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Satellite and Mobile Network Operator Cooperation Models for Efficient Handover in 6G-TN-NTN [†]

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Abstract

Cooperation between satellite and mobile network operators enables the integration of non-terrestrial satellite networks (NTNs) with terrestrial networks (TNs), allowing users to seamlessly switch from Mobile Network Operators (MNOs) to Satellite Network Operators (SNOs) in areas with limited MNO coverage or during high-speed travel. However, mobility issues, such as connection failures, the ping-pong effect, and high interruption times, can occur during these transitions. This paper examines various cooperation models, including roaming and handover protocols, and proposes key enhancements to these models to reduce service interruption time. It also discusses the use of machine learning (ML) techniques to reduce the above mobility issue and increase the success rate of cooperation among network operators.

Keywords: handover; roaming; machine learning

1. Introduction

Integrating satellite non-terrestrial (NTNs) and terrestrial networks (TNs) enables ubiquitous network access, requiring 5G user equipment (UE), such as handheld devices, vehicle devices and high-speed trains, to connect to both networks directly [1]. For terrestrial mobile network operators, the economics of providing ubiquitous coverage in their service area may not be viable when using traditional terrestrial means. Even in well-connected countries, terrestrial coverage can be spotty in rural and remote areas, or in case of emergencies and disaster relief, connectivity may be disrupted even in urban areas [2]. Ubiquitous connectivity is possible through communication satellites at a much lower infrastructure investment than that provided by terrestrial-only solutions. However, efficient cooperation between mobile network operators and satellite network operators is required to realize the integration of TNs and NTNs. In this paper, we explore the performance of various cooperation models, including roaming and handover protocols, to enable seamless switching between networks for users. Additionally, we explore the potential of utilizing machine learning (ML) techniques with these protocols to reduce mobility issues, such as connection failures and the ping-pong effect, and minimize interruption time, thereby enhancing cooperation among network operators.

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2. Handover or Roaming?

The UE's mobility within the network operator's coverage, known as the Home Public Land Mobile Network (HPLMN), is handled through a handover procedure. On the other hand, when the UE changes its serving mobile network, for example, crossing a country's borders or entering an area within a country without its coverage, the mobility procedure from its HPLMN to another network operator, called the Visited Public Land Mobile Network (VPLMN), is handled using the roaming procedure.

2.1. Handover

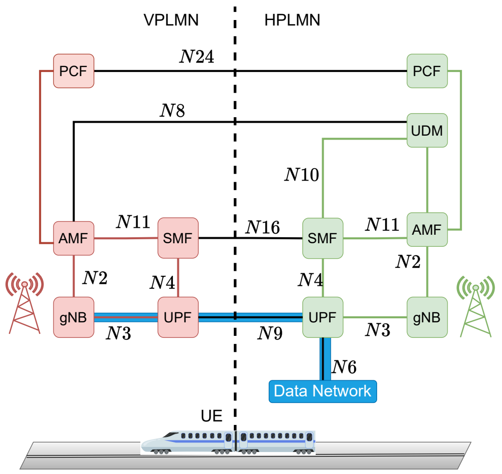
A handover procedure is primarily needed when a UE or device moves from the coverage area of one cell to another within the same network operator. This procedure consists of three main phases. The first is the preparation phase, which includes UE measurement reporting, the handover decision from the source cell, and the selection of the target cell. Next is the execution phase, during which the UE detaches from the source cell and performs synchronization with the target cell. Finally, the completion phase changes the path data from the source cell to the target cell. The following are techniques used for handover [3].

a. Baseline HO (BHO): The UE measures signals from multiple cells, which include the source gNB and neighboring gNBs. It then sends a measurement report to the source gNB. When the source gNB decides to initiate an HO, it selects a target gNB from the list of neighboring gNBs and sends an HO request via the 5G Xn/N2 interface. The target gNB performs admission control, and if it has available resources, it responds with an HO request acknowledgment to the source gNB. Then, the source gNB sends an HO command to the UE to initiate HO with the target gNB. Subsequently, the UE detaches from its current source gNB and connects to the new target gNB.
b. Conditional HO (CHO): In BHO, the network decides when to initiate the HO, which can lead to HO failure if the UE fails to receive the HO command or, after receiving the HO command, if the signal strength between the UE and the target gNB drops quickly. The UE lacks flexibility in choosing the target gNB, as it receives only one target gNB from the source gNB, thereby increasing the HO failure probability. To mitigate this, the CHO technique is employed; the UE receives an HO command in advance during a good channel signal, which includes multiple target gNB configuration parameters and execution conditions. This allows the UE to evaluate these conditions, and when the execution conditions are met, it detaches and connects to the best target gNB.
c. L1/L2 Triggered Mobility (LTM): In BHO and CHO, which rely on L3 measurements, the UE detaches from the source cell/gNB to synchronize with the target cell/gNB, leading to delays due to reconfiguration and synchronization. This increases service interruption time. To minimize this, LTM HO can be employed, allowing the UE to use L1 measurement reports for synchronization with the target cell while remaining connected to the source cell, though LTM mainly supports intra-gNB handovers.
d. RACH-less HO (RHO): In RHO, during the BHO or CHO procedure, the random access channel (RACH) procedure is skipped, allowing a UE to have dedicated RACH resources that can directly connect with the target cell. This approach reduces the interruption time that occurs during the RACH procedure.

