Towards Modeling and Evaluation of ETCS Real-Time Communication and Operation

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Abstract

The future European Train Control System (ETCS) will be based on mobile communication and overcome fixed blocks. It is introduced in order to increase track utilization and interoperability throughout Europe while reducing trackside equipment cost. Data processing on board the train and in radio block centers as well as the radio communication link are crucial factors for the safe and efficient operation. Their real-time behavior under inevitable link failures needs to be modeled and evaluated. The paper presents a stochastic Petri net model of communication failure and recover behavior. A second model for the exchange of location and movement authority data packets between trains and radio block centers is presented and analyzed. Performance evaluation of the model shows the significant impact of packet delays and losses on the reliable operation of high-speed trains.

Key words: European Train Control System, Moving Block Operation, Modeling, Petri Nets, Performance Evaluation

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1 Introduction

Train control is an important part of the railway operations management system. Traditionally it connects the fixed signaling infrastructure with the trains. With the European Union ERTMS/ETCS project (European Rail Traffic Management System/European Train Control System), a standardized European train control system is being designed, which will gradually replace the

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great number of different train control systems in use today. It will allow trains to cross borders without the need to change locomotive or driver, as it is still necessary today.

At the final stage of ETCS implementation throughout Europe, more or less all train control infrastructure will be either on-board the trains or distributed in control centers. There is no need for optical signals, wheel counters, or a fixed arrangement of track parts into blocks. Trains and control centers are connected by mobile communication links. The safety of passengers depends on the communication system reliability. Real-time communication and information processing thus play a major role for the implementation of ETCS.

The importance of quality of service parameters for the communication and specification of the real-time behavior of subsystems has been addressed in the specifications of ETCS (see e.g. [1,2]). The requirements are however not very detailed, e.g. no distributions are considered, but only probabilities of meeting certain deadlines. While it is important to specify subsystem characteristics, the real-time behavior of the system as a whole can only be assessed by looking at their interaction. This paper goes a first step into that direction by evaluating one safety-critical communication structure together with its failure behavior.

In addition to offer interoperability between the different European railroad companies, another major goal is to increase track utilization for high-speed trains. It is obvious that dropping the standard block synchronization of trains and migrating to a virtual block system has the potential of allowing closer distances between trains. Transmission errors in the communication system influence the minimum possible distance between trains and thus the maximum track utilization. This dependency is addressed and evaluated in the paper for the first time. Communication system, failure behavior and safety braking of trains are modeled and analyzed using different performance evaluation techniques in the following. The results show that the vision of driving in brake distance behind another train with ETCS would lead to a very unreliable train behavior.

The mentioned evaluations can only be done using some kind of model, independent of whether it is a simulation program or based on a formal modeling technique. In this paper variants of stochastic Petri nets [3] are used to describe the functional and timing behavior of ETCS train communication. Petri nets [4] and their stochastic timed extensions have proven to be a useful formalism for real-time systems. They are considered to describe discrete event systems in a concise and appropriate way. An additional advantage is the availability of many different analysis and simulation techniques as well as software tools. Petri nets have been used in the context of real-time systems many times, see e.g. [5–7].

Most of the work in the area of train control systems deals with *qualitative* aspects like validation of correctness, absence of forbidden safety-critical states etc. Yet in a real-time system like a distributed communication-based train control system, critical safety questions can only be answered when also *quantitative* aspects are considered and evaluated. Failures and other external influences on the model require stochastic model values, but fixed values for deadlines or known processing times are equally important. Modeling and evaluation techniques need to support both in order to be applicable in this area.

Train control and related systems have been modeled and analyzed in the literature. In [8] the ETCS communication structure is modeled with colored Petri nets. The model is used for a division of the system into modules, visualization of the functional behavior, and a check of different scenarios. A verification of the radio-based signaling system together with a case study of a rail/street crossing is carried out in [9]. Live sequence charts are used to model the system, which is analyzed with the Statemate software tool. The ETCS radio block center is formally modeled and validated in [10]. Message sequence charts are used to model and check different scenarios. The ETCS train traffic is compared with today's standard train control operations in Germany in a simulation study of Deutsche Bahn (German railways company) [11]. Using a proprietary simulation program, the movement of a set of trains through an example line is simulated. The results say that ETCS operation in its final stage will increase track utilization by about 30% for the example. However, the communication is not modeled, and failures are not taken into account.

