Application of 5G new radio for satellite links with low peak-to-average power ratios

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Summary
The aim of the paper is to consider feasibility of 5G new radio (NR) over satellite links also known as nonterrestrial networks (NTNs). Large propagation delay and Doppler frequency shift are challenges like high peak-to-average power ratio (PAPR) of 5G NR signal because satellite systems would like to operate at very low-power amplifier back-off values. This paper provides a brief summary of progress in initial synchronization and uplink random access in both the literature and standardization. Furthermore, the paper explains what is the relationship between low PAPR and power amplifier back-off and the density of reference symbols by showing that 2-dB back-off values can be attained using sufficient reference symbol density. Finally, open issues that need clarification are listed.

KEYWORDS
back-off, mobile radio systems, physical layer, power amplifier, satellite communication, standardization

1 | INTRODUCTION

The integration of satellite communication (SATCOM) and 5G new radio (NR) systems is currently an active topic of research and undergoes intense standardization activity. The satellite systems have the potential to not only solve coverage problems but also temporarily boost capacity in hot spots. This integration permits better interoperability, as well as joint signal design and chip manufacturing that in its turn reduces overall costs. Indeed, the SATCOM usage cost should be reduced along this process to make satellite systems a more attractive alternative. In the 3GPP standardization body, the SATCOM integration into the 5G specifications is termed nonterrestrial networks (NTNs), and the first integration results should be published already in Release 17 (year 2021).

Actually, the satellite and 5G NR integration can occur at two levels. First, 5G could use existing legacy satellite networks such that slicing, network function virtualization, and related issues need to be considered. Second, it can also occur at the signal level such that satellite systems use directly the 5G NR interface. In the 3GPP, the technical report TR38.811 \(^1\) studies challenges of the integration, whereas solutions to open problems are reported in the TR38.821. \(^2\) Moreover, architectural aspects are addressed in the report TR23.737. \(^3\) Regarding the network architecture, the SATCOM interface can be used for direct end user access or as a backhaul solution. Equally important, research projects such as the SaT5G \(^4\) and SATis55 \(^5\) also investigate the integration of satellite and mobile communication systems, and valuable information can be found in their respective deliverables.

Furthermore, there already exist related contributions that overview the integration problem, while discussing challenges and providing potential solutions. For instance, Kohdelli et al. \(^6\) initially consider satellite channel challenges on the physical (PHY) and medium access control (MAC) layer procedures of the 5G NR systems and thereafter propose solutions, for example, to implement random access. Considering

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networking aspects, Boero et al. first review the main research results on software-defined networking and network functions virtualization, discuss open challenges, and then identify a possible roadmap account for different network virtualization levels. Gobal and BenAmmar consider a multimode user terminal configuration to introduce a layered approach encompassing network, data link, and physical layers and then present an architectural framework. And yet Liolis et al. summarized the underlying concepts, objectives, challenges, and also addressed the corresponding research pillars of the European Commission Horizon 2020 5G Public Private Partnership Phase 2 project “SaT5G” (Satellite and Terrestrial Network for 5G). In the context of enhanced mobile broadband and narrowband Internet of things applications, Guidotti et al. assess the impact of the satellite radio channel features on the physical layer waveform design and MAC layer procedures as well.

This paper focuses on the signal level integration and overviews recent developments in the physical (PHY) layer concerning the initial access and the uplink random access process. Moreover, we also discuss new results on the relationship between reference symbol (RS) density in a time-frequency raster and very low-power amplifier back-off desired in satellite systems. Especially, this paper studies the feasibility of using 5G NR over satellite links and corresponding changes needed in the standard, devices’ algorithms, and system operation. Consequently, sufficient solutions are used in the verification part, and other potentially more optimal algorithms are not developed.

In fact, large propagation delays and possibly large Doppler frequency shifts constitute the main integration challenges in this paper—note that not all satellite systems are affected by the latter. The most straightforward solution is to use precompensation whereby user devices use the satellite trajectory and their own position to calculate and then compensate the respective propagation delay and Doppler frequency shift. Alternatively, network-based assistance can also be used; however, this functionality may not be fully supported by end user terminals or access points. This paper looks for other alternatives.

