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# Reliability challenges of 5G and Beyond networks applications in high-speed trains

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5G and Beyond networks are expected to be reliable solutions to support new and complicated wireless communication scenarios. As high-speed railway systems are booming all around the world, they bring about novel challenges to the 5G and Beyond networks to support high mobility usage. Railway communication functionality has higher performance requirements than other use cases. These requirements will be satisfied by providing an ultra-reliable 5G and Beyond system and seamless handover procedures under high mobility. On the one hand, the system faces failures from its virtual and physical layers. On the other hand, high mobility creates radio issues on handover and interrupts network services. Network service reliability performance can be guaranteed by continuous end-to-end user plane connectivity. This connectivity is maintained by successful handover during radio zone changes. Handover is a signaling process in the control plane. Therefore, the railway network service reliability analysis requires a combined perspective of user and control planes. This paper investigates the possible challenges of high-speed railway network service reliability and examines the impacts of various factors. By using discrete event simulation, we calculate the onboard network communication service reliability during its mission. The impacts of different telecommunication network deployments on network and service reliability are compared. Simulation results provide insights into estimating service performance and propose feasible solutions to improve service continuity and reliability for railway operators and network providers.

*Keywords*: Mobile network, 5G and Beyond, Reliability, High-speed trains, Discrete event simulation.

## 1. Introduction

For more than 20 years, ground-to-train communication has relied on the GSM-R system based on 2G. The International Union of Railway (UIC) decides to launch a new system, Future Railway Mobile Communication System (FRMCS), to replace it. As pointed out by UIC (2020), the goal is to usher in 5G for rail networks. GSM-R, often reinforced with redundancy in the application, has been, so far, one of the most reliable systems (He et al. (2016)). Although GSM-R is still a universal solution for the communication between the train and control center, there are many reasons to upgrade this system, such as the end of the GSM-R system life-cycle and the need to improve the quality of service and quality of experience (Masur and Mandoc (2009)).

5G and Beyond is undoubtedly the most advanced telecommunication system that will enhance the quality of railway services. The 5G New Radio (5G NR) extends to a higher spectrum band (Niu et al. (2015)), enabling a higher data transfer rate. The 5G Core will be fully virtualized (Bonati et al. (2020)), providing a flexible and tailored network to train services.

Nevertheless, just as GSM needs to be upgraded with further enhancements specific to the requirements to become GSM-R, 5G and Beyond networks need to be carefully implemented and designed to adjust to the specific requirements of railroad operation.

According to 3GPP (2022), seamless communication is crucial for train control service as it conveys important signals guaranteeing the operation of trains. Onboard, seamless communication is also required to provide high-quality services.

However, communication in the high-speed railway scenario faces many challenges. As discussed by Fan et al. (2016), most of these challenges could be grouped under four categories:

accurate channel estimation, advanced signal processing, optimized network deployment, and effective mobility management. Since this work addresses reliability-related issues, we focus mainly on network deployment and mobility management. The failure of the network facility is one of the main reasons a train loses its communication service since it would need to connect to different base stations during its movement. The faster a train moves, the faster it needs to change the anchoring base stations, thus the more network elements it uses during a given time. In network management, HandOver (HO) procedure can be another crucial reliability challenge. As 5G and Beyond networks introduce a high spectrum band, the dense small-cell (Al-Falahy and Alani (2017)) layout increases HO frequency for high mobility end-users. HO signaling procedure reliability becomes thus more important for providing a seamless connection to high-speed trains.

Some works have addressed the 5G reliability problem, considering low-mobility or non-mobility users (Farooq et al. (2015); Qu et al. (2018); Thiruvasagam et al. (2022)). Some works have investigated the HO process management under high mobility and sought to find a better way to avoid wrong HO, failed HO, or missed HO (Song et al. (2014); El Banna et al. (2020); Sönmez et al. (2020); Tanveer et al. (2022)). Nevertheless, little attention has been paid to the impact of network infrastructure failure and HO procedure failure on the reliability and availability of high-speed train communication service.

