A RELIABLE SURVEILLANCE STRATEGY FOR AN AUTONOMOUS RAIL COLLISION AVOIDANCE SYSTEM

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Abstract: In this paper we present a detailed surveillance strategy concept for a Rail Collision Avoidance System (RCAS) that is based on direct train-to-train communication. Similar to existing systems in air and maritime transport, the RCAS approach allows vehicle autonomous detection of imminent collisions. Designed as a safety overlay system, it shall warn and advise train drivers in such situations. Apart from an onboard localization unit, which relies on satellite navigation signals, the system architecture does not require any other infrastructure. We will define the content of the broadcasted messages, which shall allow each railway vehicle to assess the traffic situation in its vicinity under all operational conditions. A variable transmission rate of messages ensures both, timely warning and an efficient use of communication channel resources in different scenarios like e.g. on regional network lines or in large shunt yards.

Keywords: Railway transport, surveillance, autonomous, collision avoidance, train control

INTRODUCTION

Actual statistics of the International Union of Railways (UIC) show that there are three significant train accidents in Europe every day [1], despite of millions of Euros which have been invested in trackside and in-train safety equipment. Most of the catastrophes in railroad transport are caused by collisions as illustrated in **Figure 1**. Today, only the operation center has an overall overview of the traffic situation, and a train driver has to be informed of a hypothetical collision by the operation center staff.

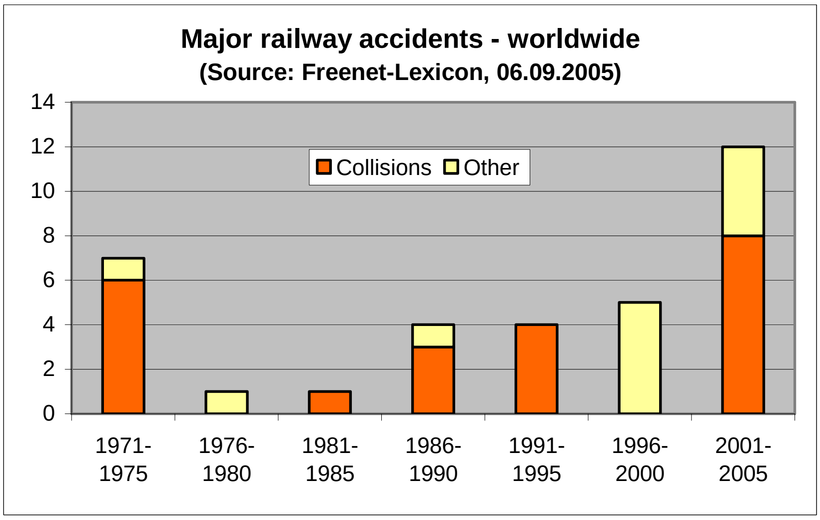

Figure 1: Causes for railroad catastrophes worldwide between 1971 and 2005

Figure 2: Rail construction vehicle as potential collision threat

Even with Automatic Train Control (ATC) systems like the future European Train Control System (ETCS) a significant amount of collisions cannot be prevented, because they occur between trains and other kinds of obstacles like construction vehicles (see **Figure 2**), construction workers or pedestrians and vehicles on level crossings.

VEHICLE AUTONOMOUS COLLISION AVOIDANCE

While maritime, air, and road transport have a vehicle integrated collision avoidance system available or in the development phase [2], there is no satisfying solution of this type of technology in railway transportation. Usually such systems rely on position determination and direct communication among vehicles. Alike we propose a Rail Collision Avoidance System (RCAS), that operates autonomous.

For this purpose each railroad vehicle shall be equipped with onboard sensors that provide updated Position, Velocity and Time (PVT) information. PVT and additional data is then regularly broadcasted to all other RCAS equipped units in the surrounding. By analyzing the received messages from other units the complete traffic situation can be assessed, thereby allowing the warning and advising of a train driver in case of a collision threat, long before the danger is visible and early enough to completely avoid it. Since braking distances of trains can be several kilometers long, a sufficient range for the direct train-to-train communications link is required. Moreover a reliable message transmission must be guaranteed in all the different scenarios within a railway network.