The reminder of this paper is organized as follows. In Section 2, the uplink random access process and related issues, such as timing advance calculation and transmission, and related guard interval are addressed. In Section 3, we overview physical layer issues and discuss the proposed solutions. In particular, this section tackles the downlink and uplink synchronization problem with very large Doppler frequency shift and addresses the uplink random access signal design. Section 4 covers the novel aspects of the paper and explains how low back-off and reference density are related. Note that each section includes relevant state-of-art review of the topics under consideration. Finally, we draw conclusions in Section 5.

1.1 Briefly about satellites systems

To begin with, we provide few relevant facts about SATCOM systems. The geostationary orbit (GEO) satellites are above the Equator at about 35,800-km altitude, medium Earth orbit (MEO) satellites are between 2,000-km and GEO orbit, and low Earth orbit (LEO) satellites between 160 and 2,000 km. Furthermore, highly elliptical orbit (HEO) satellites have an elliptical route with varying propagation delay. Consequently, one-way propagation delays are 120 ms for GEO, 7−120 ms for MEO, and 0.5−7 ms for LEO systems. GEO satellites are stationary such that Doppler frequency shift is insignificant. Considering a MEO system at 10,000-km altitude, the maximum Doppler frequency shift and the corresponding maximum Doppler frequency shift change rate at 2-GHz carrier frequency are ±15 kHz and −6 Hz/s, respectively. If the carrier frequency increases to 30 GHz, the maximum Doppler frequency shift is now ±225 kHz, while the maximum Doppler frequency shift change rate becomes −90 Hz/s. The Doppler frequency shift becomes even more severe with the LEO system orbiting at 600-km altitude. In fact, the maximum Doppler frequency shift and the corresponding maximum Doppler frequency shift variation at 2 GHz become ±48 kHz and −544 Hz/s, respectively. Furthermore, at 30 GHz, the maximum Doppler frequency shift is ±720 kHz, whereas the maximum Doppler frequency shift variation becomes −8.16 kHz/s. Indeed, LEO satellites are moving over 7,000 km/s, while terrestrial velocities, for which 5G NR was initially designed, a few hundred km/h. Furthermore, the satellite footprint or satellite beam coverage on Earth surface could be larger than 1,000 km in one dimension, such that the satellite system coverage area could be larger than the maximum terrestrial cell size.

As a result, all satellite systems exceed the propagation delay of terrestrial systems, which becomes problematic for the uplink random access process as discussed in this paper. Large Doppler frequency shift, on the other hand, is a concern only in satellite systems where satellites move with respect to the Earth surface such as LEO, MEO, and HEO. The high dynamic range of 5G NR signal affects all satellite systems.

The network architecture constitutes another important aspect of the satellite deployment scenarios. In traditional transparent satellite systems (that are amplify-and-forward structures), a base station (gNB) locates at a satellite system’s ground segment. Satellites that have on-board processing capability could have gNB. We denote the 5G NR base station in satellite systems as NTN gNB to distinguish it from the terrestrial system. In satellite systems employing the 5G NR, the user device is called the NTN terminal. It could be used in direct user access, that is, as an user equipment (UE) or as a gateway to a terrestrial base station (indirect user access). The combination of the NTN terminal and the gNB can also be formed as a relay node (RN). These alternatives are illustrated in Figure 1. Obviously, also a link from a satellite to a ground segment may be based on the 5G NR in the on-board processing case.

The downlink in 5G NR satellite systems is from the satellite to the NTN terminal and uplink the reverse. This paper is looking at downlink initial access and uplink random access process as well as downlink data transfer merely for the indirect access because there a highly directional antenna is typically used that results in a single path radio channel. The results may differ in multipath channels that potentially occur in the direct access, but principles are the same.
The much longer propagation delay afflicting all satellite systems is the main problem undermining the uplink random access procedures, whereas the larger Doppler frequency shift is the main concern when detecting the uplink random access signal (this topic is discussed in Section 3).

The uplink random access process is implemented following either a contention-based or contention-free procedure. In the first step, an NTN terminal sends an uplink random access signal denoted as the physical random access channel (PRACH) signal within the corresponding random access slot according to the gNB synchronization signal (SS). Upon receiving a PRACH signal, the gNB calculates the timing advance (TA) value for that particular terminal and sends it along with other relevant information in a random access response (RAR) message. This process also includes contention resolution procedures for solving possible conflicts if more than one terminal access the medium at the same time.