This paper aims to take up the challenges of 5G and Beyond reliability analysis in high-speed train applications. We developed a 5G and Beyond network element model and a moving train model. Combined together, these two models reflect the real communication-related problems a train could encounter during its mission. The reliability and availability of 5G and Beyond network and train telecommunication service are estimated by carrying out discrete event simulations. The main contributions of this work are the following:

- Main challenges in high-speed train communication are discussed
- Moving train model and network component model are developed to represent their state changes
- Handover procedure and re-establishment procedure are both considered for high-speed train scenario
- The perspectives of reliability and availability from the network operator and high-speed train service user are compared

The paper has been organized in the following way. We briefly introduce the high-speed train service problem in section 2. In section 3, we present the 5G and Beyond network model and the train model. A high-speed train mission scenario is presented, and the simulation results are given in section 4. Finally, section 5 concludes the work with some remarks and outlines future works.

## 2. Problem statement

We consider a generic 5G and Beyond network composed of the Radio Access Network (RAN) and the Core Network (CN). The network architecture is presented in Figure 1. RAN, which transmits, receives, converts and processes the signal, comprises a set of gNB base stations, and each is composed of Radio Units (RUs), Distributed Units (DUs) and Central Units (CUs). The CN, consisting of different Virtual Network Functions (VNFs), that take charge of aggregation, authentication, service control, etc., is divided into the User Plane (UP) with User Plane Function (UPF), and the Control Plane (CP), including VNFs such as Access Management Function (AMF), Session Management Function (SMF), Data Management (UDM), Authentication Server Function (AUSF), etc. As an end-user, a train will connect to the RU with the best signal that covers the area it passes via a 5G NR air interface. Once the train is registered to the network, it will request a Protocol Data Unit (PDU) session to start an end-to-end UP connectivity between the UE and Data Network (DN). This connectivity is supported by User Plane, that is, RU, DU, CU-UP, UPF, and the links between them.

The main problem addressed in this work is the reliability and availability-related challenges of communication services applied to high-speed trains. More precisely, a train is considered connected to the internet if the user is registered to the network and it has initiated a PDU session and the whole user plane allocated by the PDU session is reachable and available to the train. We distinguish in the paper two kinds of connection failure: the failure related to User Plane failure and the failure related to reachability.

### 2.1. *User Plane failure*

When a train starts to travel on the railway, we assume that it is already registered to the 5G and Beyond network. While the train is running, failures from different parts of the network will impact the communication service in different ways:

- If the gNB facility (including RU, DU, and CU-UP) fails, the train directly loses the connection to DN. There are two possible solutions to reconnect to the DN. If there is another available gNB covering the train, then the train will try to re-establish the connection via this available gNB by a re-establishment procedure. Otherwise, the train becomes unconnected and untraceable. Communication service is stopped. The train will wait until the gNB is repaired or until it enters an available gNB coverage area.
- If the UP in CN fails, i.e., UPF-UP fails, the end-to-end communication service is interrupted, yet the train is still connected to the gNB. The communication service resumes after the recovery of CN UP.

The Re-establishment procedure (3GPP (2021)) is simplified by considering the call flow involving only the RU, DU, CU, AMF, and UPF.

### 2.2. *Reachability failure*

Since the train is in high mobility, the RU to which it connects can only serve a specific area, as shown in the radio layout example in Figure 2. To guarantee a seamless connection, the train regularly changes the connected RU by HO process at the overlapping covered by multiple RUs. There are different types of HO regarding the implementation and layout of 5G (3GPP (2021)). In the scope of this work, we consider two of them:

- Inter gNB-DU and Intra gNB-CU Handover: In this HO procedure, the new and old gNB-DUs are connected to the same CU. The signaling message will not necessarily be sent to CN. This procedure will involve messaging over the source and target RUs, DUs, and their CU.
- Inter gNB-CU Handover: In this HO procedure, the signaling will involve messaging over the source and target gNBs (including RUs, DUs, CU), AMF, and UPF.