In principle, the RCAS approach is very similar to TCAS/ADS-B [3] (Traffic Alert and Collision Avoidance System / Automatic Dependent Surveillance - Broadcast) used as a “safety overlay system” in aeronautical transport, which is as well controlled by a number of operation centers. The advantages of such infrastructure-less vehicle autonomous collision avoidance system are:

- Additional safety which is independent of the regular traffic control mechanisms.
- System works independently of the nature of fail operation.
- Only one properly working communication link is needed.
- No changes are required on the existing infrastructure.
- Lower costs compared to infrastructure based systems; the onboard unit price is marginal compared to the vehicle price.
- Continuous “roll-out” is possible; safety increases with number of units.
- Potential to increase efficiency in the future, e.g. shorter distances between following vehicles.

Railway specific boundary conditions

While the principle of infrastructure-less vehicle autonomous collision avoidance is well established in aeronautics, as well as it is the case in maritime transport with the AIS (Automatic Identification System), none of the existing systems is applicable to railway transport, because of its very specific boundary conditions:

1. Movement patterns are highly deterministic because of the guidance by the rails. In conflict situations a train driver can only break or accelerate. The switches are controlled by the railway control centre only.
2. Movement vectors which are in line can also occur in nominal conditions e.g. when trains are coupled or when one train overtakes another one on a double track line. Moreover, the tracks are very close, which requires highly accurate position determination.
3. Punctually there are very high user densities in a railway network like e.g. at large shunting yards. Because the available frequency band is limited, in such areas the resulting high data rate must not degrade the reliability of message transmission.
4. Lines are sometimes under ground (tunnels), under roofs in train stations or they pass through dense forests and hilly areas. Such topological scenarios are challenging with respect to the required range of the direct train-to-train communication as well as for GNSS satellite signal reception.

THE RAILWAY COLLISION AVOIDANCE SYSTEM – RCAS

The above listed railway specific boundary conditions require new design considerations for the three major components of an infrastructure-less collision avoidance system for trains illustrated in **Figure 3**. In this paper the focus lies on the surveillance strategy and the resolution concept in case of a conflict. Nevertheless this implies stringent requirements to aspects of the communications link, like the message rate and - according to the broadcasted information - the message length.

Figure 3: Major components of an infrastructure-less collision avoidance system for trains

Operational scenarios

In railroad transport well-defined collision scenarios can be distinguished in different modes of operation. In **Figure 4** the situation is illustrated for a head-on, a rear-end and a flank collision scenario. In terms of requirements on the train-to-train communications link - especially on the range and the message repetition rate, the first one is the most demanding, since the remaining braking distances decrease for both trains according to their momentary speed.

In addition to these pure train collision scenarios many more collision threats are addressed with the RCAS approach. First of all, any railway carriage or vehicle shall be equipped with an RCAS transceiver. This way incidents during shunting, but also accidents with e.g. construction vehicles can be prevented. Also construction workers can be warned of

Figure 4: Head-on, rear-end and flank collision scenarios in railroad transportation

approaching trains if they carry handheld-sized units. With additional onboard sensors mudflow, fallen rocks, animals or disrooted trees on the track and broken branches on the catenary can be automatically reported to nearby trains. Even overlapping cargo due to displacement can be detected.

A significant number of collisions occur at level crossings. Here a stationary RCAS unit that surveys the road and interfaces the future C2C (car-to-car) communication system can forewarn both, train and car drivers.

Topological scenarios

The topological scenarios describe the different parts of the whole railway network. In a first analysis published in [4] we investigated the different topological scenarios in railroad transport and identified

- regional lines,
- train stations
- and shunting yards

as those scenarios which are relevant for the RCAS system design. Main lines with high speed services are not considered, because there the safety level is already very high due to extensive technical equipment and train control mechanisms.

