Model and Analysis of 5G Network Registration Procedure in Public Safety Scenarios

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***Abstract*— This work presents a simulation model developed in the Network Simulator 3 (NS-3) network simulator to investigate the 5G registration process when many pieces of User Equipment (UE) attempt to register simultaneously. At mass events such as concerts and parades, UE density can reach 10 devices per square meter, which may congest the Random Access Opportunity (RAO), lead to increased preamble collisions, and heighten the risk of registration failure. This makes the issue particularly relevant for public safety scenarios where reliable network access is essential. The model reproduces key elements of the 5G random access procedure, including contention-based preamble selection in the range from 0 to 63 according to 3rd Generation Partnership Project (3GPP) specifications. By modeling collisions and successful preamble transmissions, it enables analysis of the number of registration attempts required under varying UE loads and helps identify when the registration process becomes unreliable and whether prioritized registration mechanisms should be considered in future standards. Simulation results show that collision risk rises with UE count, and that at 20 UEs there is about a 0.2 percent chance of requiring four registration attempts, which may result in failure depending on the configured preamblesTransMax value. These findings indicate that further study is needed to identify optimal registration parameter settings for different network scenarios.**

Keywords—Mobile Communication; 5G; Simulation; NS-3.

I. INTRODUCTION

The fifth generation of mobile communication, called 5G, was introduced to support enhanced Mobile BroadBand (eMBB), massive Machine-Type Communication (mMTC), and Ultra Reliable Low Latency Communication (URLLC). These goals were defined to allow 5G to fulfill a number of distinct and varied use cases such as high-quality video streaming, massive Internet of Things (IoT) deployments in the industry and potentially to meet the strict requirements associated with Mission Critical Communication (MCC) [1] [2].

Of particular note is the widespread ongoing research into 5G as a technology for Mission Critical Push To Everything (MCPTX) and Public Protection and Disaster Relief (PPDR) [3] [4].

Similarly to other mobile communication technologies, there is a limit on the available resources a gNB (gNodeB) can provide to the associated UEs, which depends on a number of factors such as the available bandwidth, noise, coding, and modulation schemes, etc. Since there is rarely if ever only a single UE associated with a gNB the sources have to be distributed between the UEs. This gives rise to complexity as the required Quality of Service (QoS) requirements for each UE or application may vary significantly. For instance, a voice call requires minimal bandwidth but has strict latency requirements, as opposed to file downloads where the throughput is important, but latency and jitter are largely irrelevant [5].

There are a number of features in 5G that allows the network to differentiate and shape the QoS for the Ues such as 5QI [6], Allocation and Retention Priority (ARP) [7], network slicing, Reflective Quality of service Attribute (RQA) etc. In order to accommodate MCC, which for instance is relevant during first responder incidents, ARP allows the network to disconnect devices with lower priorities. In other words, this allows operators to provision resources according to the service type and priority of the user, ensuring that high-priority or time-sensitive traffic is treated with the urgency it requires.

However, this prioritization does not extend to the initial network registration process which is contention based. This means regardless of whether the device belongs to a first responder in a crisis or a regular user, all of the UE must undergo the same Random Access (RA) procedure when attempting to register on the network. In this procedure, UEs randomly select one preamble from a predefined set of 64 and attempt to initiate communication with the gNodeB. If multiple UEs select the same preamble in the same slot, a collision occurs, and the affected UEs must retry after a random backoff. This process repeats until a successful attempt is made or a maximum number of attempts is reached, at which point the UE abandons its registration effort.

This lack of registration prioritization could be problematic in high-density environments such as concerts, sport events or festivals etc. In such scenarios, a high number of UEs attempting to register on the network may lead to registration failures for a significant portion of UEs, including those operated by emergency services, which could delay or prevent critical communications from being established. This in turn may significantly hinder first responders' ability to coordinate.

