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Low Latency V2X Applications and Network Requirements: Performance Evaluation

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***Abstract*— Vehicle-to-Everything (V2X) communication promises improvements in road safety and efficiency by enabling low-latency and reliable communication services for vehicles. Besides using *Mobile Broadband* (MBB), there is a need to develop *Ultra Reliable Low Latency Communications* (URLLC) applications with cellular networks especially when safety-related driving applications are concerned. Future cellular networks are expected to support novel latency-sensitive use cases. Many applications of V2X communication, like collaborative autonomous driving requires very low latency and high reliability in order to support real-time communication between vehicles and other network elements. In this paper, we classify V2X use-cases and their requirements in order to identify cellular network technologies able to support them. The bottleneck problem of the medium access in 4G *Long Term Evolution* (LTE) networks is random access procedure. It is evaluated through simulations to further detail the future limitations and requirements. Limitations and improvement possibilities for next generation of cellular networks are finally detailed. Moreover, the results presented in this paper provide the limits of different parameter sets with regard to the requirements of V2X-based applications. In doing this, a starting point to migrate to Narrowband IoT (NB-IoT) or 5G - solutions is given.**

I. INTRODUCTION

In addition to classical Mobile Broadband (MBB) applications, the next generation of cellular network development is driven by demands of Internet of Things (IoT) applications. In the context of the next generation mobile networks, IoT applications have been categorized into two classes: massive Machine Type Communication (mMTC) and Ultra Reliable Low Latency Communication (URLLC) [1]. While mMTC involves a large number of low cost devices with high requirements on long battery life and scalability, URLLC targets mission critical applications [2] where latency and reliability of the communication are of highest priority. This involves applications in factory automation, smart grids, and Vehicle-to-Anything (V2X) communication. Therefore, low latency and high reliability requirements for IoT use cases become critical.

V2X communication is one of the key technologies in Intelligent Transportation Systems (ITS), providing wireless connectivity between cars, infrastructure elements, and pedestrians [3]. V2X is extremely challenging due to the characteristics of the nodes involved in the network, such as high relative speeds and fast changing network topology producing highly versatile transmission conditions. Moreover, real-time application requirements, such as very low end-to-end latency and very high reliability (packet delivery ratio) also pose a challenge for V2X communication. For nearly a decade, Dedicated Short Range Communication (DSRC) based on IEEE 802.11p has been studied, and it appeared as a promising wireless technology for local V2X communications [4], [5], [6]. However, recent studies [7], [8] show that the evolution of cellular networks has enabled LTE to become the preferred communication technology for V2X. The main reasons are already available infrastructure, longer range, higher data rates, and lower end-to-end delay.

Starting in the late 2014, the Third Generation Partnership Project (3GPP[1]) presented support for MTC in the radio access network in release 12 [9]. A User Equipment (UE) category Cat0 with extended coverage, simplified design, extended battery life, reduced cost, and bandwidth of 20MHz was introduced. In release 13, 3GPP introduced another UE category CatM [10] to support MTC use cases with a reduced bandwidth of 1.4MHz. This UE category has the advantage of being able to use the control messages from legacy LTE and operate with the current LTE standards and infrastructure.

With the inclusion of Machine to Machine (M2M) traffic into cellular networks, the increased traffic and number of devices pose a challenge for the network to achieve high efficiency. In LTE, the procedure to gain access to the network resources is known as *Random Access* (RA) and is performed by each UE in the network before sending/receiving any user-plane data. Dawaliby *et al.* [11] evaluated LTE CatM performance in terms of throughput, jitter, latency and range. Nevertheless, their work does not evaluate the random access procedure. Many studies [12], [13] aim to evaluate the M2M traffic through simulations and identify the capacity and limitations of channel access methods of LTE. However, these studies use UE categories with larger system bandwidth. Therefore, the literature lacks an in-depth analysis and evaluation of LTE channel access for the low-bandwidth M2M UE category CatM. This is the main motivation for the work presented in this article. To this end, we investigate the performance of CatM random access and present the evaluation results. The contributions of this paper

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are summarized as follows:

- A description of the latency-critical use cases of V2X communications and requirements.
- LTE random access evaluation for CatM UE category through realistic simulations.
- Random access issue identification that leads towards higher latency in LTE networks.

