WHITEPAPER

Non-Terrestrial Networks: Coverage Enhancement in 3GPP Rel-18

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Abstract

Satellite communications were incorporated into the fold of 3rd generation partnership project (3GPP) with a goal to expand cellular connectivity worldwide. The aim remains to cover everyone with a broadband-like 5th generation (5G) non-terrestrial network (NTN) and connect everything with an Internet-of-Things (IoT)-based NTN. Several challenges associated with incorporating flying base stations in a cellular network have already been addressed by the wireless research community. A major issue that lingers is the basic one of expanding coverage. Given that satellites are several orders of magnitude farther away from a cellular device than a cell tower is in a terrestrial network, coverage enhancement for NTN is more challenging than for its terrestrial counterpart. In this paper, we explore the challenges of coverage enhancement and the progress that has been achieved to this end.

I. Introduction

Satellite communications is an old concept that predates modern cellular communications[1]. However, there has always been a gap between cellular and satellite communications. This has prevented the former from achieving the ubiquity of the latter and the latter from achieving the market penetration of the former. With 3GPP focusing on bridging this crucial gap, the foundations for a truly ubiquitous 6th generation (6G) cellular communication system have been laid with 5G NTN[2][3].

The final 5G standard before 5G-Advanced was 3GPP Release 17 (Rel-17)[4]. Rel-17 focused on addressing essential minimum features for enabling a commercial smart phone to connect to the 5G network via satellite(s) or other non-terrestrial payloads (e.g., uncrewed aerial vehicle, drone, balloon, etc.). Dashtaki[5] provides a comprehensive overview of the novel features introduced to incorporate satellites in the radio access network in Rel-17. There were three main aspects that were tailored for NTNs, including satellite and other non-terrestrial payload networks. First, timing and frequency synchronization for NTNs were enhanced to compensate for increased round-trip time of NTN links and significantly higher Doppler effects caused by a moving transmission/reception point (i.e., satellite). Second, resource scheduling in the time domain was modified to prevent time-compensated uplink transmissions from resulting in a non-causal system. Finally, the increased stop-and-wait gap introduced by the lengthy propagation distance between a user equipment (UE) and the satellite was mitigated by improved hybrid automatic repeat request (HARQ) scheduling methods.

Since Rel-17 focused on supporting the essential minimum features to make NTNs operable in a 3GPP framework, it rightly focused on primitive setups and strong device assumptions. For example, Rel-17 provides emergency connectivity, for example, for someone lost in the woods or for livestock monitoring in remote areas. Some examples of such primitive setups and strong device assumptions are the reliance on a line-of-sight path and on a global navigation satellite system (e.g., global positioning system (GPS)) module within the UE. In the upcoming releases, 3GPP is investigating relaxing some of these restrictions to expand the applicability of NTNs.

II. Link Budget in NTN

Due to the nature of end-to-end communications with an aerial platform, an NTN has the apparent benefit of having a line-of-sight path between the two end terminals, i.e., UE and the satellite. However, there are two main factors that impact the link budget in NTNs. First, the propagation distance between the UE and the aerial platform is between 600 kilometers to about 36,000 kilometers for satellite-based NTN[6]. This is several orders of magnitude higher than a typical cell radius in conventional terrestrial cellular network. Despite the potential line-of-sight path, the pathloss due to large propagation distances attenuates the electromagnetic signal. Furthermore, the reliance on a line-of-sight path introduces a strong limitation to the applicability of NTN. Requiring a device to always point to a satellite in the sky implies that the UE cannot, for example, be carried in a pocket or a bag, or be placed in an indoor environment, e.g., a cabin, or a building. Therefore, additional outdoor-to-indoor, or O2I, losses need to be factored in while determining link budgets for NTNs.

