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# Model-based dependability evaluation of a Wireless Communication System in a Virtually Coupled Train Set

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## Abstract:

A new paradigm based on the concept of virtual coupling of train sets is being elaborated to provide innovative solutions so as to increase efficiency, operational flexibility, line capacity, competitiveness among market players and quality of consumer experience. Train-to-Train (T2T) and Train-to-Ground (T2G) wireless communications will be the backbone for the implementation of the virtual coupling functionalities. In the present paper, we perform a model-based dependability analysis of the wireless communication system under virtual coupling operation. Namely, Stochastic Colored Petri Net (SCPNet) models are developed to depict the exchanges of the various information needed under virtual coupling operation. Dependability evaluation is then performed by means of simulation. In particular, the impact of various communication parameters is scrutinized while taking into account different operational scenarios. The obtained results allow the identification of the most impacting aspects on dependability analysis and provide valuable inputs to support the technological choices in terms of communication to implement virtual coupling.

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*Keywords:* Virtual Coupling (VC), Virtually Coupled Train Set (VCTS), Stochastic Colored Petri Net (SCPNet), Platooning, Train to Train (T2T) communication, Cooperative Braking.

## 1. INTRODUCTION

The main driving force for the Virtually Coupled Train Sets (VCTS) concept is the replacement of the mechanical coupling mechanism and the cooperative movement of trains running on the same line. VCTS enables to build longer consists (single vehicle or a group of vehicles which are not separated during normal operation) between two or more train sets (Flammini et al. (2018), Goikoetxea (2016)). The VCTS concept leverages cooperative movement, which relies on mutual exchange of relevant information such as speed, location, braking curve, among train sets. It allows trains to run at a closer distance than that allowed by traditional Absolute Braking Distance Supervision (ABDS) concept, see Figure 1. In the cooperative movement concept, a train considers the speed and braking curves of the front train, in addition, to those of itself. Thus, the distance between trains is further reduced. Coupled with the moving block operation, which applies, for example to the European Rail Traffic Management System (ERTMS) Level 3 (Ghazel (2014)), even more gain in terms of capacity is expected.

VCTS aims to achieve multiple objectives such as to enhance efficiency and flexibility in consist building, increase line capacity, increase operational flexibility, reduce infrastructure costs and enhance competitiveness versus road

transportation. Consists inside a VCTS can also dynamically modify their composition on the move, *i.e.*, virtual coupling/decoupling of platoons (two or more consists virtually coupled together). VCTS is a distributed system; thus, operations can take advantage of swarm intelligence, unlike today's railway system, which is characterized by centralized intelligence. Because of the swarm concept, VCTS has multiple direct T2T communication among VCTS consists unlike traditional centralized paradigm, where the communication is only between a consist and the zone controller (T2G). The core of the VCTS concept is the capability of the consists of a VCTS to exchange relevant information via dedicated communication links and the ability to maintain headway (distance between trains) control strategy. In the present work, we focus on the dependability (availability, mean time to failure) evaluation of the communication system in a virtual coupling (VC) scenario.

In Parise et al. (2019), authors describe the VC concept and reason about why a system that is hybrid of relative sensors, train to train communication and absolute sensors is required for its implementation. The paper also describes possible future communication technology that can be candidates for VCTS implementation depending on different phases of VC and distance between trains.

In Song and Schnieder (2019), the authors discuss the

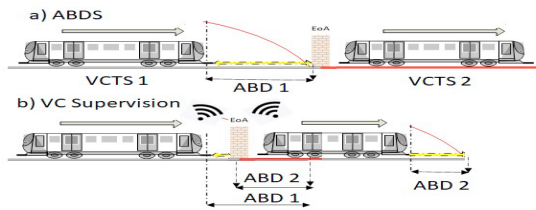


Fig. 1. Virtual coupling: relative braking distance (Canesi and al. (2020))

availability and performance analysis of a T2T data communication system with the help of Stochastic Petri Nets (SPN). The impact of the bit error rate and transmission rate on the update interval and the availability has been analysed. Moreover, the impact of total length and length of different sections of a message on performance is also evaluated.

In Flammini et al. (2018), the authors conduct a performance analysis of several operation modes, namely : ERTMS Full Supervision mode (FS), FS combined with Virtual Coupling and Partial Supervision. With the help of Stochastic Petri Nets, this paper analyzes the impact of parameters such as the coupling and decoupling delays on the line capacity.

In Nguyen et al. (2016), the dependability analysis of the T2G LTE-based communication for train control application in the case of the urban Communication Based Train Control (CBTC) system is presented. Namely, the paper investigates the impact of communication parameters such as transmission delay, retransmission mechanism, and handover performance, on the dependability parameters of the communication system between train and zone controller. The case of Movement Authority (MoA) update is considered for the safe movement of train, while maintaining a safe headway.

