Cyclic Prefix Reduction for 5G Non-Terrestrial Networks

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***Abstract*—The cyclic prefix (CP) in 5G New Radio (NR) serves dual purposes: mitigating multipath and enabling single-tap equalization by transforming linear convolution into circular convolution. While the 3GPP standard mandates a CP duration of 7 % of the OFDM symbol duration, this study proposes reduced CP durations tailored for non-terrestrial networks (NTN), where satellite communication channels are predominantly frequency-flat. By exploring frame structures with 10 ms periodicity aligned with the 5G NR standard and leveraging subcarrier spacings above 60 kHz, this paper evaluates the feasibility of reduced CP durations in NTN scenarios. We analyze synchronization trade-offs, focusing on timing advance, accuracy, and error constraints to optimize performance.**

***Index Terms*—cyclic prefix, 5G NTN, timing accuracy**

I. Introduction

The cyclic prefix (CP) is a fundamental feature of orthogonal frequency division multiplexing (OFDM), which is the selected waveform in 5G New Radio (NR) [1]. The main purposes of the CP are combating multipath interference and simplifying equalization at the receiver [2]. CP achieves these two objectives by transforming the linear convolution of the signal with the channel impulse response into a circular convolution, enabling a simple single-tap equalization in the frequency domain. The price to pay is an increased overhead and the consequent throughput reduction.

In 5G NR [1], the duration of the normal CP corresponds approximately to the 7 % of the OFDM symbol duration. 5G NR also defines an extended cyclic prefix (ECP), which has a significantly longer duration. The ECP is designed to address severe multipath environments, such as those in urban scenarios with large delay spreads. However, the ECP introduces a higher overhead and is rarely used in practice due to its inefficiency in typical 5G deployments, where the normal CP is sufficient for most channel conditions [2].

In satellite communications, the channel is often frequency-flat due to minimal multipath components, reducing the necessity for a long CP [3]. Indeed, a highly directive antenna, such as the one typically used in very small aperture terminals (VSATs), performs a spatial filtering of the incoming signal reflections, significantly reducing the multipath. Hence, in satellite applications it is desirable to reduce the CP duration without removing it completely, since the single-tap equalization in the frequency domain is still a very useful feature. On the other hand, the uplink timing uncertainty caused by satellite mobility and varying distances becomes the main synchronization challenge. Non-terrestrial networks (NTNs), particularly in non-geostationary orbit (NGSO) scenarios, require a re-evaluation of the trade-off between CP duration and synchronization accuracy, targeting an increase of the spectral efficiency while satisfying the synchronization accuracy requirements.

This paper investigates reduced CP durations for NTNs, proposing three frame structures compatible with 5G NR. These frame structures have the same frame duration as in the standard 5G NR, but allocate the time saved by reducing the CP to the transmission of data. These additional data may be inserted by violating the 5G NR frame structure at different levels: by introducing additional subframes in a frame, or slots in a subframe, or OFDM symbols in a slot. The proposed CP durations are then translated into accuracy and synchronization requirements, whose feasibility assessment is left for future work.

II. Standard and New Frame Structures

In standard 5G NR [1], the duration of the CP scales linearly with the subcarrier spacing (SCS) as follows:

$$T_{CP} = 144 \cdot 64 \cdot 2^{-\mu} \cdot T_c \tag{1}$$

where μ is the numerology index (from $\mu = 0$ for 15 kHz, to $\mu = 6$ for 960 kHz) and T_c is the reference sampling period defined as $T_c = 1/(480 \cdot 10^3 \cdot 4096) = 0.509$ ns. In a system with a 15 kHz SCS, the CP duration is approximately 4.76 µs, and with a 60 kHz SCS, it is approximately 1.19 µs. Additionally, a longer CP is used for the first OFDM symbol of every half-subframe [1]. This allows each half-subframe to have a duration of exactly 0.5 ms. This longer CP facilitates a precise timing synchronization and the reductions of potential alignment errors. The first part of Fig. 1 shows the standard 5G NR frame structure for a SCS of 120 kHz, where each subframe contains 8 slots and the longer CP is marked in bright green.

All the proposed frame structures maintain the standard 10 ms frame periodicity to ensure compatibility with 5G NR, while changing the structures of the various elements within the frame. In the following, three frame structures are proposed, where the time saved by reducing the CP duration is allocated to increase the number of subframes in a frame, or the number of slots in a subframe, or the number of OFDM symbols in a slot. These structures are designed for subcarrier spacings starting from 60 kHz, as recommended for NTNs especially in frequency range 2 (FR2), e.g., in Ka-band [4]. The first of the following structures is also applicable to the lower SCSs, down to 15 kHz.