The remainder of this paper is organized as follows: Section II presents the latency-critical V2X use cases and their requirements. Section III provides an in-depth detailed description of the Random Access procedure in LTE. In section IV, we present the simulation evaluation and analyze the obtained results. Section V concludes the paper.

II. LATENCY CRITICAL V2X USE-CASES

Intelligent transportation systems aim to provide improved movement and journey experience by using information technology, vehicle on-board sensors, and communication between vehicles. The automotive market is evolving towards fully connected cars, which on one hand improves user experience, but also helps in automated driving, assisted overtaking, collision warning, and traffic efficiency services. Several use cases of ITS/V2X[2] are under consideration in general and few of them fall under URLLC with stringent latency requirements. We characterize the latency-critical use cases of V2X based on different requirements and summarize them in Table I. Optimization of road traffic and automated driving pose new challenges for communication system design. The requirements for the communication systems result from different use cases of ITS, such as collision warning, autonomous driving and traffic efficiency services [14], [15]. Three main categories of latency critical V2X applications are as follows:

A. Collision warning

Collision warning includes warning notifications to/from the vehicles that are in the hazardous conditions. Collision notification becomes most important when all other means of avoiding the accident fail. The vehicles can control their speed, direction, and acceleration to avoid the collisions based on these messages. The requirements of collision warning vary, depending on the scenarios, such as highway or urban traffic and result in a required latency between 10ms and 100ms [14]. The collision warning message could be from the network to a vehicle or from vehicle to vehicle. In both cases, the latency requirement needs to be fulfilled by the network.

B. Autonomous driving

According to [14], there are six defined levels of autonomous driving where the first level only assists the human driver while the sixth level is for the driver-less fully autonomous vehicles. The increase in the levels is determined by the features offered by the vehicle toward autonomous driving. A fully autonomous vehicle requires no human assistance, thus, for cooperative driving it requires stringent latency and reliability. Vehicles can benefit from the information coming both from other vehicles or from the network. The received information then helps vehicles to adapt to the traffic and road conditions. Therefore, the cellular communication system needs to support a 10ms higher bounded latency [14] while ensuring minimum reliability requirements.

C. Traffic efficiency

In the majority of traffic efficiency-oriented use cases, vehicles and other elements on the road either upload their stats (e.g., position, speed, acceleration) or event information (e.g., road condition and traffic situation). These data transmissions are usually periodic and small sized. The data from these transmissions could be used in an extended way to support more complex and novel services and applications [14], such as see-through, bird's eye view for intersections, vulnerable road user discovery. These services have high communication requirements, as mentioned in Table I, that the cellular network should fulfill.

III. RANDOM ACCESS IN LTE

A typical LTE network consists of a Radio Access Network (RAN) and a Core Network (CN) [16]. RAN consists of the base stations called evolved NodeB (eNB) and mobile devices known as User Equipment. The CN consists of different components, such as Mobility Management Entity (MME), Home Subscriber Server (HSS), Serving Gateway (SGW) and Packet Data Network Gateway (PDN-GW or PGW) to provide specific features required by the network. The data transmissions in the RAN between eNB and UEs use a frame structure based on sub-frame which is 1ms in time and consists of 14 symbols. In the frequency domain, the bandwidth is defined in terms of Physical Resource Blocks (PRB). One PRB consists of 12 sub-carriers of 15 kHz each. A system with six PRBs implies a bandwidth of 1.4MHz including the guard band. The guard band on each side of a six PRBs bandwidth occupies 160 kHz each and is used to avoid any interference from adjacent channels.

To send/receive user-plane data, a UE needs to access some resources from the available system bandwidth. The eNB allocates resources to UEs after the completion of access procedure. A UE performs access procedure whenever:

- New data is available to transmit but without uplink synchronization. A UE can only transmit on uplink resources if it is time-synchronized,
- Recovering from a link failure,
- Changing of state from *idle*[3] to *connected*[4],
- Performing a handover.

There are two different types of random access defined in LTE:

[2]ITS systems with V2X communication capabilities

[3]The radio is inactive in this state but the IP address is assigned. The UE is known to Evolved Packet Core (EPC) but unknown to eNB.

[4]The radio is active in this state and UE is known in both EPC and eNB.