Similarly to Nguyen et al. (2016), in the present work, we analyse the impact of communication parameters on dependability attributes in the context of virtual coupling. But unlike the previous case, which considers only a single communication link between train and zone controller for MoA update, we consider multiple communication links between each two VCTS consists, for maintaining a safe headway for the VC platoon. We will present a general approach, which can be used in the future for testing any candidate communication technology, such as those presented in Parise et al. (2019) or others. Evaluation of line capacity is outside the scope of this paper, but we will introduce the functionalities, which involve events from the opening of virtual coupling until the decoupling phase. The communication performance while executing these functionalities can also be analysed based on the developed SCPN models. It should be noted here that the work of Song and Schnieder (2019) can be appropriately adapted to our model. For example, instead of handling one message at a time, multiple concurrent message copies need to be handled because of the retransmission mechanism.

Our work falls within a more general effort, which is being undertaken in the railway domain, that aims to reduce onsite testing as much as possible . The objective is to

drastically reduce the cost and effort in railway projects. In particular, railway stakeholders are willing to widen the application of model-based techniques, and specifically the use of formal methods in engineering control, command and signalling systems for railway. The remainder of the paper is structured as follows: in Section 2, we will describe the Virtual Coupling concept, namely its functional architecture and main functionalities. In Section 3, we will present performance parameters that we aim to investigate for VCTS. For each functionality, we will analyze the impact of communication errors that give rise to events, which are safety-critical or which affect the performance. Next, we will discuss how to model and evaluate the performance of each VCTS function using SCPN models and simulation. In Section 4, we will present a case study that illustrates the analysis of the communication performance, while considering different communication parameters and operational scenarios. Finally, conclusions and future research works are given in Section 5.

## 2. VCTS CONCEPT

### 2.1 Definition

The VCTS concept is currently under development in the framework of Shift2Rail program (<https://shift2rail.org>). This paper will provide general concept and information required for dependability analysis of T2T communication for train sets moving under VC supervision. The detailed architecture, functionality and operational scenarios, *etc.* are presented in the deliverable(Canesi and al. (2020)) but are out of the scope of this paper and are confidential.

The platooning strategy consists of creating different platoons, assigning trains to different platoons, when and where to join and leave the platoon, managing stopping stations *etc.* and the details to execute the whole strategy. It is evaluated based on service demand from customers and mathematical, Artificial Intelligence (AI) and Machine Learning optimization algorithms. This strategy is communicated to the zone controller / RBC (Radio Block Centres) who coordinates with trains to execute the platooning strategy.

### 2.2 Movement of trains under virtual coupling supervision

Virtually coupled trains leverage cooperative braking distance supervision and moving block to maintain small headway. In cooperative braking supervision, the train should also consider the parameters (speed, braking capacity *etc.*) of the train in front in addition to that of itself. As shown in Figure 2, the ZC (zone controller)/RBC initiates the virtually coupling procedure based on the platooning strategy. ZC /RBC sends the platooning strategy to all the trains of the planned virtually coupled platoon. Based on the information received from ZC/RBC, trains exchange relevant information and perform a secure handshake before establishing a communication.

Trains exchange relevant information required for movement under virtual coupling supervision. The following train approaches the front train under the ABDS until the handover place after which coupled trains move under VCS (virtual coupling supervision) .

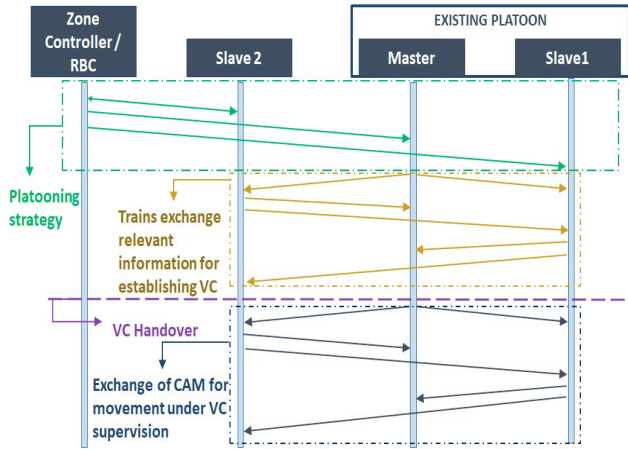


Fig. 2. VCTS concept (Canesi and al. (2020))

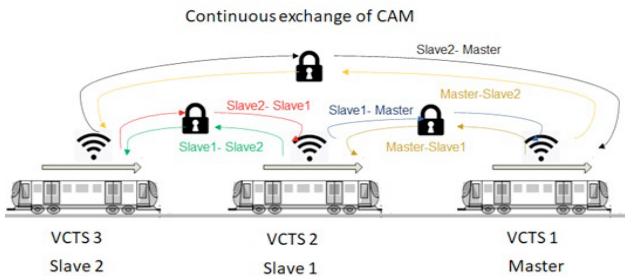


Fig. 3. Supervising Train Separation Distance (Canesi and al. (2020))

Supervising train separation distance while trains are moving under VCS requires a continuous exchange of cooperative awareness messages consisting of speed, distance, braking curve etc. Based on the exchanged CAM, following trains reduce speed or accelerate to maintain a safe distance from the rear end of the preceding train, and eventually from the following train.

