deserts, mountains, and remote rural areas. In particular, the 3GPP narrowband IoT (NB-IoT) technology [1] not only plays a pivotal role but is a leading solution on the path to commercialization. It offers a simple, standardized, and cost-efficient solution for monitoring, tracking, and surveillance in such remote areas.

The communication protocols regulating the connectivity of these simpler devices to the eNodeB are inherited from long term evolution (LTE), originally designed for the terrestrial

infrastructure. However, the protocol performance significantly degrades when a user equipment (UE) communicates with a satellite, as the vastly greater distances introduce substantial round-trip delays. Furthermore, since a satellite’s coverage area is much larger than that of a terrestrial cell, the illuminated footprint enables the simultaneous connection of a massive number of devices. Consequently, traditional handshaking protocols that implement resource negotiation not only experience severe performance degradation but also become highly inefficient for coordinating spectrum access among large number of UEs. To overcome this issue, the early data transmission (EDT) protocol was introduced in Release-15 [2] allowing the UE to attempt delivery of data before completing the 4-step access negotiation [3], [4]. Although this solution successfully reduced overhead, additional enhancements are necessary for the protocol access mechanism to efficiently support NTN massive connectivity. Ultimately, Release-19, finalized in December 2025, standardized the contention based Msg3 early data transmissions (CB-Msg3-EDT) (also referred to simply as CB-EDT) [5], [6] for NB-IoT over NTN. By enabling devices to transmit data directly without prior negotiation and allowing resource sharing, CB-EDT effectively eliminates most of the communication overhead.

A relevant feature of CB-EDT is the transmission of multiple MAC-level replicas of a packet, aiming to increase the probability that at least one of them is received interference-free even under random access (RA) contention. The idea follows the principles of diversity slotted ALOHA (DSA) [7], as well as of more advanced research directions on grant-free access based successive interference cancellation [8]–[11].

In this perspective, while access protocols for NB-IoT have been the subject of intensive research, insights on the benefits of the newly introduced CB-EDT over EDT and 4-step RA for direct-to-satellite IoT connectivity remain largely unexplored [5]. To address this gap, we provide a MAC-level study of CB-EDT in a low-Earth orbit (LEO) satellite scenario, focusing on massive connectivity as a key business driver.

II. 3GPP ACCESS PROCEDURES

This section provides some minimum background information on the three 3GPP access procedures currently defined for NB-IoT NTN connectivity and considered in this work.

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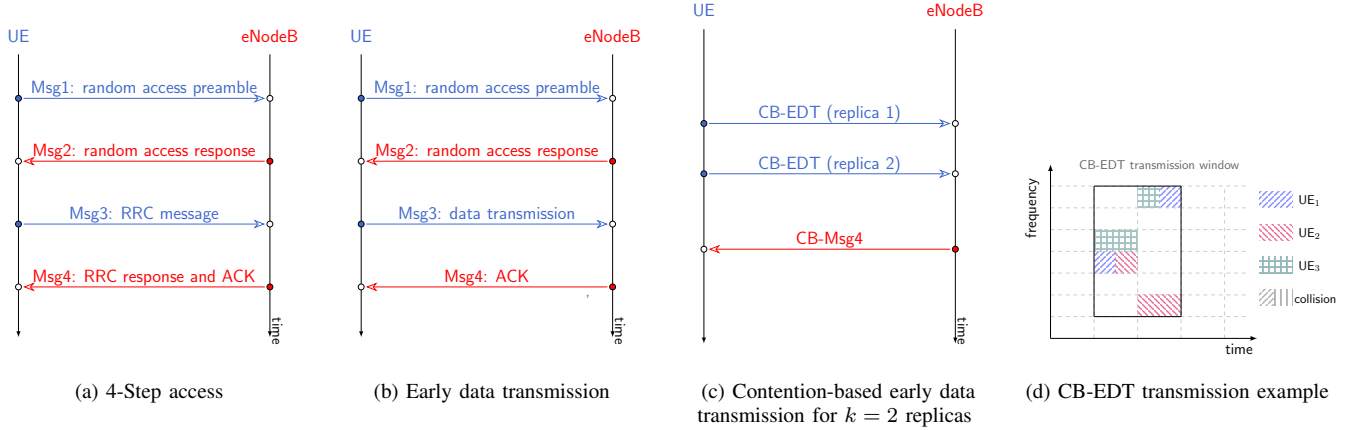


Fig. 1. Direct-to satellite NB-IoT access procedure.