Modeling and evaluation of complex systems is only feasible with the support of appropriate software tools. Design, analysis and simulation of the models presented in the paper is done using the tool TimeNET [12]). It offers non-Markovian uncolored and colored Petri net modeling and numerical analysis as well as simulation algorithms.

The remainder of the paper is organized as follows: After a brief overview of the ETCS communication architecture, a model for the communication system failures is developed an analyzed in Section 3. Train operation with moving and fixed blocks is explained in Section 4. Section 5 describes how a safety-critical part of the ETCS communication system is modeled and presents results of a real-time behavior evaluation.

2 The European Train Control System

In order to facilitate fast and efficient train traffic across borders in Europe, a unified European Train Control System (ETCS) [1] is under development in several European countries. The normal fixed block operation with mechanical elements, interlockings and optical signals will be substituted by a radio-based computerized train control system. The system receives commands about the train routes that are to be set, and directs wayside objects along these routes. To simplify migration to the new standard, ETCS defines three levels of operation. In this paper the final implementation level 3 is considered. A more detailed description of ETCS can be found in [13].

With the ETCS Level 3, radio communication replaces the traditional trackside signals, which allows considerable savings in infrastructure and maintenance costs. No trackside monitoring system is necessary as trains actively report their head and tail positions as well as train integrity to Radio Block Centers (RBC) periodically. RBC also trace the locations of trains, and transmit track descriptions as well as so-called *movement authority* messages to them. Moving block operation allows higher speeds and shorter headways and thus increased capacity. An essential advantage is the reduction in life cycle costs through the abolition of the devices for track occupancy monitoring and trackside signals.

For the communication between train and RBC the GSM (Global System for Mobile Communications) technology was chosen as the base technology because of availability and cost considerations. Additional functions which are tailored to the needs of railroad use (like area addressing, automatic international roaming etc) have been defined as Railway GSM (GSM-R [14,2]). GSM-R communication takes places between trains and base transceiver stations (BTS) which are placed alongside the tracks. BTS are connected to base station controllers (BSC) by cable, from where messages are sent to RBC via ISDN.

3 An ETCS Communication System Failure Model

Reliable data packet exchange is crucial for the reliable operation of ETCS. In this section, a quantitative model of the failure and recovery behavior of the communication base system is presented and analyzed. The results will later be used to examine moving block operation and the necessary data exchange while taking into account the reliability of the communication channel.

The model is based on the following sources of information about the qualitative and quantitative behavior of the communication system and its failures: A Quality of Service parameter specification (maximum connection establishment delay etc.) is given in [2]. Allowed parameter ranges for some system design variables (like the minimum time between two subsequent position reports sent by a train) are specified in [15]. Some additional assumptions (mean time to complete the on-board train integrity check etc.) have been taken from a description of simulation experiments carried out by the German railways company [11].

The communication link between train and RBC is always connected in normal operation mode. In that situation the following failures may happen: **Transmission errors** occur from time to time, possibly due to temporarily bad radio signal conditions. There is no action necessary, because after a short time the link is operable again. **Connection losses** may happen e.g. due to longer radio signal problems in areas where the radio coverage is not complete. The train hardware detects this state after some timeout and tries to establish a new connection. There is a slight chance of failing to establish such a connection until a certain timeout has elapsed, after which the connection establishment procedure starts over again. **Handovers** take place every time the train crosses the border between the communication areas of two neighboring base transceiver stations (BTS). The train connects to the next BTS automatically, but this may take some time.