The speed of trains, the separation distance between trains and the dependability of operation depend significantly on the performance of the T2T communication system. Therefore, this paper presents a preliminary study demonstrating how to model and analyze the dependability of a communication system in a virtually coupled train set.

Several wireless technologies could be suitable for VCTS such as ITS-G5, LTE, 5G in the millimetric bands, etc. The suitability of the communication technology and its performance changes, depend on the factors such as radio environment, communication range, speed and separation distance. These factors affect communication system performance by impacting communication parameters such as for example BER (bit error rate) or Packet error rate and end-to-end communication delay.

Therefore, in this work we present a general modelling and evaluation approach that shows how the communication system's dependability attributes are changing depending on some parameters, namely communication delay, BER and number of trains inside the virtually coupled platoon.

### 3. DEVELOPMENT OF THE BEHAVIOURAL MODELS FOR PERFORMANCE ANALYSIS

In this section, we will recall the main objectives of our work and the performance parameters to be considered for VCTS.

#### 3.1 Problem Statement

Safety and performance are two essential aspects of VCTS evaluation. The safety aspect is related to the safe movement of trains by maintaining a safe headway between trains under VC supervision as well as ABDS (ATP supervision). Nguyen et al. (2016) presents an approach and some results for safety evaluation in ABDS scenario. In this paper, we will present the approach and results in VC supervision scenario (*movement of trains under virtual coupling supervision*), as discussed in subsection 2.2. The performance (e.g. line capacity) is evaluated for a specific platoon composition and strategy while considering a specific operational scenario. Such evaluation enables us to assess the gain in terms of line capacity and operational efficiency. For performance evaluation, we need to consider all the manoeuvres (from VC initiation to the termination of VC and trains movement under ABDS) for the entire journey holistically, as discussed in subsection 2.2. While such a holistic evaluation is outside the scope of this paper, we provide the basis for such an evaluation in the following.

#### 3.2 Considered communication parameters

We have taken the same communication parameters than in Nguyen et al. (2016).

- **Transmission delay:** let  $D_z$  ( $D_t$ ) be the end-to-end transmission delay of the packet exchanged between a train and the zone controller (another train). We will use *normal log* distribution for the delay instead of exponential distribution to better handle lower and upper bounds.
- **Retransmission mechanism:** when a message is sent from train to train (CAM- during Supervising Train Separation Distance),  $n$  more copies are created. When the transmitting train receives an *ack* ( $T_{ACK}$  time to receive *ack*) by the receiving train, these copies are deleted. After a fixed delay (retransmission time  $T_{RE}$ ), if the transmitting train does not receive an *ack* from the receiving train, the transmitting train sends another packet. Retransmission is repeated until an *ack* is received or all the message copies are exhausted.

The retransmission is a safety strategy which is implemented as a result of hazard and risk analysis to achieve required safety. Retransmission policy is used for messages between zone controller / RBC and trains (initiation request for virtual coupling, secure handshake and exchange of relevant information) and messages between trains (secure handshake, exchange of relevant information and continuous CAM).

- **Obsolescence deadline:** after a deterministic delay  $D$ , a message is not considered as valid. A message is also regarded as invalid in case of packet loss.

### 3.3 System Modeling and Simulation

Stochastic Colored Petri Net (SCPN) is a mathematical modelling formalism that can be used for the evaluation of time-dependent behaviours, see Gehlot and Nigro (2010). It combines the strength of GSPN (Generalised Stochastic Petri Nets, see Talebberouane et al. (2016)) with a high-level programming language, making SCPN very powerful in modelling large, complex and dynamic systems in a compact way. We recall that our objective is to conduct the evaluation of several dependability attributes pertaining to communication in the context of virtual coupling.

Let us examine the following scenario: we focus on a railway line with an existing platoon, which has one master (VCTS1) and one slave (VCTS2) as illustrated in Figure 3. ZC (zone controller)/RBC communicates with another slave (VCTS1) and commands it to join the existing platoon to form a new platoon (VCTS1+VCTS2+VCTS3), (see Figure 3).

Under ATP (Automatic Train Protection) supervision (ABDS), the MoA is updated based on train-zone controller communication (single communication link). However, under VC supervision, the headway is updated based on T2T communication. We have to consider  $n \times (n - 1)$  communication links, where  $n$  is the number of trains inside the platoon. For example, in the case of the scenario exposed in Figure 3 that shows 3 VCTS units in the platoon, a total of 6 communication links correspond to Master-Slave1, Master-Slave2, Slave1-Slave2, Slave2-Slave1, Slave2-Master and Slave1-Master. For the communication system to be working (UP), messages from all the six communication links need to be received within the deadline. If anyone or more messages are missing the communication system is considered down. For simplifying the model, we have considered the same (PE-packet error /BER - bit error rate) for communication between each VCTS units regardless of the distance between them.

