TACKLING SATELLITE MOBILITY IN LEO-BASED NON-TERRESTRIAL NETWORKS

Principles and Enhancements of Feeder Link Switch

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Non-terrestrial networks (NTNs) will constitute a cornerstone of the next-to-come sixth-generation technology. Specifically, low-Earth orbit (LEO) satellite constellations play a crucial role, either as a stand-alone networking solution or as a complement to terrestrial networks, in providing network access and services anywhere and anytime with lower latency than geostationary satellites. However, LEO's narrow coverage areas and mobility will likely cause service interruptions whenever the link between the NTN platform and the NTN gateway (GW) (i.e., the feeder link) becomes unavailable. The Third Generation Partnership Project (3GPP) has defined a set of feeder link switch over procedures, which may lead to a long procedure duration and, hence, long service interruptions, especially in the case of NTN GWs located far from each other. To cope with the mentioned issues, this article proposes a novel feeder link switch over procedure, which exploits inter-satellite links (ISLs) to implement, through a chain of LEO satellites, virtual visibility between an LEO satellite and an NTN GW that is not in direct sight. This aims at reducing the time of feeder link switch over and avoiding service disruptions. The advantages of the proposed "ISL-aided" feeder link switch over procedure over the one defined by 3GPP are assessed via simulative campaigns.

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Introduction

In future wireless systems, the non-terrestrial network (NTN) will be a fundamental support to the terrestrial segment to provide global connectivity [1], [2].

The interest of academia and industry in NTNs is motivated by the strongly felt need to investigate solutions to new challenging technological issues and use cases, such as softwarization/virtualization, network slicing, Internet of Space Things, integrated terrestrial networks and NTNs, multilayer and sustainable 3D networks, and mobile edge computing functionalities on air and space platforms.

The NTN radio access, as specified by the Third Generation Partnership Project (3GPP), encompasses three main components: NTN terminals, NTN platforms, and NTN gateways (GWs) [3]. NTN terminals include handheld terminals and very small aperture terminals, which may or may not support the global navigation satellite system and are connected to the NTN platform through the *service link*. NTN platforms generate a footprint of either fixed or moving elliptical beams over a certain area and may embark a transparent or a regenerative payload. In the former case, the NTN platform acts as a mirror in the sky, and the gNodeB (gNB) is located on the ground. In the latter case, the NTN platform may host either the gNB or the gNB distributed unit (gNB-DU) on board, whereas the gNB central unit (gNB-CU) is located on the ground. NTN platforms may be interconnected with each other through inter-satellite links (ISLs) while being connected to the NTN GW through the so-called *feeder link*.

Among the NTN platforms, low-Earth orbit (LEO) satellites are attracting interest from researchers and telco communities owing to the capability to provide network access and services anywhere and anytime. However, since LEO satellites are characterized by fast speed along their Earth orbits and narrower coverage areas than geostationary orbit satellites, frequent feeder link breaks may occur between an LEO satellite and an NTN GW on the ground. The 3GPP has defined two feeder link switch over modes: *hard* and *soft*. The hard feeder link switch over foresees that only one feeder link toward a single NTN GW can be active at a time, thus implying service interruption for the time necessary to activate a new feeder link toward a new NTN GW. Differently, two feeder links toward two different NTN GWs can exist simultaneously in the case of soft feeder link switch over. Obviously, the *soft* mode can only be performed when an LEO satellite can see at least two NTN GWs simultaneously; if not, only the *hard* one is feasible. Feeder link switch over is, therefore, one of the main issues in LEO-based NTNs [4], involving different NTN GWs and an NTN platform, which calls for the design of effective procedures to ensure seamless service continuity and reduce the risk of service interruption to the served NTN terminals.

Research works from the literature deal with NTN GW diversity by designing smart NTN GW switching solutions based on quality of service (QoS) requirements and propagation forecasts [5] and by proposing strategies for NTN GW deployment [6] and satellite handover [7] leveraging the multiple-input multiple-output (MIMO) technology [8]. However, to the best of our knowledge, the literature lacks a study on feeder link switch over procedures able to overcome the limitations of the ones defined by the 3GPP in [3].

In this article, we start from the basics of feeder link switch over and propose to enhance the standard 3GPP procedure by leveraging ISLs among NTN platforms to enable the NTN platform to view beyond its visibility cone with the help of other NTN platforms. Despite exploiting ISLs has been investigated in the literature and tested in commercial solutions for data transmission, we propose to utilize ISLs for the different purpose of improving the performance of feeder link switch over w.r.t. the standard 3GPP switch over procedure and evaluate to what extent the proposed solution is effective in guaranteeing service continuity. The aim of the proposed “ISL-aided” feeder link switch over procedure is to 1) perform soft feeder link switch over even when the NTN platform is not in the direct sight with the next NTN GW while it is still connected to the previous one; 2) reduce the time of soft and hard feeder link switch over; 3) avoid service interruption to the served NTN terminals; and 4) transfer collected data, alert messages, or urgent information to the NTN GWs on the ground as fast as possible, especially for certain use cases, such as remote sensing.