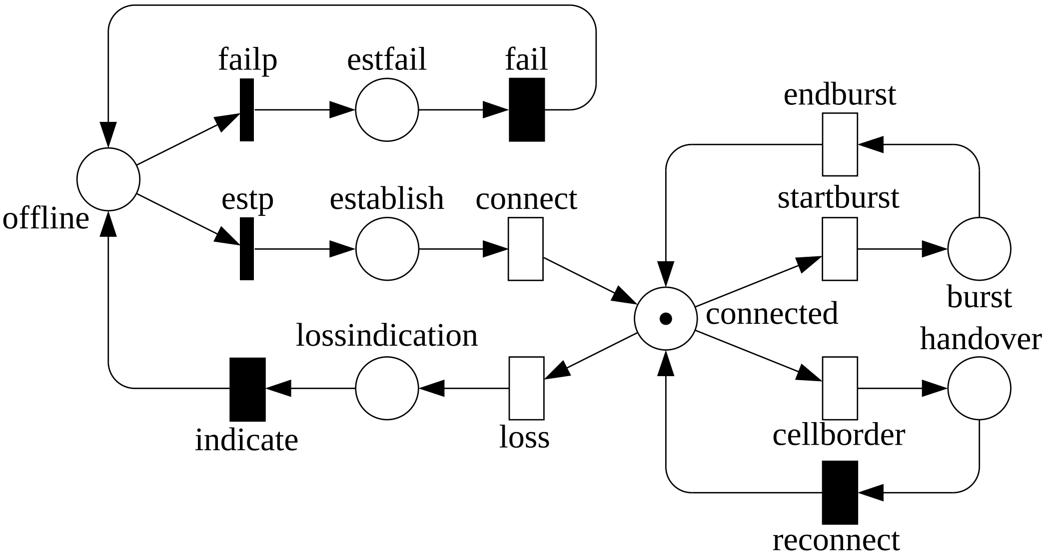

Fig. 1. Failure and recovery model for GSM-R communication channel

Figure 1 shows a *deterministic and stochastic Petri net* [16] model of the described behavior. The firing delays and distributions have been chosen as follows. One unit of model time means one second in reality.

Transition `startburst` models the beginning of a transmission error. It has an exponentially distributed firing delay because of the stochastic nature of transmission errors. The corresponding firing time is comparable to a mean time to failure of the communication link due to transmission errors. The specification requires this value to be greater than or equal to 7 seconds for 95% of all cases. From the density and distribution functions of the exponential distribution $f(x) = \lambda e^{-\lambda x}$ and $F(x) = 1 - e^{-\lambda x}$ we can calculate the necessary parameter λ value: $\lambda = -\frac{\ln p}{x} \approx 0.00733$ with probability $p = 0.95$ and $x = 7$. Transition `endburst` models the end of the transmission problem. The delay is assumed to be memoryless and the specification requires it to be smaller than one second in 95% of all cases. Thus the transition is exponential with parameter $\lambda \approx 3$ ($F(1) = 1 - e^{-\lambda} = 0.95$).

The crossing of a cell border and connection setup with a new BTS is modeled by transitions `cellborder` and `reconnect`, respectively. Normally the BTS are situated a few meters away from the track and have a typical density of $0.1 \ldots 0.3$ BTS per km. Another source specifies 7 km as the mean BTS distance, which is adopted here. Unlike for personal use of a mobile phone, handovers happen quite often due to the speed of the train. ETCS is required to work for speeds up to 500 km per hour (139 meter per second). Thus the worst-case mean time between two handovers is 50.4 seconds. The firing delay of `cellborder` is thus exponentially distributed with parameter 0.0198 (the mean delay being equal to $1/\lambda$). From the specification we know that a reconnection is required to take at most 300 msec, which is taken as a worst case with a deterministic transition `reconnect`.

Following the specification, a complete connection loss takes place only rarely, namely 10^{-4} times per hour or $2.77 * 10^{-8}$ per second. The parameter of the exponential transition `loss` is set accordingly. There is a certain amount of time needed to detect the communication loss, which is required to be not greater than one second. This is modeled by the deterministic transition `indicate` with one as the fixed delay.

After being offline, the train communication system tries to reestablish the link at once. The requirements specify that a connection attempt must be successful with probability 99.9%, while in the remaining cases the establishment is canceled after 7.5 seconds and retried. This behavior is modeled with immediate transitions carrying the success/fail probabilities `estp` and `failp`, and the deterministic transition `fail` with delay 7.5. Connection establishment times are random, but required to be less than 5 seconds for 95% of the cases. The corresponding firing distribution of transition `connect` is thus exponential with parameter 0.6.

The model shown in Figure 1 depicts states and state transitions of the communication link. The initial state is `connected`. It is obvious that there will always be exactly one token in the model, letting the Petri net behave like a *state machine*, and the reachability graph is isomorphic to the net structure.

Because in every marking there is at most one transition with non-exponentially distributed firing delay enabled, the model can be numerically analyzed with standard DSPN algorithms [17]. Numerical analysis of the example is computationally inexpensive due to its small state space. Despite of the “stiffness" of the problem (e.g. firing rates of transitions `endburst` and `loss` differ by eight orders of magnitude) the exact solution is a matter of seconds. A simulation with proper confidence interval control would take quite some time because of the mentioned rare events.