Furthermore, this process includes timers to control its triggering and operation; hence, it is needed to adjust their duration to cope with the propagation delays of satellite systems either via direct extension or, for example, using an initial offset value. Because the PRACH signal requires a guard interval to avoid overlapping with other scheduled signals, it is also necessary to extend this guard interval to each satellite system accordingly. Notice that such interval should not be designed to the worst case because the difference between scenarios is very significant. Different from Long-Term Evolution (LTE) system where guard interval is incorporated into the PRACH frame structure, in the 5G NR system, the scheduler handles it directly. As a result, this problem becomes a vendor specific, and new flexible NTN system friendly schedulers need to be (re)designed.

The maximum TA value currently supported in the 5G NR standard is 2 ms at 15-kHz subcarrier spacing (SCS), 1 ms at 30-kHz SCS and so on, which is clearly not sufficient for all satellite systems. These values are due to reasons that the TA value is sent in the RAR message using 12 bits and each SCS has its own basic time period for TA calculations. Therefore, both TA calculation at a gNB (allow larger values) and its transmission may need modifications in the standard.

The common minimum delay, also known as differential delay, has been recently considered as an effective alternative to reduce the values of the satellite delay range to be reported. This minimum delay is determined with respect to the differential distance between the satellite nadir and the beam coverage edge. Then, the gNBs broadcast this information per beam basis to the connected NTN terminals. Although this approach reduces the values of the delay range to be reported, it is still insufficient because the satellite footprint is much larger than a typical terrestrial cell size. As a result, the RAR message needs to be adjusted to accommodate more bits that are required for transmitting the TA value in satellite scenarios.

It is also necessary to consider implementation issues related to the mobility and delay ambiguity in satellite systems. In this context, mobile satellites are seen as (virtual) base stations so that handovers are also triggered by the base station mobility and in-between beams of a satellite system.

2.1 An experiment

One testbed in the SaT5G project was devoted for verifying these aspects. Indeed, the TA calculation and TA value transmission were modified such that longer delay could be handled. In addition, the timers were extended and guard interval increased. It was shown that without these modifications, connections with an emulated satellite link were not possible, because connection forming failed. With modifications, connection was successfully formed, and the so formed satellite system was used to verify both direct end user access and backhaul use case, as the NTN terminal was also connected to a base station of a 5G test network to provide a backhaul connection.

![Figure 1](https://example.com/figure1.png)
This testbed was implemented using the Open Air Interface software and USRP software-defined radio units. However, the 5G NR implementation of the frequency division duplex (FDD) mode used in satellite systems was not available during the project execution. Thus, the LTE interface, which provides an implementation of the uplink random access process similar to the 5G NR, was used to verify this concept (more details are shown in a SaT5G project deliverable13).

3 | DOWNLINK SYNCHRONIZATION

In the PHY layer, the large Doppler frequency shifts experienced by satellite systems cause carrier frequency offset (CFO) at the receiver. As it will be shown next, the proposed solutions do not require significant changes in the standards; however, it will be still needed to account for the Doppler frequency shift values experienced by NTN transceivers in SATCOM systems.

Radio channel is another important aspect to consider when assessing satellite systems. Typically, terrestrial deployments with narrow beam antenna array experience a single path channel.1 End users operating in the direct access mode suffer multipath fading channel degradation. In this configuration, the link budget becomes a limiting factor because handheld devices usually have low antenna gains when compared with narrow beam antennas—this fact may limit achievable data rates or connectivity.

At the technical level, CFO-related problems have to be solved, and indeed, there must be certainty that these can be managed. The issues occur in initial downlink and uplink synchronization. After the initial detection, when the initial time and frequency synchronization are successfully performed, a typical (existing) receiver is able to perform CFO and timing tracking as confirmed by results presented in the 3GPP work group report TDOC R1-1912291.14 The reason is that initial CFO estimation brings CFO down to level that can be handled by a typical receiver.

As aforementioned, the SATCOM systems exhibit large CFO values when compared with terrestrial deployments. In this context, a NTN terminal needs to detect the SS from the serving base station, whereas a gNB needs to detect the PRACH signal sent by the NTN terminal. However, when the CFO is too large, a typical receiver fails to properly detect either the SS on downlink or PRACH on the uplink.