A. 4-Step Random Access Process

As per the legacy LTE standard, one of the access procedures in NB-IoT is based on 4-Step RA, as illustrated in Fig. 1a. A high level description is provided here, the interested reader is referred to, e.g., [2], [5] for further details.

To initiate an RA procedure, the UE waits for the start of a random access opportunity, which is a priori configured by the eNodeB with a given periodicity. The four steps are described in the following.

Step 1: The first message is the RA preamble (Msg1), transmitted in a contention-based manner following the slotted ALOHA principles over the narrowband physical random access channel (NPRACH). The preamble consists of a pure sine wave, sent using single-carrier frequency hopping to exploit frequency diversity. The total duration of this transmission depends on the preamble length and the number of repetitions, which are determined by the selected preamble format and the coverage enhancement (CE) level of the UE.¹ Each device randomly selects a preamble sequence from an available pool.

Steps 2 and 3: Following the preamble transmission, the UE monitors the downlink control channels for a Msg2 (also known as random access response (RAR)) from the eNodeB within a configured response window. Upon successful reception of Msg2, the UE transmits the connection request (Msg3) using the uplink resources granted in Msg2.

Step 4: The final step is the contention resolution message (Msg4). This procedure resolves collisions occurring when multiple devices select the same preamble but only one transmission is successfully decoded by the eNodeB. Upon successful decoding of Msg4, the UE proceeds to transmit its payload using resources allocated on the narrowband physical uplink shared channel (NPUSCH).

If two or more devices select the same preamble in Step 1, a collision occurs. If the collision is not resolved (i.e., the UE does not receive Msg2 or Msg4), the device enters a backoff period. During this period, it waits for a random

¹The CE level is determined based on the values of the reference signal received power broadcasted by the eNodeB.

number of RA opportunities, determined by the configured backoff window, before reattempting the transmission. This process is repeated until success or until a maximum number of attempts is reached.

B. Early Data Transmission

Introduced in Release-15, EDT simplifies the RA procedure to reduce latency and energy consumption by enabling the UE to transmit a small data payload within Msg3 [12], as shown in Fig. 1b. The UE indicates its intention to use the EDT procedure by selecting an NPRACH preamble from a dedicated pool for Msg1. The network broadcasts these preamble configurations along with the maximum transport block size supported for Msg3, thereby defining the upper limit on data size permitted for EDT. Similar to the 4-step approach, the eNodeB responds to Msg1 with a RAR, which in this case also includes a grant for Msg3 transmission. The UE then uses this grant to transmit its payload.

Since the preamble transmission remains contention-based, collisions may still occur when multiple UEs select the same preamble. In such cases, the colliding devices receive identical grants and transmit Msg3 over the same resource, potentially leading to decoding failure at the eNodeB. If the transmission is not successfully resolved (i.e., no contention resolution message is received), the UE reattempts access following the configured backoff procedure.

C. CB-EDT

Introduced in Release 19, CB-EDT is a purely contention-based scheme in which the UE directly attempts transmission without accessing the NPRACH, as shown in Fig. 1c. Similar to the standard EDT, CB-EDT is applicable when the data payload is less than or equal to a configured transport block size. The UE then transmit its payload following the DSA protocol [7], sending multiple copies (*replicas*) of the same data packet. For each replica, the UE randomly selects a different time occasion (TO), and for each selected TO, a corresponding frequency resource is also chosen at random. To support this operation, the eNodeB periodically configures and

allocates resources within the NPUSCH. This configuration provides the UE with the necessary parameters, including the number of TOs, the number of frequency resources, the NPUSCH periodicity, and the required number of replicas.

Two relevant remarks are in order. First, the CB-EDT approach foresees the use of multiple copies of a MAC-level packet, aiming to increase the probability that at least one of them will be retrieved without interference (i.e., not collided). The scheme operates on top of any message repetition strategy for coverage enhancement employed at the physical layer, meant to improve the decoding probability of a single MAC packet against noise and channel impairments [5]. Second, CB-EDT implements a true RA channel for data transmission. As such, collisions are always possible, and the overall performance of the scheme will be driven by how the receiver can handle such conditions, e.g., by leveraging replicas to perform successive interference cancellation.