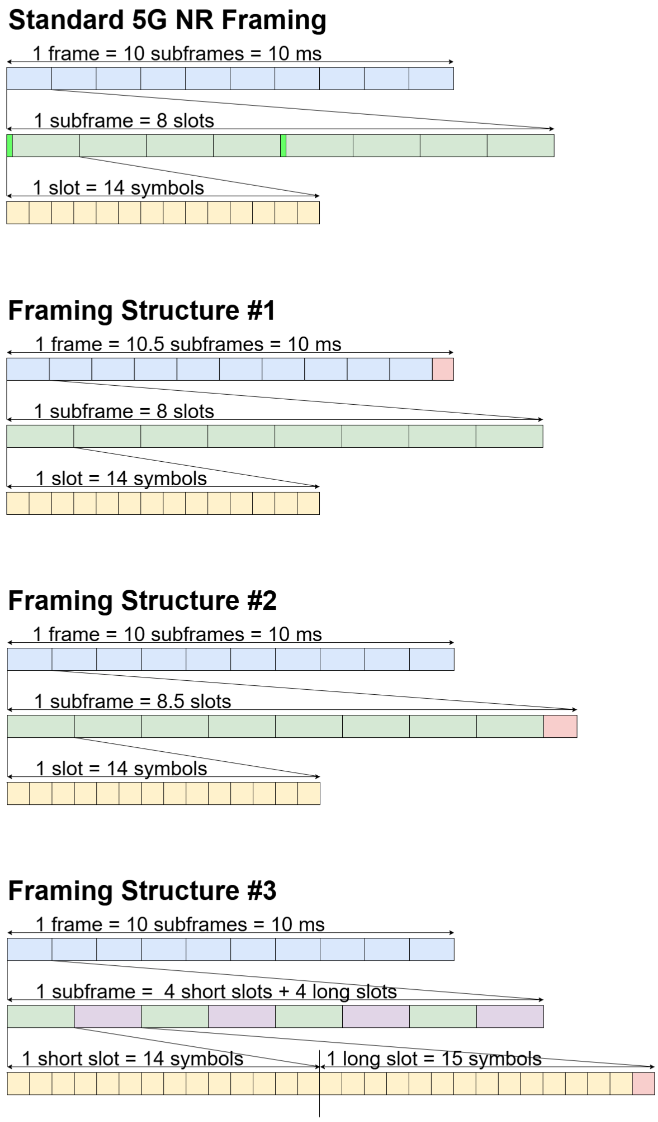

Fig. 1. Frame structures for a SCS of 120 kHz.

A. *Frame Structure # 1*

In frame structure # 1 (FS1), the duration of the CP is reduced in order to accommodate an additional half subframe, marked in red in the second part of Fig. 1. This means that a FS1 frame contains 10.5 subframes instead of 10 as mandated by the 5G NR standard. Each FS1 subframe now lasts only 0.9524 ms instead of 1 ms. The internal structure of the FS1 subframe is identical to that of a regular 5G NR subframe, except for one detail: all the CPs in a FS1 subframe have the same duration. This is not the case in regular 5G NR, where the first symbol of each half subframe has a longer CP. The price to pay for the additional half subframe in the FS1 frame is therefore the disruption of the 0.5 ms periodicity. With FS1, the overhead due to the CP is reduced to 2.04 % of the OFDM symbol duration. The features of FS1 are reported in Table I.

TABLE I
FS1 FEATURES

SCS (kHz)	# extra slots/frame	T_{CP} (ns)
60	2	340.16
120	4	170.08
240	8	85.04
480	16	42.52
960	32	21.26

B. *Frame Structure # 2*

Frame structure # 2 (FS2) maintains 10 subframes of 1 ms in a frame, exactly like regular 5G NR, but alters the structure of the subframe. Each subframe now contains a number of additional slots, compared to regular 5G NR. The third part of Fig. 1 shows the subframe structure for a SCS of 120 kHz, where the additional half slot (i.e., 7 OFDM symbols) is marked in red. The slot structure is the same as in regular 5G NR. As reported in Table II, FS2 is not compatible with 60 kHz spacing. It is worth noting that, even though all the CPs have the same duration, the 0.5 ms periodicity is satisfied for all the SCSs except for 120 kHz. This means that for these SCSs there is always an OFDM symbol starting every 0.5 ms. The resulting overhead is 0.84 %.