The remainder of the article is organized as follows. The “Related Works” section investigates related works in the literature. The “The 3GPP Feeder Link Switch Over” section summarizes 3GPP feeder link switch over procedures. The “Novel Feeder Link Switch Over Procedures” section describes our proposed “ISL-aided” feeder link switch over procedure. The “Performance Evaluation” section illustrates a performance analysis conducted to assess the effectiveness of performing feeder link switch over aided by ISLs and involving other NTN platforms in the discovery of the next NTN GW in visibility. Some key aspects to investigate are discussed in the “Open Issues” section, and conclusions are drawn in the “Conclusions” section.

Related Works

Fifth-generation (5G) NTN platforms exploit diverse available bandwidths, such as *Ku*-band (i.e., 12–18 GHz), *Ka*-band (i.e., 28 GHz), *Q*/*V*-band (i.e., 37–53 GHz), and sub-6-GHz band. Optical bands are also used for the feeder link from the NTN GW to the NTN platform [9]. However, the extreme data rates that are assured by *Q*/*V* frequency are at the expense of serious susceptibility to meteorological effects. In [7], a GW handover strategy is proposed to trace the capacity fluctuations of feeder links during weather impairments and considers QoS requirements to optimize data forwarding among NTN GWs.

Another solution to cope with severe rain attenuation is GW diversity, which guarantees feeder link availability. In [5], a novel diversity scheme built on switch and stay combining is proposed to avoid system overhead due to frequent NTN GW switching by activating only the NTN GW that does not cause performance degradation. In [10], a smart GW diversity strategy is designed to address QoS management in very high throughput satellites through a holistic framework combining sophisticated algorithms of link outage prediction and efficient re-routing algorithms to minimize network congestion. In [11], an algorithm considering several data propagation parameters is proposed to control NTN GW switching in smart diversity.

A further issue arising from the use of Q/V frequency bands is the best choice of the sites where NTN GWs can be deployed. In [8], MIMO feeder links are used to double the bandwidth in the service link by activating two NTN GW antennas per feeder link. Also, in [12], the MIMO technology is applied to implement a handover strategy that maximizes the quality of communication, whereas [6] investigates NTN GW deployment in the space–ground integrated network with the aim to maximize network reliability and satisfy the limitation in the capacity of satellite links. In [13], a multilevel relay protection method exploiting feeder link switches based on a greedy algorithm is proposed for a distributed network.

In [14], we conduct an early analysis of the performance in terms of data loss in the service link when performing the two standard 3GPP feeder link switch over procedures (i.e., soft and hard). In this article, we specifically focus on investigating new procedural solutions that go beyond existing 3GPP methodologies and, with respect to them, reduce the time of feeder link switch over.

The 3GPP Feeder Link Switch Over

Feeder link switch over is activated to manage the interruption of a feeder link connection between an NTN platform and an NTN GW and the establishment of a new feeder link between that NTN platform and the next NTN GW in visibility. The procedure is illustrated in Figure 1, which highlights that a service interruption may occur in case the NTN platform disconnects from an NTN GW (at T1, the feeder link with NTN GW 1 breaks), and there is no possibility of establishing a new feeder link with another NTN GW (the NTN platform is in view of NTN GW 2 only at time T2).

As specified in [3], 3GPP has defined two feeder link switch over modes:

- *Soft*: Two feeder link connections are applicable during the transition, thus enabling service continuity.
- *Hard*: Only one feeder link connection is applicable during the transition, thus implying signal unavailability.

The 3GPP feeder link switch over procedures differ not only by feeder link switch over mode but also by payload type.

The hard procedure may either use accurate time information or ephemeris data. In the former case, the handover command is sent to all NTN terminals by the NTN platform before the old feeder link connection with the old NTN GW drops to initiate the handover procedure immediately. The handover command includes the activation time that is triggered after the new feeder link is established with the new NTN GW. In the case of large NTN footprint size, sending handover commands from the NTN platform to a large number of NTN terminals in a short time is a challenging task; thus, it is preferable to exploit NTN platform ephemeris and/or the NTN terminal location to compute the time of handover.

