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High-mobility 5G communication service: availability and reliability analysis

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Abstract—5G, the latest generation of cellular technology, is designed to support the various use cases of multiple industries. Railway transport is one of the most challenging usage scenarios the 5G system encounters. The telecommunication network service provided by 5G is crucial to guarantee the quality and safety of train traffic. Therefore, estimating the availability and reliability of such network service is necessary. This article separates spatially and temporally the 5G network into subsystems. This article also provides methods and calculation expressions for evaluating the availability and reliability of subsystems as well as the overall network service.

Index Terms—5G, network service, service availability, reliability, railway.

I. INTRODUCTION

With the fast worldwide development of railway systems, especially high-speed railways, the demand for mobile services has dramatically grown during the last decade. It is necessary to provide stable and reliable railway services to the massive passenger flow. The current railway-oriented telecommunication system, GSM-R, faces a decommission issue and can no longer satisfy the demanding requirements of high-speed transport service [1]. A new telecommunication network based on 5G is designed to be the successor of the GSM-R [2].

The unavailability and unreliability of network service are the main factors that seriously impact train service. Once the connection is lost, the train cannot be tracked, and signal transmission with the control center and information exchange will be interrupted. As communication networks become more complex, finding a practical way to estimate and improve the network service availability and reliability for railway communication service usage before replacing the current telecommunication system with 5G is essential.

This paper introduces a method to spatially and temporally regroup the 5G system into subsystems for high-mobility communication services. The network service availability and reliability are evaluated by combining series-parallel system availability and reliability analysis of the subsystems.

The structure of this paper is organized as follows. The telecommunication network for high-mobility users is introduced in Section II. Section III presents the regrouping of the network system and the method to assess network availability

and reliability. Section IV focuses on series-parallel subsystem availability and reliability analysis. Numerical evaluation is showcased in Section V. Finally, Section VI concludes the paper with some remarks.

II. 5G NETWORK FOR RAILWAY COMMUNICATION

In a 5G network, an End-to-End (E2E) service connection is established through a Radio Access Network (RAN), which connects devices to other parts of a network via radio connections, and a Core Network (CN), which manages the connection to the service platform or the internet. By introducing Network Function Virtualization (NFV) and Software Defined Networking (SDN) technologies [3] into 5G, the network is virtualized and can be flexibly deployed and easily managed. After virtualization, RAN and CN are virtualized, for example, as microservices in containers hosted on physical infrastructure.

When a 5G network is applied to high-mobility scenarios, some components may need multiple instances and be distributed along the railway track due to the radio coverage distance constraints and service latency requirements. A user will only connect to the RAN components covering it, as shown in Fig. 1. Therefore, at a given position, the train only establishes an E2E connection via the reachable local RAN components. The local RAN is connected to an aggregated CN. The CN components are often located in a data center far from the RANs. Sometimes, a train is reachable by multiple RAN components, like in Zone 2 in Fig. 1. This zone is also called an overlapping area, covered by multiple radio antennas. Sometimes, the train runs in the zone covered by only one RAN radio antenna, as Zone 1 in Fig. 1.

The 5G network is supposed to provide various high-availability and high-reliability railway communication services, including voice and data communication. These services are based on user plane E2E communication. This E2E communication requires all user plane network components to operate correctly. Inspired from [4], under the context of 5G for high-mobility trains, the network service availability can be defined as the probability that the E2E connection is available at any instant. Reliability is often used to characterize if a

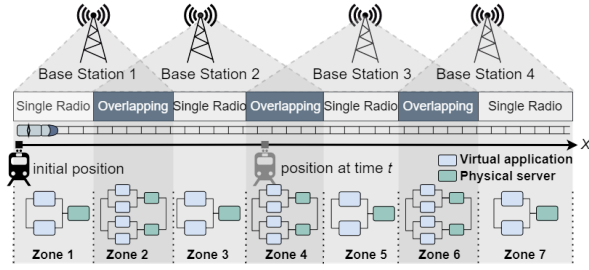


Fig. 1. Example of 5G network along a railway track.

system is appropriately working during a specific period of time [5]. The 5G network we consider is a repairable system. We use Mean Time To Failure (MTTF), the average time the E2E connection lasts, and Mean Time To Repair (MTTR), the average time to repair the E2E connection, to estimate the network service reliability. When the time moment in the availability definition t tends to infinity, the steady-state availability equals $MTTF/(MTTF + MTTR)$ [6].