As part of coverage enhancement for NTNs, 3GPP studied the typical link budget and coverage performance for various data and control channels in different realistic NTN environments in Rel-18[7]. The evaluated channels and use cases were: physical uplink shared channel (PUSCH) for voice over internet protocol (VoIP), PUSCH for low data rate service, physical uplink control channel (PUCCH) format 1 with 2 bits, PUCCH format 3 with 11 bits, physical random access channel (PRACH) formats 0, 2, and B4, PUSCH Msg3, PUCCH for Msg4 HARQ-acknowledgement (ACK), synchronization signal block (SSB), physical downlink shared channel (PDSCH) for VoIP, PDSCH for low data rate service, PDSCH for Msg3, PDSCH for Msg4, physical downlink control channel (PDCCH), and broadcast PDCCH, wherein the target data rates for VoIP and “low data rate” are 4.75 kbps and 3 kbps, respectively.

Table 1 shows some example metrics that were considered for coverage performance evaluations. Eventually, 3GPP decided to focus primarily on uplink channels, and based on the performance evaluation results, PRACH and PUCCH for Msg4 HARQ-ACK during the random-access (RA) procedure were identified to be the coverage bottleneck channels in NTN. The rest of this paper summarizes research and standardization progress towards enhancing coverage in PRACH and PUCCH for Msg4 HARQ-ACK in 5G NR communication systems.

Table 1 Example metrics used for coverage performance evaluations on uplink channels in Rel-18 NTN

	PUSCH	**PUCCH**	**PRACH**	**PUSCH Msg3**
BLER	10% initial BLER	Format 1: DTX to ACK: 1%; NACK to ACK: 0.1% Format 3: 1%	1% missed detection at 0.1% false alarm	--
UE TX chains	1, 2 (optional)	1	1, 2 (optional)	1, 2 (optional)
Repetitions	Type A, Type B (optional)	Max 8	--	--
Frequency hopping	w/ and w/o	w/	--	w/ and w/o
Format	--	1: 2 bits UCI 3: 11 bits UCI	0, B4, 2	--

III. Coverage Enhancement

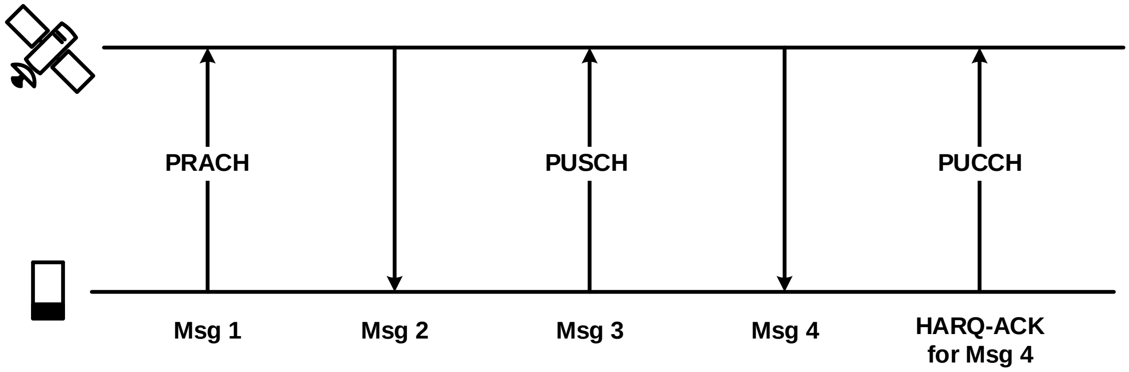

Figure 1 Message exchange between a UE and a satellite during an RA procedure.

Figure 1 shows an illustration of the various uplink and downlink message exchanges between a UE and a satellite during a four-step RA procedure. The two channels, PRACH (also referred to as preamble, RA preamble, RACH, or Msg1) and PUCCH for Msg4 HARQ-ACK (which is one of the PUCCH messages transmitted without a dedicated PUCCH configuration), that were identified to be enhanced, are both critical components of an RA procedure. As a result, although coverage performance was evaluated for NTN, performance enhancement solutions are likely to be adopted transparent of the access type (i.e., for both NTNs and terrestrial networks). Signs of this were seen in 3GPP where PRACH coverage enhancement was tackled for terrestrial networks[8] with the designed solutions applying as baseline for NTNs, and PUCCH for Msg4 HARQ-ACK enhancements were designed by NTN participants[9] with the developed solutions rolling over to terrestrial access as well.