TABLE I: Requirements for latency-critical use cases for V2X. The communication traffic type, depending on the ITS application, can be either periodic or event triggered.

Use Case	Latency (ms)	Reliability (PLR)	Device density (/km^2)	Number of devices per cell	Comm. range (m)	% of mobile devices	Mobility speed (km/h)	Traffic type
Collision warning	10 to 100	10^{-3} to 10^{-5}	Urban-3000, Highway-500	Urban-300, Highway-50	Urban-500, Highway-2000	>90	Urban<100, Highway<500	Event triggered
Autonomous driving	10	10^{-5}	Urban-3000, Highway-500	Urban-300, Highway-50	Urban-500, Highway-2000	>95	Urban<100, Highway<500	Event triggered
Traffic efficiency	<100	10^{-3}	3000	300	2000	>80	<500	Periodic

i **Contention-based:** the UE tries to access the network by randomly selecting a preamble[5] from a pool of predefined preambles. Collisions can occur in this type of access.

ii **Contention-free:** the eNB informs the UE about which preamble to use for access procedure in order to avoid collisions. This type of random access is mainly used for the handover procedure.

To access the network resources, a contention-based Random Access (RA) procedure is performed by a UE on a dedicated physical channel called Physical Random Access Channel (PRACH). This PRACH spans six PRBs and its periodicity is defined by the *PRACH Configuration Index* parameter which is transmitted by eNB. PRACH periodicity varies from a minimum of one slot in every two frames (i.e. 20ms) to a maximum of one slot in every sub-frames (i.e. 1ms). Figure 1 illustrates different *PRACH Configuration Index* options. The length of RA slot in time domain is defined by the format of the access request and varies from 1ms to 4ms. Figure 2 illustrates the contention-based random access procedure which consists of four messages exchanged between the UE and the eNB.

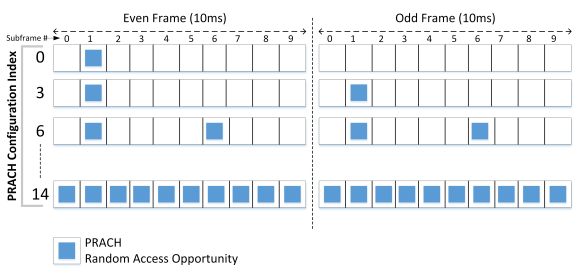


Fig. 1: *PRACH Configuration Index* example. The minimum value of *PRACH Configuration Index* is 0 which corresponds to one RA opportunity every two frames, while *PRACH Configuration Index* 14 represents RA opportunity in every subframe. There are four different preamble formats available. These *PRACH Configuration Index* values are for format 0.

[5]Preamble is a sequence defined by Zadoff-Chu codes [16] by performing cyclic shift.

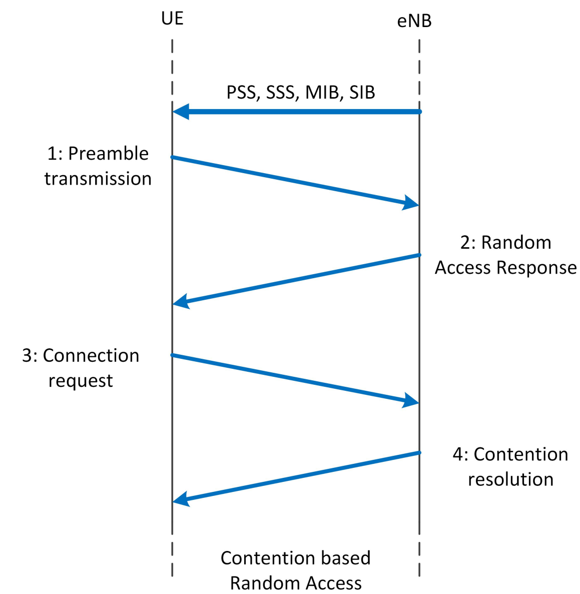


Fig. 2: Message flow of contention-based RA in LTE. 1) preamble transmission from UE to eNB: an indication from UE to eNB for an attach request, 2) eNB responds with RAR message: contains the scheduled resource for message3, 3) UE sends a connection request, 4) eNB informs UE about completion of RRC connection.