In this context, this work presents a simulation model built in NS-3 that simulates the 5G network registration process. The model allows multiple UEs to attempt registration simultaneously by randomly selecting preambles in line with standard specifications. The number of attempts required to complete registration for various numbers of UEs is simulated for a multitude of random seeds and the results interpreted. This enables the potential registration delays and failure rates and provides a foundation for analyzing the shortcomings of current access procedures in mission-critical contexts. Ultimately, the findings aim to determine if there is a need for revisiting the 5G access design to accommodate priority-aware registration mechanisms.

A. Crowd & Device Density in Emergency Scenarios

To evaluate whether the 5G registration process is sufficient under extreme conditions, it is important to consider real-world environments where contention is likely to occur. High-density public events such as concerts, festivals, and parades can involve crowd densities that exceed 7 people per square meter. This threshold marks the onset of crowd turbulence, a phenomenon that contributed to the fatalities at the 2010 Love Parade disaster in Duisburg, Germany. The same study notes that local densities can spike to over 9 people per square meter [10].

The festival in Roskilde in Denmark in 2000, where nine people died during a Pearl Jam concert, also exhibited crowd behaviors consistent with extreme local densities. Observations from the event describe phenomena such as holes opening in the crowd, which are indicators of dangerously high compression and instability, which aligns with a density of at least 7 people per square meter [11] [12].

In parallel, mobile device penetration in Western countries is high. For example, World Bank data shows that Germany has approximately 1.2 mobile subscriptions per person [13]. This suggests that in high-density environments, the number of mobile devices per square meter can realistically range from 6 to 10. This density of UEs attempting to register at the same time presents a significant challenge to the contention-based Random-Access Channel (RACH) procedure defined in 3GPP specifications.

II. REGISTRATION PROCESS

A. Overview

In a 5G standalone architecture, the process of UE registration begins with synchronization and decoding of essential network information, followed by contention-based Random Access (RA) to establish a connection with the network. The UE first detects Synchronization Signal Block (SSB), which contains Primary Synchronization Signal (PSS), Secondary Synchronization Signal (SSS), and Physical Broadcast Channel (PBCH). From the PBCH, the UE extracts the Master Information Block (MIB), which includes information such as the system frame number, subcarrier spacing, and the scheduling of System Information Block 1 (SIB1).

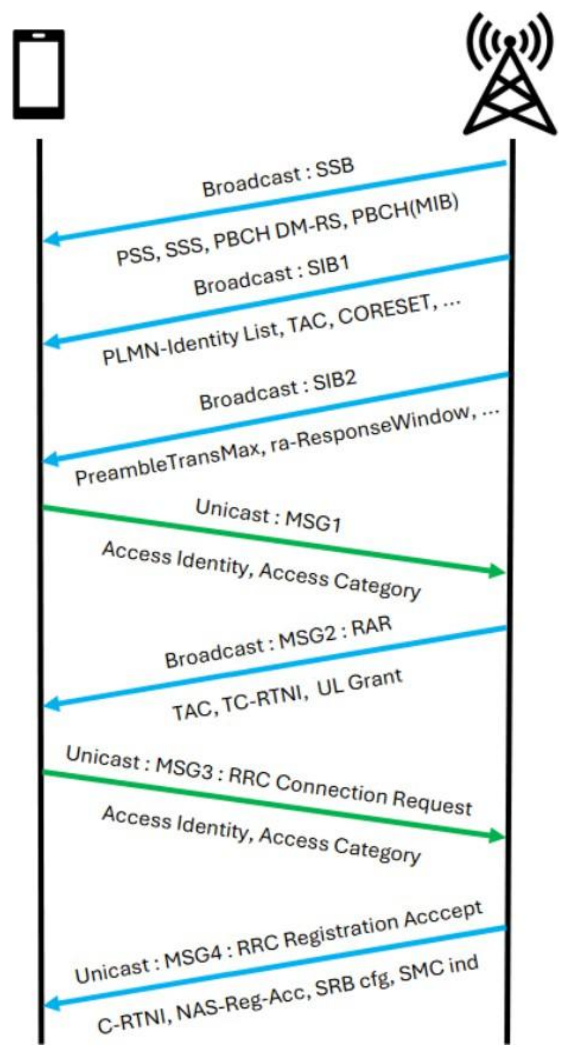

Figure 1. Example of successful registration attempt.