In the case of a regenerative payload-based NTN platform with gNB on board, the NTN platform exits from a specific geographic area served by an NTN GW and thus needs to connect to a new NTN GW. The NTN platform may cover an area that is either under the current access and mobility management function (AMF) or under a new AMF. When remaining within the coverage area of the current AMF, the NTN platform uses a new IP address to connect to the new NTN GW; by exploiting the multiple transport network layer association (TNLA) feature,

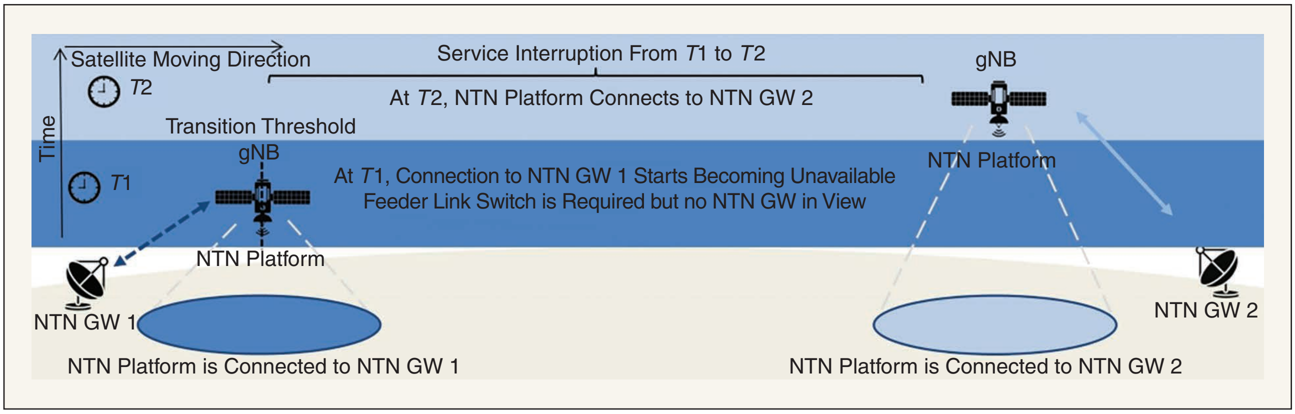


FIGURE 1 An illustration of the 3GPP feeder link switch over procedure.

When entering a coverage area of a new AMF, the NTN platform sets up the NG connection with the new AMF while still keeping the NG interface with the old AMF.

it could add the new Stream Control Transmission Protocol (SCTP) IP address before removing the old SCTP IP address. Otherwise, the NTN platform may use the current IP address to maintain the SCTP with the current AMF by exploiting either Mobile IP or Proxy Mobile IP. The next-generation (NG) interface remains unaffected after the NTN platform connects to the current AMF via the new NTN GW. When entering a coverage area of a new AMF, the NTN platform sets up the NG connection with the new AMF while still keeping the NG interface with the old AMF.

In the case of a regenerative payload-based NTN platform with a gNB split, the gNB-DU that is on board the NTN platform exits from a specific geographic area served by an NTN GW and thus needs to connect to a new NTN GW. The NTN platform may cover an area of the current gNB-CU or of a new gNB-CU. When remaining in the coverage area of the current gNB-CU, the NTN platform uses a new IP address to connect to the new NTN GW and, by exploiting the multiple TNLA feature, could add the new SCTP IP address before removing the old SCTP IP address. Otherwise, the NTN platform may use the current IP address to maintain the SCTP with the current gNB-CU by exploiting either Mobile IP or Proxy Mobile IP. The F1 interface remains unaltered after the NTN platform connects to the new gNB-CU. When entering a coverage area of a new gNB-CU, the NTN platform sets up the F1 connection with the new gNB-CU, but the F1 interface with the old gNB-CU cannot be preserved, since one gNB-DU can connect to only one gNB-CU. One possibility is that the NTN platform carries two gNB-DUs, one for connection to the old gNB-CU and another for connection to the new gNB-CU. Regarding the F1 connection with the old gNB-DU, the F1 procedure may be enhanced; for example, the satellite/gNB-DU and gNB-CU may suspend the F1 interface and keep the application-level configuration data when the satellite/gNB-DU leaves, then resume the F1 interface when the satellite/gNB-DU connects to the same gNB-CU later.

Novel Feeder Link Switch Over Procedures

In this section, we discuss the possibility of enhancing the standard 3GPP feeder link switch over procedure by enabling ISLs in case an LEO satellite exits from the visibility cone of an NTN GW and is not in the direct sight of another NTN GW.

It is worth noting that the proposed "ISL-aided" feeder link switch over procedure can be leveraged by satellites with regenerative payload with full gNB or gNB-DU functionalities on board, as long as ISLs are supported according to [3].

