Random Access Process Analysis of 5G New Radio Based Satellite Links

Harri Saarnisaari, Ayotunde O. Laiyemo, Carlos H. M. de Lima
Centre for Wireless Communications, University of Oulu, Finland.
(e-mail: harri.saarnisaari@oulu.fi)
(Laiyemo is currently with Nokia, FI)

Abstract—**Integration of the satellite component into the fifth generation (5G) new radio (NR) system is an ongoing activity within the 3GPP standardization body. However, as the 5G NR system is primarily designed for terrestrial applications, its direct usage with satellite communications may raise problems whose solutions affect its underlying design principles and operation. This paper addresses this adaptation and then analyses the suitability of the 5G NR random access procedure for satellite usage. Although many of the already standardized configuration parameters and procedures are flexible enough and can be used without modifications, the timing advance (TA) calculations, its value transmission, as well as associated timers' configuration require reworking. Furthermore, we also observed the guard interval needed by the physical random access signal may be reduced using the so called minimum common delay that has to be transmitted to the terminals.**

Index Terms—**5G, satellite communication, RACH, timing advance.**

I. INTRODUCTION

THE integration of satellite communications into the fifth generation (5G) terrestrial network is crucial due to the 5G envisioned ability to connect virtually everyone and everything [1]. This integration has been started and networks involving satellite links or high altitude platforms are generally known as non-terrestrial networks (NTN) in the standardization process . In fact, satellite connections could be used not only to sustain backhaul links, but also to establish direct user equipment (UE) connections as indicated in the 3GPP's non terrestrial network (NTN) access document [2]. Hereafter, both the UE and the satellite backhaul connecting devices are referred to as the NTN terminals.

There are two categories of satellite systems (SSs): i) an amplify and forward structure called the bent-pipe SS, and ii) an on-board processing SS also known as the regenerative SS that has processing capacity in the satellite. Whereas the former includes the base station (gNB in 5G) functionalities in ground terminals of the SS, the latter implements (some of) these gNB procedures in the satellite. The selected deployment structure (either bent-pipe or regenerative) clearly impacts the respective propagation delay between the NTN terminal and the serving gNB.

5G new radio (NR) was originally designed for terrestrial communications with relative short gNB to UE distances. Hence, its direct use with satellite systems (links) is severely affected by long propagation delays meaning that selected parameter values are typically inappropriate (too small) and

cause problems. Another radio link related problem caused by SSs is the high Doppler frequency shift of mobile satellites [2].

The applicability of the 3GPP LTE interface to satellite transmission was presented in [3], where an inter transmission time interval (TTI) interleaving technique is used to adapt the retransmission method for the satellite links. Equally important, an uplink synchronization method for a satellite-LTE system was introduced in [4]. Therein, the proposed approach focused on the large beam sizes of the satellite system so as to divide UEs within the beam coverage into groups with respect to their round trip delay (RTD) and then assumed the method for determining the link distances in terrestrial network can be applicable to the NTN. In a related work, a convergence layer in various use cases was proposed in [5] to match LTE with satellites. Furthermore, LTE adaptation for satellites has been presented in [6].

In the 5G field, satellite channel impairments that pose severe challenges to the realisation of a seamless satellite-5G NR integration and their impact on physical and MAC layer procedures were discussed [7]–[9]. It was observed, among other things, that timing advance (TA) and uplink random access have issues and need clever solutions, which were discussed. Furthermore, 3GPP and its working groups are looking for solutions of which [10] is a good example about TA related solutions.

In this paper, we focus on the uplink random access process including TA. In particular, the random access channel (RACH) procedures for 5G NR networks are examined and the impact of their application on the satellite links is assessed. We highlight the observed problems and propose viable solution(s). The solutions and discussion herein provide an alternative view to the problem than the references mentioned in the previous paragraph.