If the HO procedure fails, the train stays connected to the previous RU. When the RU is no longer reachable to the train, the train will be disconnected from the network and need to re-establish the connection to resume the communication service.

### 2.3. *Availability and reliability*

To analyze the reliability challenges, the reliability-related terms should be well defined. For the considered network, we define the availability and reliability from both network and high-speed train communication service perspectives:

- We define /boldnetwork availability as the percentage value of the amount of time the network operator can provide end-to-end service and response to CP singling messages everywhere by using the 5G and Beyond network deployed in a considered area, divided by the total considered time.
- We define /boldnetwork reliability as the ability of the 5G and Beyond network to provide end-to-end connection and response to CP singling messages everywhere in a considered area. We measure network reliability using the Mean Time To Failure (MTTF) of the considered network system.
- We define /boldtrain network communication service availability as the percentage value of the amount of time the end-to-end communication service is delivered, divided by the amount of time the train network communication service is expected to be delivered.
- We define /boldnetwork communication service reliability as the ability of the communication service to perform as required for a given

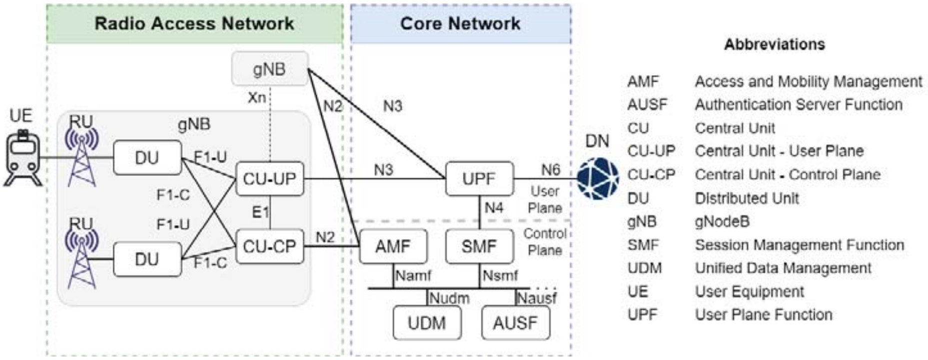

Fig. 1. 5G network architecture.

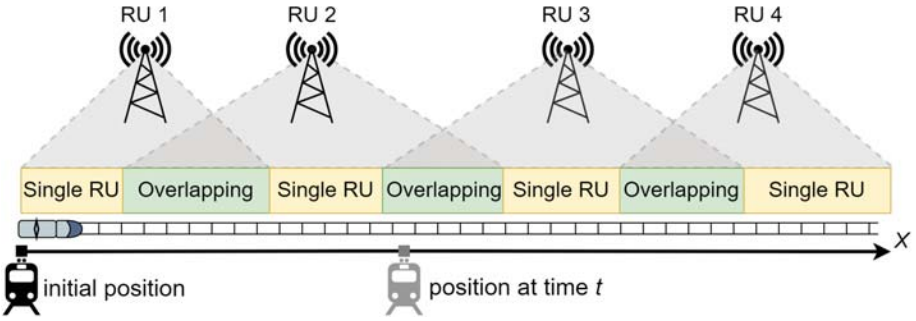

Fig. 2. An example of 5G gNB RU layout along a section of railway.

time interval under given conditions. We describe network communication reliability using MTTF of the train communication service.

## 3. Discrete event simulation model

We separate the considered system into two parts: the network facility, “Telecommunication network”, and the service user, “high-speed train”. A telecommunication network is a set of network functions composed of virtualized applications and physical resources. The train, whose position is known at a given moment, will consume the service the reachable network functions provide.