The main purpose of exploiting ISLs is to quickly reach the next available NTN GW through one or more hops in space, thus reducing the inactivity time, which is the time that elapses since the satellite exits from the visibility cone of an old NTN GW until it enters the visibility cone of a new NTN GW. As an LEO satellite usually belongs to a constellation of satellites that follow specific paths in space, its neighbors in the constellation are a priori known and do not change over time. Thus, no major computational effort is required to determine the endpoints of intra-constellation ISLs.

Figure 2 illustrates how ISLs are exploited in the case of soft feeder link switch over mode to guarantee service continuity. For the sake of simplicity, we focus on the case of one ISL only; however, more ISLs can be

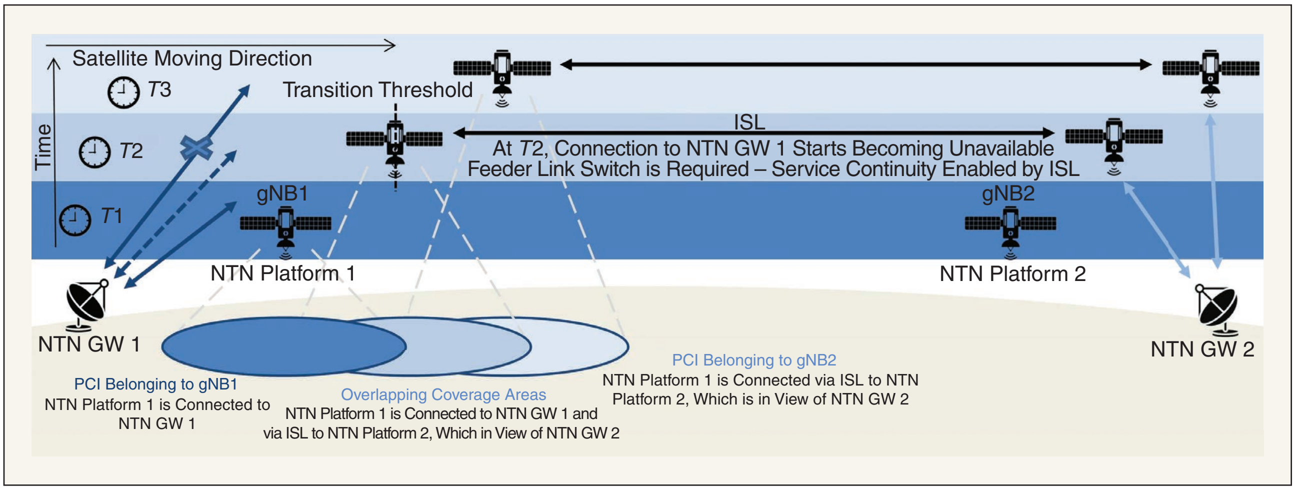
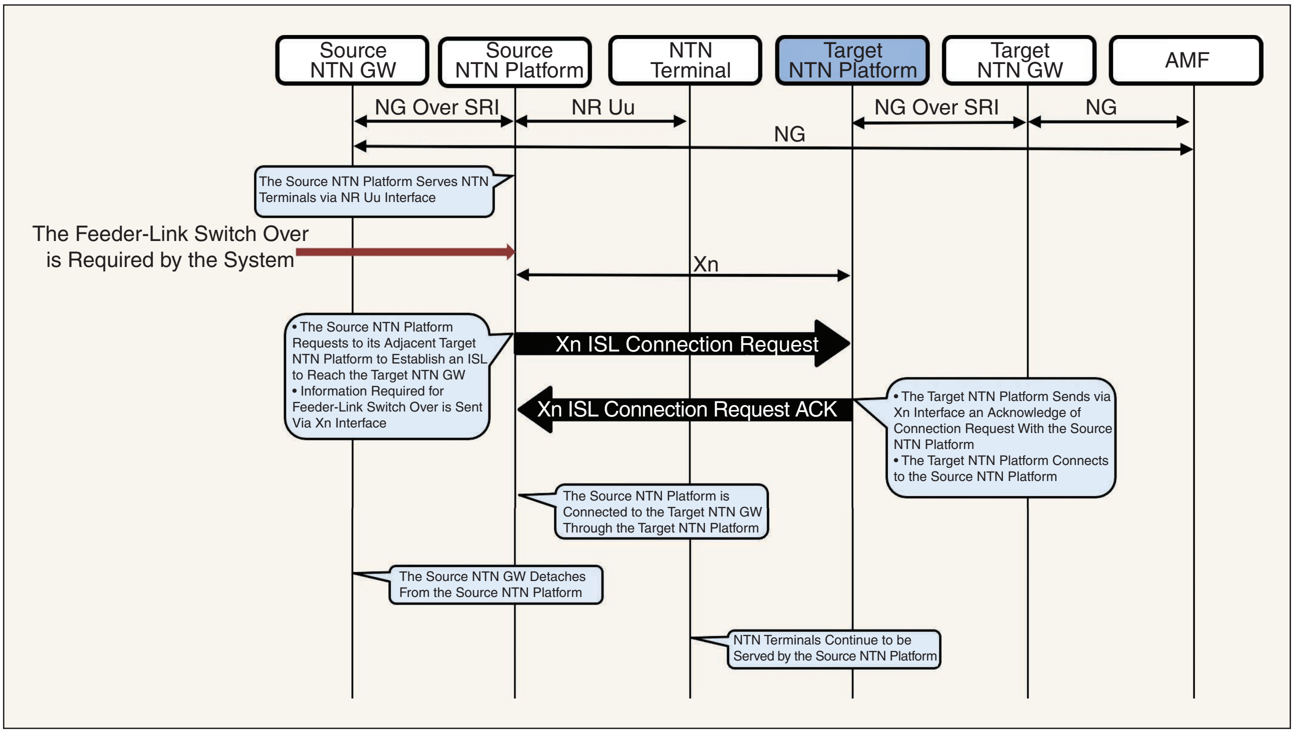