2.2. Roaming

The roaming procedure is initiated when the UE changes connectivity from its HPLMN to VPLMN, typically when crossing country borders or entering an area without HPLMN coverage. Depending on the network architectures, there are two types of roaming: home-routed (HR) and Local Breakout (LBO) roaming [4].

a. Home-routed (HR) roaming: In HR roaming, the data traffic is redirected from the HPLMN to VLPMN via the N9 reference point, and both Session Management Functions (SMFs) V-SMF and H-SMF are communicated via the N16 reference point as shown in Figure 1a [5,6]. In this case, the SMF in the HLPMN (H-SMF) selects the User Plane Function (UPF) in the HLPMN, and the SMF in the VLPMN (V-SMF in this case) selects the UPF in the VLPMN.
b. Local Breakout (LBO) roaming: In this roaming, both the SMF and all UPF(s) are under the control of the VPMN and do not require redirecting data from the HLPMN to VLPMN. The AMF provides UE location information to the SMF of the VLPMN to select the UPF near the UE location [5,6].



(**a**) (**b**)

Figure 1. Roaming 5G system architecture reference point representation [4] (**a**) HR roaming. (**b**) LBO roaming.

The main challenge of roaming is that the connection between the UE and its home network remains active until the signal is completely lost. Once the signal is lost, the UE begins to synchronize with the VPLMN, following a process similar to the one it followed when it first connected to the network. However, this procedure results in a significant interruption of service time [7]. To reduce interruption time, mobility procedures based on UE idle mode and connected mode, along with different interface solutions between the HPLMN and VPLMN, have been proposed in the literature, as detailed in Section 3.

3. Discussion on Mobility Solutions

The roaming procedure is well-known among MNOs and does not require extensive coordination with other MNOs. However, this procedure leads to a high user plane interruption time. Here are some solutions provided in the literature regarding HR roaming [6,8].

- Release with redirect (RwR) with or without N14: RwR is a procedure where the UE is actively sent to idle mode and then executes the idle-mode mobility procedure. Compared to the conventional HR roaming procedure, RwR removes the interruption time until the UE connection is completely lost and, also, the UE network searching time. The procedure requires the UE to re-attach and re-authenticate to the visited network, which can be done with or without the N14 interface (in the absence of N14, using the N8, N9, and N16 interfaces to connect between the home and visited network) as shown in Figure 2.

- Inter-PLMN handover: Here, in addition to the interfaces of RwR with N14, it includes the N2 interface to exchange the UE context information between the source gNB of the home network and the target gNB of the visited network; see Figure 2. This N2 interface allows the UE to remain in connected mode, thus reducing interruption time.

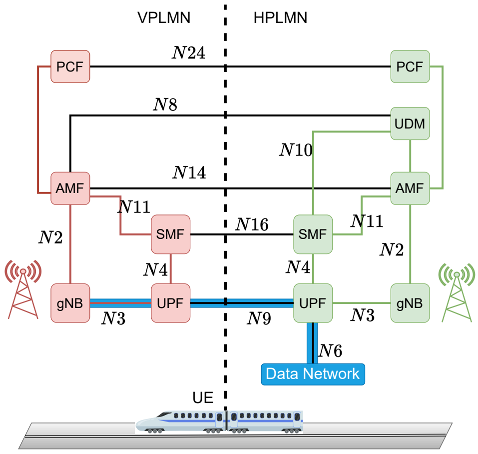


Figure 2. Home routing concept with N14.

4. Challenges and Proposed Enhancements

The above solution can improve UE connectivity when it switches between MNOs. However, for using the above solution between the SNO and MNO, the following challenges needed to be addressed.