### 3.1. *5G network model*

The 5G and Beyond network comprises different elements, such as DU, CU, and AMF in Figure. 1. We assume they all have similar behavior as shown in Figure. 3. They all start from a working state (W) and may fall into a failed state (F) due to software and hardware reasons. This failure will be detected and identified (N). Finally, it will be either fixed automatically in the case of software and application issues or repaired manually (R). When the element is not in the state (W), all end-users relying on this element fail to use the element, leading to a service connection or a signaling procedure (re-establishment or HO) failure.

### 3.2. *Train model*

From an end-user’s perspective, the train is always in a moving situation. We divide the train’s mission into a series of rounds. Each round is represented by Figure. 4. A round starts from the state where the train is initially connected to $i^{th}$ RU.

If the train runs into a Single RU area, it will stay at the connected state unless the connection fails (some of the network elements it uses are in states (F)). If the failure is due to UPF-UP, the train can return to the connected state when UPF-UP is repaired. If the gNB fails, the train will try to re-establish the connection to $i^{th}$ RU if the failed gNB is repaired, and the train then goes back to the connected state. If the train fails to re-establish the connection, it will remain disconnected until a successful re-establishment to $j^{th}$ RU when entering an overlapping zone, where $j \neq i$.

If the train runs into an overlapping area, it can request HO when a better signal is found. If the HO procedure succeeds, the train will connect to $j^{th}$ RU, where $j \neq i$. If the HO procedure fails, the train will retry HO until the train runs outside of the $i^{th}$ RU covering zone. Then the train will re-establish the connection instead of requiring HO. In this area, the connection is also at risk of facility failure. As the train runs in an overlapping area, another RU always exists. Should $i^{th}$ RU fails, it would immediately try to re-establish the connection to the other RU, $j^{th}$ RU, where $j \neq i$.

Both the HO and re-establishment processes change the state of a train by generating a call flow. The re-establishment process changes a train from a non-connected state to a connected state. The HO process allows a connected train to be handed over to another available RU. The train remains connected throughout the HO process.

### 3.3. *Interactions between two models*

The two models work together in the simulations. When a train starts either a HO or a re-establishment process, it informs the corresponding network elements that they will be needed or no longer be needed by the train. When a network element changes its state from (W) to (F), for instance, it will inform the train of the failure. If the train is already connected to the network, it will be disconnected and request a re-establishment process.

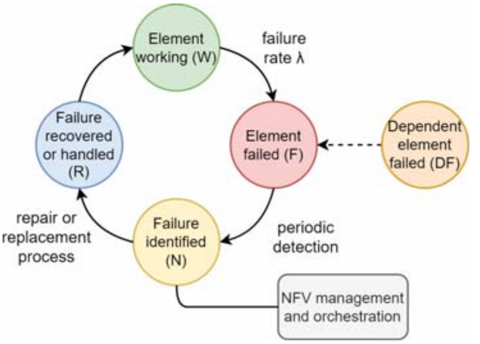

Fig. 3. 5G and Beyond network element model.

## 4. Simulation and results

We implement the proposed models in section 3 with the SimPy environment. We consider a railway line of 100 km with locally distributed RAN and one aggregated CN. The gNBs in RAN consist of co-located RUs and DUs at the edge data center and one aggregated CU at the gNB level data center. RUs are assumed to be purely physical equipment and are equally spaced alongside this 100 km line. First RU is at the starting point of the railway, and the last RU is at the endpoint. The RUs in this study can cover an area with a radius of 5 km using the spectrum it can provide. The failure process of the network system is given in Table 1, according to the data provided by the network service suppliers. The composition of our envisioned 5G and Beyond network is given in Table 2. Throughout the simulation, one train runs every hour from the start to the end of the line at a fixed speed of 200 km/h. All network links in this study are assumed ultra-reliable.