FIGURE 2 An illustration of the new soft feeder link switch over procedure. PCI: physical cell identity.

used among satellites belonging to the same or even to diverse constellations. This last interesting option is left as a future research issue given the complexity of the aspects that follow, as better explained in the "Open Issues" section. Figure 2 shows that service continuity toward NTN platform 1 is still guaranteed when the connection to NTN GW 1 fails and NTN GW 2 is not yet visible (i.e., at the instant T2) owing to the establishment of an ISL with NTN platform 2.

Figure 3 illustrates the new soft feeder link switch over procedure that exploits ISLs among nearby satellites and is based on the NTN platform's ephemeris information and NTN GW's location. Specifically, we consider a New Radio (NR)-based NTN system. Accordingly, all air interfaces among the NTN nodes are represented. Initially, the NTN terminals are served by the source NTN platform via the NR–Uu interface. When the feeder link switch over is required, the *source* NTN platform (i.e., the NTN platform that is going to exit from the visibility cone of the source NTN GW) requests a properly selected *target* NTN platform to set up an ISL to reach the target NTN GW via the Xn interface. The policies for the selection of the target NTN platform are implementation specific and dependent on the key metric for the network operator (e.g., delay, security, or ownership). A simple working assumption could be to select the target NTN platform as the one closest to the source NTN platform and connected to an NTN GW, which we refer to as the *target* NTN GW. Subsequently, the target NTN platform acknowledges the connection request to the source NTN platform through the same interface, thus accepting the connection with the source NTN platform. Then, information required for feeder link switch over is sent to the target NTN platform via the Xn interface. The feeder link switch over is transparent to the NTN terminals since the LEO satellite cell will not disappear from the NTN terminals' perspective. Therefore, the source NTN platform continues to serve NTN terminals. Finally, the feeder link switch over procedure is completed by releasing the old feeder link between the source NTN GW and the source NTN platform and maintaining the new feeder link between the target NTN GW and the target NTN platform, in turn, connected to the source NTN platform via ISL.

If the proposed "ISL-aided" solution is implemented, a rule for releasing the ISL also shall be defined. It can happen, in fact, that the chosen target LEO satellite (currently acting as a relay) is going to come out of the coverage of the target NTN GW. In this case, a new procedure of *feeder link release* is required 1) to prevent the source LEO satellite from keeping a useless ISL toward a relay LEO satellite that is leaving the coverage area of the target NTN GW and 2) to trigger the release of the feeder link from the target NTN GW to the outgoing relay LEO satellite and establish a new "direct" feeder link to the incoming source LEO satellite (which in the meantime has moved into a situation of direct visibility).



The Source NTN Platform Serves NTN Terminals via NR Uu Interface

The Feeder-Link Switch Over is Required by the System

- The Source NTN Platform Requests to its Adjacent Target NTN Platform to Establish an ISL to Reach the Target NTN GW
- Information Required for Feeder-Link Switch Over is Sent Via Xn Interface

- The Target NTN Platform Sends via Xn Interface an Acknowledge of Connection Request With the Source NTN Platform
- The Target NTN Platform Connects to the Source NTN Platform

The Source NTN Platform is Connected to the Target NTN GW Through the Target NTN Platform

The Source NTN GW Detaches From the Source NTN Platform

NTN Terminals Continue to be Served by the Source NTN Platform

FIGURE 3 The 3GPP soft feeder link switch over procedure enhanced by ISL.