4.1. Latency Associated with Mobility Signaling

The propagation delay in NTNs is more significant than that in TN systems, which increases the interruption time when UE utilizes both the SNO and MNO at different times, even when N14 and N2 interfaces are utilized. The interruption time may account for the signaling delay from the satellite to the 5G core SNO, and then from the 5G core SNO to the 5G core MNO, which finally goes from the 5G core MNO to the gNB. The following mobility enhancement can be utilized to reduce the interruption time

a. Unified 5G core with RHO: This allows the SNO to use the 5G core of the MNO infrastructure as a gateway, instead of having a dedicated 5G core for the SNO. In this case, the satellite acts as a gNB, like MNO gNBs, and a handover procedure can be carried out. To minimize the signaling propagation delay needed to connect the UE to the SNO, it is preferable to use an RHO procedure where a dedicated RACH resource is allocated to the UE.
b. ML-assisted Inter-PLMN handover: In this case, an ML prediction technique can be used to predict in advance when the UE is required to switch from the MNO to SNO. The prediction can be a function of user location, speed, and signal strength. Hence, while the UE is still connected with the MNO, the MNO can send all the required information in advance via the N14 interface to the SNO. As a result, the UE can establish a connection with the satellite more quickly.

4.2. Mobility Issues

When implementing the above proposed enhancements to improve the roaming procedure from conventional roaming to a more efficient handover procedure, it is crucial to configure mobility-triggering parameters correctly. For instance, the time-to-trigger values, which determine when a UE switches between networks, and the threshold values that indicate the necessary signal level difference between networks for initiating the switch must be set correctly. Improper configuration of these parameters can result in connection failures, unnecessary network changes, and unnecessary network switches, known as "ping-pong." For instance, for situations where MNO coverage is not available, and for high-speed UEs, the UE should be aware of this in advance, as MNO coverage is limited and requires switching to the SNO; otherwise, it leads to the mobility issue mentioned above.

Proposed Solution: ML-assisted Mobility Robustness Optimization

Here, we propose an ML-based CHO approach that employs an elevation angle of the UE relative to the gNBs, in addition to the Reference Signal Received Power (RSRP)-based handover approach, which is mainly used in the BHO. First, it selects the candidate target gNB based on RSRP measurement. Then, the ML model predicts the elevation angle of the UE movement ahead relative to the targeted MNO gNB for l consecutive values. When all l consecutive elevation angles are higher than the threshold elevation angle of θ degrees, the UE is connected to the target gNB; otherwise, it switches to the SNO network or remains connected with the SNO if it was initially connected.

5. Numerical Results

5.1. Mobility Interruption Time Analysis

Here, we show how a unified 5G core with RHO and ML-assisted inter-PLMN HO can significantly reduce the time of UE service interruption. For comparison, we analyze a benchmark scheme for inter-PLMN handover in the context of the HR concept, specifically when a UE switches from an MNO to an SNO. The service interruption time for the benchmark is given by

$$T_{benchmark} = T_{UEdelay} + T_{RACHdelay} + T_{UPFdelay} \tag{1}$$

$T_{UEdelay}$ is the time from the UE receiving the HO command to the time the UE starts transmission of the new RACH, which is given by

$$T_{UEdelay} = T_{UEprocessing} + T_{IU} + T_{marigin} + T_{delta}. \tag{2}$$

where $T_{UEprocessing}$ is the UE processing time, T_{IU} is the Synchronization Signal Block (SSB) and the RACH occasion associated period, $T_{marigin}$ is the time for SSB post-processing, and T_{delta} is time for fine time tracking and acquiring full timing information of the target cell [9].

$T_{RACHdelay}$ is the time required to connect with the target SNO satellite. Assuming the UE uses a contention-based RACH to connect with the target SNO satellite [10], the $T_{RACHdelay}$ is obtained as

$$\begin{aligned} T_{RACHdelay} =& T_{msg1} + T_{msg2} + T_{msg3} + T_{msg4} + \\ & T_{SatSNOprocessingmsg1} + T_{UEprocessingmsg2} + \\ & T_{SatSNOprocessingmsg3} + T_{UEprocessingmsg4}, \end{aligned} \tag{3}$$

where T_{msg1}, T_{msg2}, T_{msg3}, and T_{msg4} are the propagation delays to exchange the msg1, msg2, msg3 and msg4 between the UE and the satellite while $T_{SatSNOprocessingmsg1}$, $T_{UEprocessingmsg2}$, $T_{SatSNOprocessingmsg3}$, and $T_{UEprocessingmsg4}$ are the corresponding times required to process the *msgs*, respectively.