III. SYSTEM DECOMPOSITION

Since not all network components are usable for the train at a given position and time, it is possible to simplify the 5G system by considering different subsystems when assessing the network service availability and reliability.

We set the length of the considered railway as S . Alongside this rail line, N Base Stations $BS = \{bs_1, bs_2, \dots, bs_N\}$ are evenly distributed from the start $x = 0$ to the end $x = S$ of the line. Each base station bs_n can effectively transmit radio signals to end users in a zone with a radius r_n . We divide this rail line into M zones $Z = \{z_1, z_2, \dots, z_M\}$ such that in zones $z_i, z_j, \forall i, j \in \{1, 2, \dots, M\}$, for the corresponding effective covering Base Station ensembles $c_i, c_j \subseteq BS$, we have $c_i \neq c_j$. If in zone z_i , $card(c_i) = 1$, it is called a single covering zone. If $card(c_i) \geq 2$, then it is called overlapping zone.

Fig. 1 shows how zones reconstitute a telecommunication network. The whole system comprises virtual and physical components for RAN and CN. At the moment t , the train is in the middle of the train line of zone z_4 and is reachable to the second and third Radio Base Stations. The covering Base Stations are $c_4 = \{bs_2, bs_3\}$. Each Base Station can establish an E2E connection by a series-parallel network function system, which is composed of two virtual applications and one physical server (a simplified demonstrative example). These two series-parallel systems are also in parallel and form a subsystem for zone z_4 . When the train enters zone z_5 , the only effective covering Base Station is $c_5 = \{bs_3\}$. The subsystem for zone z_5 consists of two virtual components and one physical component. With M zones, the entire system can be regrouped into M subsystems.

The availability of a train network service is the average percentage of available time that the train can connect to the Data Network via at least one subsystem. The reliability of a train network service is the capacity to provide E2E connection

without failure, which is characterized by the Mean Time Between Failures (MTBF) of the service in the present study.

The availability and reliability of one subsystem provide the availability and reliability for the communication service of a train running at this specific zone. Although some components could belong to multiple subsystems by this regrouping, the failures of these subsystems are assumed to be independent. For the train use cases, these subsystems are temporally and spatially independent. At a given moment t , the train is located only at one position and connects to only one subsystem. The train service's available time can be computed as the sum (superposition) of the available time of those subsystems it passes.

$$A_{train} = \frac{\sum_{i=0}^M A_{subnet_i} \cdot T_i}{T_{total}} \times 100\% \quad (1)$$

Equation 1 calculates the service availability. A_{subnet_i} is the availability of the i -th subsystem. T_i is the train passing time at zone z_i . The train network service availability shows the percentage of time the train can use the E2E communication during the trip.

The number of failures of the train service for a given duration that the train stays in the subsystem can be deduced from the reliability of the subsystem. Then, by assuming these subsystems are independent, it is possible to extract the MTBF for the overall train service.

$$MTBF_{train} = \frac{T_{total}}{\sum_{i=0}^M \frac{T_i}{MTTF_i + MTTR_i}} \quad (2)$$

In Equation 2, the sum of $MTTF_i$ and $MTTR_i$ is the MTBF of the i -th subsystem. T_i is the train passing time at zone z_i . The passing time divided by MTBF at zone z_i is the number of failure occurrences when the train passes zone z_i . The train network service reliability indeed describes how often an E2E service interruption may happen during the trip.

IV. SUBSYSTEM AVAILABILITY AND RELIABILITY

A first assumption to simplify the considered subsystems model is that all components, whatever their nature, physical or virtual, their failure processes follow the exponential law, and so do their repair processes. Based on this assumption, we create a state space model of the subsystem. The m -th subsystem is an ensemble of m_k components, $S_m = \{e_1, e_2, \dots, e_{m_k}\}$. There will be 2^{m_k} states in total, as each element can be either working or failed.