The main difference between the new hard feeder link switch over procedure (not shown due to space constraints) and the soft procedure is that only one feeder link can be established at a time. This implies the disconnection between the source NTN GW and the source NTN platform and, then, the activation of the ISL between the source NTN platform and the target NTN platform, which is, in turn, connected to the target NTN GW. In the soft feeder link switch over, the NTN terminals are covered and served by the cell of the source NTN platform, which is simultaneously connected to both the source NTN GW and the target NTN GW (via the ISL with the target NTN platform) during the transition time. The only service losses that can occur are due to changes in the channel conditions. Differently, in the hard feeder link switch over, the cell served by the source NTN platform is no longer kept alive during the transition time as the feeder link toward the source NTN GW is detached before enabling the ISL between the source NTN platform and the target NTN platform, which is connected to the core network through the feeder link with the target NTN GW. This leads to service drops.

It is worth noting that the new "ISL-aided" feeder link switch over procedure is particularly effective in enhancing both hard and soft 3GPP procedures as it avoids service interruptions. The latter are, in fact, due to the lack of visibility of the NTN platform from any NTN GW and the consequent time of forced inactivity until the NTN platform enters the coverage cone of a new NTN GW. Therefore, when one NTN platform cannot see two NTN GWs at the same time, establishing ISLs with other NTN platforms makes it possible to drastically reduce or even avoid the service outage time of the 3GPP soft and hard feeder link switch over procedures, respectively.

Table 1 outlines the benefits and drawbacks of both the standardized feeder link switch over options (i.e., 3GPP hard and 3GPP soft) and the proposed feeder link switch over solutions (i.e., "ISL-aided" hard and "ISL-aided" soft).

Performance Evaluation

In this section, a performance analysis is conducted to assess the effectiveness of performing feeder link switch over aided by ISLs. Specifically, we compare the duration of our proposed procedure leveraging ISLs (referred to as "ISL-aided") with the standard 3GPP procedure wherein the LEO satellite performs the feeder link switch over procedure by itself without collaborating with any other LEO satellite (referred to as "direct"). Furthermore, we highlight that the proposed solution enables a meaningful data gain (i.e., capacity savings) owing to uninterrupted connectivity.

It is worth noting that exploiting ISLs among NTN platforms is advantageous when NTN GWs are placed far from each other and, during the transition interval, the NTN platform cannot see the next target NTN GW. In such conditions, 3GPP soft feeder link switch over cannot be performed, since the involved NTN platform cannot see the two NTN GWs simultaneously. According to our proposed schema, a sort of "virtual visibility" can be realized owing to the exploitation of ISLs;

TABLE 1 *A comparison of feeder link switch over procedures.*

Feeder Link Switch Over Procedure	*Benefit*	*Drawback*
3GPP hard mode	• Procedure managed by the source satellite.	• Service interruption until a new feeder link is established, even if the source satellite is in visibility with more than one NTN GW. • If the source satellite is not in visibility with any NTN GW, the time of service interruption increases by including the time the source satellite enters the visibility cone of the target NTN GW.
3GPP soft mode	• Procedure managed by the source satellite. • No service interruption if the source satellite is in visibility with at least two NTN GWs.	• Service interruption until a new feeder link establishment only in cases where the source satellite is in visibility with one NTN GW at a time.
ISL-aided hard mode	• No service interruption except for the time required to establish the new feeder link, even when only one NTN GW is in visibility.	• Procedure involving more than one satellite, implying an increase in the feeder link establishment duration, and a control overhead for managing the "ISL-aided" procedure. • Service interruption due to the new feeder link establishment.
ISL-aided soft mode	• No service interruption, even in the case in which only one NTN GW is in visibility.	• Procedure involving more than one satellite and a control overhead for managing the "ISL-aided" procedure.

this reduces the inactivity time of 3GPP hard feeder link switch over.

For the above considerations, we evaluated the performance in terms of the time of feeder link switch over (i.e., the duration of the procedure) by comparing "ISL-aided" hard and "direct" hard procedures. In particular, the time of feeder link switch over is composed of the following contributions, whose relevance is dependent on the procedure performed: time of no visibility, time of inter-satellite communications, and time of feeder link interruption. In the "direct" hard procedure, the time of no visibility has the greater impact on the overall procedure duration, the time of inter-satellite communication is null, and the time of feeder link interruption is computed as the time to enable the new feeder link when the satellite is in coverage with the target NTN GW. This last contribution is the same for the "ISL-aided" hard feeder link switch over procedure, for which, however, the time of inter-satellite communications is calculated according to the distance to the target NTN GW, and the no-visibility time is null. Furthermore, we measured the data gain that may be achieved by the "ISL-aided" procedure, computed as the amount of additional data that are delivered owing to the absence of interruption w.r.t. the "direct" procedure, when considering a 2.5 Gb/s channel capacity on the optical link.