Several solutions have been proposed to address such uplink and downlink synchronization problems. For instance, a new PRACH signal implementation and a large CFO aware signal processing solution were discussed in TDOC R1-1911860.15 Alternatively, a longer signal was also considered, because the respective sensitivity is improved.15 A new, extended PRACH (e.g., with a long cyclic prefix [CP]) was considered also in the TDOC R1-1912725.16 Therein, it was also claimed "that additional complexity is needed at the UE receiver to achieve robust performance on synchronization" (a similar approach was also proposed in the TDOC R1-191047917).

Because the PRACH signal with normal SCS (i.e., multiple of 15 kHz) is similar to the primary SS (PSS) implementation in the 5G NR, the technique proposed by Saarnisaari et al18 for PSS detection in large CFO is also suitable for PRACH signals. In fact, the processing principle is based on a multiarm receiver in a way similar to the solution presented in TDOC R1-1911860.15 Each arm corresponds to one potential CFO, where the number of arms (their separation in frequency) depends on the expected CFO uncertainty and signal length.18 By using this solution, the receiver detects the signal and provides initial timing and CFO estimates.

The proposed multiarm receiver is illustrated in Figure 2. Similar solutions have been previously employed in the global navigation satellite systems (GNSS) with fast moving satellites. Such multiarm receiver can be implemented in either a serial or parallel fashion rendering on average slower or faster processing times (note that a hybrid implementation is also possible). The results in Saarnisaari et al18 show that the PSS signal can be detected with probability one at −6-dB signal-to-noise ratio (SNR) per resource element (RE), or subcarrier, which actually fulfills the 5G NR requirement. After the initial CFO estimation, a typical correlation receiver is sufficient to detect the secondary SS (SSS). Note that the studies in Saarnisaari et al18 did not consider nonlinearities in the satellite channel (see Section 4 for more details). Our investigations show that similar performance is achieved in presence of nonlinearities and applied crest factor reduction. In fact, spread spectrum signals, such as the PSS, SSS, and PRACH, are expected to operate well even in very bad propagation conditions and one bit analog-to-digital converters.

In the uplink direction, NTN terminals need to transmit different CFO values to the gNB. The TA ensures that these signals are received about the same time. In the 5G NR, standard gNBs can only handle just small CFO variations such that there is need to develop algorithms to operate with satellite CFOs.20 It has been proposed in the TDOC R1-191224721 that gNBs send CFO corrections to UEs after the initial access so as to deal with the large frequency differences. Finally, it is reminded that Morelli et al22 provide a tutorial view of the OFDMA synchronization issues touching also the discussed issues.

4 | DATA RECEPTION WITH LOW PAPR

This section addresses the nonlinearity of high-power amplifier (HPA) in satellite systems which compromises the integration of SATCOM and 5G NR. In fact, the HPA is expected to operate close to the saturation point, although the 5G signals have very high dynamic range. Our results show
that the standard approach is sufficient in few situations, but the operators need to properly configure the RS density and operate on a limited set of modulation and coding (MODCOD) values particularly if the link budget remains at the lowest acceptable level.

Low peak-to-average power ratio (PAPR) and the respective low HPA back-off enhance (i) the communication range for a given MODCOD scheme, (ii) the received signal level (SNR), and (iii) the power efficiency of a HPA. These are important aspects in spaceborne communications where satellites have a limited power supply and large signal attenuation. Indeed, the current satellite standard called DVB-S2 operates on about 0 dB output back-off (OBO) level for QPSK and 8PSK modulations. This is far less than the values seen in LTE or 5G NR systems where 6-dB values have seen with PAPR reduction and more than 10 dB without such techniques. Finally, note that the 5G NR requires PAPR reduction methods that are transparent to the receiver.11

As a result, the PAPR reduction constitutes a challenge to integrate the 5G NR signal as a part of the (future) SATCOM systems. In fact, many PAPR or crest factor reduction techniques have been proposed for the orthogonal frequency division multiplexing (OFDM) signals since their introduction.24 Although clipping is a valid alternative in this situation, it causes undesired out-of-band radiation such as does also passing the 5G PAPR or crest factor reduction techniques have been proposed for the orthogonal frequency division multiplexing (OFDM) signals since their introduction.24 Although clipping is a valid alternative in this situation, it causes undesired out-of-band radiation such as does also passing the 5G NR signal through nonlinear region of a HPA. The iterative clipping-and-filtering (ICF) method is suitable for the 5G NR and basically nulls the out-of-band subcarriers after clipping in an iterative manner until the desired clipping level is achieved. Unfortunately, the ICF adds clipping noise to the signal (as observed in Armstrong25) that increases with the number of iterations: the respective noise is about 15 and 25 dB below the signal level for 2- and 6-dB clipping ratio, respectively (this effect depends on the FFT size and the number of active subcarriers). Furthermore, the ICF method maintains the out-of-band energy (OOBE) levels within the original OFDM signal limits.26 Typically, papers about ICF assume that oversampling is used (as in the original proposal25), though the oversampling values are not specified. Herein, we use the standard 5G NR oversampling values by considering zero padding at the band edges.