An example of a subsystem with three elements (two identical virtual component instances and one server) is the subsystem in Zone 1. The two virtual functions are in parallel to provide redundancy. If one virtual component fails, the other keeps the subsystem's virtual part alive. The server and the virtual functions are in series. The whole subsystem fails if the only server or the parallel virtual part fails.

In this subsystem, each component is either in the state "Working" or "Failed". TABLE I gives the entire eight subsystem states. The reliability of a repairable series-parallel system can not directly be solved using tools like the Reliability Bloc

Diagram. The state space models are preferred. We build a Markov chain [7] with this list of possible states. The possible transition paths are shown in the figure of Continuous-Time Markov Chains (CTMC) in Fig. 2. λ and μ represent the element failure and repair rate respectively. With the help of the transition rate matrix of the CTMC, the stationary distribution of the CTMC, π can be obtained. We can then deduce the subsystem's availability.

TABLE I
STATES OF THE SUBSYSTEM CONTAINING TWO VIRTUAL COMPONENTS
AND ONE SERVER

Chain State	Component state			System state
	Virtual 1	Virtual 2	Server	
1 (1,1,1)	Working	Working	Working	Working
2 (0,1,1)	Failed	Working	Working	Working
3 (1,0,1)	Working	Failed	Working	Working
4 (1,1,0)	Working	Working	Failed	Failed
5 (0,0,1)	Failed	Failed	Working	Failed
6 (1,0,0)	Working	Failed	Failed	Failed
7 (0,1,0)	Failed	Working	Failed	Failed
8 (0,0,0)	Failed	Failed	Failed	Failed

The set of chain states $CS \in \{1, 2, 3, 4, 5, 6, 7, 8\}$ corresponds to the combination of component states in the subsystem. Simulation results show that the subsystem stays short at a transient state and moves fast to a steady state. A detailed example will be given in Section V-A. Supposing $p(i, t)$, $i \in \{1, 2, 3, 4, 5, 6, 7, 8\}$ represents the probability of the subsystem being at state i at time t . In steady-state SS , the probability of the subsystem at states $\{1, 2, 3\}$ is $p(SS = \text{"Working"}) = \lim_{t \rightarrow +\infty} p(\{1, 2, 3\}, t)$. This distribution gives us a rapid answer to compute subsystem availability, which is equivalent to the sum of the first three items of π .

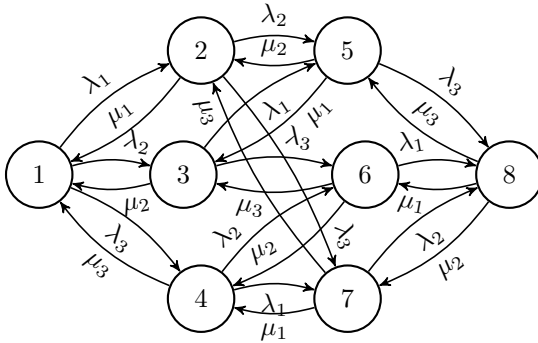


Fig. 2. Subsystem represented by a Continuous-Time Markov Chain.

The stationary distribution of the subsystem states $\pi = \{p_{1\infty}, p_{2\infty}, \dots, p_{8\infty}\}$ can be directly computed from the transition matrix of the CTMC. The availability of the series-parallel subsystem by adding the stationary distribution of all "Working" states is:

$$A_{subnet} = \sum_{i=1,2,3} p_{i\infty} \quad (3)$$

However, it could be more complicated when computing the subsystem's reliability. Instead of looking at all changes of states, we consider two Discrete-Time Markov processes: the failure process and the repair process.

For the failure process, we consider the transitions inside "Working" states and from "Working" states to "Failure" states. This process starts from the subsystem's recovery and ends with the state changed to $CS \in \{4, 5, 6, 7\}$, represented by recurrent states, as shown in Fig. 3. The transition probability of this Discrete-Time Markov Chain is deduced from the CTMC. It shows how the subsystem definitively changes from one state to another. Each transition corresponds to a state-changing event. For example, the state-changing probability from state 1 to state 2 in Fig. 3 is the probability of moving to state 2 after the first state-changing event from state 1. We use variables τ_1, τ_2, τ_3 to represent the failure time of component 1, 2 and 3. The state-changing probability from state 1 to state 2 is $\text{Prob}\{\min(\tau_1, \tau_2, \tau_3) = \tau_1\} = \frac{\lambda_1}{\lambda_1 + \lambda_2 + \lambda_3}$.