Following transmission, the UE monitors the downlink for a response message (Msg4), which may indicate successful reception, provide a backoff indicator, or assign downlink resources. If no response is received, or if a backoff indicator is provided, the UE retransmits according to the configured procedure, up to a maximum number of attempts.

An example of CB-EDT is shown in Fig. 1d for three users transmitting $k = 2$ in two times occasions.

III. SYSTEM MODEL

We consider a network consisting of a LEO satellite providing NB-IoT connectivity to ground-based UEs. A regenerative payload architecture is assumed, where the eNodeB is located onboard the satellite to perform signal and data processing. The system serves stationary UEs equipped with global navigation satellite system (GNSS) receivers to pre-compensate the Doppler shift and the link propagation delays caused by the motion of the LEO satellite. The round-trip time is τ .

Newly generated traffic is modeled following a Poisson process of intensity λ [UE/s]. Each UE attempts transmission of its payload, and its traffic contribution ceases when the message is delivered or a maximum number of trials is reached. A bandwidth $B = 180$ kHz is assumed to be allocated to both NPRACH and NPUSCH. All messages are sent with power P_{tx} , with a fixed payload size of L^{data} bits. As discussed, NB-IoT may resort at the physical layer to a repetition mechanism to ensure successful decoding of a data packet, with a MAC packet mapped into several subsequent transmissions that can be combined at the eNodeB to accumulate energy and improve SNR. The number of repetitions (R_{data}) is determined by the measured CE level. We focus on a single CE level to clearly evaluate the access protocol. The overall time needed to send one MAC packet is then denoted by t_{data} .

For the sake of our evaluation, a collision channel will be assumed.² Accordingly, if two or more messages are transmitted over the same uplink resources, the eNodeB cannot

retrieve information. On the other hand, a message that does not experience a collision is always decoded. This applies to Msg1 and Msg3 for the 4-step RA and EDT, as well as for the CB-Msg3 in the case of CB-EDT. We recall that, for the first two approaches the UE cannot deliver its payload if its preamble collides, whereas for CB-EDT collisions would directly involve the payload. In all cases, we denote by P_{fail} the probability of such event, to which the UE responds by entering a backoff phase, whose duration corresponds to a random number of opportunities,³ uniformly drawn from the set $[1, \beta]$. After the backoff, another attempt is performed, with a maximum of b_{max} attempts.

The following subsections provide the parameters for each specific access procedure and the assumptions regarding system configuration. The MAC layer is analyzed in isolation using PHY abstractions.

A. 4-Step NPRACH parameters

The model assumes the full 180 kHz bandwidth is allocated to the NPRACH to maximize successful UE admission, followed by NPUSCH scheduling. We consider NPRACH Format 1, characterized by a subcarrier spacing of 3.75 kHz and a base preamble duration of $t_{\text{Msg1}} = 6.4$ ms. The required number of preamble repetitions, denoted by R_{Msg1} , is determined by the UE's CE level, with $R_{\text{Msg1}} \in \{1, 2, 4, 8, 16, 32, 64, 128\}$. Consequently, the duration of a NPRACH transmission opportunity is given by $t_{\text{NPRACH}} = t_{\text{Msg1}} \cdot R_{\text{Msg1}}$.

During an access attempt, UEs randomly select a preamble from a pool of $N_{\text{pre}} = 48$ orthogonal sequences. The NPRACH resources are allocated periodically, with a periodicity P_{NPRACH} defined by the standard as $P_{\text{NPRACH}} \in \{40, 80, 160, 240, 320, 640, 1280, 2560\}$ ms. This periodicity is constrained by the number of repetitions, as P_{NPRACH} must be sufficient to accommodate the complete preamble transmission duration as well as the subsequent data transmission phase. Specifically, we assume a strict time separation between NPRACH and NPUSCH without time multiplexing. This approach is justified in dense network scenarios to maximize the availability of access resources. A UE waits for the next NPRACH opportunity to start the access process. The average waiting time is assumed to be