For instance, the power amplifier efficiency can be improved by 30% if its OBO is reduced from 6-dB level down to 2 dB, which is significant.27 However, most of the related PAPR reduction studies concentrate on the resulting PAPR levels that are much higher than 2 dB. This is most probably due to fact that the corresponding bit error rate (BER) and block error rate (BLER) are degraded by using such low PAPR levels. Considering the integration of 5G NR and SATCOM, the target clipping level was set so high (8 dB at 10−2 CCDF level) that signal distortion was not observed.15 The TDOC R1-191272728 presents interesting results on the effects of HPA nonlinearity for different OBO levels in the context of 5G NR signals. In addition, it also shows that the performance loss is just 1–2 dB at low modulation order (QPSK) even if the input back-off (IBO) and OBO are at 2-dB level. Therein, authors use RSs in the receiver but do not specify the density of the RS structure, and they also observed that higher order MODCODs suffer from larger losses. Authors also use both traveling-wave tube amplifier (TWTA) and solid state PA (SSPA) models, whereas the former is more demanding for higher order modulations. Tabulated models are also used, though equation based models are available.21 It is also observed in the TDOC that standard 5G NR error vector magnitude (EVM) requirements could be relaxed because satellite systems can operate at lower losses when compared with the typical EVM levels accepted in terrestrial systems. In the SaT5G deliverable it was observed that data in the 5G NR SS block can be received with low BLER even at low PAPR levels. Data in the SS block are accompanied with very dense RSs because every fourth subcarrier is a RS and this could be a key factor for such a performance.

It was shown18 that transmitting high-power RSs in the SS block enhances the overall performance that is expected to hold for the data block as well (this improvement is mainly due to better channel estimation). In the satellite environment with limited transmit power, such high-power signal distorts the quality of the received signal. This is mainly due to the fact that the corresponding bit error rate (BER) and block error rate (BLER) are degraded by using such low PAPR levels. Considering the integration of 5G NR and SATCOM, the target clipping level was set so high (8 dB at 10−2 CCDF level) that signal distortion was not observed.15 The TDOC R1-191272728 presents interesting results on the effects of HPA nonlinearity for different OBO levels in the context of 5G NR signals. In addition, it also shows that the performance loss is just 1–2 dB at low modulation order (QPSK) even if the input back-off (IBO) and OBO are at 2-dB level. Therein, authors use RSs in the receiver but do not specify the density of the RS structure, and they also observed that higher order MODCODs suffer from larger losses. Authors also use both traveling-wave tube amplifier (TWTA) and solid state PA (SSPA) models, whereas the former is more demanding for higher order modulations. Tabulated models are also used, though equation based models are available.21 It is also observed in the TDOC that standard 5G NR error vector magnitude (EVM) requirements could be relaxed because satellite systems can operate at lower losses when compared with the typical EVM levels accepted in terrestrial systems. In the SaT5G deliverable it was observed that data in the 5G NR SS block can be received with low BLER even at low PAPR levels. Data in the SS block are accompanied with very dense RSs because every fourth subcarrier is a RS and this could be a key factor for such a performance.

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RSs reduce the transmit power available for data, thus establishing a trade-off between the power allocation of RS and data. However, neither PAPR reduction methods nor HPA was included in that work so that this paper provides new insights to these results as well.

### 4.1 Simulation results

To carry out our investigation, we assume the receiver antenna (at ground) to be highly directional, and consequently, we use a single path radio channel model with Gaussian noise. The simulated signal includes both the SS block and data slots. The SS block complies with the current standards by containing the PSS and SSS signals and physical broadcast channel (PBCH) data that have RSs (denoted as demodulation RSs, DMRS) at every 4th subcarrier. As described in Saarnisaari et al., the SS block is utilized to first detect PSS and make initial CFO and time-of-arrival estimation and thereafter detect SSS and perform more precise CFO estimation. These estimated values are then used in the remaining processing so as to make the results more realistic. The Doppler frequency shift and change rate are modeled as uniform random variables with lower and upper limits given by ±720 kHz and ±8 kHz/s, respectively.