We describe this Markov Chain of failure process by a stochastic transition matrix P_F . The initial state is the state of the very moment that the subsystem is repaired to "Working" state. The chain has a final state as the failure process always ends with the connection becoming unavailable. That is the state of the very moment that the subsystem for the first time goes into "Failure" state. Since state 8 is not a direct "Failure" state and is only reachable from another "Failure" state $CS \in \{4, 5, 6, 7\}$, state 8 is not engaged during this process. As a result, we define the process initial state distribution π_F^0 and final state distribution π_F^∞ . We get the following relations:

$$\pi_F^0 = [p_{F1}^0, p_{F2}^0, p_{F3}^0, p_{F4}^0, p_{F5}^0, p_{F6}^0, p_{F7}^0, p_{F8}^0] \quad (4)$$

$$\pi_F^\infty = [p_{F1}^\infty, p_{F2}^\infty, p_{F3}^\infty, p_{F4}^\infty, p_{F5}^\infty, p_{F6}^\infty, p_{F7}^\infty, p_{F8}^\infty] \quad (5)$$

$$\lim_{k \rightarrow +\infty} \pi_F^0 \times P_F^k = \pi_F^\infty \quad (6)$$

where:

$$\sum_{i=1}^8 p_{Fi}^0 = 1, \text{ and } p_{Fi}^0 = 0 \text{ for } i \in \{4, 5, 6, 7, 8\}$$

$$\sum_{i=1}^8 p_{Fi}^\infty = 1, \text{ and } p_{Fi}^\infty = 0 \text{ for } i \in \{1, 2, 3, 8\}$$

For the repair process, we consider the opposite. All start from "Failure" states $CS \in \{4, 5, 6, 7\}$. This process ends by reaching the states $CS \in \{1, 2, 3\}$, represented by recurrent states, as shown in Fig. 4. The transition probability is also deduced from the CTMC of the subsystem.

We describe this Markov Chain by a transition matrix P_R . The initial state is the state of the very moment that the subsystem failed to "Failure" state. The final state is the state of the very moment that the subsystem, for the first time, goes into "Working" states. Since state 8 is only reachable from another "Failure" state $CS \in \{4, 5, 6, 7\}$, the initial "Failure" state can not be 8. As a result, we define the process initial state π_R^0 and final state π_R^∞ .

We get the following relations:

$$\pi_R^0 = [p_{R1}^0, p_{R2}^0, p_{R3}^0, p_{R4}^0, p_{R5}^0, p_{R6}^0, p_{R7}^0, p_{R8}^0] \quad (7)$$

$$\pi_R^\infty = [p_{R1}^\infty, p_{R2}^\infty, p_{R3}^\infty, p_{R4}^\infty, p_{R5}^\infty, p_{R6}^\infty, p_{R7}^\infty, p_{R8}^\infty] \quad (8)$$

$$\lim_{k \rightarrow +\infty} \pi_R^0 \times P_R^k = \pi_R^\infty \quad (9)$$

where:

$$\sum_{i=1}^8 p_{Ri}^0 = 1, \text{ and } p_{Ri}^0 = 0 \text{ for } i \in \{1, 2, 3, 8\}$$

$$\sum_{i=1}^8 p_{Ri}^\infty = 1, \text{ and } p_{Ri}^\infty = 0 \text{ for } i \in \{4, 5, 6, 7, 8\}$$

When the subsystem is in steady state, we have:

$$\pi_F^\infty = \pi_R^0 \quad (10)$$

$$\pi_R^\infty = \pi_F^0 \quad (11)$$

By solving Equations 4 - 11, we obtain the initial and state distribution of “Working” and “Failure” states.