The reminder of this paper is organized as follows. Section II gives an overview of the 5G NR RACH procedures. Thereafter, problems and their solutions are identified: Section III addresses the PRACH guard interval, while the timing advance procedure and its updating rate are discussed in Sections IV and V, respectively. Moreover, modifications to the standard random access procedure are considered in Section VI. Finally, conclusions and final observations are drawn in Section VII.

II. RACH PROCEDURE OVERVIEW

The random access process is used during the initial access when a UE wants to join the network, to re-establish the

connection and handover to a different serving cell. There are two types of random access (RACH) procedures which are contention and non-contention based. The former is used carry out the initial access and re-establish broken connections, while the latter is employed in connected mode related events, such as, beam change. In addition, all UEs can potentially transmit over the same RACH slot in the former, whereas the gNB assigns a certain RACH slot for the UE operating in the latter.

By the time the random access procedure starts, it is assumed that the downlink synchronization has been completed and, consequently, the UE knows when and where it can execute the first step of the RACH process. Fig. 1 illustrates the two types of RACH procedures and related messaging as specified in [11]. As shown in Fig. 1(a), four messages are exchanged between the NTN terminal and the gNB in order to solve all ambiguities and establish a connection. Notice that the gNB does not initially know the corresponding propagation delay or identity of the UE in this case. On the other hand, the UE is known and less messages are needed in Fig. 1(b), since the serving gNB assigns specific RACH resources to the target UE.

After the NTN message 1 or PRACH signal, the satellite responds within a time window with a random access response (RAR) message. If the RAR message is received within the corresponding time window, the requesting NTN terminal decodes its response message and starts the radio resource control (RRC) process by first self-configuring and then replying an RRC connection request for uplink scheduled transmission. However, a collision occurs when multiple NTN terminals chose the same preamble in step 1. The contention resolution message is used to resolve possible collision/contention. If the NTN terminal does not receive the RAR message within its time window, the PRACH preamble is retransmitted after the back-off timer.

In the terrestrial systems the base stations are static. However, as mentioned, in satellite systems they also could be mobile since fast moving satellites could include gNB functions. Also in the case that the gNB is at the ground sector of the SS, moving satellites could be seen as mobile gNBs. This means that handovers are needed also due to gNB mobility, not just due to UE mobility.

There could be intra and inter gNB handovers among other in 5G NR. The former may be a beam change and the latter gNB change. In satellite systems a beam (footprint at ground) could be considered as a beam of one gNB. In this case satellite is understood to include one gNB. However, it is also possible to understand that different satellite beams belong to different gNBs. The choice is up to the operator. The selected approach obviously affects the handovers and their classification.

In what follows, we initially identify which technical challenges hinder the usage of the aforesaid RACH process in the satellite systems and propose viable solutions based on the available 5G NR specifications.

III. PRACH GUARD INTERVAL

The random access preamble is usually sent in a RACH slot that includes the cyclic prefix, the preamble sequence,
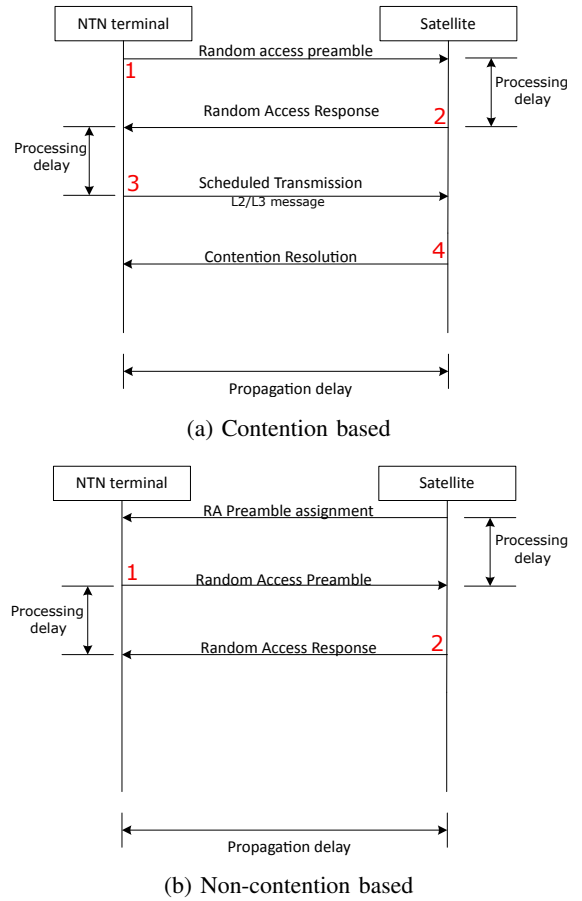