For the listed scenarios the maximum speed is 160 km/h. In case of emergency braking the maximum braking distances are in the order of 1 km. Depending on the weather and rail conditions this can increase due to reduced fraction. Moreover, to allow for a secure (non passenger imperilling) braking of fast passenger trains, more than 2 km are necessary with the corresponding brake configuration. For the head-on collision scenario this means we need to guarantee a communication range of at least 5 km and need to have a high message repetition rate to loose a minimum of braking distance when the two trains approach the communication range.

More constraints arise from the high rail vehicle densities in large shunting yards. For instance in Maschen near Hamburg, at the second largest shunting yard in the world, several hundred trains with more than 4000 freight carriages are handled per day. Due to regulatory issues the transmit power and bandwidth in the envisaged frequency band around 460 MHz, which is dedicated to railway applications, is limited. Thus we face a strong limit on the data rate, which means we have to use the message bits economically and we need to minimize the message rate. This is contradictory to the head-on collision scenario of two fast passenger trains, where we want to detect the threat as early as possible. The solution is to adapt the message rate, as we will describe later in this paper.

System architecture

On board of each rail vehicle an intelligent RCAS unit is foreseen, comprising a transceiver and a processor unit as illustrated in **Figure 5**. For accurate track resolving localization, a combination of GNSS receiver, odometer and eddy current sensor can be used [5]. The last one not only improves the accuracy along the track by detecting rail clamps, but also allows identification of switches and the switch stand by unique signatures. Aided by an electronic map this guarantees precise PVT information even in tunnels, under roofs of train stations and in shunting yards.

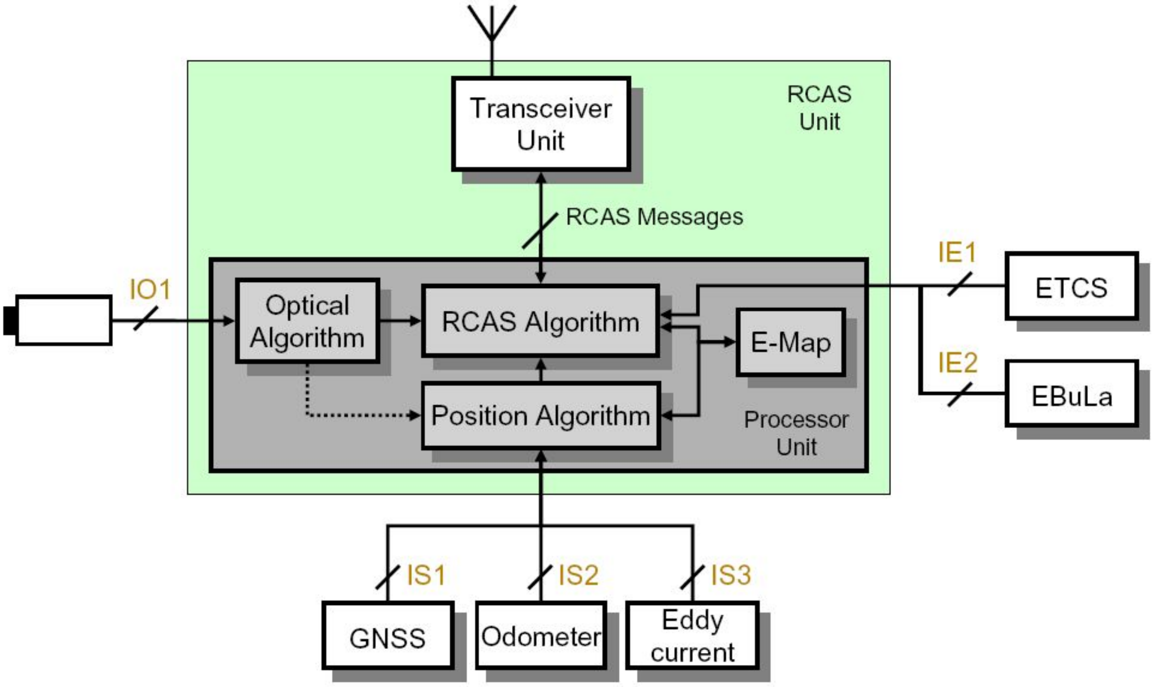

Figure 5: RCAS system unit architecture

In order to avoid collisions by overlapping cargo, to survey the catenary and the track, or to monitor the end of the train, a camera can be installed and connected to provide additional safety relevant information. Furthermore, an interface to an electronic schedule like the German EBuLa can give information on the planned route and speed of the train. In the future ETCS will even support online updates on this data.