It is worth noting here that the use of coloured petri nets (SCPN) allows for keeping relatively compact models for the description of such complex scenarios. This benefit would not be possible with non-coloured petri nets (*i.e.*, GSPN in our case).

- **Why did we consider (one hop) direct communication among all the VCTS units?**

Figure 4 shows a linear chain like communication strategy; VCTS1 will send its configuration periodically to VCTS2 but not to VCTS3. Therefore, the updated CAM evaluated by VCTS3 will only consider the configuration of VCTS2 (at time  $nT$ , where  $T$  is period), until it receives the next configuration parameter from VCTS2 at time  $nT + \text{'time to update CAM'}$ . VCTS2 configuration at this time  $nT + \text{'time to update CAM'}$  considers the parameters (at time  $nT$ ) from VCTS1 as well as VCTS3, but this is already too late. Therefore, each VCTS unit should receive configuration parameters from all other VCTS units in the VC platoon. That is why we have considered direct communication ( $n \times n-1$  communication links, as shown in



Fig. 4. Linear communication ( $(2 \times n-1)$  communication links)

Figure 3)) instead of linear communication ( $2 \times n-1$  communication links, as shown in Figure 4)) or any other communication scheme that has fewer communication links as that of direct communication. Direct communication is necessary for VC trains running at a very close distance as the communication bypasses the reaction delay of the transmission system and sensors. In Parise et al. (2019), authors describe the VC concept and reason why a hybrid system of relative sensors, train to train communication and absolute sensors is required for its implementation.

However, if we also relay messages from previous VCTS units with the own message of VCTS units (multi-hop), then we can overcome the above-discussed problem; see Jens et al. (2009) for details. In case periodic messages of each VCTS units and the relayed messages are transmitted independently, then multi-hop is not more efficient than single-hop transmission. Multi-hop can perform better if we use intelligent transmission strategies such as multiplexing of VCTS's own and relayed messages. Every message has header information such as physical layer and medium access layer control data and security-related information. We save overhead on the header by multiplexing messages as one hop direct transmission has  $n \times n-1$  headers while chain like multi-hop transmission has  $2 \times n-1$  headers. The saving on the header gets prominent as the number of VCTS units gets increased beyond a threshold. Therefore, we will compare single-hop to multi-hop transmission performance in our future work when the number of VCTS units in a platoon is high.

#### 3.4 SCPN Model: Supervising Train Separation Distance

As mentioned in the problem statement, present work evaluates the communication system's performance in a virtual coupled train sets moving under VC supervision. In this paper, we will use the TimeNET tool (Kelling et al. (1996)) which allows editing and simulation of SCPN models. Figure 5 and Figure 6 present the SCPN model of the CAM exchanged between VCTS subsystems as shown in Figure 3. The SCPN model is shown in two parts due to space constraint.

After the VC handover, CAM messages are exchanged between each two VC subsystems in parallel. As shown in Figure 3, there are six communication links, which are Master-Slave1, Master-Slave2, Slave1-Slave2, and so on. In Figure 5, tokens at place '*comm\_link*' (box1) represent CAM messages corresponding to each communication link. These CAM messages are transmitted periodically with period  $T_s$  (box2). Transition '*T2*' (box3)

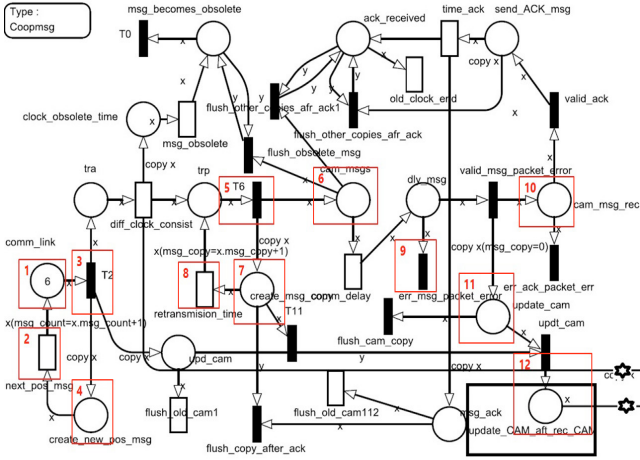


Fig. 5. SCPN Model: Supervising Train Separation Distance first part

(having a deterministic firing delay of  $T_s$ ), place 'create\_new\_pos\_msg' (box4) and transition 'next\_pos\_msg' generate these messages periodically. Original CAM messages reach place 'cam\_msgs' (box6) through transition 'T6' (box5), while  $n$  copies of these CAM messages are transmitted periodically with the help of place 'create\_msg\_copy' (box7) and transition 'retransmission\_time', which emulates the retransmission delay  $TRE$  (box8).

All CAM messages have a communication delay  $Dt$ , which is represented by transition 'comm\_delay' (infinite server). Transition 'err\_msg\_packet\_error' (box9), with a probability  $PET$  that represents message loss due to packet error. Valid messages are received with probability  $1 - PET$  at place 'cam\_msg\_rec' (box10).