The results of the numerical analysis. show that the connection is working with a probability of 99.166%. This is worse than the required availability of 99.95% as specified in [2]. This requirement is commented to be a coverage requirement, although we see from the model evaluation that already the allowed handover downtimes violate this requirement. In fact, handovers account for more than 70% of the overall unavailability. To avoid their impact on the communication link, there are discussions about installing two independent GSM-R devices in each train. For instance in the Rome-Naples ETCS installation all electronic units have been duplicated for a higher reliability and availability. The connection to the next BTS can then be carried out when the train gets close to the cell border, thus avoiding any offline state due to handovers. Bursts are responsible for another 29% of communication outage, while the other failures have only a small influence.

The failure model as presented above is now condensed into a smaller model, to make the later evaluation of a combined failure / moving block operation model less time consuming. This is possible because the failure model does not depend on the operation model. By doing so, there will be a tradeoff between model complexity and accuracy. We decided to condense the failure model into a two-state system with the basic states `ok` and `failed`. The corresponding stochastic Petri net (GSPN) is shown in Figure 2.

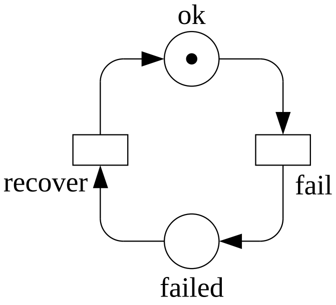

Fig. 2. Condensed failure model

The question is then how to specify the transition firing rates to minimize the approximation error. The main characteristic of the failure model is the mean availability, which shall be equal in the exact and condensed model. Thus the probability of having one token in place `ok` needs to be 0.99166. The second restriction which we impose on the condensed model is to keep the mean sojourn time in state `ok` exactly as it was in the full model. This time is the reciprocal value of the sum of all transition firing rates going out from the state, in our case $1/(\lambda_{startburst} + \lambda_{cellborder} + \lambda_{loss}) \approx 36.77$ and thus

$\lambda_{fail} = 0.02719$. From the balance equations it is then straightforward to $\lambda_{recover} = 3.236$.

4 Train Operation With Moving Blocks and Fixed Blocks

In this section the position report message exchange and emergency braking due to communication problems under ETCS moving block operation is explained. This is used in the subsequent section to derive and analyze a corresponding Petri net model. The second part of the section describes the standard block operation to compare its track utilization later with the results for the ETCS moving block operation.

The paper investigates the dependency between the maximum throughput of trains and reliability measures of the communication system. The maximum utilization will be achieved if trains are following each other with a minimum distance. The question is then how close after each other can trains be operated theoretically under ETCS? We assume in the following a continuous track without stops, on which trains follow each other with a maximum speed v (current high-speed trains have a maximum speed of 300 km/h) and a distance s. Moreover, for the following considerations we arbitrarily select w.l.o.g. two trains (*Train1* and *Train2*) that directly follow each other.

Continuous operation is facilitated by the new notion of virtual *moving blocks*. Because there is no fixed block assigned to a train, and no physical block borders exist, the train movement is controlled by exchanging messages with the radio block center (RBC). Each train checks periodically its integrity and sends the integrity information together with the current position of the train head to the RBC. The time needed to check the train integrity is specified to be in the range between 2 to 5 seconds. Let Δt denote the time between two successive position reports of *Train1*. The requirements definition specifies $\Delta t \geq 5sec$. It is obvious that more frequent position reports will facilitate smaller train distances s, thus we choose $\Delta t = 5sec$.

The integrity/position report is sent via GSM-R to the RBC and processed there, which takes typically 0.5 sec. The resulting information is sent to the following *Train2*, telling him either that everything is fine to go on driving (by sending a new *movement authority* packet) or that an emergency braking is necessary immediately.