(a) Contention based

(b) Non-contention based

Fig. 1: (a) Contention-based and (b) non-contention based random access processes in 5G NR.

TABLE I: RTT values for satellite systems.

	RTT bent pipe [ms]	RTT on board [ms]
GEO (height 35 786 km)	477	239
MEO (height 2 000 km)	26.6	13.3
LEO (height 600 km)	8	4

and guard interval (GI). The length of the cyclic prefix and the preamble sequence are determined by the selected RA preamble format [12]. The guard interval prevents the PRACH signal overlapping with other (data) transmission. The needed guard interval is influenced by the round trip time (RTT) between the gNB and the furthest UE since in 5G (and 4G, 3G, 2G) the closest UE could be by the gNB (zero distance). The RTT of the satellite systems are much larger than the maximum terrestrial values as shown in Table I for a few satellite heights. It can be seen that the values are large compared to typical terrestrial cell sizes.

In 5G NR, the gNB is controlling the guard interval [13]. In LTE, the GI is included in the PRACH signal and slot such that there is improvement in flexibility in 5G. This means that the gNB does not schedule any other transmissions during the expected RACH slot. In that sense the handling of large GIs of satellite systems is straightforward. PRACH transmission times are controlled by the gNB in the form of a

TABLE II: Differential distance for satellite systems assuming 400 km and 1400 km beam size.

	differential distance [km]	
	beam size 400 km	beam size 1400 km
GEO (height 35 786 km)	2	27
MEO (height 2 000 km)	40	441
LEO (height 600 km)	121	923

PRACH configuration [12] sent to the terminal in the system information. PRACH transmission possibilities occur several times per frame (10 ms) [12]. Consequently, based on the values on Table I, the subcarriers used for PRACH must be reserved just for PRACH unlike in the terrestrial systems. This raises a question, are there any means to prevent this wasting of capacity?

Assuming that the minimum separation distance between the satellite and its ground beam is known, a terminal can subtract this value (*i.e.*, minimum RTT) from its transmission time calculations. The remaining part then corresponds to the differential distance (D2 - D1) illustrated in Fig. 2. Actually, this operation would significantly reduce the maximum GI values as shown in Table II, at least for GEO and MEO satellites. Since the beam size remains the same in these calculations, the difference is larger for lower orbit satellites. The calculations assume that the minimum distance (nadir) is to the other end of the beam and the maximum to another beam end and the beam footprint size is 400 km or 1400 km. In reality, the beam sizes vary a lot depending on a satellite system [2], but these calculations give a hint what kind of values could be expected and the larger value could be seen as the worst case.

As a result of these calculation, the required worst case GI could be reduced down to about 3 ms and could be tailored to different satellite systems. This could be calculated per beam in a dynamic fashion and the beam based value could be transmitted to NTN terminals. The information could be send in the system information, which requires a new system information message in the 5G standard. Alternatively, a fixed value per satellite system could be used that is installed into the NTN terminal. However, this is not very flexible way since manual updates are required if changes occur. Third approach could be based on known NTN terminal and satellite orbits in which case this value could be calculated by the NTN terminal. However, this cannot be assumed to be generally valid and it is vulnerable to location errors.