When a CAM message is received, as represented by a token at place 'updated\_cam' (box11), the other copies of the same CAM message are flushed with the help of transition 'flush\_cam\_copy'. Based on the received CAM message, the receiver updates its CAM parameters (speed, acceleration etc.) to maintain a safe headway. In the model, as shown in Figure 5 and Figure 6, the received CAM message is modelled as a token at place (box12) 'update\_CAMaft\_rec\_CAM'. As shown in Figure 6, transition 'cam\_msg\_update' (box13) models the time required by a train to update its parameters based on the received CAM message. In turn, the receiver sends the updated parameters (as CAM messages) back to the transmitting train. The updated CAM message (receiver → transmitter) goes through a similar process as the (transmitter → receiver) CAM message, as shown in Figure 6. The updated CAM message, which is received by the transmitting train, modelled as a token at place 'update\_cam1' (box14), is sent to place 'cam\_received' (box15) via transition 'updt\_cam1' (box16). All the other copies of the updated CAM are flushed via transition 'flush\_cam\_copy1'. If the CAM message is not received with updated parameters within the deadline ( $2xD + \text{time to update CAM}$ ), then a token from place 'all\_cam\_msgs\_sent' (box16) triggers transition 'cam\_msg\_missed', moves to place 'msg\_mas\_sl' (box17) and ultimately triggers transition 'T121' to reach a state where the communication system is down, which is represented by a token at place 'sysdown' (box18).

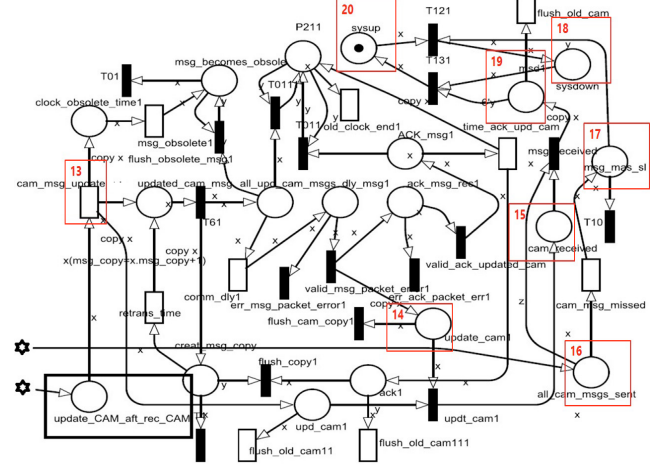


Fig. 6. SCPN Model: Supervising Train Separation Distance second part

If the updated CAM message is received by the transmitting train, then the token from place 'cam\_received' (box15) moves to place 'msd1' (box19) via transition 'msg\_received'. The communication is considered as available for a period  $T_s$  if the updated CAM w.r.t. all the communication links (6 in this case) are received. Therefore, as soon as all CAM arrive, the tokens move through transition 'T131' to place 'sysup' (box20), which models the availability of the communication. In case the system is already up, these tokens are flushed via transition 'flush\_old\_cam' before the arrival of a new CAM message. Place 'clock\_obsolete\_time' receives a token corresponding to a CAM message of each communication link, periodically, to monitor the obsolete time. In case the communication delay exceeds the obsolete time, the CAM message is considered as invalid and is flushed from place 'cam\_msgs' via transition 'flush\_obsolete\_msg'.

#### 4. DEPENDABILITY ANALYSIS: RESULTS

As results, we will present the impact of different parameters such as 'transmission error', 'transmission latency' and 'number of VCTS units inside a virtually coupled platoon' on dependability. Results will help us trace back the requirements to physical/architectural/strategical elements that impact these parameters.

##### 4.1 Input parameters

We recall here that every  $T_s$ , each VCTS unit sends a CAM message to each other VCTS unit, so as the receiving VCTS unit updates its parameters and sends back updated CAM to the transmitting VCTS unit as shown in Figure 3. We will use  $T_s$  as a time unit for evaluating the dependability parameters. If the updated CAM is received back, the system is available for that period; otherwise, the system is down.

Table 1 represents the values for all the input parameters that we used in our model.

Table 2 summarizes the simulation results for the dependability attribute downtime, which is the average period for which the communication system is unavailable. Column 'Mean value' gives the mean value of the simulated downtime. Here, the confidence interval for 95 % confidence

is high even after 40 to 80 minutes of simulation (this time refers to the time the simulation ran on our system). For example, in the case of 3 VCTS units ( $N=6$ ), this confidence interval (as shown in Table 2) is obtained even after a model simulation time of more than 50 million ms (millisecond) (simulation time on system +1 hour). Therefore, in our future work, we will explore paths to improve this confidence interval. One interesting way is to use rare event simulation techniques such as that discussed in Zimmermann et al. (2016).