However, if a communication packet is delayed or lost on either the communication up-link (*Train1*→RBC) or down-link (RBC→*Train2*), *Train2* needs to decide on its own at what point of time emergency braking is inevitable out of safety reasons. There is obviously a deadline t after the last movement

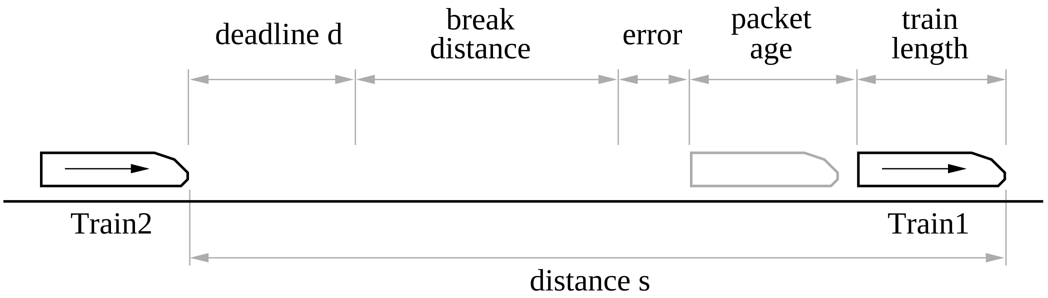

Fig. 3. Train distance and deadline

authority has been received, after which the train needs to be stopped. The worst-case assumption is that after the last integrity check has been completed, a part of the trains carriages are lost from the main train and stop where they are or there is an accident In moving block operation the movement authority therefor shall never exceed the min safe rear end of the preceding train [1].

We would like to investigate the deadline and its dependency on the train head-to-head distance s (see Figure 3 for an illustration). First of all the train length (about 410 m for the German high-speed train "ICE") needs to be subtracted from the distance. Second, when the results of the position/integrity report of *Train1* arrive at *Train2*, the information is already some time old. Typical minimum (maximum) delays d can be estimated as follows: 2 (5) seconds to complete the integrity check, 0.5 (1) seconds end-to-end delay of position message to the RBC, 0.5 seconds to process the information there, again 0.5 (1) seconds for the downlink transfer to *Train2* plus assumed 1.5 seconds to process the information in the train and start braking if necessary. Packet ages when arriving at *Train2* thus range typically between 5 and 9 seconds. Then there is a location error of not more than 20m possible in the position report of *Train1*. The emergency braking distance needs to be subtracted as well, being between 2300 and 2800m depending on the actual speed. For simplicity we assume in the following braking distance plus train length plus position error as $l = 3000m$. The deadline t is then given by $t = \frac{s-l}{v} - d$.

The old type of block operation of trains ensures train safety by fixed blocks, in which only one train may be located at any moment. Its operation is based on trackside equipment: Each block begins with a main signal and ends at the main signal of the following block. Wheel counters check train integrity at the end of each block.

A train must not enter the block if the corresponding main signal shows red. A approach signal is needed because with bad weather conditions and high train speeds the train driver might not be able to stop the train before the main signal after seeing it. The approach signal can not be located before the previous main signal. One problems of blocking operation is the "discretization" of track space, which leads to a waste of track utilization. From the throughput point of view the blocks should therefore be as small as possible. The minimum block size must be bigger than the distance from a approach signal to its main signal, which needs to allow for the maximum braking distance of a train.

The maximum theoretical train throughput is achieved when we assume an unlimited number of trains with identical speed v, that follow each other with a fixed head-to-head distance s. For a train to drive through a green approach signal of block i, the previous train must have left block i already. The minimum distance therefore includes twice the block length (assumed here to equal the braking distance for current high-speed trains: 2800m), the train length (410m), and a safety distance (50m). From the railroad literature it is known that the minimum travel distance between two trains in block operation also needs to obey a time to prepare the travel path (10 sec), signal view time (12 sec), and time to resolve the travel path (6 sec). At a speed of 300km per hour of high-speed trains the theoretical minimum distance between two trains is 8393m.

It should be noted that these considerations are only done to theoretically compare ETCS moving block operation to the old way of operating a block system. In reality, efficient operation of high-speed trains would not be possible in that way. Real-life block sizes are between 2000m and 4000m, and approach signals are located 1000m ahead. Different national systems for high-speed train operation exist in Europe. In Germany an electronic system with trackside antenna cables allow much smaller block sizes and train driver information about the next train.

5 Performance Evaluation Using Petri Net Rare-Event Simulation

Figure 4 shows a Petri net model for the ETCS movement authority data exchange as explained in Section 4. This model is a revised version of the one presented previously [13]. The upper left part models the generation and transmission of movement authority messages in a straightforward way. The failure behavior of the communication link is given by the condensed model as derived in the previous section. It is connected to the main model in a way that all messages are lost (tokens are removed from places `sendingUp` and `sendingDown`) as long as the link is failed.