Each transition step corresponds to a sojourn time in the Discrete-Time Markov Chain in the CTMC. We define the state sojourn time T_i^s as the mean time between the subsystem entering state i and leaving the state i in the CTMC. We also define the mean state failure time T_i^F as the mean time between the subsystem entering “Working” state i and the first time entering a “Failure” state. It is the sum of a set of transition steps in the Discrete-Time Markov Chain for the failure process. The MTTF we intend to compute is the mean state failure time of all “Working” states.

$$MTTF = \sum_{i \in \{1, 2, 3\}} \frac{p_{Fi}^0}{\sum_{j \in \{1, 2, 3\}} p_{Fj}^0} \cdot T_i^F \quad (12)$$

Note that for this case, $\sum_{j \in \{1, 2, 3\}} p_{Fj}^0 = 1$.

The Markov Chain of the failure process in Fig. 3 gives the following relations:

$$T_1^F = T_1^s + \frac{\lambda_1}{\lambda_1 + \lambda_2 + \lambda_3} \cdot T_2^F + \frac{\lambda_2}{\lambda_1 + \lambda_2 + \lambda_3} \cdot T_3^F \quad (13)$$

$$T_2^F = T_2^s + \frac{\mu_1}{\mu_1 + \lambda_2 + \lambda_3} \cdot T_1^F \quad (14)$$

$$T_3^F = T_3^s + \frac{\mu_2}{\lambda_1 + \mu_2 + \lambda_3} \cdot T_1^F \quad (15)$$

For Equation 13, the average failure time T_1^F includes the time spent in different steps. In the first step, the subsystem leaves state 1 and spends time T_1^s , the CTMC sojourn time in state 1. According to the state transition probabilities, from state 1, the subsystem may change to state 2, 3, or 4. In the next step, the process ends if the subsystem directly fails to state 4. Otherwise, it will spend time T_2^F and T_3^F accordingly for the rest of the failure process. The average failure time of state 2 and 3 can be represented similarly in Equations 14, 15. Finally, the MTTF is obtained by solving Equations 12 - 15.

The MTTR is the total transition time of a subsystem being repaired during failure. We define the mean state repair time T_i^R as the average time between the subsystem entering a specific “Failure” state i and the first time entering a “Working” state. Therefore, the MTTR is the mean sojourn time at all “Failure” states.

$$MTTR = \sum_{i \in \{4, 5, 6, 7, 8\}} \frac{p_{Ri}^0}{\sum_{j \in \{4, 5, 6, 7, 8\}} p_{Rj}^0} \cdot T_i^R \quad (16)$$

Note that for this case, $\sum_{j \in \{4, 5, 6, 7, 8\}} p_{Rj}^0 = 1$ and $p_{R8}^0 = 0$.

The Markov Chain of the repair process in Fig. 4 gives the following relations:

$$T_4^R = T_4^s + \frac{\lambda_1}{\lambda_1 + \lambda_2 + \mu_3} \cdot T_7^R + \frac{\lambda_2}{\lambda_1 + \lambda_2 + \mu_3} \cdot T_6^R \quad (17)$$

$$T_5^R = T_5^s + \frac{\lambda_3}{\mu_1 + \mu_2 + \lambda_3} \cdot T_8^R \quad (18)$$

$$T_6^R = T_6^s + \frac{\mu_2}{\lambda_1 + \mu_2 + \mu_3} \cdot T_4^R + \frac{\lambda_1}{\lambda_1 + \mu_2 + \mu_3} \cdot T_8^R \quad (19)$$

$$T_7^R = T_7^s + \frac{\mu_1}{\mu_1 + \lambda_2 + \mu_3} \cdot T_4^R + \frac{\lambda_2}{\mu_1 + \lambda_2 + \mu_3} \cdot T_8^R \quad (20)$$

$$T_8^R = T_8^s + \frac{\mu_1}{\mu_1 + \mu_2 + \mu_3} \cdot T_6^R + \frac{\mu_2}{\mu_1 + \mu_2 + \mu_3} \cdot T_7^R + \frac{\mu_3}{\mu_1 + \mu_2 + \mu_3} \cdot T_5^R \quad (21)$$

For Equation 17, the average repair time T_4^R includes the time spent in different steps. In the first step, the subsystem leaves state 4 and spends time T_4^s , the CTMC sojourn time in state 4. According to the state transition probabilities, from state 4, the subsystem may change to state 1, 6, or 7. In the next step, the process ends if the subsystem is directly repaired to state 1. Otherwise, it will spend time T_6^R and T_7^R accordingly for the rest of the failure process. The average failure time of states 5, 6, 7, and 8 can be represented similarly. Finally, the MTTR is obtained by solving Equations 16 - 21.