The analysis discussed so far in this paper is based on the assumption that all the communications between VCTS units are identical and independent from each other. Therefore, we can use the simulation result of one of the cases such as  $N=6$  (VCTS units =3) to evaluate the downtime (dt) and availability (av) of other cases that have different number of VCTS units 2, 4, 5 and 6 (i.e.,  $N=2, 12, 20$  and 30). This analytical use of simulation results helps to verify the simulation results and also helps in evaluating the dependability attributes of platoons that have a higher number of VCTS units.

Considering the simulation result for  $N=6$  (VCTS unit=3), let us denote by  $P$  the availability of a single communication link. Therefore, the global availability of the system considering all the 6 periodic messages between VCTS units can be expressed as:  $av_6 = P^6$ . Consequently, the probability of down time is:  $dt_6 = 1 - P^6$ .

From Table 2, we can notice that:  $dt_6 = 6.76E - 04 = 1 - P^6$  (for 'transmission loss due to packet error' = 0.1), and  $P = 0.9998872 (D = 1 - P = 1.12E - 04)$ .

In the case of a platoon with two VCTS units ( $N=2$ ), the probability of downtime is:  $dt_1 = 1 - P^2 = 2.23987E - 04$ .

It can be noticed that the mean probability value for downtime obtained obtained by means of simulation (with a confidence interval of  $[1.0; 1.50]E - 004$ ) is  $1.25E - 04$ , which is quite close to the corresponding analytical value of  $1.12E - 04$ . This is a relevant indication regarding the trustworthiness of the simulation results.

In what follows, we will evaluate the probability of downtime for a platoon with 4 VCTS units ( $N=12$ ). The corresponding values are as follows:  $av_{12} = P^{12} = 0.9986568$ , and  $dt_{12} = 1 - P^{12} = 1.34E - 03$ .

The mean probability value for downtime obtained via simulation is  $1.32E - 03$  (with a confidence interval

Table 1. Input parameters

Trans. delay(Dt)	packet error(PET)	CAM period
5ms	0.1	200ms
obsoL.deadline(D)	retrans (TRE)	msg copies (retrans)
50ms	8ms	3
deadL.(updt.CAM)	update CAM	
$2xD + updt.CAM(t)$	1000ms	

Table 2. Performance results

N	Simulation		Rel. error	Analy.+Sim.
	Mean value	Conf. intv.		
2	$1.25E-04$	$[1.0;1.5]E-004$	0.2	$1.12E-04$
6	$6.76E-04$	$[5.41;8.10]E-004$	0.2	base
12	$1.32E-03$	$[1.06;1.58]E-003$	0.2	$1.34E-03$

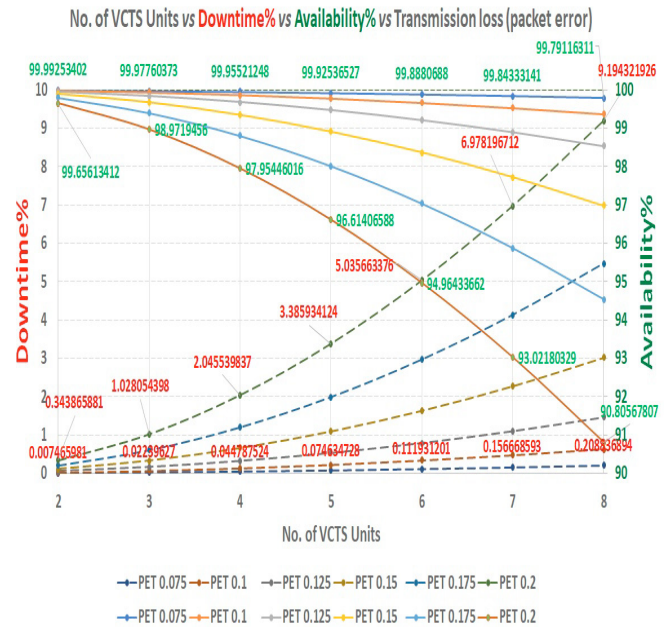


Fig. 7. Impact of platoon size and packet error on dependability attribute

Transmission loss due to Packet error	Downtime percentage					
	0.075	0.1	0.125	0.15	0.175	0.2
2	0.0074666	0.0223987	0.0526871	0.1093301	0.2006073	0.3438659
3	0.0223963	0.0671812	0.1579779	0.3276318	0.6006154	1.0280544
4	0.0447875	0.1343172	0.3157063	0.6541903	1.1976234	2.0455398
5	0.0746347	0.2237618	0.5256232	1.0879378	1.98806	3.3859341
6	0.1119312	0.3354549	0.7873978	1.6274601	2.967219	5.0356634
7	0.1566686	0.4693216	1.1006182	2.2710036	4.1293063	6.9781967
8	0.2088369	0.6252721	1.4647924	3.0164854	5.4674964	9.1943219

Fig. 8. Impact of platoon size and packet error on dependability attribute

$[1.06; 1.58]E - 003$ ). Similarly as for the case  $N=2$ , the obtained simulation value is close to the corresponding analytical value of  $1.34E - 03$  and gives a pretty significant indication.