For the application of the chosen simulation method (RESTART, see below), a Petri net place was needed in which the number of tokens can be used as the thresholds and final event. For this reason the time until deadline t is “counted” with tokens in place `count`. For a reasonable number of possible thresholds we define 20 as the number of tokens modeling the violation of the deadline. The deterministic firing time $\tau_{\texttt{Tick}}$ of transition `Tick` then needs to be set accordingly depending on the deadline under evaluation: $\tau_{\texttt{Tick}} = \frac{d}{20}$.

Every time a new movement authority arrives at the second train (place `arrived`), the current elapsed time is set to zero: transition `reset` fires and removes all tokens from place `count`. After an exceeded deadline the train stops and we assume a `Resetup` time of 15 minutes before the train can move on. Movement authority packets arriving during that time are dropped (transition `drop` has lower priority than `reset`).

The end-to-end transmission delay for messages is specified in the requirements as being between 0.4 and 0.5 seconds on the average, but being less than 0.5 for 95%, less than 1.2 seconds for 99%, and less than 2.4 seconds in 99.99% of all cases. This timing behavior could be modeled only by *generalized transitions* with expolynomial firing delays, how they are allowed in the class of *extended and deterministic stochastic Petri nets* (eDSPNs [17]).

For the performance evaluation of the model the numeric analysis cannot be used, because the restriction of not more than one enabled non-exponential transition per marking is violated. For a discrete time scale the resulting state space size would be too big because of the complex and highly differing firing delays. Thus simulation was the only choice, but standard methods could only be used for a limited number of evaluations. Acceptable stopping probabilities are naturally very small, and thus a rare-event simulation technique was needed to successfully derive the measure of interest.

RESTART (repetitive simulation trials after reaching thresholds) [18] is an efficient method to deal with low probabilities in a simulation. It belongs to the class of importance splitting techniques among the rare event handling

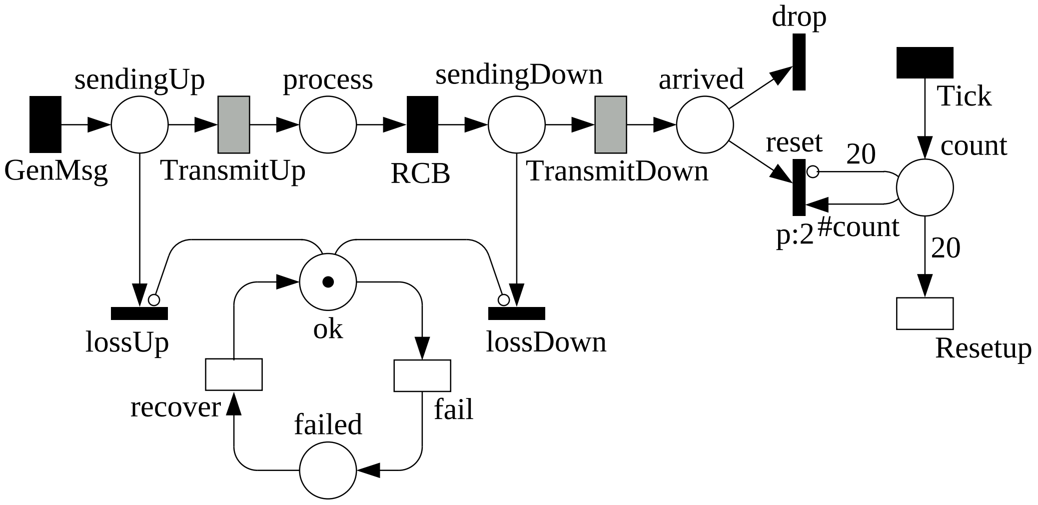

Fig. 4. Model of communication during moving block operation

methods. The idea behind it is the following. Assume that we want to estimate the probability of being in a rare state A of a system (e.g. a failure), starting from an initial state s_0 that is not rare (like normal operation condition). The RESTART method makes the rare event "happen more often" in the simulation by considering state sets (called thresholds) $S_i, i = 0 \dots k$ of the system that include each other and the rare event A as $A \subset S_k \subset S_{k-1} \subset \dots \subset S_0$ with $s_0 \in S_0$. Thus we can express the rare state probability as $P(A) = P(A|S_k)P(S_k|S_{k-1}) \dots P(S_1|S_0)P(S_0)$.