$$\bar{W}_{\text{init}}^{4S} = \frac{P_{\text{NPRACH}}}{2}. \quad (1)$$

In case of a Msg1 collision, the backoff period for the 4-Step procedure ranges from a minimum of P_{NPRACH} to a maximum of βP_{NPRACH} , resulting in an average backoff waiting time of

$$\bar{W}_{\text{bo}}^{4S} = \frac{(\beta + 1)P_{\text{NPRACH}}}{2}. \quad (2)$$

The transmission times for Msg2, Msg3 and Msg4 are denoted by t_{Msg2} , t_{Msg3} and t_{Msg4} respectively.

²This allows the MAC layer to be analyzed in isolation using PHY abstractions to understand the limits of each protocol.

³An opportunity corresponds to the next available NPRACH allocation for 4-step RA or EDT, and to the next scheduled RA NPUSCH resources, for CB-EDT

B. EDT parameters

EDT follows the 4-Step mechanism for Msg1 and Msg2, and piggybacks the data transmission within Msg3. The feasible values imposed by the standard for R_{Msg1} and P_{NPRACH} also coincide with those of the 4-Step scheme. Different from the 4-Step, in EDT Msg4 is the contention resolution and acknowledgment message.

By avoiding a separate data transmission phase after connection setup, the total occupancy time is reduced. Consequently, the required P_{NPRACH} duration can be shorter compared to the standard 4-Step procedure. The waiting time for EDT, denoted by $\bar{W}_{\text{init}}^{\text{EDT}}$, and the backoff time for EDT, $\bar{W}_{\text{bo}}^{\text{EDT}}$, are evaluated as in the 4-step procedure given in (1) and (2), respectively.

C. CB-EDT parameters

We denote by N_{TO} the number of time occasions, allocated one after the other over the NPUSCH, during which each UE can transmit k payload replicas. For baseline comparison, we set $N_{\text{TO}} = k$ throughout our work. The waiting time required for the UE to transmit in CB-EDT is assumed to be

$$\bar{W}_{\text{init}}^{\text{CB-EDT}} = \frac{N_{\text{TO}} t_{\text{data}}}{2}.$$

If the eNodeB fails to decode a user's signal, the CB-EDT backoff period extends from a minimum of $N_{\text{TO}} t_{\text{data}}$ to a maximum of $\beta N_{\text{TO}} t_{\text{data}}$, with an average backoff time

$$\bar{W}_{\text{bo}}^{\text{CB-EDT}} = \frac{(\beta + 1)}{2} N_{\text{TO}} t_{\text{data}}.$$

IV. KEY PERFORMANCE INDICATORS

We evaluate the trade-offs among the standard NB-IoT access mechanisms by focusing on three key performance indicators relevant to satellite networks: service completion time, energy per successful bit, and spectral efficiency.

Service completion time

The delivery latency of data is generally not a critical issue for the majority of NB-IoT applications, which are inherently delay-tolerant. However, it presents a significant resource bottleneck due to the fact that a LEO satellite is visible only for a limited period of time. In this context, increasing the service completion time directly consumes the restricted time resources of the visibility window.

To quantify the efficiency of the access procedures, we evaluate the expected *service completion time* denoted by \bar{S}^{AP} . This is defined as the time elapsed from the initial device access attempt until the successful reception of the acknowledgement message, or, in case of failure, until the maximum number of allowed attempts is reached and the last negative acknowledgement message is received.

The expected service completion time is calculated as

$$\begin{aligned} \bar{S}^{\text{AP}} = & \sum_{i=1}^{b_{\text{max}}} (1 - P_{\text{fail}}) (P_{\text{fail}})^{(i-1)} [i \cdot t^{\text{AP}} + (i-1) \bar{W}_{\text{bo}}] \\ & + (P_{\text{fail}})^{b_{\text{max}}} [b_{\text{max}} \cdot t^{\text{AP}} + (b_{\text{max}} - 1) \bar{W}_{\text{bo}}] \quad [\text{s}]. \end{aligned}$$

where the sum accounts for the probability of failing the data reception $(i-1)$ times and succeeding on the i -th attempt, while the final term accounts for the probability of failing all transmission attempts.