Figure 7 and Figure 8 present the impact of platoon size and packet error on the considered dependability attribute (Availability and Downtime). On the other hand, Figure 9 and Figure 10 represents the impact of platoon size and communication delay on these dependability attributes.

**Case of dependence of the communication links.**

We recall here that the above results are based on the assumption that each communication link has the same communication parameters, leading to same availability, and is independent of each other. In such cases, we can simulate the dependability parameters for the simplest case, for example, a platoon with two VCTS units (i.e.,  $N=2$ ), and we use the obtained result to analytically evaluate more complex cases, for example, a platoon with five VCTS units ( $N=20$ ).

However, if the dynamics of the communication links are not independent of each other, we can not analytically extrapolate the dependability attributes of complex cases based on the results of the simplest case. In case of dependency of the behaviours of the communication links, we have to rely on simulation only. For example, in the discussed model, as shown in Figure 6, we considered that

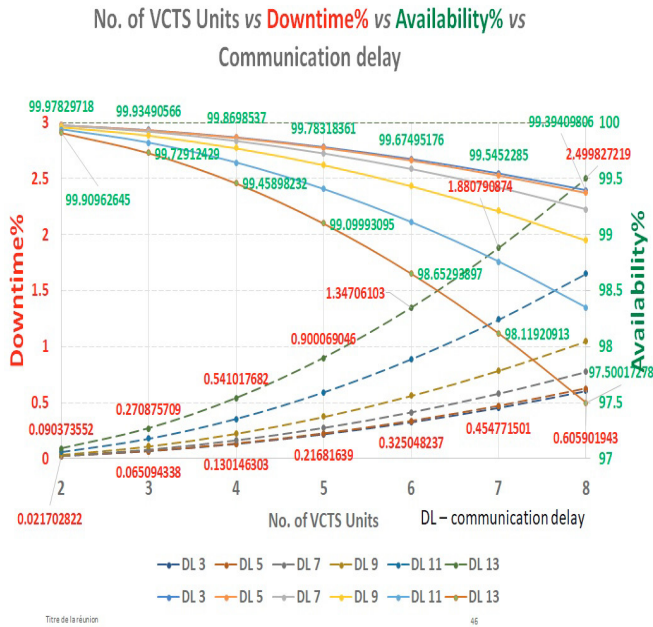


Fig. 9. Impact of platoon size and communication delay on dependability attribute

Comm delay(ms)	Downtime percentage					
	3	5	7	9	11	13
2	0.021703	0.022399	0.027738	0.037672	0.059487	0.090374
3	0.065094	0.067181	0.083191	0.112975	0.178355	0.270876
4	0.130146	0.134317	0.166313	0.225822	0.356391	0.541018
5	0.216816	0.223762	0.277035	0.376087	0.593279	0.900069
6	0.325048	0.335455	0.415264	0.563599	0.888598	1.347061
7	0.454772	0.469322	0.580887	0.788148	1.241822	1.880791
8	0.605902	0.625272	0.773765	1.049481	1.652326	2.499827

Fig. 10. Impact of platoon size and communication delay on dependability attribute

each VCTS unit could handle or update all the CAM messages simultaneously. For example, VCTS3 receives one message each from VCTS1 and VCTS2 periodically, and as soon as these messages are received (shown by corresponding tokens at place 'update\_CAM\_aft\_rec\_CAM'), these messages are processed without any queue or waiting time. This simultaneous processing of any number of messages is implemented using a transition with holds an 'infinite' server. However, in a more realistic case, let us assume that a receiving train (VCTS 3) has a stochastic processing time for updating CAM messages and that the train can only handle 5 pairs, that is 10 (a pair has CAM from VCTS1 and VCTS2) periodic messages simultaneously. Therefore, all the following messages that arrive at the VCTS unit during the processing have to wait in a queue.

Queuing at VCTS can be implemented easily in the above model by replacing place 'update\_CAM\_aft\_rec\_CAM' (inside box) in Figure 5 and Figure 6 by the structure inside the green box in Figure 11. Each VCTS unit can handle 10 messages concurrently. Therefore we have to set a capacity of 30 to place 'update\_CAM\_aft\_rec\_CAM' (as the platoon has 3 VCTS unit), which is the highest number of tokens allowed at a given time in this place. In case more messages are received by a train, messages will wait in a queue at place 'Queue\_updt\_CAM'. Queuing strategy at both place 'update\_CAM\_aft\_rec\_CAM' and 'Queue\_updt\_CAM' will be set as FIFO (First In First Out).