One solution is to introduce new PRACH configurations if the existing ones are not enough. Basically, there could be rare RACH slots such that there is time for data transmission in between the RACH slots. However, the existing values allow RACH slot periodicity to vary from 10 ms to 160 ms and within each period PRACH could be send in one or more places [13, sec. 16.2]. Values could be decided based on what other means, explained above, offer. The work is not necessarily easy since there are several satellite systems and orbits and both the backhaul case and direct UE access case must be covered, and the needs in these use cases may be different. Anyway, these new configurations could be implemented just by vendors offering NTN devices.
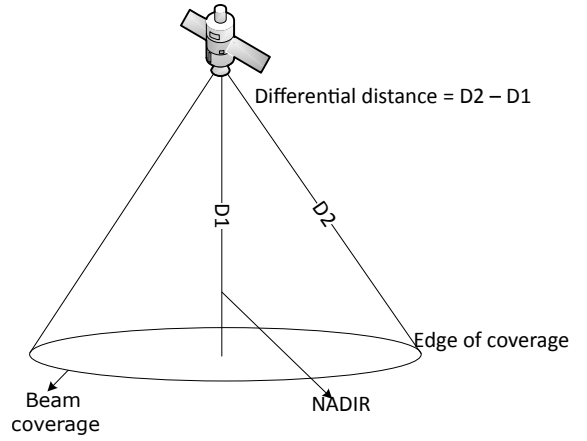

Fig. 2: Differential distance in the context of satellite links.

In satellite systems, handovers do not necessarily occur very frequently. In a backhaul usage the "line is on" most of the time such that RACH process is needed very rarely. For example, if PRACH is allowed once per 10 ms and differential delay could be adopted, PRACH would take only (about) 30% of capacity of these subcarriers. This is one thing that could be elaborated more in the future: how often PRACH is actually needed in different satellite systems and how to set corresponding PRACH configurations.

IV. TIMING ADVANCE VALUE

The RAR message sent by the satellite in response to the random access preamble in step 1 as shown in Fig. 1a consists of a temporary C-RNTI, timing advance (TA), and uplink grant for L2/L3 message. While the assignment of a temporary C-RNTI and uplink grant for L2/L3 message do not require any modification, the timing advance will require some adjustment to support the large link distances existing on the satellite links. Timing advance information in RAR message is the first timing correction, sent by the satellite to the NTN terminal, so that after applying this correction, all the uplink signals from the NTN terminals will be time aligned when reaching the gNB. The timing advance is a negative offset employed by the NTN terminal between the start of a received downlink subframe and a transmitted uplink subframe.

A. TA Range

TA value T is calculated as [14, sec. 4.2] $T = N_{TA}T_c$, where $T_c = 0.509$ ns, and

$$N_{TA} = T_A \times 16 \times 64/2^\mu, \tag{1}$$

where $\mu = 0, 1, \ldots, 5$ defines the subcarrier spacing (from 15 kHz to 480 kHz) and $T_A = 0, \ldots, 3846$. Obviously, the largest TA is at the smallest 15 kHz sub carrier spacing (SCS). Since TA presents two way delay, the maximum value corresponds 300 km cell size at 15 kHz SCS, 150 km at 30 kHz SCS and so on. If, and when, larger SCS values are desired in satellite systems, these TA values are obviously too small. Consequently, some ways to circumvent the situation have to be found. In what follows, two methods are proposed to extend the timing advance range.

TABLE III: Maximum TA and field length required for satellite systems for 15 kHz and 120 kHz SCS: Method 1.

	required TA value 15 kHz	required TA value 120 kHz	field length [bits] 15 kHz	field length [bits] 120 kHz
5G terrestrial	3 846	3 846	12	12
GEO	457 813	7 324 993	19	23
MEO	128 220	2 051 505	17	21
LEO	11 793	188 678	14	18

TABLE IV: Maximum TA and field length required for different differential delay for 15 kHz and 120 kHz SCS: Method 2.

differential delay [ms]	TA value 15 kHz	TA value 120 kHz	field length [bits] 15 kHz	field length [bits] 120 kHz
1	3 838	61 395	12	16
2	7 675	122 790	13	17
4	15 349	245 580	14	18
10	38 372	613 949	16	20

Fig. 3: Distance change due to satellite mobility at 7.5 km/s.