TABLE II
FS2 FEATURES

SCS (kHz)	# extra slots/subframe	T_{CP} (ns)
60	0	1190.5
120	0.5	70.04
240	1	35.02
480	2	17.51
960	4	8.76

C. *Frame Structure # 3*

Like FS2, frame structure # 3 (FS3) maintains 10 subframes of 1 ms in a frame. The FS3 subframe has the same number of slots as in regular 5G NR, but two types of slots are introduced, each one with a different number of OFDM symbols. Each FS3 half-subframe has $2^{\mu-2}$ normal slots with 14 OFDM symbols (marked in green in the last part of Fig. 1, for a SCS of 120 kHz) and $2^{\mu-2}$ longer slots with 15 OFDM symbols (marked in purple in the last part of Fig. 1, where the 15-th symbol is highlighted in red). The 0.5 ms periodicity is satisfied for all the considered SCSs, and the features of FS3 are reported in Table III. The resulting overhead is 3.45 %.

TABLE III
FS3 FEATURES

SCS (kHz)	# extra symbols/half-subframe	T_{CP} (ns)
60	1	574.74
120	2	287.37
240	4	143.68
480	8	71.82
960	16	35.92

III. Impact on Timing Advance

Synchronization in NTNs depends on accurately estimating the round-trip delay between the user equipment (UE) and the satellite [3]. Reduced CP durations require precise timing advance (TA) updates to ensure a correct alignment in the uplink. TA is a mechanism used to ensure that uplink transmissions from different UEs arrive at the satellite in a time-synchronized manner. This synchronization is critical in OFDM systems to prevent inter-symbol interference and maintain orthogonality among subcarriers [2]. TA is generated by the network during the initial access phase or after a handover event. The process involves the following steps:

- Measurement of round-trip delay: the network measures the time taken for a signal to travel from the gNB (gateway) to the UE and back. This measurement accounts for the propagation delay due to the satellite's altitude and mobility.
- TA command computation: based on the round-trip delay, the network computes the TA command, which indicates how much earlier the UE should start its uplink transmission.
- Transmission of TA command: the computed TA command is sent to the UE as part of the physical downlink control channel (PDCCH) signaling.
- Application at the UE: the UE adjusts its uplink transmission timing according to the TA command, ensuring that its signals arrive at the satellite at the correct instance.

Frequent TA updates and frequency estimation are required in particular by non-geostationary (NGSO) satellite applications to accommodate the Doppler effect and the accumulated timing drift.

In the following, the impact of the proposed reduced CPs to some of the requirements for TA is assessed. Since with NGSO satellites the slant range (i.e., the distance between satellite and UE) changes during the satellite pass, the propagation delay changes over time too [5]. The CP duration should accommodate the TA error:

$$T_{CP} \geq \delta T_{TA} = r_{TA} \Delta t \tag{2}$$

where δT_{TA} is the TA error, r_{TA} is the TA variation rate, and Δt is the TA update period. The TA variation rate can be computed as

$$r_{TA} = \frac{2\Delta D}{c T_R} \tag{3}$$

where $\Delta D = D_{max} - D_{min}$ is the maximum change in slant range (with D_{min} coinciding with the satellite altitude and D_{max} depending on the elevation angle of the satellite), c is the speed of light, the factor 2 accounts for the round trip, and T_R is the time required for the UE to experience the slant range change ΔD. Finally, T_R can be computed as

$$T_R = \frac{\theta}{\omega_{sat}} \tag{4}$$

where θ is the angle at the center of the Earth between the satellite and the UE, and $\omega_{sat} = \sqrt{GM(R_E + h_s)^3}$ is the satellite angular velocity, where G is the gravitational constant, M the Earth mass, R_E the Earth radius, and h_s the satellite altitude.