SIB1 contains information like PLMN-Identity List, Tracking Area Code (TAC) and the scheduling of all other system information blocks. Based on the information in SIB1, the UE can locate and decode SIB2, which provides details related to the registration procedure, such as the available number of preambles and the maximum number of attempts allowed. Once the UE has decoded SSB, SIB1 and SIB2, it initiates the contention-based random-access procedure. This involves selecting a random preamble among the available ones, which is at most 64. The UE transmits this preamble during the next available Random Access Opportunity (RAO), a time window defined by the network in which an UE may attempt to initiate access.

If multiple UE choose the same preamble and transmit during the same RAO, a collision occurs. In a successful attempt with no collision, the gNB receives the preamble and responds with Msg2, the Random-Access Response (RAR). Msg2 includes the Timing Advance Command (TAC), Uplink Grant (UL Grant), and a temporary Cell Radio Network Temporary Identifier (C-RNTI). The UE then transmits Msg3, known as RRC Connection Request, which contains a Radio Resource Control Setup Request (RRCSetupRequest) along with its access identity and, in some cases, security parameters.

This step may also experience contention if multiple UEs proceed with the same preamble. Assuming Msg3 is received without collision, the gNB responds with Msg4, typically a Radio Resource Control Setup (RRCSetup) message, signaling that contention has been resolved and the UE can proceed to the next steps in establishing its connection and completing registration. A successful registration attempt is illustrated in Figure 1.

B. Preamble Collisions

The amount of time an UE uses on the registration phase, assuming it succeeds, depends on the number of collisions it experiences in the registration phase and the Backoff Indicator (BI), which is determined by the network.

The number of collisions that an UE is likely to experience depend directly on the number of preambles available to choose from and the number of UEs choosing randomly from these preambles.

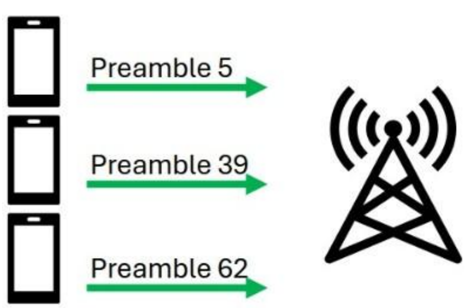

Figure 2. Three UEs picking different preambles in the registration process during Msg1.

Currently there are 64 preambles standardized, although the mobile network operator can choose to limit the amount of available preambles. If the UEs pick unique preambles as in Figure 2, the registration will proceed as illustrated earlier in Figure 1.

In the case where some of the UE pick the same preamble, they are unable to complete the registration phase. However, UEs that pick different preambles are not affected and can still proceed with the registration. Such an example is shown in Figure 3.

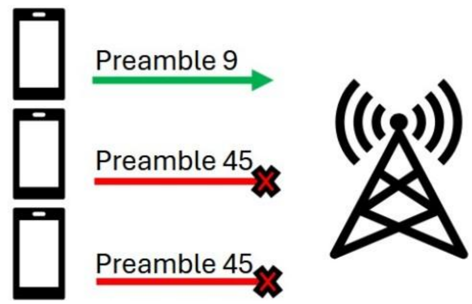

Figure 3. Three UEs picking preambles in the registration process during Msg1, with the mid and bottom UE randomly choosing the same, which causes a collision.

Each time after a failed attempt, the UE has to wait a fixed time determined by the BI. This means that if there is a collision, then all the affected UEs will wait the same fixed amount of time and, therefore, will join the same upcoming RAO. The relationship between the indicator and the time to wait is shown in Table I. Waiting a fixed time contrasts to other classical Carrier Sensing Multiple Access (CSMA) where the backoff time is random [8].

TABLE I. BACKOFF PARAMETER VALUES.

Index	Backoff Parameter value (ms)
0	5
1	10
2	20
3	30
4	40
5	60
6	80
7	120
8	160
9	240
10	320
11	480
12	960
13	1920
14	Reserved
15	Reserved

If the UE fails to register too many times and reaches the maximum number of allowed preamble transmission attempts, the registration is considered a failure, and the UE stops attempting to register on the network.