In the data part, the density of DMRs is varied both in the time and frequency domains. In the time domain, one slot of 14 OFDM symbols includes one, four, or seven OFDM symbols with DMRs in every rth subcarrier, where r could be 6, 12, or 24. In our simulation, the full band is used such that 3,300 subcarriers are active out of 4,096 (FFT size) and 60-kHz SCS is used though results scale to other SCS as well. The PBCH data in the SS block are coded using about 1/5 rate polar coding, whereas the block size in the data part is 1,024 information bits long and uses 1/2 rate LPDC coding (note that larger block sizes would provide even better results). The Matlab 5G toolbox is used to implement the aforesaid coding schemes, and finally, QPSK modulation is used in simulations.

The channel estimation uses the least squares method, whereas the zero forcing method is employed for equalization. At low SNR regime, a single RS is not necessarily sufficient to perform channel estimation; hence, averaging should be used. In a single path channel, it could be over all RSs. However, in this paper, averaging is limited to 10 RSs in the frequency domain and at maximum to one slot (of 14 OFDM symbols) in time domain, because the system may be also used also in frequency selective channels. The well-known SSPA model is used to model the HPA with parameter value 3.1 The simulation chain is illustrated in Figure 3.

The ICF approach previously discussed in Section 4 is used here for PAPR reduction with FFT size 4,096 (the SaT5G deliverable defines and discusses this approach in details). From the SaT5G deliverable, only three iterations (one initialization and two additional rounds) are used because it was observed that any additional repetition provides marginal improvement. The SSPA model with large a parameter value equal to 30 was used for (hard) clipping. The PAPR reduction scheme is illustrated in Figure 4. The desired PAPR reduction level was set to 2 dB, and finally, the OBO of the HPA was set to 2 dB.

Figure 5 compares the PAPR level of the standard 5G NR signal with the PAPR level after PAPR reduction as well as after HPA. The complementary cumulative distribution function (CCDF) of the event that the signal power level is larger than the PAPR value on the x-axis is shown. As can be seen from this figure, the ICF reduces the PAPR to the desired level of 2 dB, and the HPA does not increase it with this configuration.

Figure 6 presents the results for the PBCH data in the SS block. In this study, we simulated 7,000 SS blocks for each SNR value such that suitable results are obtained until $10^{-3}$. Erroneously decoded SS blocks were not observed above $-2$ dB/RE. It is obvious that at low SNR values, NTN terminals may have to receive the SS block several times before it can successfully decode the data. However, because data transmission typically requires positive SNR values, the SS block is usually received correctly in practice.

Figures 7 and 8 show the BLER and BER results for the data part, respectively. To build these curves, we consider up to 12 dB/RE SNR and simulate 84,000 data blocks for each SNR value such that BLER and BER results are obtained down to $10^{-4}$ and $10^{-6}$, respectively. Herein, we aim to
assess how the DMRS density affects the results. In these figures, we identify the result curves as $TxFy$, where $Tx$ indicates how many OFDM symbols within a slot conveys the DMRS information and $Fy$ indicates the density of the corresponding DMRS symbols in the frequency domain (every $y$th is DMRS). Moreover, we also indicate the temporal integration using the $\text{oneT}$ and $\text{allT}$ identification: whereas the former represents no integration, the latter means that all DMRS in a slot are averaged in the time domain. In the frequency domain, we average over 10 DMRS symbols and calculate the equalizer coefficients over all subcarriers within the spread of these symbols. Notice that in the time domain, the equalizer coefficients in the $\text{oneT}$ case are valid until the next DMRS containing OFDM symbol, and in the $\text{allT}$ case, they are valid for all symbols within a slot.