The considered satellite altitudes are in low Earth orbit (LEO) and in medium Earth orbit (MEO): 600 km, 1200 km (which are compatible with the specifications for low LEO and high LEO in [6]), and 8000 km. By using (3) and (4), and inverting (2), it is possible to obtain the maximum TA update period for a given minimum elevation angle. The results for the different satellite altitudes are shown in Figs. 2-4, respectively. From Fig. 2 for example, it can be seen that with an altitude of 600 km, a minimum elevation angle of 30°, and a SCS of 120 kHz, 5G NR requires a TA update every 22 ms, while 6.6 ms are required for FS1, 2.8 ms for FS2, and 11.2 ms for FS3. As a consequence, updating the TA at the UE using the synchronization signal block (SSB) received in the downlink is not sufficient for the proposed frame structures, since the SSB is transmitted by the gNB typically every 20 ms [3]. Also, reducing the SSB periodicity would significantly reduce the data throughput, neutralizing the throughput gain obtained by reducing the duration of the CP. Further, reducing the SSB periodicity in NTNs would go in the opposite direction of the 3GPP, which is now considering increasing the SSB periodicity to support beam-hopping in NTNs. An alternative approach could be resorting to the system information block # 19 (SIB19), which provides information specific to NTNs and is broadcast with a periodicity defined by the network operator depending on the dynamics of the network itself [3].

IV. Impact on Timing Accuracy

The duration of the CP impacts also on the timing accuracy budget, where several timing errors are taken into account. To ensure reliable operations, all these timing errors (including the guard time) should not exceed half of the CP duration by design. Following the same approach detailed in [7], the timing accuracy budget can be approximately expressed as follows:

$$\frac{T_{CP}}{2} = T_g + T_d + T_p + T_r + T_a + T_f + T_m \tag{5}$$

where

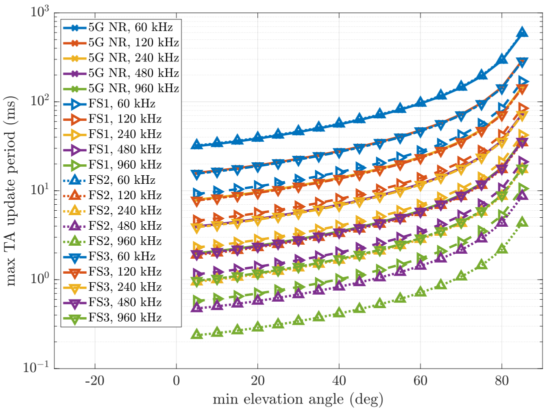

Fig. 2. Maximum TA update period for different minimum elevation angles, for h_s = 600 km.

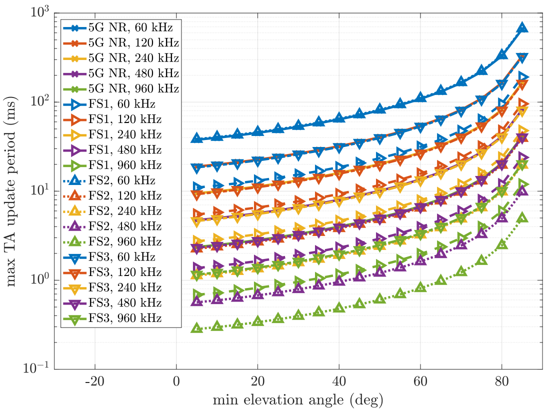

Fig. 3. Maximum TA update period for different minimum elevation angles, for h_s = 1200 km.

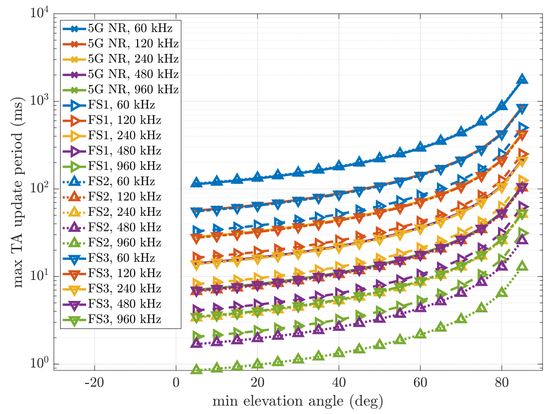

Fig. 4. Maximum TA update period for different minimum elevation angles, for h_s = 8000 km.