A routine solution to enhance coverage is to repeatedly transmit the message multiple times until a sufficiently high effective signal to noise ratio is achieved at the receiver. While the idea is simple and sound, engineering an optimized solution for implementation requires thorough study. For example, which entity (e.g., satellite, base station, UE) determines whether the UE must perform repetitions, what are the triggering conditions for performing repetitions, how to repeat the transport block (e.g., whether to perform frequency hopping, whether to repeat consecutively), how, if, and when does the UE request repetitions, how, if, and when does the base station provide grants for repetitions, are some of the many design questions that need to be addressed. As a guiding star, designs for Msg3 repetitions, which were standardized in Rel-17, were used as a baseline.

Msg3 Repetitions

Rel-17 introduced PUSCH repetitions for Msg3 retransmissions (also referred to as PUSCH scheduled by downlink control information (DCI) with cyclic redundancy check (CRC) scrambled with temporary cell – radio network temporary identifier (TC-RNTI)). The following is a brief summary of the answers to some of the design questions mentioned above. The UE receives configuration parameters for Msg3 repetitions including a Msg3 reference signal received power (RSRP) threshold. The UE determines propagation conditions by checking if the RSRP of a downlink pathloss reference signal (e.g., SSB or channel state information reference signal (CSI-RS)) is above or below the Msg3 RSRP threshold. Under poor channel conditions, i.e., when the RSRP of the downlink pathloss reference signal is below the Msg3 RSRP threshold, the UE indicates this to the base station by choosing an RA resource, from an RA resource set associated with Msg3 repetitions, for transmitting the Msg1 (i.e., PRACH or RA preamble). The base station then determines the number of repetitions to schedule for the Msg3 transmission and indicates this via the Msg3 grant. The UE then performs the number of Msg3 repetitions as indicated in the transmission grant.

Msg1 Repetitions

The above procedure from Rel-17 Msg3 repetitions was used as a baseline for designing Msg1 repetitions in Rel-18. Like Msg3, Msg1 repetitions are also classified as a feature and included within the 3GPP *feature-combinations* framework. Note that some of the following details are based on agreements made in 3GPP meetings thus far[1] and may change by the time the final Rel-18 specification is released.

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[1] As of September 2023.

1. *Source of determination*: The primary aspect to resolve for performing Msg1 repetitions is to determine which entity (i.e., UE itself or the base station) decides whether the UE must/can perform Msg1 repetitions. For the case of random access when the UE is in connected mode (e.g., an RA procedure for handover), the base station may be able to decide whether the UE should perform Msg1 repetitions, since the base station is aware of the propagation channel conditions to and from the UE. However, an RA procedure can also be initiated by the UE for initial access. In such cases, the UE is the only entity that can potentially determine the channel conditions. To accommodate idle mode or cold-start UEs, Rel-18 supports a UE to itself determine whether it should perform repetitions based on the channel conditions.
2. *Triggering condition*: When the RA procedure is initiated for a connected mode UE (e.g., for the case of handover), the base station determines whether the UE should perform Msg1 repetitions based on a proprietary implementation. For example, the base station can examine historical and/or current values of channel state information and radio link quality between the UE and the base station (and the potential target base station) and determine whether the UE should perform Msg1 repetitions. The base station then indicates, in a handover configuration, the number of repetitions the UE should perform for Msg1 transmission. For a UE initiating the RA procedure (e.g., for initial access), the UE determines whether to perform Msg1 repetitions and how many Msg1 repetitions to perform based on RSRP thresholds. For example, the base station may provide four options for the number of repetitions – 1, 2, 4, 8. The base station may further provide three RSRP thresholds for determining one of the four numbers of repetitions. Based on a comparison of the SSB/CSI-RS-RSRP with the RSRP thresholds, the UE may determine the number of Msg1 repetitions to perform. Note that the UE determining the number of Msg1 repetitions based on the RSRP thresholds may only be for the initial Msg1 transmission attempt. For following retransmissions or retransmission attempts (i.e., in case of failures when an RA response corresponding to the Msg1 transmission is not received by the UE), fallback from a lower number of repetitions to a higher number is supported when the number of Msg1 transmissions/retransmissions reaches a configured value (configured by RRC).
3. *Resource determination*: For the case of network-triggered RA (e.g., RA procedure for handover), the base station provides the time, frequency, and beam-related resources associated with the indicated number of Msg1 repetitions. However, for initial access, the base station is unaware of the channel quality to and from the UE. Therefore, the base station provides several possible candidate RA resources to the UE, each associated with a respective number of Msg1 repetitions. Using such an association, the base station expects to receive a certain number of Msg1 repetitions corresponding to