A. *Message 1, Preamble Transmission*

Whenever a UE requires access to network resources, it selects the next available RA slot to send the access request that includes a preamble. There are 64 pseudo-random preambles in total. The information about available preambles for contention-based RA is periodically disseminated by eNB. The eNB reserves some of the preambles for handover procedure and can detect different preambles transmitted in the same RA slot due to the orthogonality of these preambles. However, randomly chosen identical preamble - transmitted by two or more UEs in the same RA slot - results in a collision, since eNB cannot decode the preamble in this case. Furthermore, a collision can go undetected if one of the colliding preambles is received with higher SNR, as explained by Polese *et al.* [13]. After sending the preamble, the UE waits for a time window starting 3 subframes after the preamble transmission to receive the second message of the RA procedure from eNB. The eNB broadcasts the duration of waiting window that is defined between 2ms and 10ms [12]. The preamble for each access request is randomly selected among those available for the contention-based random access.

B. Message 2, Random Access Response

After successfully decoding the received preambles, eNB computes a number called Random Access Radio Network Temporary Identifier (RA-RNTI) for each preamble. RA-RNTI is computed based on the RA slot used to send the preamble. The eNB then sends Random Access Response (RAR) which includes a temporary identifier, referred to as Cell Radio Network Temporary Identifier (C-RNTI), detected preamble index, an uplink scheduling grant for UE to send the connection request, and a timing alignment for UE to synchronize with eNB.

The RAR is addressed to all UEs that send the preamble message in a specific RA slot. If the received RAR does not contain the preamble identifier (associated to the preamble sent by the UE), the UE performs a random back-off time. A collision can go undetected, if two UEs are at the same distance from eNB and the eNB receives same preamble constructively from both devices. In this case, eNB adds the preamble identifier and scheduled uplink resource for third message in RAR and eventually a collision occurs in Message-3, as both UEs with undetected collision transmit at the same time.

C. Message 3, Connection Request

The UE transmits a connection request message which includes C-RNTI and the reason for access request. With the transmission of connection request, the UE initiates a contention resolution timer. An undetected preamble collision can lead to a collision again in this phase, as multiple UEs might transmit connection request simultaneously. Therefore, eNB cannot send an acknowledgment for connection request and UE retransmits connection request. Upon reaching maximum number of allowed connection request retransmissions, UE declares access request failure and starts the RA procedure again.

D. Message 4, Contention Resolution

Upon receiving connection request, eNB responds with a contention resolution message. A UE will declare a failure to access request if it does not receive contention resolution message, and, in such case, starts the RA procedure from preamble transmission phase. With each unsuccessful access attempt, the UE increments the preamble transmission counter. The network is declared unavailable when the counter reaches the maximum allowed preamble retransmissions.

IV. PERFORMANCE EVALUATION

This section presents the evaluation of the random access procedure for LTE CatM. Due to lower cost, higher range, and longer battery life, CatM is a suitable candidate for ITS specific applications. In this paper, our aim is to evaluate the delay that UEs with limited bandwidth (e.g. CatM) undergo while trying to access the LTE network. To this end, we use one of the most accurate open-source system-level simulators, i.e. network simulator (ns-3[6]). The ns-3 LTE module provides the implementation of the Evolved Packet Core network and the LTE protocol stack. The current implementation of the LTE module uses ideal random access procedures, i.e. only the first two messages of the RA procedure (see section III) are modeled. Moreover, in this configuration, RACH is not subject to radio propagation as well. To mitigate this lack of realism, the work from Polese *et al.* [13] is used. They implemented a *realistic RACH*[7] model for ns-3 LTE module. Their work focuses on wide-band (5MHz) M2M communication. Table II presents the network simulation parameters. For the evaluation, simulations were performed for 3GPP CatM UE category with a bandwidth of 1.4 MHz (i.e. 6 PRBs). After obtaining the system information transmitted by the eNB, the UEs start RA procedure. The results shown in this paper are means calculated from 10 independent simulation runs.