We can draw the following conclusions by carefully evaluating the numerical results. Our baseline scenarios correspond to the reference curve without ICF and HPA, that is, an ideal case with estimated timing, CFO and channel. By comparing $T2F6\text{oneT}$, $T4F6\text{oneT}$, and $T7F6\text{oneT}$ with the reference curve, it can be seen that a higher DMRS density in the time domain is helpful. In fact, by further increasing the DMRS density, it is possible to achieve performance comparable to the ideal case (less than 1 dB away) and if SNR/RE is higher than 4 dB the losses vanish (flawless transmission).
In addition, the difference between T7 and T4 is less than 2 dB at low BLER values, but it is more than 4 dB between T7 and T2 (or every second vs. every seventh OFDM symbol has DMRSs). By comparing T7F6oneT and T7F6allT, it can be concluded that temporal integration of RSs is not a good idea. A reason for that might be the loose slot-by-slot-based CFO tracking used here and this situation would probably enhance if an improved CFO tracking would be applied. Another reason is that the clipping procedure affects the OFDM symbols (and the enclosed RSs) individually and therefore disturbs CFO tracking such that a dense RS density could be only option. Finally, by comparing T7F6oneT, T7F12oneT, and T7F24oneT, it can be concluded that a denser DMRS spread in the frequency domain is also beneficial although going from every sixth to every 12th does not mean a big difference.

5G NR DMRS structure is very flexible and includes many alternatives. The DMRS allocation scheme that is used here does not follow exactly the implementation described in the 5G NR, though the values (density) are similar. Therefore, the results are still valid for the 5G NR. Some examples of the actual allocations are shown in ShareTechnotes 5G pages. All in all, we observe that the standard 5G NR data transmission is feasible for satellite systems. However, the operators still have to configure a suitable set of parameters for the reference DMRS density and most probably limit modulation order and coding rates as well.

5 | CONCLUSIONS

In this paper, we reviewed the integration of the standard 5G NR and SATCOM systems regarding the physical layer and uplink random access process. Throughout our investigations, we observed the current standards require few adjustments to account for the SATCOM-specific requirements, for example, when considering the maximum CFO of satellite systems. In addition, vendors also need to address practical problems, for example, how to handle large CFO in the receiver. Only by doing so, the NTN capable devices (UE, gNB) will become a reality. Furthermore, operators need to properly configure the RS density as well as the MODCOD orders.
In order to answer these questions, this paper addressed the TA calculation and transmission, PRACH guard interval and initial access both downlink and uplink direction. Moreover, we also investigated how the RS density in time-frequency grid affects the overall system performance. In fact, by reducing the PAPR down to 2-dB level, we can boost the typical 5G NR power amplifier efficiency to be used in satellite links. Although it is possible to successfully pass a 5G NR signal with low MODCOD values through nonlinear HPA with low back-off, our investigations show that it is important to reduce PAPR and limit the out-of-band emissions before the HPA.

One objective was to evaluate feasibility of 5G NR to satellite links by studying the joint effect of PAPR reduction, HPA, channel estimation and the density of RSs in time and frequency domains. However, though the used solutions were sufficient, they may not necessarily be optimal, and furthermore, items were not fully studied. Therefore, the following topics are of special interest for future research:

- What is the optimal RS density in the time-frequency grid and the related optimal equalization in various channels (see 3GPP for satellite channel models)?
- What is the lowest clipping level supported with small performance degradation?
- How does the RS power level affect results (in SATCOM, this consumes power from data because the total power is limited)?
- Are there better low complexity PAPR reduction schemes with minimal out-of-band emission that could still achieve very low PAPR levels and HPA back-off?
- How can low PAPR levels be supported with higher order modulation and also with BPSK (that is not in the 5G NR downlink standard but in the uplink with the DFT-s-OFDM option)?
- How do the data block length and coding rate in general affect results?

It is worth noticing that scheduling is another interesting integration issue not directly handled in this paper. Actually, schedulers are vendor-specific and the standard just defines a general framework. In the uplink direction, a multiuser satellite link may be difficult to implement, and thus, an OFDMA scheduling may not be the best solution. Instead, TDMA or FDMA-TDMA hybrid could become a better alternative. Consequently, research is required to find better alternatives for uplink scheduling by taking into account uplink CFO, power level variations among users and maybe even timing variations. In addition, data traffic patterns could also affect the operation of the scheduler algorithm. If the satellite beam is serving several terrestrial base stations (backhaul), the traffic patter becomes different from that experienced when serving UEs or combination of UEs and base stations.

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None reported.

CONFLICT OF INTEREST
The authors declare no potential conflict of interests.

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