the RA resource on which it received the Msg1. We begin by first addressing *time* resource determination. Two kinds of resource divisions are supported in Rel-18. The first is where RA channel occasions (ROs) are divided into groups, i.e., RO groups, wherein each RO group is associated with a respective number of Msg1 repetitions. The second is where RA preambles are divided into different sets, each for either single Msg1 repetition or multiple Msg1 repetitions. For the case of RO groups, the UE first determines the best SSB/beam for the RA procedure. Using an SSB-RO mapping, the UE determines the starting RO in the RO group associated with the determined number of Msg1 repetitions, and thereafter determines all remaining ROs for the remaining repetitions. Note that each RO in an RO group is associated with the same SSB and the number of valid ROs in an RO group is equal to the number of Msg1 repetitions associated with that RO group. The determination of frequency and beam resources is relatively more straightforward than the time domain resource determination. In Rel-18, the starting resource blocks for all Msg1 repetitions are the same, and each of the Msg1 repetitions are transmitted with the same uplink transmit beam associated with the SSB selected for the RA procedure.

After transmitting the Msg1 with repetitions, the UE must determine an RA radio network temporary identifier (RA-RNTI) to detect PDCCH for Msg2 reception. Different from a single Msg1 transmission pre-Rel-18 where RA-RNTI is computed based on the RO used for the Msg1 transmission, in Rel-18, the RA-RNTI is computed based on the last valid RO in the RO group associated with the transmitted number of Msg1 repetitions. This is regardless of whether the UE transmitted a Msg1 repetition in the last valid RO, i.e., even if the UE drops a repetition in the last valid RO (e.g., due to power control or data prioritization), it still uses the last valid RO for computing the RA-RNTI. Similar to RA-RNTI computation, the UE starts the RA response window for detecting PDCCH for Msg2 after the last symbol of the last valid RO in the RO group corresponding to the transmitted number of Msg1 repetitions regardless of whether the UE transmitted a Msg1 repetition in the last valid RO.

Rel-18 does not support Msg1 repetitions for contention free RA for beam failure recovery and contention-free RA that is triggered by a PDCCH order.

Msg4 HARQ-ACK Repetitions

While HARQ-ACK information for Msg4, which is transmitted via PUCCH, is also an uplink RA message similar to Msg1 and Msg3, the similarities do not go much further. Therefore, solutions to support PUCCH repetitions for Msg4 HARQ-ACK were designed separately from Msg1 repetitions. The following presents aspects of Msg4 HARQ-ACK repetitions in the same manner as above.

1. *Source of determination*: Unlike Msg1 transmission, where there could be no prior uplink transmissions, Msg4 HARQ-ACK transmission is preceded by two other uplink RA messages, Msg1 and Msg3. As a result, the base station has a fairly solid idea of the channel conditions based on the reception signal strength of the two uplink messages before Msg4. Therefore, in Rel-18, it is up to the base station to determine the number of repetitions for Msg4 HARQ-ACK (e.g., based on signal strengths/qualities of Msg1 and/or Msg3), regardless of which entity initiates the RA procedure.
2. *Triggering condition*: Repetitions for Msg4 HARQ-ACK are triggered similar to Msg1 and Msg3 repetitions, which is when channel conditions are poor, i.e., coverage enhancement is needed. While this determination is done by the base station, the base station must be aware of whether the UE supports (i.e., capable of performing) PUCCH repetitions for Msg4 HARQ-ACK. This issue was resolved in Rel-17 for Msg3 repetitions by partitioning the RA resources, wherein UEs requesting (and thereby those that are capable of performing) Msg3 repetitions pick an RA resource for transmitting Msg1 from a *Msg3-repetition-dedidicated* RA resource set, and UEs that are not requesting, pick from the other. The issue with extending such a solution to indicate PUCCH repetition capability for Msg4 HARQ-ACK is that it further fragments RA resources (note that there are several features in Rel-17 that have already severely fragmented RA resources and *Msg4 HARQ-ACK repetition* feature potentially doubles the number of fragments). Hence, Rel-18 exploits the other uplink message (i.e., Msg3) transmitted before Msg4 HARQ-ACK, and supports indicating PUCCH repetition capability for Msg4 HARQ-ACK via medium access control (MAC) layer signaling in Msg3 PUSCH.
3. *Resource determination*: Based on the capability indication received via Msg3 PUSCH, the base station determines whether the UE is capable of PUCCH repetitions for Msg4 HARQ-ACK, and if so, the number of repetitions to perform for the Msg4 HARQ-ACK repetitions based on the signal strength of the received uplink RA signal(s). The base station indicates the number via the DCI scheduling Msg4. The UE then picks the resources from the common PUCCH configuration associated with the number of repetitions to perform the Msg4 HARQ-ACK transmission.