For each access procedure, the duration of an attempt is

$$t^{\text{AP}} = t_s^{\text{AP}} + t_{\text{OH}}^{\text{AP}}$$

composed by the sum of the service time t_s^{AP} and service overhead $t_{\text{OH}}^{\text{AP}}$. The service overhead t_{OH} accounts for the total duration of control signaling and propagation delays required to establish the connection and receive an acknowledgement. We evaluate t^{AP} for each procedure below.

Note that P_{fail} depends on the access procedure and, in the case of CB-EDT depends also on the receiver implementation. This value is evaluated empirically in the simulations.

A. 4-Step NPRACH

The service time for the 4-Step procedure is expressed as

$$t_s^{4\text{S}} = \bar{W}_{\text{init}}^{4\text{S}} + t_{\text{OH}}^{4\text{S}} + R_{\text{data}} \cdot t_{\text{data}}.$$

The overhead $t_{\text{OH}}^{4\text{S}}$ accounts for the preamble transmission, RAR Msg2, connection request (Msg3), contention resolution (Msg4) and the acknowledgement, considering also all associated round-trip times. This yields

$$t_{\text{OH}}^{4\text{S}} = t_{\text{NPRACH}} + t_{\text{Msg2}} + \tau + t_{\text{Msg3}} + t_{\text{Msg4}} + \tau + \tau + t_{\text{ack}}.$$

Note that three round-trip delays (τ) are considered (Msg1-2, Msg3-4, Data-ACK).

B. EDT

The service time for the EDT procedure is given by

$$t_s^{\text{EDT}} = \bar{W}_{\text{init}}^{\text{EDT}} + t_{\text{OH}}^{\text{EDT}} + R_{\text{data}} \cdot t_{\text{data}}.$$

The overhead $t_{\text{OH}}^{\text{EDT}}$ is significantly reduced compared to the 4-Step approach because the payload is piggybacked onto Msg3, and Msg4 serves as both the contention resolution and the acknowledgement. Only two round-trip delays are considered, leading to

$$t_{\text{OH}}^{\text{EDT}} = t_{\text{NPRACH}} + t_{\text{Msg2}} + \tau + t_{\text{Msg4}} + \tau.$$

C. CB-EDT

The service time for the CB-EDT is given by

$$t_s^{\text{CB}} = \bar{W}_{\text{init}}^{\text{CB}} + t_{\text{OH}}^{\text{CB}} + k \cdot R_{\text{data}} \cdot t_{\text{data}}. \quad (3)$$

The overhead in CB-EDT is minimal, consisting only of the confirmation message (Msg4) and its propagation delay relative to the data transmission, as the preamble phase is completely eliminated

$$t_{\text{OH}}^{\text{CB}} = t_{\text{Msg4}} + \tau.$$

Parameters			
P_{tx}	23 dBm	L_{data}	50 bytes
τ	14 ms	W_{SAT}	420 s
t_{data}	16 ms	R_{data}	5
β	4	b_{max}	4

4-Step	EDT	CB-EDT
$t_{NPRACH} = 25.6$ ms	$t_{NPRACH} = 25.6$ ms	$k = 2, 3$
$t_{Msg2} = 12$ ms	$t_{Msg2} = 12$ ms	$N_{TO} = k$
$t_{Msg3} = 2$ ms	$t_{ack} = 1$ ms	$t_{ack} = 1$ ms
$t_{Msg4} = 4$ ms		
$t_{ack} = 1$ ms		

TABLE I
SYSTEM PARAMETERS

Energy per successful information bit

We evaluate the system *energy per successful information bit* received, denoted as E_{bit} , as the ratio of the average energy consumed by all UEs during the access procedure to the average number of information bits successfully delivered to the eNodeB within the satellite pass with arrival rate is λ .

This metric allows us to translate access protocol improvements directly into extended battery life. It is expressed as

$$E_{bit} = \frac{\bar{n}_{succ}^{AP}(\lambda) \cdot L_{data}}{n_{UE} \bar{E}^{AP}} \quad [\text{Joule/bits}]$$

where $\bar{n}_{succ}^{AP}(\lambda)$ represents the average number of payloads successfully decoded by the satellite at an user traffic rate of λ , n_{UE} is the total number of users accessing the channel during the satellite pass and \bar{E}^{AP} denotes the average energy consumed by a single UE.