Simulations have been carried out by means of an ad hoc developed MATLAB simulator, which allows deploying satellite constellations given the number of satellites per constellation, the satellite orbital height, the inclination angle, and the coverage angle; the NTN GWs can be located by indicating the latitude and longitude coordinates.

In the reported study, without losing generality, we have considered a constellation composed of 10 NTN platforms, which are LEO satellites equipped with regenerative payloads. NTN platforms orbit around the Earth at varying orbital heights (i.e., 600, 800, 1,000, 1,200, and 1,400 km) with a variable round trip delay (RTD), and the two NTN GWs are positioned from time to time at varying distances. Specifically, the first NTN GW is fixed and is located at a latitude of 0° and a longitude of 0°, whereas the second NTN GW is positioned at a latitude of 0°, and the longitude varies (i.e., 40°, 60°, 80°, 100°, 120°, 140°, 160°, and 180°). The RTD of the feeder link between the NTN GW and the NTN platform is modeled as specified in the 3GPP Technical Report [15].

According to our proposed schema, a sort of "virtual visibility" can be realized owing to the exploitation of ISLs; this reduces the inactivity time of 3GPP hard feeder link switch over.

In computing the time of feeder link switch over, we have neglected the time of packet processing and considered 1) the RTD; 2) the inactivity time, expressing the time interval from when a satellite exits the coverage area of an NTN GW to when it enters the coverage of the new NTN GW (typically in the "direct" case); and 3) the time of ISL, representing the signal transmission time between two satellites that depends on the used technology (exclusively in the "ISL-aided" case). In this article, optical wireless communication has been considered for ISL, as suggested in [1].

Figure 4 depicts the time needed to perform the "direct" feeder link switch over, according to which the NTN platform performs the procedure without involving any other NTN platform. The metric is analyzed under varying orbital heights of the satellite constellation and distances from the two considered NTN GWs. As can be seen, this time decreases with increasing orbital height if two closer NTN GWs are considered. This happens because the NTN platform footprint size increases, thus allowing 3GPP "direct" feeder link switch over, which is not possible at lower orbital heights with narrower NTN platform footprint sizes, because the NTN platform may not see two NTN GWs at once, thus introducing inactivity

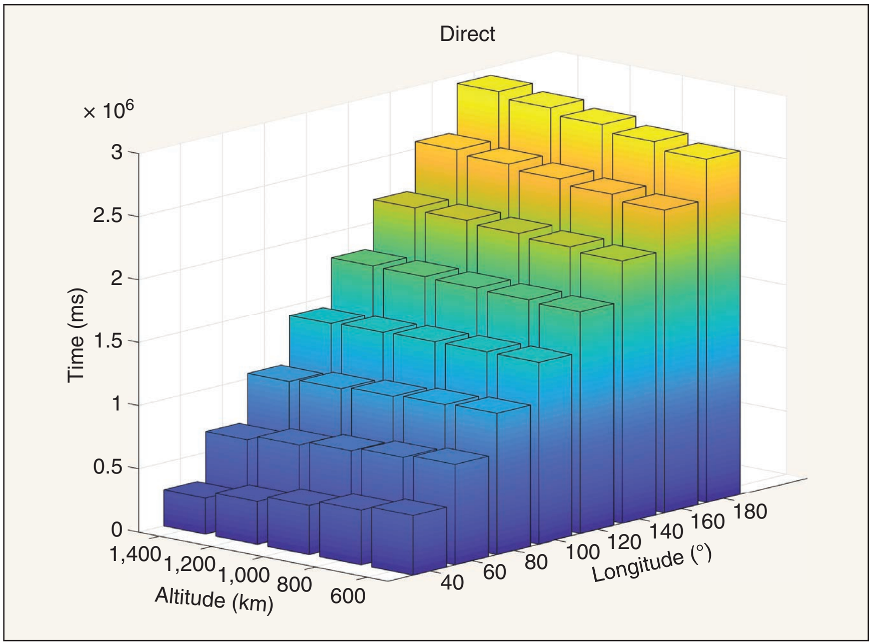


FIGURE 4 The time of the feeder link switch over for the standard 3GPP procedure (i.e., "direct") when varying the distance between the two NTN GWs and the orbital height.

In conclusion, the results obtained testify to the advantages deriving from the ISL exploitation to reduce the time for performing feeder link switch over procedures.

time. Furthermore, the 3GPP "direct" procedure requires a time that increases with the distance between the two NTN GWs and reaches values close to one hour in the worst case (i.e., highest orbital height and inter-NTN-GW distance) because of the long interruption times required by the NTN platform to reach the next NTN GW. Therefore, enhancements to the 3GPP "direct" procedure are required to cope with this severe limitation.