$T_{UPFdelay}$ is the time required to establish the data path from the MNO to SNO, which includes the control signal communication time between the SNO of the satellite and the

SNO of the UPF, the SNO of the UPF and the MNO of the UPF, and the SNO of the satellite and the UE, and the corresponding processing time, which is written as follows.

$$T_{UPFdelay} = 2(T_{SatSNOtoSNOUPF} + T_{UPFSNOtoUPFMNO} + T_{UPFSNOprocessing}) + T_{SatSNOprocessing} + T_{UPFMNOprocessing} + T_{SatSNOtoUE}. \quad (4)$$

For the proposed unified 5G core with RHO, assuming that the SNO and MNO utilize the same UPF, we can reduce the $T_{UPFdelay}$, and in addition, by using the RHO, we can exclude the $T_{RACHdelay}$, which is given by

$$T_{UnCoreRACHlesHO} = T_{UEdelay} + T_{UPFdelayUncore}, \quad (5)$$

$$T_{UPFdelayUncore} = 2T_{SattoUPF} + T_{UPFprocessing} + T_{SatSNOprocessing} + T_{SatSNOtoUE}. \quad (6)$$

For the proposed ML-assisted inter-PLMN HO, an ML prediction technique is applied in advance when the UE is required to switch from the MNO to SNO; thus all necessary UPF exchange between the MNO and SNO can be carried out in advance. Hence, $T_{UPFdelay}$ can be reduced to $T_{SatSNOtoUE}$, while other delays are calculated the same as the benchmark scheme, which is given by

$$T_{MLassitedPLMNHO} = T_{UEdelay} + T_{RACHdelay} + T_{SatSNOtoUE} \quad (7)$$

Comparing (5) and (7) with (1), we can observe that the service interruption is reduced when the proposed unified 5G core with RHO and ML-assisted inter-PLMN HO is applied. For example, given the values $T_{IU} = 30$ ms, $T_{margin} = 2$ ms, $T_{delta} = 0$ ms, and the propagation delay between two points is 4 ms. Additionally, the processing time for each *msgs* signal at the UE or gNB is 2 ms, while the processing time for the other signals at the UE, gNB, and UPF is 20 ms each. The service interruption time for the unified 5G core with RHO and ML-assisted inter-PLMN handover is 84 ms and 104 ms, respectively, both of which are lower than the benchmark of 176 ms.

5.2. ML-Based MNO and SNO Cooperation Analysis

We explore the cooperation between the SNO and MNO in a Railway Scenario to enhance connectivity in high-speed trains as depicted in Figure 3. The SNO connectivity can provide service in situations where MNO coverage is insufficient. This is particularly relevant to train movements along railways in urban, suburban, and rural areas. Network switching from the MNO to SNO may occur when the probability of network availability for the MNO decreases, for example, when the train moves from an urban or suburban area to a rural area, where MNOs have fewer gNBs deployed. The train can switch back to the MNO once it detects adequate signal coverage.

For the simulation, we consider a railway distance of 100 km. The scenario involves a high-speed train traveling from one place to another, as illustrated in Figure 3. A total of 23 gNBs are deployed in a sparse formation to represent both urban and rural areas. Each gNB is equipped with two Remote Radio Heads (RRHs), all operating at a frequency of 2.5 GHz. We utilize a rectangular antenna array with dimensions of 8 by 8 per RRH, featuring a maximum antenna element gain of 8 dBi. The transmit power for each RRH is set at 39 dBm. The height of the gNB is considered 25 m, the UE is 1.5 m, and the maximum 3D coverage distance for the RRH is 872 m. The train is traveling at a speed of 500 km/h and has a person onboard with a handheld device connected to the network. Additionally, a Low Earth Orbit (LEO) satellite is positioned at an altitude of 600 km to provide coverage over the 100 km railway. All other parameters and the pathloss model required to calculate the RSRP for the MNO and SNOs can be found in [11] and [10], respectively.