The expected energy consumed \bar{E}^{AP} for a given access process can be evaluated as

$$\bar{E}^{AP} = P_{tx} t_{tx}^{AP} \left[\sum_{i=1}^{b_{max}} i \cdot (1 - P_{fail}) (P_{fail})^{i-1} + b_{max} \cdot (P_{fail})^{b_{max}} \right]$$

where t_{tx}^{AP} is the time expended in transmissions by the access process. In particular we have

$$\begin{aligned} t_{tx}^{4S} &= t_{NPRACH} + t_{Msg3} + R_{data} \cdot t_{data} \\ t_{tx}^{EDT} &= t_{NPRACH} + R_{data} \cdot t_{data} \\ t_{tx}^{CB-EDT} &= k \cdot R_{data} \cdot t_{data}. \end{aligned}$$

Spectral efficiency

We define the *spectral efficiency* denoted with η_{SE} as the ratio of the total successfully delivered information bits when the user arrival rate is λ to the total time-frequency resources consumed during the satellite pass. It is expressed as

$$\eta_{SE} = \frac{\bar{n}_{succ}^{AP}(\lambda) \cdot L_{data}}{B} \quad [\text{bits/s/Hz}].$$

V. NUMERICAL RESULTS

We consider a LEO satellite orbiting at 600 km. Table I reports the parameters used to evaluate the different access protocols. Based on these, the PRACH period is $P_{NPRACH} = 240$ ms for the 4-Step procedure and $P_{NPRACH} = 160$ ms for EDT. The numerical results are presented in the following, where two receiver implementations of CB-EDT are evaluated.

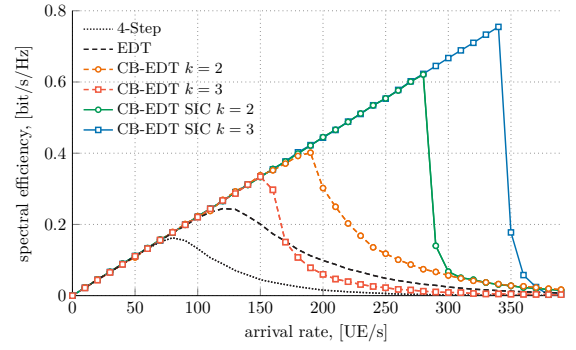


Fig. 2. Spectral efficiency as a function of the arrival rate.

On the one hand, a baseline eNodeB, in which a UE's data payload is successfully recovered only if at least one replica arrives collision-free. Taking Fig. 1d as an example, UE₂ and UE₃ each have one interference-free replica and are therefore successfully decoded, whereas UE₁ cannot be decoded with this implementation. On the other hand, we consider an enhanced receiver incorporating successive interference cancellation (SIC). This iterative algorithm decodes a payload, reconstructs its signal, and subtracts it from the received waveform. This mechanism enables the recovery of additional payloads that would otherwise be lost due to collisions. Referring to Fig. 1d, after decoding UE₂ or UE₃, the receiver cancels their replicas from the slots interfering with UE₁. This renders UE₁ interference-free, enabling its successful decoding.

As a first result, we report in Fig. 2, the spectral efficiency as a function of channel traffic for the 4-Step, EDT, and CB-EDT access procedures. The results highlight the superior performance attained by the Rel.-19 solution, which achieves better utilization of the available resources by reducing signaling overhead and exploiting packet replicas. Furthermore, the use of SIC significantly enhances the spectral efficiency by enabling the recovery of collided packets, allowing the system to sustain higher UE/s [8]. From this standpoint, the additional receiver complexity needed to implement interference cancellation appears well justified when massive connectivity is targeted, by virtue of the significant improvements that can be enjoyed. Notably, in terms of spectral efficiency, the solution with $k = 3$ replicas is the most beneficial when SIC is implemented.

Further insights are offered by Fig. 3, which shows the expected service completion time as a function of channel traffic. It is apparent that the performance of 4-Step and EDT procedures degrade rapidly as the number of UE/s increases, due to the increase in collision probability. Moreover, the expected access completion time saturates relatively quickly, confirming that the system is beset by interference and new UEs are simply not able to deliver their payload, spending time and energy in unsuccessful attempts until the maximum number of backoff trials is reached.