In Figure 5, we show the results achieved by considering the proposed "ISL-aided" feeder link switch over procedure in terms of both the data gain and the time required to perform the procedure in the worst scenario analyzed in Figure 4 (i.e., the highest inter-NTN-GW distance). The results highlight that the "ISL-aided" procedure clearly outperforms the 3GPP "direct" one by achieving a much lower time of feeder link switch over, which is less than 200 ms in the worst case. Specifically, this significant reduction in time is due to the inter-satellite communication via ISLs, which makes it possible to almost nullify the interruption time with a consequent gain in terms of delivered data up to about 7,300 Gbit.

In conclusion, the results obtained testify to the advantages deriving from the ISL exploitation to reduce the time for performing feeder link switch over procedures.

Open Issues

This article shows an initial proof-of-concept study addressing the enhancement of feeder link switch over procedures in 5G/6G NTNs. The promising achieved results lead us to consider the envisaged procedure very interesting and pave the way for further insights on the below optimization aspects that remain to be investigated.

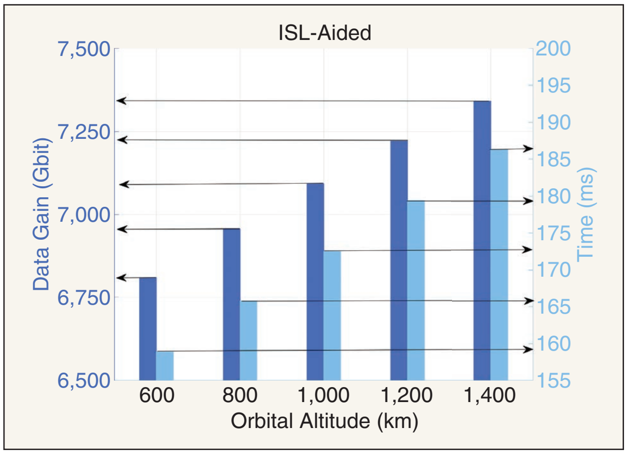


Figure 5 The data gain and time of feeder link switch over for the proposed "ISL-aided" procedure under varying orbital heights for a longitude of 180°.

A primary need is to design more efficient solutions for the selection of NTN platforms to be used as "intermediaries" toward the target NTN GW (destination) that allows for further reductions in the execution times of the proposed procedure. In this perspective, it is worth considering, as already mentioned, the implementation of a procedure that takes into account the possibility of exploiting optimal multihop paths to the target NTN GW. This implies the need to perform a sort of path discovery and then a routing protocol, which can optimize certain objective functions (e.g., minimize the delay to reach the new NTN GW) by accounting for the LEO satellites' mobility along their orbit, the copresence of multiple LEO satellite constellations on different orbits, and the consequent overall topology of the LEO satellite-based NTN segment. Once the optimized path is identified, the involved LEO satellites shall be informed about their next satellite hop; the target NTN GW; the total number of satellite hops; and, hence, the number of ISLs. The exact step-by-step implementation of the routing algorithm, the reduction in the computational complexity and execution time, and the evaluation of the maximum number of satellite hops tolerated are key features that shall be the subjects of future research.

A further aspect to investigate is the optimization of the feeder link release procedure, even in the case of a chain of ISLs. In the latter case, it is necessary to design how to dynamically recalculate the chain from the source NTN platform to the target NTN GW whenever any of the NTN platforms involved in the path fails to establish either an ISL or a feeder link to the target NTN GW.

Finally, additional research effort shall be put into introducing and analyzing "backward ISL establishment," which is extremely advantageous in the case of both hard and soft feeder link switch over. Indeed, when a satellite is about to exit from the visibility cone of the current NTN GW and a new NTN GW is not immediately visible, the satellite can request and establish a backward ISL with the previous satellite belonging to its constellation in order to maintain the feeder link with the old NTN GW and, at the same time, to get closer to the new NTN GW, thus reducing the time of service interruption and allowing the soft feeder link switch over procedure to be triggered, instead of being obliged to resort to the hard one.

Conclusions

In this article, we focused on feeder link switch over, representing one of the major issues coming out of LEO satellite mobility. We first surveyed the existing feeder link switch over procedures defined by the 3GPP. Then, we illustrated a new procedure that exploited the communication among satellites via ISLs to speed up the feeder link switch over procedure. Furthermore, we conducted proof-of-concept simulations, which confirmed that the time of feeder link switch over for our proposed "ISL-aided" procedure was remarkably reduced with respect to the 3GPP "direct" procedure under different values of distance between two NTN GWs and NTN platform orbital height.

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