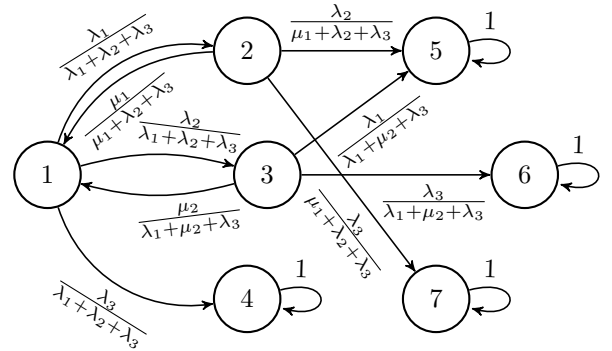


Fig. 3. Failure process represented by a Discrete-Time Markov Chain.

Although only a three-element system is demonstrated, the proposed method can also be applied to any series-parallel system. However, the state space will increase exponentially with the number of considered components.

V. NUMERICAL EVALUATION

A. Example of a three-element subsystem

Now we consider a system with two virtual components, #1 and #2, and one physical component, #3. The virtual components are the applications that are often threatened by operational failures. The physical component often refers to a physical server where the applications are hosted, which is less likely to fail. Repairing a virtual component takes only

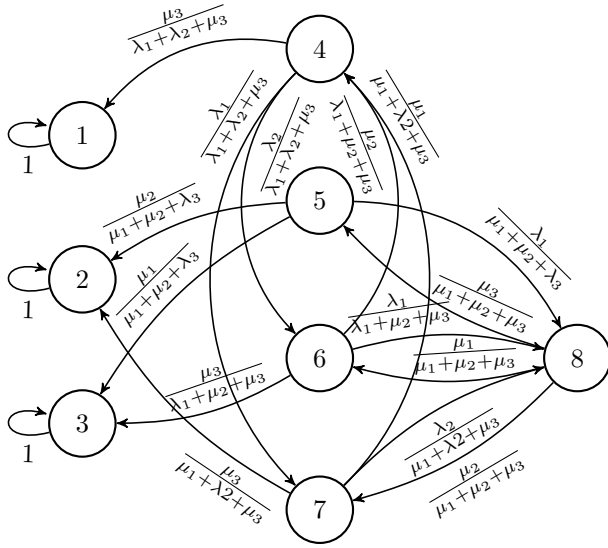


Fig. 4. Repair process represented by a Discrete-Time Markov Chain.

a few seconds by restarting the application. However, when a physical server fails, it must be repaired manually. TABLE II shows the failure and repair rates.

TABLE II
FAILURE AND REPAIR RATES OF COMPONENTS

Failure process			
Component	Symbol	Rate [hour ⁻¹]	MTTF
1 - virtual	λ_1	0.005	200 hours
2 - virtual	λ_2	0.005	200 hours
3 - physical	λ_3	0.0002	5000 hours
Repair process			
Component	Symbol	Rate [hour ⁻¹]	MTTR
1 - virtual	μ_1	360	10 seconds
2 - virtual	μ_2	360	10 seconds
3 - physical	μ_3	1	1 hour

After building the CTMC model and the transition rate matrix, we calculate the transient availability of such system as shown in Fig. 5. Initially, the brand new subsystem has 100% availability. After a few hours, it gradually drops to the stationary availability around 99.98%. The steady state of this CTMC also gives us a similar result as shown in TABLE III. The availability of the subsystem is $A_{subsystem} = p_{\infty}^1 + p_{\infty}^2 + p_{\infty}^3 = 99.9800\%$. This shows that, at a stationary state, 99.9800% of the time, this subsystem is available to provide application service to the end user.