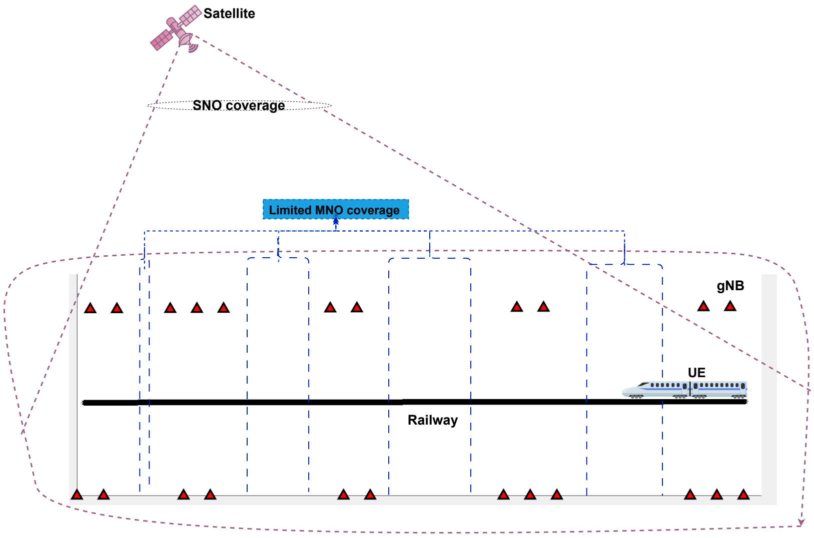


Figure 3. SNO and MNO cooperation for continuous connectivity in the high-speed train scenario.

Table 1 illustrates how the cooperation between the MNO and the SNO can enhance connectivity in a high-speed train scenario. The comparison features a benchmark scheme based on the RSRP with handover configuration parameters, including time-to-trigger (TTT) and hysteresis (hys) values of 256 and 3, respectively. This includes scenarios with only the MNO network as well as cases where both the MNO and SNO are available. In this case, the technique used for handover is baseline HO (BHO).

Table 1. Handover performance comparison.

Network Avaliablity	Techniques	TTT (ms) Configuration Values	hys (dB) Configuration Values	HO Success Rate (%)	HO PP Rate (%)	HOF Rate (%)
MNO only	BHO	256	3	13.828	7.2144	86.172
MNO & SNO	BHO	256	3	92.982	35.088	7.0175
MNO & SNO	ML-based CHO	256	3	94.872	17.949	5.1282

The proposed solution using an ML-based CHO approach employs the same TTT and Hys for a fair comparison with BHO. This approach focuses on predicting the elevation angle of the high-speed train relative to the targeted gNB of the MNO for four consecutive instances $(l = 4)$. When all the predicted elevation angles exceed the threshold of $\theta = 0.78$ degrees, the high-speed train successfully connects to the target gNB. Otherwise, it switches to the SNO network or remains connected to the SNO if it was initially connected.

Table 1 shows that cooperation between the MNO and SNO results in a higher handover success rate, while also decreasing the handover failure rate compared to using the MNO alone. Furthermore, applying ML-based CHO in MNO and SNO cooperation can further improve the success rate and further decrease the ping-pong and failure rates. The RSRP over time, obtained by smoothing the signal, is illustrated in Figure 4 for both the benchmark schemes and the proposed method. Relying solely on the MNO results in low RSRP during specific time intervals, as the MNO does not cover some areas of the railway. In contrast, combining the MNO with the SNO leads to an increase in RSRP, demonstrating that the SNO effectively complements the areas not covered by the MNO.

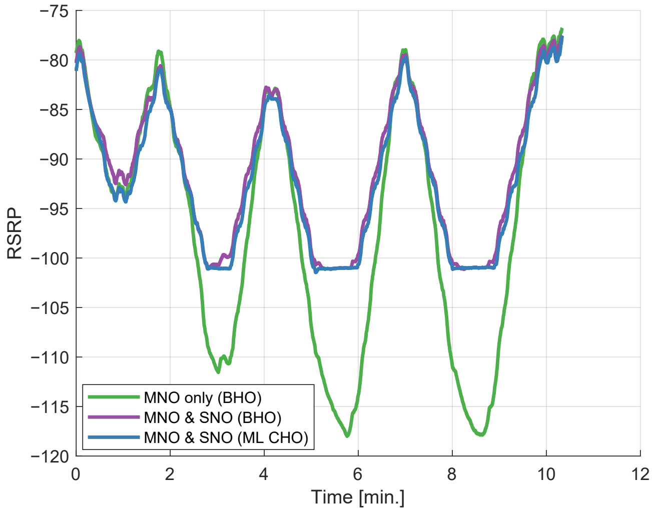


Figure 4. Comparison of RSRP between the benchmark and the proposed method.

6. Conclusions

In this paper, we demonstrate that cooperation between MNOs and SNOs can enhance user connectivity, particularly in scenarios where MNO coverage is limited. However, current network architectures and technologies are primarily designed for MNOs, which can result in high service interruption time and mobility issues when users switch from MNOs to SNOs. To address these challenges, we propose a unified 5G core with RACHless HO and ML-assisted inter-PLMN handover, both of which can significantly reduce service interruption time. Additionally, an ML-based handover solution can mitigate mobility issues, such as connection failures and the ping-pong effect, while improving the success rate of cooperation between MNOs and SNOs.

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