B. Method 1

Direct extension of the maximum TA range is an obvious solution. The bits it requires are shown in Table III for 15 kHz and 120 kHz SCS (different TA step sizes). Calculations include 1400 km footprint such that the cell edge is at 700 km from the centre. GEO is at 35786 km, MEO at 10000 km and LEO at 600 km. The TA value must cover two way propagation (RTT on board). It can be seen that the number of required bits is heavily affected by used satellite system and beam size. Indeed, GEO satellites could reach rather north or south locations such that the distance is actually significantly larger (over 40000 km [2]) and a bit or two more may be needed.

The extra bits above 12 have to be transmitted to the NTN terminal before it sends message 3 and only the RAR message is available. This means that the timing advance size in the RAR message has to be enlarged in the NTN systems, if this method is applied.

C. Method 2

Satellites have fixed orbits, such that there is a minimum common propagation delay to all NTN terminals within the beam coverage. Therefore, instead of evaluating the TA based on the link distance between the satellite and the NTN terminal, the timing advance can be obtained based on the difference to the minimum distance. In this case the required TA value depends on the footprint size such that with small footprints changes are not necessarily needed. However, with large footprints such as in GEO systems, the differential delay could be significant, several ms or even above ten ms [2].

Table IV shows the required TA value and the number of bits for a few differential delay values. Again, TA value includes two way propagation (or twice the given delay difference).

The minimum distance could be send in a system information on a beam based since it may vary depending on satellite location in its orbit. Once the NTN terminal receives the minimum distance it us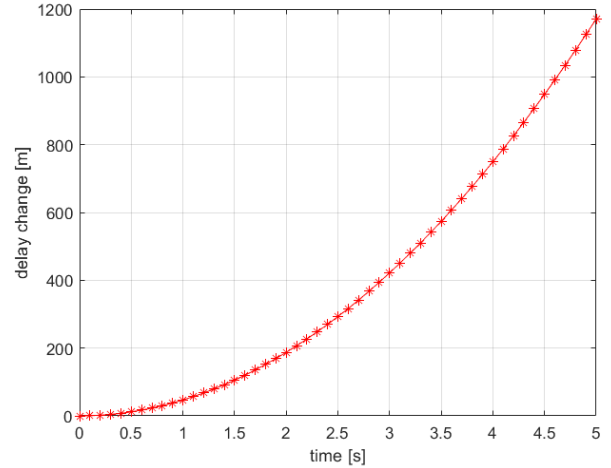es this value to adjust it transmission time in the RACH process. This method is not solving the problem for the large footprint systems since extra bits are needed in the RAR message.

If compared to method 1 it can be seen that in the LEO case, if the footprint is small, there is no difference in the number of required extra bits. However, method 2 is typically more efficient for MEO and LEO systems. Method 2 was observed to be a good way to reduce the required guard interval (GI) in section III, such that this solution has also other benefits.

V. ABOUT TA UPDATE RATE

After being initially set with the RAR message, the TA value is updated if needed [13], [14]. TA updates are transmitted in MAC messages using 6 bits and have the form $[-31...32] \times 16 \times 64/2^\mu T_c$. The term $16 \times 64/2^\mu T_c$ in (1) defines the minimum step size of the timing adjustment command. The minimum TA step size is 156 m at 15 kHz, 78 m at 30 kHz, 39 m at 60 kHz and 20 m at 120 kHz SCS, respectively. On the other hand, the maximum TA value command can correct delay changes of 4.8 km, 2.4 km, 1.2 km and 0.6 km, respectively. On the other hand, the signals from different UEs must arrive to the gNB within the cyclic prefix (CP) that is 1.4 km for 15 kHz, 700 m for the 30 kHz, 350 m for 60 kHz and 175 m for 120 kHz SCS, respectively [12, sec. 5.3.1].