TABLE III
STATIONARY STATE DISTRIBUTION OF THE SUBSYSTEM

State	Probability	State	Probability
1	9.99772e-1	5	1.92857e-10
2	1.38857e-5	6	2.77715e-9
3	1.38857e-5	7	2.77715e-9
4	1.99954e-4	8	3.85715e-14

As for reliability, two Discrete-Time Markov Chains are built for failure and repair processes. The subsystem repair processes are assumed to be parallel, i.e., each component can fail or be repaired independently. Equations 4 - 11 give the initial and final states of failure and repair processes as shown in Table IV.

TABLE IV
INITIAL AND FINAL STATE DISTRIBUTION

Failure process		Repair process	
p_{F1}^0	9.99278e-1	p_{R1}^{∞}	9.99278e-1
p_{F2}^0	3.60850e-4	p_{R2}^{∞}	3.60850e-4
p_{F3}^0	3.60850e-4	p_{R3}^{∞}	3.60850e-4
p_{F4}^{∞}	9.99278e-1	p_{R4}^0	9.99278e-1
p_{F5}^{∞}	6.93943e-4	p_{R5}^0	6.93943e-4
p_{F6}^{∞}	1.38789e-5	p_{R6}^0	1.38789e-5
p_{F7}^{∞}	1.38789e-5	p_{R7}^0	1.38789e-5

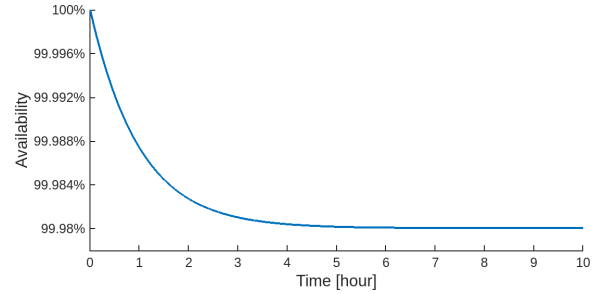


Fig. 5. Transient availability of the subsystem.

Using Equations 12 - 21, we obtain the MTTF and MTTR of the subsystem. MTTF of the subsystem is 4996.53 hours, and MTTR is 0.999307 hours. The physical server failure primarily dominates the subsystem failure time, and the repair time is also dominated by physical server repair because, unlike the virtual components, the physical component is not designed with redundancy in the subsystem. That shows that a possible way to improve the subsystem availability is to reduce physical component failure and repair time.

B. From subsystem to the whole system

The considered railway is 100 km long. A train runs at a constant speed, 200 km per hour. We assume the trains are well-timed and always pass the zone at a fixed time. The information of each zone is given in TABLE V.

It is imagined that along the railway line, all Radio Base Stations with their connected components in Fig. 1 have the same structure. Each of them forms a sub-network as the one in Section V-A. In Zone 1, 3, 5, and 7, the subsystem is the same as in Section V-A. While in Zone 2, 4, and 6, the subsystems are in the form of two sub-networks of Section V-A working in parallel. The reliability and availability of these subsystems are computed following the proposed method.

The average available network service time and average number of network service failures when a train passes each

TABLE V
SUBSYSTEM CHARACTERISTICS OF EACH ZONE

Zone	Expected passing time [min]	Availability	MTBF
1	3.6	99.980004%	4997.5 hours
2	6.6	99.999996%	1426.5 years
3	2.4	99.980004%	4997.5 hours
4	4.5	99.999996%	1426.5 years
5	3.3	99.980004%	4997.5 hours
6	6.0	99.999996%	1426.5 years
7	3.6	99.980004%	4997.5 hours

of the seven zones are given in TABLE VI. By summing up the result in the subsystems, the total mean network service available time of the 100 km route is 29.99742 minutes out of a 30-minute ride. The network service availability is 99.9914%. The total mean number of generated failures is $4.30441e-5$. In other words, there will be one failure about every 11616 running hours, which is one failure every 16 months if the train keeps running on this railroad section 24 hours per day.