III. MODEL

The model was created using network simulator 3, usually called NS-3. NS-3 is a discrete event simulation framework written in C++ that is widely used for research and development in networking. NS-3 enables detailed modeling of communication protocols, network devices and network technologies etc. An overview of the model is shown in the pseudocode below in Figure 4.

Pseudocode of the 5G Registration Simulation Procedure

```
for each UE do
    Set attempt count to 0
    Schedule first registration attempt at RAO
end for
while An unregistered UE exist do
    for Each unregistered UE do
        randomly select preamble p_i
    end for
    for each preamble, p_i do
        if only one UE selected preamble p_i then
            Complete UE registration
        else
            for each UE that selected preamble p_i do
                Increase the attempt count for each UE by one.
                Schedule new attempt after fixed backoff.
            end for
        end if
    end for
end while
Collect and save statistics
```

Figure 4. Pseudocode for the simulation.

The goal of the simulation model and analysis is to determine when and if registration becomes problematic due to congestion. The focus is therefore on the number of registration attempts, collisions and their distributions under varying load conditions, without regard for the exact content of the exchanged messages. Although the initial synchronization and collection of network information via MIB, SIB1, SIB2 etc. are important, they do not experience contention and therefore aren’t included in the simulation model. To determine the threshold where congestion becomes problematic the amount and distribution of collisions during the registration process is examined. In this context it’s also important to determine if any of the UEs reach the maximum transmission threshold.

To validate that the output of the model is sensible, first a simple scenario is created with 10 UEs and the simulation runs for 100 different random seeds. After each simulation the number of devices that have used 1, 2, ... N attempts are logged and finally the combined result for all 100 seeds analyzed. Using this method, the results for 10 UE are obtained and can be seen in Figure 5. From Figure 5, the number of attempts required to register the UE on the network were 1, 2 and 3 for the 100 seeds.

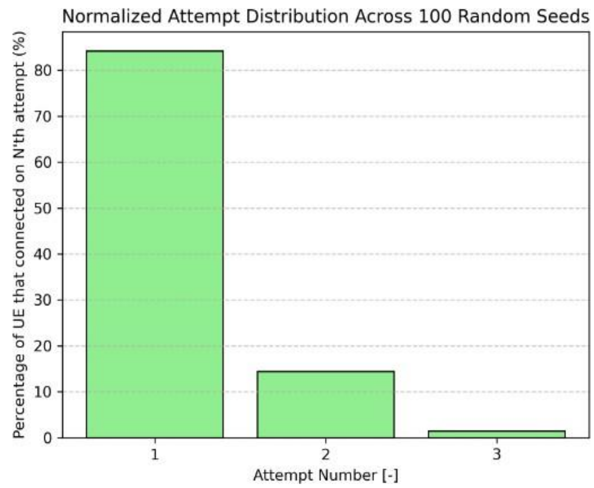

Figure 5. Probability of completing registration in the N-th attempt for 10 UEs.

Above 80 and 10 percent of the time, 1 and 2 attempts were sufficient. respectively, while around 2% of the time 3 attempts were needed. This is sensible as the chance of collision is not yet that high and therefore most UE register on the first attempt. There are also very few cases where 3 attempts are used. This is sensible, since the vast majority of devices complete registration in the first attempt, meaning the risk of collision in the second attempt is much smaller. Based on the same data used to generate Figure 5, a boxplot is made to get a better understanding of the underlying distribution. This is shown in Figure 6.