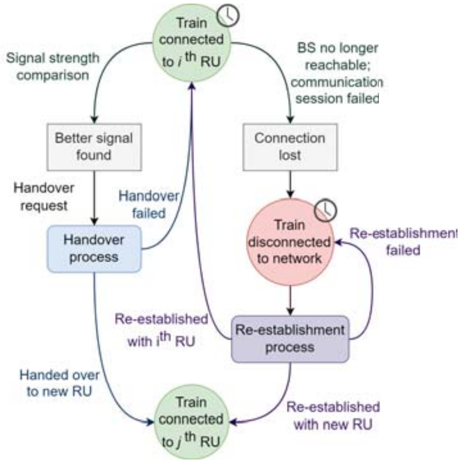

Fig. 4. High-speed train model.

Table 1. Failure processes of network system.

| Item | MTTF | repair time |
|---|---|---|
| RU | 50 years<br>constant failure rate | 1 hour<br>fixed repair time |
| Virtual application (container) | 52 days<br>constant failure rate | 10 s<br>$U(0, 10)$ continuous uniform distributions |
| Server | 1 year<br>constant failure rate | 1 hour<br>fixed repair time |

Table 2. Components of network system.

| Items | Instances | Description |
|---|---|---|
| RU | Variable | Physical equipment |
| DU | 1 for 1 RU | 1 app and 1 server |
| CU | 1 pair for 8 DUs | 2 apps and redundant servers |
| UPF | 1 in total | 2 apps and redundant servers |
| AMF | 1 in total | 1 app and redundant servers |

### 4.1. *Unreliable Radio Unit*

In the first scenario, we simplified the network elements to better explain the different perspectives from the network and the train. We consider that only RUs will fail in the network, and the rest of the system is highly reliable. We investigate how the density of radio installations may impact the network and service communication reliability.

From the network operator's perspective, the network availability and reliability are strictly defined by considering the capability to provide end-to-end connection and signaling message response at every position (including both single RU zones and overlapping zones) in the considered area. From the train's perspective, the system we consider is changing between a single RU system and an overlapping system dynamically as it travels.

We simulate the trains traveling through the railway for 100 000 hours (about 11 years) and estimate the availability and the MTTF of train network communication service. Via Monte-Carlo simulation, we compared the impact of different numbers of RUs, varying from 12 to more than 20. Figure. 5 and 6 show the availability and reliability metric MTTF for network and service. A direct computation of the series system helps us validate this result.

Obviously, neither availability nor reliability from these two perspectives is the same. For operators, when the number of RUs is below 20, some parts of the railway are always covered by a single RU. The more RU installation is dense, the larger the number of these single RU zones. The network availability and MTTF thus decrease with the number of RUs. However, if when the number of RUs is more than 20, there is a sudden jump. In fact, the RU setup is considered fully redundant everywhere, covered by at least two RUs (this redundant layout, in reality, is often not affordable for a network operator). The network service availability obtains nine nines (99.9999999%), and the MTTF is largely improved.

For train service, it only considers the RUs it can connect to at its position. A failed RU far from where the train is would not impact end-to-end service delivery for the train. At the overlapping zone, the re-establishment procedure helps the train to resume the connection if one of the

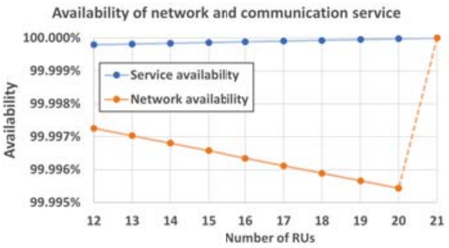

Fig. 5. Number of RUs' impact on network and service availability.

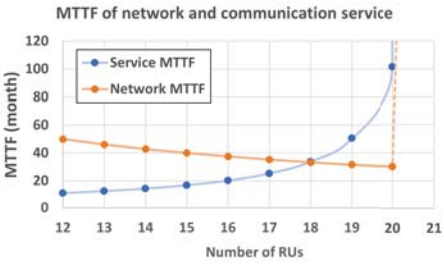

Fig. 6. Number of RUs' impact on network and service MTTF.