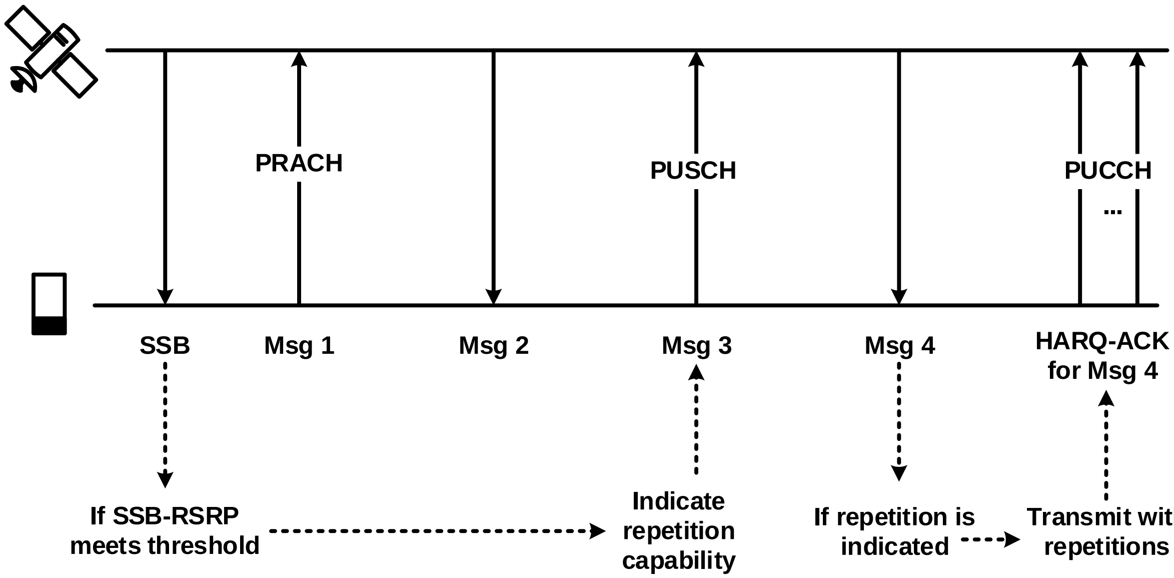

Figure 2 Example steps involved in indicating a capability for and performing repetitions of Msg4 HARQ-ACK.

Figure 2 shows a summary of the example steps involved in indicating a capability for and performing repetitions of Msg4 HARQ-ACK. Rel-18 provides flexibility for the network to receive PUCCH repetition capability indication from the UE based on an RSRP threshold. When such an RSRP threshold is configured, a UE supporting PUCCH repetitions for Msg4 HARQ-ACK is expected to transmit its capability indication only when the RSRP of the downlink reference signal (e.g., SSB or CSI-RS) is less than the RSRP threshold. This reduces signaling when the UE is already in a *good-coverage* region where it is not expected to perform Msg4 HARQ-ACK repetitions. If no such threshold is configured, any UE capable of supporting PUCCH repetitions for Msg4 HARQ-ACK indicates the capability. In response to the capability indication in Msg3 PUSCH, the UE may receive an indication, of the number of repetitions to use for transmitting the Msg4 HARQ-ACK, via a downlink assignment indication field in the DCI with CRC scrambled by TC-RNTI. The UE performs the PUCCH repetitions (or not) as instructed by the base station.