Assuming that a LEO satellite at 600 km height is directly above and moves fast with velocity 7.5 km/s [2], the change of propagation distance between the satellite and the NTN terminal is shown in Fig. 3. It can be seen that at least in this case the delay change is within CP at 120 kHz for about 2 s and within the minimum TA step about 0.7 s. Therefore, most likely TA updates need to be sent just a bit more frequently than usual though this analysis should be made also for other scenarios. Anyway, 5G NR is flexible in this sense and sufficient rate for the TA updates could be managed. The TA change is not valid immediately but after some slots [12, sec. 4.2]. This may affect the rate at which TA commands must be send. Furthermore, the NTN terminal is (or should be)

able to check if delay compensation is working properly using the received downlink timing information [12, sec. 4.2]. The NTN terminal is therefore capable to follow propagation delay changes and compensate for them.

VI. EXTENDED RACH PROCESS DURATION

One major difference between terrestrial and non-terrestrial networks is the magnitude of the propagation delay in relation to the processing delay. In the traditional terrestrial network, the maximum possible propagation delay is indeed a small fraction of the processing delay. Hence, the time duration to complete a RACH process is mainly dominated by the latter. However, when considering that satellite links are much longer than those in the terrestrial network supporting cell size of at most 300 km, the time duration required to complete the RACH procedure is expected to be dominated by the respective longer propagation delay. For instance, assuming a fixed processing delay of 3 ms (it depends on the computational capability of the transmitter/receiver), a terrestrial network with the largest supported cell size of 300 km requires 13 ms to complete a RACH process without collision. On the other hand, a regenerative GEO satellite link needs 550 ms to complete the RACH process. Similarly, regenerative MEO and LEO satellite links at nadir heights of 10000 km and 600 km will complete the RACH process in 196 ms and 35 ms, respectively.

The delays affect also the timers of the RACH process. This means that the RAR timer and the contention resolution timer have to be adjusted correspondingly depending on the used satellite system. These timers are configurable and their values are sent to the NTN terminal by the gNB in the system information.

VII. CONCLUSIONS

In this paper, we investigated how to apply the 5G NR random access procedure to non-terrestrial networks. Based on our investigations, it was observed that even though a few components can be used without modifications – due to the 5G NR high flexibility – others need changes depending on the particular satellite system. The primary reason for that is the much longer propagation delay of satellite systems when compared to terrestrial systems, for what 5G NR has been originally designed.

It was observed that the guard interval of the physical RACH signal (PRACH) is not problem, because it is controlled by the scheduler. However, owing to the longer propagation delay in satellite system, it was proposed to use the delay difference between the minimum common delay in a satellite beam and the actual delay so as to reduce the corresponding guard interval. This requires the minimum delay to be transmitted in a system information.

Timing advance value in terrestrial systems corresponds to the maximum cell size of 300 km (at 15 kHz SCS), which is inadequate for satellite systems and larger (more bits) TA values should be send in the RAR message. The number of bits was then calculated for specific use cases showing that up to 10 additional bits may be needed depending on satellite system. Notice that the minimum distance approach could reduce the number of required additional bits. The command procedure

for TA updates in 5G NR is readily quite flexible already, but maybe new PRACH configurations are still needed for NTN systems. Furthermore, the timers associated with the RACH process must be configured properly.

The required changes are not generic but depend on both the satellite system and the sub carrier spacing. Therefore, further investigations of different satellite systems are needed in order to find suitable set of new parameters for the NTN capable RACH process. This paper just highlighted these open issues and discussed viable solutions, though did not delve into the details of various satellite systems.

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