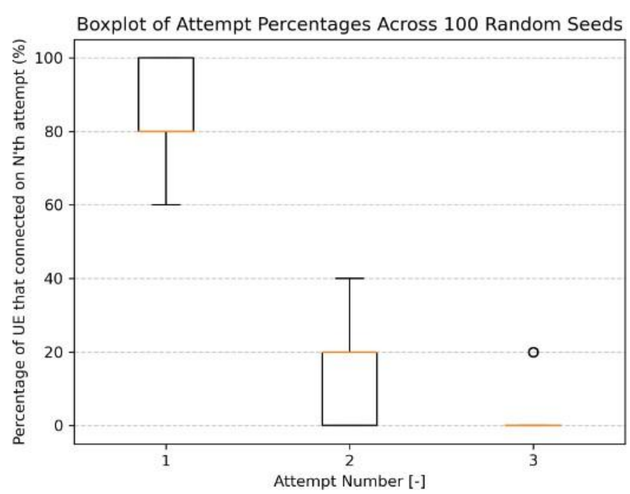

Figure 6. Boxplot of the probability of completing registration in the N-th attempt for 10 UEs.

As expected, the whiskers and the box edges are all a multiple of 10, because there are 10 UEs, so each UE corresponds to 10% in this scenario. In addition, as expected based on the low percentage for three attempts in Figure 5, it can be seen that Figure 6 contains an outlier.

IV. Results and Discussion

To investigate the dynamics of collision and retransmission during the registration phase, multiple simulation scenarios were constructed, each with a varying number of concurrently registering UEs. These scenarios allowed for controlled observation of how increasing contention influences registration reliability. Particular attention was given to the number of attempts required for successful registration, as there is a maximum number of allowed attempts.

In order to conclude whether the amount of transmission is problematic, it is necessary to define the maximum amount of allowed preamble transmissions. The allowed values of the network parameter called PTM (PreambleTransMax) are defined in TS 38.331 [9] and shown in Table II below.

TABLE II. ALLOWED VALUES FOR PREAMBLETRANSMAX.

Enum Value	Maximum Attempts
n3	3
n4	4
n5	5
n6	6
n7	7
n8	8
n10	10
n20	20
n50	50
n100	100

It is the mobile network operator who decides which value of PTM is used in the network. With these values in mind the simulation is carried out for 10, 20, 30, 40, 60, 80 and 100 UE respectively to examine the impact on the number of registration attempts required. The results can be seen in Figure 7 below.

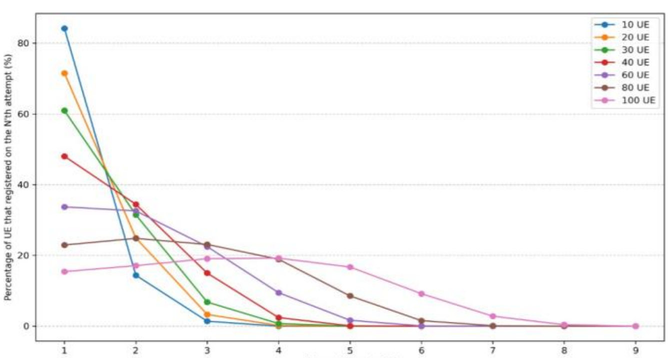

Figure 7. Probability of completing registration in the N-th attempt for 10, 20, 30, 40, 60, 80 and 100 UEs.

Based on Figure 7, it can be concluded that for 60 UE and lower, the chance of registering in one attempt is the highest. As the number of UEs increases beyond this number to 80 UEs, the risk of collision in the first attempt becomes so high that fewer devices register in the first attempt than the second one. The distribution of the number of attempts required can be seen in Figure 8 and is also available in Table III.

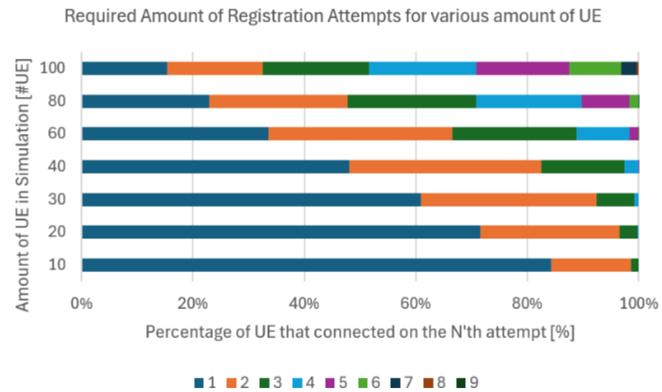

Figure 8. Distribution of the number of attempts required to register on the network for 10, 20, 30, 40, 60, 80 and 100 UEs.