Additionally, the designs and solutions that are developed for PUCCH repetitions of Msg4 HARQ-ACK in Rel-18 will likely be extended to also support PUCCH repetitions for all transmissions that are performed by the UE using common PUCCH resources, e.g., until receiving dedicated PUCCH configuration.

IV. Conclusions

NTN promises connectivity for everyone and with everything. But this cannot be achieved with caveats like an availability of a line-of-sight path, presence of devices in an outdoor environment, hardware limitations and requirements for connecting devices, and the like.

Therefore, extreme coverage is paramount for NTN. Rel-18 coverage enhancement solutions, some of which were presented in this paper, provide a strong start for one of the goals of a 6G NTN to truly provide ubiquitous connectivity where everyone and everything – anywhere in the world – are all interconnected.

Table 2 Table of Acronyms

Acronym	**Definition**
3GPP	3rd Generation Partnership Project
5G	5th Generation
6G	6th Generation
ACK	acknowledgment
BLER	block error rate
CRC	cyclic redundancy check
CSI	channel state information
DCI	downlink control information
GPS	global positioning system
HARQ	hybrid automatic repeat request
VoIP	voice over internet protocol
MAC	medium access control
NACK	negative acknowledgment
NR	new radio
NTN	non terrestrial network
O2I	outdoor to indoor
PDCCH	physical downlink control channel
PDSCH	physical downlink shared channel
PRACH	physical random-access channel
PUCCH	physical uplink control channel
PUSCH	physical uplink shared channel
RA	random access
RNTI	radio network temporary identifier
RO	random access channel occasion
RRC	radio resource control
RS	reference signal
RSRP	reference signal received power
SSB	synchronization signal block
TC-RNTI	temporary cell radio network temporary identifier
TX	transmit/transmitter
UCI	uplink control information
UE	user equipment

References

[1] https://www.groundcontrol.com/us/knowledge/a-brief-history-of-satellite-communications/

[2] 3GPP TR 38.321 V16.2.0, "Solutions for NR to support Non-Terrestrial Networks (NTN)," *Technical Report*, March 2023.

[3] 3GPP TR 36.763 V17.0.0, "Study on Narrow-Band Internet of Things (NB-IoT) / enhanced Machine Type Communication (eMTC) support for Non-Terrestrial Networks (NTN)," *Technical Report,* June 2021.

[4] 3GPP TR 38.300 V17.0.0, "NR; NR and NG-RAN Overall description; Stage-2," *Technical Specification*, April 2022.

[5] https://ofinno.com/whitepaper/state-of-satellite-access-network-standardization-in-3gpp/

[6] 3GPP TR 38.811, "Study on New Radio (NR) to support non-terrestrial networks," *Technical Report*, October 2020.

[7] R1-2205212, "Summary #3 on 9.12.1 Coverage enhancement for NR NTN," *Technical Document*, May 2022.

[8] RP-221858, "Revised WID on Further NR coverage enhancements," *Technical Document*, June 2022.

[9] RP-222654, "Revised WID: NR NTN (Non-Terrestrial Networks) enhancements," *Technical Document*, September 2022.

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Gautham's research interests include 5G/6G terrestrial and non-terrestrial communications and applications of AI/ML to communication networks. Prior to joining Ofinno, Gautham was an industrial postdoctoral research fellow at The University of British Columbia, Vancouver, BC and Sierra Wireless, Richmond, BC. He has authored dozens of publications in peer-reviewed IEEE journals, conferences, and workshops, including papers that have won multiple IEEE best paper awards. Gautham has also served as an invited reviewer for hundreds of journal and conference paper submissions and on the technical program committees of various major IEEE conferences. He holds a PhD from The University of British Columbia, Vancouver, BC, and an MS from the University of Florida, Gainesville, FL, both in electrical and computer engineering.