TABLE II: Simulation parameters used in NS3 for the evaluation of LTE CatM Random Access

Parameter	Value
Simulator version	3.24
Propagation loss model	Friis Propagation Model
eNB Tx power	43 dBm
UE Tx power	20 dBm
Downlink EARFCN	100
Uplink EARFCN	18100
Uplink bandwidth	1.4 MHz
Number of resource blocks	6
eNB noise figure	5 dB
UE noise figure	9 dB
PRACHConfigIndex	{0, 3}
Number of available preambles	{48, 54, 60, 64}
Packet interval time	100 ms
Number of eNBs	1
Simulation duration	30s

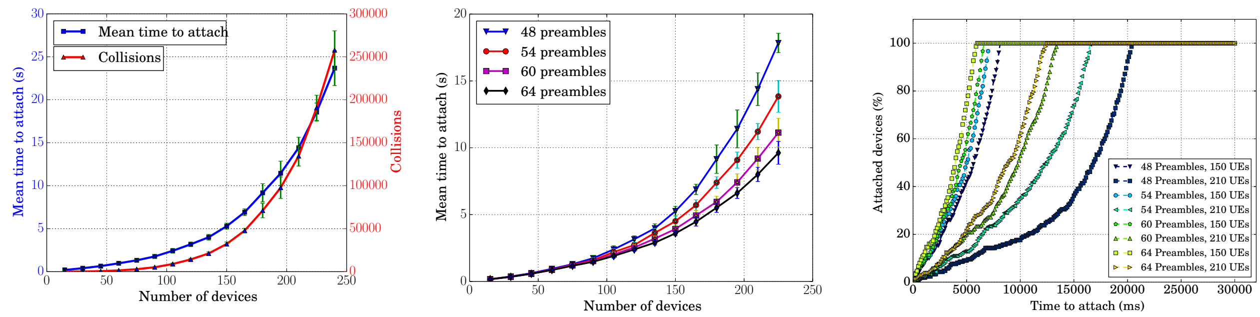
A. Access delay

Figure 3a presents the mean time to complete the RA procedure and number of collisions with increasing number of UEs trying to access the network simultaneously. The vertical lines at each point in the graph represent the variance from independent simulation runs.

It can be observed from these results that with the increase in the number of devices, the access delay increases exponentially. The large number of simultaneous access requests are possible in V2X applications, such as, in case of collisions and cooperative driving, where a large number of vehicles/devices try to access the network to exchange

[6]https://www.nsnam.org/ns-3-24/

[7]https://github.com/signetlabdei/lena-plus



(a) (b) (c)

Fig. 3: LTE CatM: (a) Mean time to complete the RA procedure (left y-axis), total number of collisions in the first preamble message (right y-axis); with increasing number of UEs simultaneously sending access requests, (b) Mean time to complete the RA procedure with different numbers of available preambles, (c) Percentage of attached devices over time with different number of available preambles.

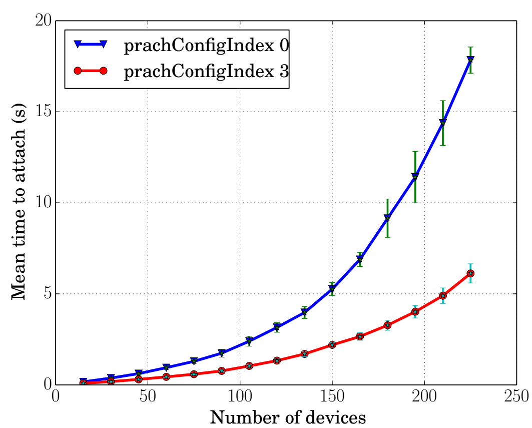


Fig. 4: LTE CatM: Mean time to complete the RA procedure with different numbers of RA slots per frame. *PRACH-ConfigIndex* 0 corresponds to one RA slot per two frames, whereas *PRACHConfigIndex* 3 equates to one RA slots per frame.

information. The increase in preamble collisions also follows an exponential growth as the access requests increase. This is due to the limited number of preambles available in the system that are selected randomly by the contesting UEs (see section III.A).

It is worth noting that an increased system bandwidth improves the performance of the RA procedure. As presented in [13], with a bandwidth of 5MHz (i.e. 25 PRBs), it takes around 1 second for 50% of the UEs to complete random access in case of 200 simultaneous access requests. The access delay has an inverse relation with available bandwidth (number of resource blocks) i.e., fewer the number of available resource blocks, higher is access delay. As compared to 5MHz bandwidth, the duration to complete RA is 10 times more in 1.4MHz bandwidth. The approach in [13] is intended to evaluate massive number of arrivals for machine type communication; however, using a bandwidth of 5MHz for MTC might not be practical due to higher device cost, shorter range, and shorter battery life. Moreover, there are other standardized categories for MTC UEs by 3GPP, such as CatM with 1.4MHz bandwidth, Narrowband-IoT [17] with 200KHz bandwidth.