TABLE VI
MEAN SERVICE AVAILABLE TIME AND MEAN SERVICE FAILURES

Zone	Available time [min]	Failures
1	3.5992801	$1.20059e-5$
2	6.5999997	$8.80260e-9$
3	2.3995201	$8.00395e-6$
4	4.4999998	$6.00177e-9$
5	3.2993401	$1.10054e-5$
6	5.9999998	$8.00236e-9$
7	3.5992801	$1.20059e-5$

According to the target requirements from [8], for some rail communication services, for example, the train coupling, the targeted communication service availability is 99.9999%. The network we considered is not yet satisfying, and some potential improvements can be made. The first improvement is adding parallel virtual components to each unitary subsystem connected to the Base Station. Instead of 2 virtual components, the unitary subsystem has been upgraded to 3. The second improvement could be adding a redundant parallel physical server to the unitary subsystem. The service availability and reliability comparison is showcased in Fig. 6. Adding parallel virtual components has less impact on availability and reliability since the virtual element is already redundant. Adding a redundant physical component can vastly improve both availability and reliability. On average, the train can connect to network service for over 10 thousand months without interruption. The availability improved to more than seven nines, largely above the requirement.

VI. CONCLUSION

This paper discussed the method of evaluating the availability and reliability of 5G network communication services applied to high-mobility users. The 5G for the railway is larger and more complex than ordinary 5G networks. We proposed decomposing the 5G communication network into spatially and temporally independent subsystems to simplify

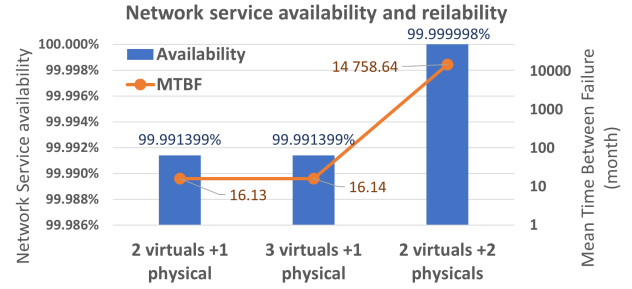


Fig. 6. Service availability and reliability comparison.

the availability and reliability assessment. We use a series-parallel model to estimate the availability and reliability of the subsystems. The overall railway communication service availability and reliability are obtained by combining the evaluation results from subsystems. A numerical example showed that this method could assess a railway communication service's availability and reliability using the network structure and components' properties.

It should be noted that the example we used in the paper is for demonstration. The actual 5G network contains lots of network functions. Even after the regrouping, its subsystems can be more complex than the three-element system. All system states and transitions should be carefully studied for the correct availability and reliability evaluation. Although numerical simulation can be more practical than building Markov Chains, the simulation will take an extremely long time to get accurate results when there are rare events. Besides, using our proposed method, it is easier to change several parameters to compare the network service performance once the Markov Chain is built.

For the next step, the collaboration with railway companies is expected in order to refine and validate the model by considering railway geographical coordinates and train schedules, adding more value to this work.

REFERENCES

- [1] R. He et al., "High-Speed Railway Communications: From GSM-R to LTE-R," *IEEE Vehicular Technology Magazine*, vol. 11, no. 3, pp. 49–58, September 2016.
- [2] International Union of Railways, "FRMCS and 5G for rail: challenges, achievements and opportunities," December 2020. [Online] https://uic.org/IMG/pdf/brochure_frmcs_v2_web.pdf.
- [3] F. Z. Yousaf, M. Bredel, S. Schaller and F. Schneider, "NFV and SDN—Key Technology Enablers for 5G Networks," *IEEE Journal on Selected Areas in Communications*, vol. 35, no. 11, pp. 2468–2478, November 2017.
- [4] M. L. Shooman, *Reliability of Computer Systems and Networks: Fault Tolerance, Analysis, and Design*. New York, NY, USA: Wiley, 2002.
- [5] A. Avizienis, J. -C. Laprie, B. Randell and C. Landwehr, "Basic concepts and taxonomy of dependable and secure computing," *IEEE Transactions on Dependable and Secure Computing*, vol. 1, no. 1, pp. 11–33, January–March 2004.
- [6] B. W. Johnson, *Design and Analysis of Fault Tolerant Digital Systems*. Reading, MA, USA: Addison-Wesley, 1989.
- [7] W.J. Stewart, *Introduction to the Numerical Solution of Markov Chains*. Princeton, NJ, USA: Princeton Univ. Press, 1994.
- [8] 3GPP TS 22.289, "LTE; 5G; Mobile communication system for railways (Release 17)", v17.0.0, May 2022.