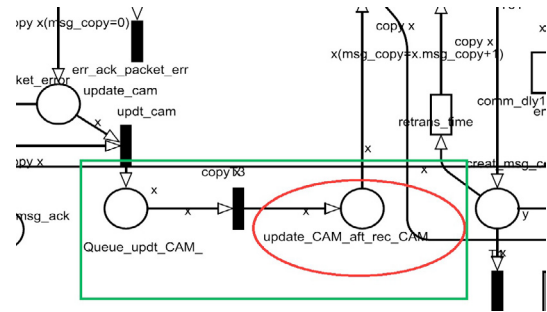


Fig. 11. Queuing at VCTS while processing of periodic CAM messages

#### 4.2 Rare event simulation technique

The obtained simulation results have a confidence interval corresponding to 20 % relative error, which is quite high. Therefore, we will use a rare event simulation technique to improve this confidence interval in a reasonable simulation duration. Namely, we will use the RESTART method, which is a rare event simulation method implemented in TimeNET Kelling et al. (1996). Zimmermann et al. (2016) and Zimmermann (2006) discuss technical details about the method and provide some illustrative examples. We will use the RESTART implementation in SPN, which allows the use of exponential, deterministic, immediate and general transitions. Unfortunately, we are not able to use the RESTART implementation with SCPN as we found a bug with the tool related to memory allocation. Therefore, in this work, we will use RESTART with SPN to evaluate its effectiveness and will use the SCPN in the future once the bug<sup>1</sup> gets fixed.

To illustrate the use of the RESTART technique, we will consider the simplest case, in which the platoon has two VCTS units, i.e., only one communication link. We will transform our model from SCPN to SPN. Due to space limitations, the model can not be exposed here.

**RESTART method:** recall that our goal is to measure the probability of communication unavailability in a steady-state, but the relevant samples are generated rarely. The underlying idea of RESTART can be explained as follows: suppose we can define some subsets of the overall state space as  $A_0, A_1, A_2$  and  $A_3$ , where  $A_3$  is the probability of the scrutinized event ('communication is unavailable' in our case), such that it is easy to evaluate the communication probability of  $A_{i+1}$  given the communication probability of  $A_i$ . RESTART measures the conditional probability of reaching a state  $A_{i+1}$  after starting in  $A_i$ , by a Bernoulli trial. If  $A_{i+1}$  is hit, the entering state is stored, and the simulation trial is split into  $R$  trials. The simulation follows each of the trials to see whether  $A_{i+2}$  is hit and so on. We can then find the probability of interest from the product of conditionals. Decreasing order of probability of occurrence of events is  $A_0, A_1, A_2$  and  $A_3$ .

In our case, the communication is unavailable when the receiving train does not receive any of the original message or copies sent by the transmitting train, or transmitting train does not receive back any of the updated message

<sup>1</sup> already reported to the tool developers



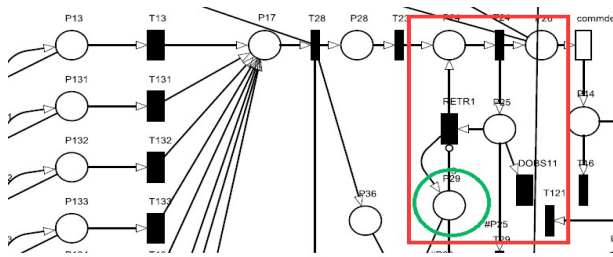


Fig. 12. part of SPN model: platoon with two VCTS unit

or copies sent by the receiving train. Message copies are transmitted every 8ms, and as soon as an *ack* message is received, the message copies are deleted. Place P9 contains copies of the CAM messages sent from the transmitter to the receiver. Place P29, which is inside the green circle in Figure 12, contains message copies of communication receiver to transmitter. The more the number of copies at these places, the closer the system is to the target event.  $\#P_i$  represents the number of tokens at place  $P_i$ . the Importance function represents the set of states in RESTART.

We define Importance Function as  $(\#P9 < 2) + (\#P29 < 2) + 4 * (\#P9 \geq 2) + 4 * (\#P29 \geq 2)$ .

We performed simulation for 300 seconds, and the obtained mean value of downtime was  $1.1253E - 004$  with a confidence interval of  $[1.049272e - 004, 1.201351e - 004]$ .

The use of the RESTART technique in our study is still quite preliminary, but in future work, we will look forward to use RESTART with SCPN models to analyse complex scenarios.

## 5. CONCLUSIONS AND FUTURE WORKS

In this paper, a model-based approach for the evaluation of the communication system under virtual coupling operation is discussed. Using SCPN, we presented preliminary results pertaining to some dependability parameters of the communication system, namely availability/downtime. We have shown that the confidence interval of the simulation results can be improved further using rare even simulation techniques such as RESTART. Therefore, in our future work we will explore in detail, the RESTART technique introduced at the end of this paper. In the present work, we limit the analysis scope to function *Supervising Train Separation Distance*. As a continuation of our work, we will widen the scope of the analysis to consider all the functionalities on line capacity, from the opening of a communication session (for virtual coupling of consists) to the decoupling of consists. We can also investigate the impact of various configurations on the system safety under virtual coupling operation. The objective is to identify the most impacting communication parameters, so as to guide the choices in terms of communication technologies that will support the implementation of the virtual coupling concept.

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