From Figure 8, it can be seen that for 30 UE there is a risk of around 1% using 4 attempts, which is above the minimum number of preambles that can be configured, as seen in Table II. This behavior illustrates how an increase in UE density can lead to a nonlinear impact on access reliability.

TABLE III. PERCENTAGE OF UES ATTEMPT REQUIRED UNDER VARYING CONCURRENT LOAD.

Tries/UE	10	20	30	40	60	80	100
1	84.20	71.55	60.97	48.05	33.51	22.95	15.43
2	14.40	24.95	31.50	34.45	33.03	24.81	17.11
3	1.40	3.30	6.80	15.00	22.33	23.10	19.09
4	0.00	0.20	0.73	2.43	9.40	18.91	19.23
5	0.00	0.00	0.00	0.08	1.66	8.55	16.73
6	0.00	0.00	0.00	0.00	0.07	1.56	9.18
7	0.00	0.00	0.00	0.00	0.00	0.11	2.82
8	0.00	0.00	0.00	0.00	0.00	0.00	0.41

The results highlight the importance of anticipating access contention in scenarios with simultaneous or synchronized UE activation. In practice, such situations may arise during coordinated service restoration, mass device reboots, or mass event emergencies where deterministic performance is critical.

V. Future Works

The current NS-3 model focuses on the core features and phenomenon in the registration process in 5G and therefore relies on some assumptions. In the future, we plan to look into the following aspects:

- *Physical Environment:* The current model does not take into account environmental factors like reflections or shadowing, which can significantly alter the time of reception and the quality of the signal received at the gNB. In the future, it would therefore be good to include a characterization of the physical environment.
- *Channel Environment:* For large numbers of UEs, it is expected that there will be significant interference between devices, which in theory could lead to none of the preambles arriving at the destination. A more complex model could take this into account.

- *Probabilistic Collisions:* There exist situations where multiple UE can select the same preamble, but the gNB can still decode one of the messages, for instance if one signal is stronger due to reflections. In the future, it would be good to simulate the chance of a message being decoded during Msg1 and Msg3 despite multiple UE selecting the same preamble.
- *UE Join/Leave Model:* In the current model, it is assumed a number of UE attempts to join during the same RAO and that no other terminals join this process. In a real environment, there is a risk of new devices joining, which both depends on the UE density and user behavior.
- *Practical experiment:* It is planned to conduct practical experiments in a real-world test environment. The experiments can help validate key assumptions in the model, reveal implementation-specific behavior, and provide a more complete understanding of how collisions and retries manifest under real operating conditions.
- *Prioritized Access:* Techniques to improve the reliability of the registration process for mission-critical devices may be improved through prioritization mechanisms. This could include strategies such as reserving a subset of preambles exclusively for high-priority UEs or applying differentiated RAO scheduling and are worth exploring.

VI. Conclusion

In this study, the behavior of the 5G registration process was evaluated under conditions where multiple UEs join the same random-access opportunity using an NS-3 based simulation model. It was demonstrated that even for few UEs, contention for resources during the random-access procedure can result in requiring multiple registration attempts due to collisions. It was found that the number of attempts required to register increased as a function of the number of UE and that when 20 UEs attempted registration concurrently, a statistical probability of approximately 0.2% was observed for requiring four registration attempts. This value is important as that exceeds the minimum selectable value for preamblesTransMax as defined in the 3GPP specifications. These results suggest that the existing configuration and handling of simultaneous registration attempts may be insufficient to meet the reliability demands of mission-critical applications in high load scenarios. The access reliability of a 5G system depends both on the choice of the preambleTransMax value and on the collision probability, which is influenced by the number of UEs, RAOs and the available number of preambles.

Based on the findings of this study, it is recommended that further work investigate how these parameters can be tuned to match the needs of different deployment scenarios, particularly those with mission critical communication requirements. The results also highlight the importance of the registration phase, which should be carefully considered in the design of future systems such as 6G.

Acknowledgment

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