EDT exhibits a slightly better behavior as it avoids two round-trips compared to the 4-Step procedure, yet eventually

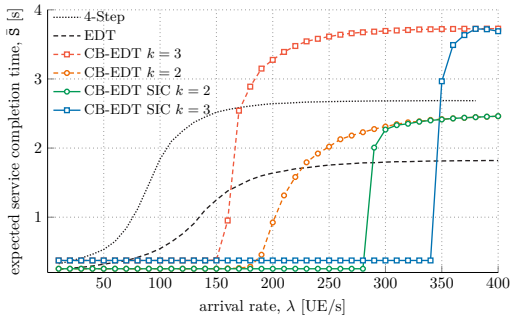


Fig. 3. Expected service completion time as a function of the arrival rate.

experiences the same bottleneck, driven by a slotted ALOHA type of contention. In contrast, CB-EDT, both with and without SIC, achieves a significantly reduced access completion time. This indicates that the system can support a larger number of UEs without triggering repeated backoff procedures.

It is interesting to note that, as far as service time is concerned, the configuration with $k = 2$ replicas outperforms the $k = 3$ case when not relying on SIC. This pinpoints a design trade-off with spectral efficiency: for the considered system parameters, allocating more transmission opportunities over the NPUSCH to send more replicas allows to successfully support larger number of UEs, yet at the expense of a longer transmission time as captured by (3). A similar observation can be made when the receiver implements SIC. For low to intermediate arrival rates ($\lambda < 280$ UE/s for the setup), the $k=2$ configuration is to be preferred. However, as the channel becomes more congested, the collision bottleneck comes into play, leading to a quick and severe degradation of the service time, due to the higher packet loss rate. The use of more replicas ($k=3$) in combination with SIC can push this effect to higher loads, as illustrated by the results on spectral efficiency. The outcome is a traffic region in which lower latencies are experienced by sending more repetitions. Even though the specific values are dictated by the considered parameters, a key take-away is that the use of CB-EDT triggers trade-offs that shall be carefully evaluated, paving the road for the use of different network configurations based on the targeted channel load and application requirements.

Finally, similar trends are reflected in the energy consumption per successfully received information bit, shown in Fig. 4. For a low arrival rate ($\lambda < 80$ UE/s), EDT consumes less energy, as it is able to successfully serve all UEs with a very low probability of backlog. However, as the arrival rate increases, the energy consumption gradually rises due to increased contention and retransmissions, which reduces the efficiency of the access procedure. It is important to note that our formulation neglects the energy consumed by the UE when receiving downlink messages. The 4-Step and EDT procedures require the UE to stay awake for extended periods to receive Msg2 and Msg4 downlink responses. Therefore, accounting for receiver power consumption would further penalize these legacy protocols, making the battery savings of CB-EDT even more pronounced.

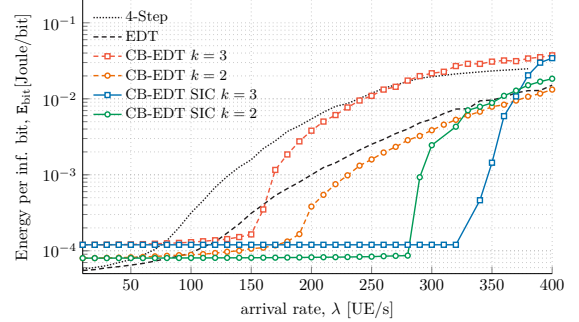


Fig. 4. Energy per successful information bit received as a function of the arrival rate.

VI. CONCLUSIONS

We studied and compared three standardized access procedures for direct-to-satellite NB-IoT scenario. The results show a significant improvement in spectral efficiency, energy consumption, and access completion time when using the CB-EDT protocol. Most notably, this approach delivers nearly a 4.5-fold improvement in spectral efficiency over the handshake protocol, drastically scaling the overall access capacity. These findings highlight the potential of CB-EDT as a strong candidate for supporting system scalability and enabling massive connectivity in future deployments.

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