- T_g is the guard time remaining in the budget once all the timing errors have been subtracted from half of the CP duration.
- T_d is the UE downlink synchronization error. At high signal-to-noise ratio (SNR), T_d can be approximated by $1/(2B)$ where B is the bandwidth of the physical broadcast channel (PBCH), which is 240 subcarriers [2].
- T_p is the uncertainty in the round-trip propagation delay.
- T_r is the error due to the TA command step size, which is half the step size itself. The TA command indicates the change of the TA to the UE in multiples of $16 \cdot 64 \cdot T_c/2^{\mu}$ [8].
- T_a is the TA adjustment accuracy. The 5G NR values in Tables 7.3.2.2-1 and 7.3C.2.2-2 in [9] are reported in Table IV, together with the values considered in this paper (FSx column). The values assumed here are arbitrary and chosen for symmetry and to complete the SCS series.
- T_f is the timing error due to the accumulated timing drift. It is defined over 160 ms (the longest delay between two consecutive SSB receptions) under the assumption of a frequency offset of 0.1 ppm. Since the timing drift scales linearly with the relative frequency, the resulting timing drift is 0.1 ppm as well.
- T_m is the timing error due to additional impairments, like the multipath delay spread. Typically, an error of 10 ns may be sufficient given the assumption of a VSAT terminal.

TABLE IV
TA ADJUSTMENT ACCURACY

SCS (kHz)	5G NR	FSx
60	$\pm 128T_c$	$\pm 128T_c$
120	$\pm 32T_c$	$\pm 64T_c$
240	-	$\pm 32T_c$
480	$\pm 10T_c$	$\pm 16T_c$
960	$\pm 6T_c$	$\pm 8T_c$

If the guard time T_g is assumed for simplicity to be zero, then it is possible to solve (5) for T_p, and compute the path length uncertainty as $E_p = cT_p$. The values used for all the other error components, as described above, are reported in Table V. The resulting T_p is negative for all the SCSs in FS1 and FS2, and for 480 kHz and above for FS3. A negative T_p means that the cumulative timing error exceeds the design limit of half of the CP duration, causing potential performance degradation. The only positive values for T_p are reported in Table VI, together with the corresponding path length uncertainty. For comparison, the value of E_p computed in [7] for 120 kHz is 63.23 m.

For the cumulative timing error not to exceed half of the CP duration with the proposed frame structures, it is necessary to reduce and optimize all the error components. In general, the optimization of (5) is an extremely complex problem as it involves the 3GPP specifications (for T_{CP}, T_g, T_r, T_a), technology aspects (T_f), the considered environment (T_m), and the accuracy of estimators (T_f, T_d, T_p). The solution of such optimization problem is beyond the scope of this paper, but it

TABLE V
ERROR COMPONENTS

SCS (kHz)	T_d (ns)	T_r (ns)	T_a (ns)	T_f (ns)	T_m (ns)
60	34.72	65.1	65.1	16	10
120	17.36	32.55	32.55	16	10
240	8.68	16.28	16.28	16	10
480	4.34	8.14	8.14	16	10
960	2.17	4.07	4.07	16	10

TABLE VI
PROPAGATION ERRORS FOR FS3

SCS (kHz)	T_p (ns)	E_p (m)
60	96.44	28.91
120	35.22	10.56
240	4.61	1.38

is worth mentioning that, by reducing these error components, it is possible to satisfy the requirement on the cumulative timing error. For example, by scaling the values of the error components in Table V by the factors reported in Table VII, the positive values for T_p shown in Table VIII are obtained. Table VIII also shows the corresponding path uncertainty. A very careful and deep analysis of protocol specifications, application requirements, and technology specifications needs to be carried out by any system designer willing to use any of the proposed frame structures to reduce the signal overhead and increase the data throughput.

TABLE VII
SCALING FACTORS

Structure	T_d	T_r	T_a	T_f	T_m
FS1	1/2	1/2	1/2	1/4	1/8
FS2	1/4	1/8	1/8	1/8	1/16
FS3	1	1/2	1/2	1/2	1/4

TABLE VIII
PROPAGATION ERRORS

Structure	SCS (kHz)	T_p (ns)	E_p (m)
FS1	60	82.37	24.69
FS1	120	38.56	11.56
FS1	240	16.65	4.99
FS1	480	5.7	1.71
FS1	960	0.23	0.07
FS2	60	567.67	170.18
FS2	120	19.92	5.97
FS2	240	8.65	2.59
FS2	480	3.01	0.9
FS2	960	0.19	0.06
FS3	60	177.04	53.08
FS3	120	83.27	24.96
FS3	240	36.39	10.91
FS3	480	12.94	3.88
FS3	960	1.22	0.37

V. CONCLUSIONS

In this paper we have proposed three frame structures based on 5G NR, where the reduction of the CP duration has allowed a reduction of the overhead and the consequent increase of the data throughput. However, a reduced CP duration has a significant impact on several timing aspects, demanding much smaller timing errors and making synchronization more challenging in practice.

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