RU in the overlapping zone fails. Therefore, the more RUs installed, the less time it spends in a single RU area, and the more service can be guaranteed by at least two RUs in the overlapping area. Then the train communication service availability increases with the density of RU installation. With more than 20 RUs in the railway, the communication service availability reaches even 11 nines. However, the Radio Unit is expensive, and it is hard to do maintenance as they are often distributed. With a limited budget, one of the possible solutions could be deploying RUs according to geographical information of the train route and upgrading the existing 3G/4G facility.

### 4.2. *Random failures*

In the second scenario, we remove the assumption of high reliability on the rest of the network. All elements in gNBs and the CN can fail. Then the system becomes more complex. Still, we compare different Radio Unit densities alongside the railway. The simulation time is 100 000 hours to generate enough failure in the system.

For the network operators, the system is considered available when all network elements work as initially expected to provide end-to-end service, re-establishment request, and HO request anywhere in the considered railway network. The time to fail is the time from when at least one network element fails to when all the failed network elements are repaired.

For the high-speed train, the service is considered available when its connection is established, and all the UP functions it uses work. HO procedure provides seamless connection as it induces no service interruption and thus enhances service reliability. On the other hand, the re-establishment procedure helps an end-user reconnect to the network from either UP or HO failure. Re-establishment can not maintain a connection and always comes with a service interruption. Therefore, unlike HO, the re-establishment procedure can only enhance service availability but does not contribute to service reliability.

The estimated reliability and availability for the network and service from the simulation are shown in Table 3. Similar to the previous scenario, while we increase the number of RUs, the network availability and reliability decrease. However, for communication service, there are more failures during a train's mission, especially minor failures when the number of RUs increases. The re-establishment procedure can guarantee availability since the overlapping area gets larger. Nevertheless, as the number of failures still increases, the MTTF gets shorter, resulting in less reliable communication service. A possible solution for enhancing reliability could be adding redundant items, which may be energy-consuming and expensive for train and network operators.

Table 3. Performance with random failures

| Number of RUs | Network availability | Network MTTF (hours) | Service availability | Service MTTF (hours) |
|---|---|---|---|---|
| 12 | 99.86058% | 55 | 99.99456% | 359 |
| 13 | 99.84895% | 52 | 99.99512% | 344 |
| 14 | 99.83789% | 50 | 99.99571% | 333 |
| 15 | 99.82612% | 48 | 99.99628% | 319 |
| 16 | 99.81485% | 46 | 99.99686% | 308 |
| 17 | 99.80219% | 44 | 99.99742% | 298 |
| 18 | 99.79151% | 42 | 99.99801% | 288 |
| 19 | 99.78031% | 41 | 99.99859% | 279 |
| 20 | 99.76875% | 39 | 99.99917% | 270 |

## 5. Conclusion

This paper discussed the reliability of 5G and Beyond network applications on high-speed trains from two different angles. Service operators often focus on the overall system availability and reliability to provide end-to-end connection and signaling requests for the end-users everywhere in the network. In comparison, a high-mobility end-user focuses only on local issues. That is why high-speed train service has a different estimation of reliability and availability than the telecommunication network itself.

We also modeled both the 5G and Beyond network and the high-speed train to simulate how high-speed train interacts with the network by re-establishment and HO procedures. The discrete event simulation helps us understand the different perspectives of network operators and service users on reliability and availability. The result also shows how they change with the density of the Radio Unit facility alongside the railway.

Our assumptions on the radio interface are ideal. Many aspects, such as weather conditions and moving speed, can cause other types of failures during the re-establishment and HO procedures. The failure rates of the system are assumed to be constant. When considering aging systems, degradation models should be applied. However, our current work has already provided valuable information on the reliability challenges of 5G and Beyond networks for high-speed train services.

The continuation of this work will focus on building an analytical model of the complex network system to validate our proposed approach and compare the performance with the discrete-event simulation. Further cooperation with railway companies will help refine the model by including additional information, such as railway geographical coordinates and train schedules, which will add more value to the approach.

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