B. Number of preambles

Two series of simulations were carried out for an in-depth analysis of LTE CatM RA. In the first part of these tests, we vary the number of available preambles while keeping other RACH parameters fixed according to Table II. Figure 3b presents the mean time taken by the UEs to complete the access procedure for different numbers of available preambles. Obviously, the best case where all 64 preambles can be used by the devices performing contention-based random access, requires the least time for larger number of devices. The difference in RA completion time is very small for less than 100 devices. As the number of UEs increases, the difference starts increasing as well. For 225 simultaneous access requests, the mean access delay almost doubles between 48 and 64 preambles. However, all V2X use cases include mobility of UEs with high speeds, which leads to handover of UEs between serving cells and utilizing a few preambles reserved for contention-free random access. Therefore, the best case i.e. 64 preambles might not be practical in those use cases.

Figure 3c shows the distribution of UEs that completed RA procedure over time. The results show that for a larger number of simultaneous arrivals (i.e. 200 UEs) and with lower number of available preambles (i.e. 48 preambles), the time to attach for initial 50% of UEs is much higher than for the remaining half of the UEs. This is explained by the fact that with larger number of UEs, more collisions occur which results in a higher access delay.

C. PRACHConfigIndex

In a second series of simulations, we analyze the effect of *PRACHConfigIndex* on the mean RA completion time while keeping other parameters fixed. As presented in figure 1,

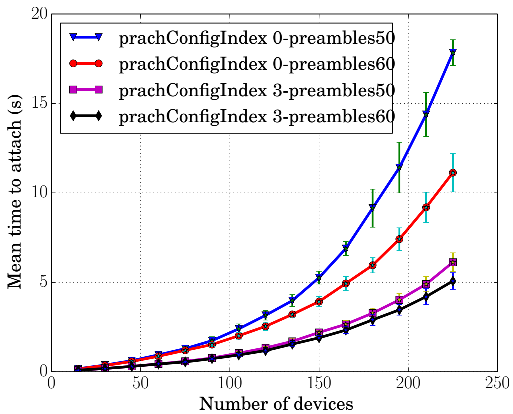


Fig. 5: LTE CatM: mean time to complete the RA procedure with different number of RA slots per frame and number of preambles.

PRACHConfigIndex 0 corresponds to one RA slot per two frames (i.e. 20ms) while *PRACHConfigIndex* 3 represents one RA slot per frame (i.e. 10ms). It is obvious from the result that for a larger number of UEs, the time to attach for *PRACHConfigIndex* 0 is three times more than the time to attach for *PRACHConfigIndex* 3 (see figure 4).

Figure 5 shows the combined impact of number of preambles and *PRACHConfigIndex*. There is a considerable decrease in the mean RA completion time with more preambles and RA slots. The right choice of RA parameters can lead to an improved performance from the system. However, RA procedure limits the minimum achievable latency of the system.

V. CONCLUSIONS

The contention-based random access operation is based on ALOHA-type access (i.e. all contesting devices transmit in the first available opportunity). This implies that, in case of simultaneous access requests from a massive number of devices, the network performance may degrade and some latency-critical application may be compromised. For example, in case of a collision on the road, a large number of vehicles would try to access the network in order to send/receive traffic information. In such scenario, the devices transmitting simultaneously may experience larger latency due to collisions on the preambles. Such application requires a seamless transfer of data in order of 10ms while current LTE network may not be able to provide such low latency.

One of the key requirements for current and next generation cellular mobile networks is to enable the support for latency-critical use cases. The increasing demands for real time communication from different applications and services pose a challenge for cellular networks. In this article, we described the latency critical use cases of V2X and discussed the requirements for the cellular networks in order to enable them to meet the requirements of these use cases. The random access procedure becomes a critical factor for machine type communication when large number of devices in each cell make data transmissions either based on some event or periodically. We evaluated random access for a low-bandwidth UE category standardized from 3GPP in release 13, through realistic simulations. In addition, we provided the limits for different random access parameter sets and number of UEs per cell for achieving required latency.

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