The RESTART simulation measures the probability of reaching a state out of set S_{i+1} after starting in S_i by a Bernoulli trial. If S_{i+1} is hit, the entering state is stored and the simulation trial is split into R_i trials. The simulation follows each of the trials to see whether S_{i+2} is hit and so on. A trial starting at S_i is canceled after leaving S_i if it did not hit S_{i+1}. The reduction in computation time results from estimating the conditional probabilities $P(S_k|S_{k-1})$, which are not rare if the sets S_i are selected properly. It can be shown that the optimal gain in computation time is achieved if the sets are chosen such that $k = -\frac{1}{2}\ln(P(A)) - 1$, $P(S_i|S_{i-1}) = e^{-2}$ and $R_i = e^2$.

The presented Petri net model of the moving block operation has been evaluated using the RESTART implementation in the stochastic Petri net package TimeNET [19]. Computations were made on a cluster of Sun workstations under SunOS. Thresholds are defined based on the number of tokens in place `count`, whereas the rare event A is defined by having 20 tokens in it. The tool selects suitable thresholds based on a prior standard simulation run with limited computation time. Near-optimal thresholds are set for numbers of tokens where the probability has been computed, while the rest are set linearly depending on a manual choice of the overall number of thresholds.

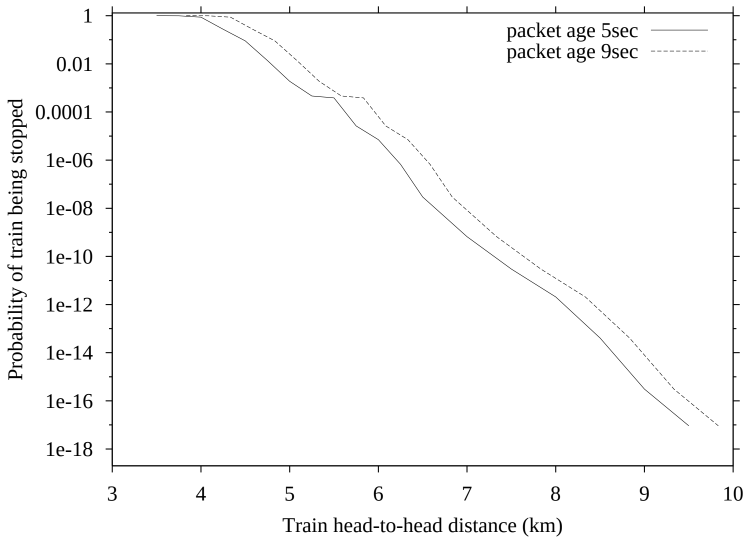

Fig. 5. Train stopping probability versus train distance

Figure 5 shows the resulting probability for a train to be stopped due to an exceeded deadline versus the train distance. To get a notion of the impact of the movement authority packet age at arrival, two curves are shown representing the minimum (5 seconds) and maximum (9 seconds) typical age. Beginning at a point where the train distance is big enough for the trains to be not almost always stopped (4 km in the 5 seconds case), the curves exhibit an almost logarithmic dependency between probability and distance.

The analysis shows a significant impact of communication delays and packet losses on the possible track utilization under ETCS level 3 / moving block operation. As it already has been pointed out previously [13], the vision of "driving in braking distance" is unrealistic. However, the refined model presented in this paper lead to more realistic values for the probability of a stopped train. Depending on the required reliability of high-speed train operation (and thus the accepted number of train brakings due to ETCS communication problems), it might be necessary to select a relatively long distance between trains. Another possibility will be to revise the current ETCS communication specifications. Compared to a theoretical setup of fixed blocks with the minimum block size, the performance measures show that an ETCS controlled train will be stopped about $1.3 * 10^{-6}$ seconds per year, or a train stops once every $7.1 * 10^{8}$ years. However, the real competitors to ETCS in terms of performance are the current national high-speed train operation systems. As they are usually based on standard electronics trackside equipment, their main problem is not communication system reliability, but installation and maintenance cost.

6 Conclusion

Model based performance evaluation is helpful during the design of fault-tolerant distributed real-time systems. The paper investigates safety-critical communication inside the future European Train Control System. Stochastic Petri nets are used to model and evaluate the failure and recovery behavior of the communication link as well as its combination with the exchange of vital train information between trains and radio block centers. Numerical results are presented which put into perspective quality of service specifications and theoretical high-speed track utilization. The model evaluations show the significant influence of communication system reliability on efficient train operation. It will be crucial for the success of the final ETCS implementation level to analyze the real-time behavior of train operation and communication system under failures with more details.

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