The core of the system is an algorithm analyzing the received information from other trains together with the PVT and train data of its own carrier. Thus it allows to advise the train driver against a potential collision, or even to initiate braking to avoid it.

Surveillance strategy

Broadcasted information

Each RCAS unit produces messages with a fixed length. These messages are transmitted with a variable rate in a broadcast mode depending on the own speed and the traffic situation in the vicinity. The proposed RCAS message format is shown in **Figure 6**. The net size is 152 bits. First of all the message type indicates the format of the Position and Route Information (PRI) block. If there is a track selective position information present, the track ID, the distance from the tracks starting node, the movement direction and, if available, the information on the

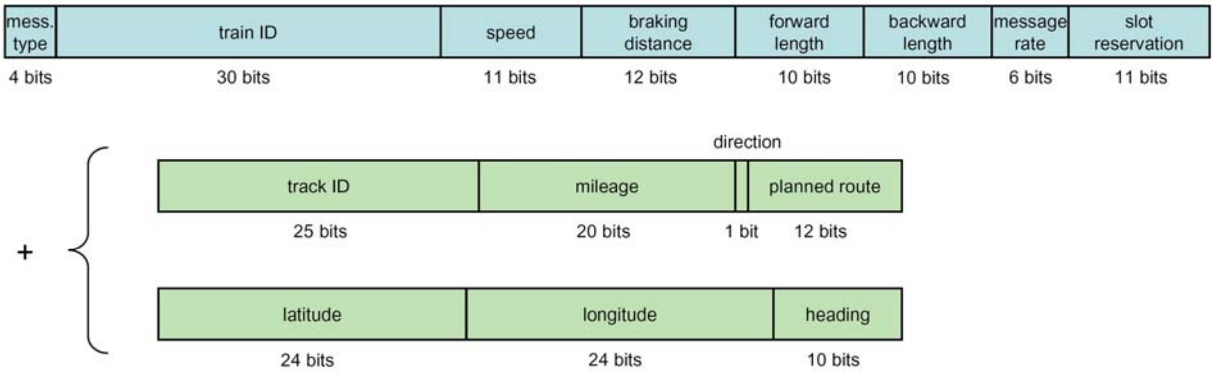

Figure 6: Description of the proposed RCAS message format

planned route are transmitted. Alternatively latitude, longitude and heading are broadcasted.

Another message type (not depicted in **Figure 6**) enables warning of other trains in case of track damage or blockage by replacing the planned route or heading information in the PRI block with an identifier for the type of threat, which is linked to the transmitted location. This same message type is also used to broadcast the identified collision point in case that TA is activated due to a conflict with another RCAS unit.

The train ID includes information about its operator, the type of train or vehicle and its danger status. The type of train information enables prioritisation of e.g. a passenger train that passes a shunting area. The danger status can be used to notify others of an extended loading gauge or if dangerous goods are carried.

The current speed, an estimate of the braking distance, and the forward and backward length of the train with respect to the localization unit are included in the message to allow other trains to identify potential collision points and to determine where and when warnings and braking advisories must be initiated.

Included in the message is also the actual message broadcast rate and information regarding the MAC (Media Access Control) scheme for the communication channel. Due to the relatively fast movement of trains and the challenging propagation conditions, no existing MAC protocol is appropriate for the RCAS system. A possible solution is developed and presented in [6].

Reliable collision detection

The most important property of a collision avoidance system is its reliability in detecting collisions in time. Moreover we must guarantee that regular operation conditions do not lead to warnings, because this would slow down train runs. Moreover, regular false alarms would

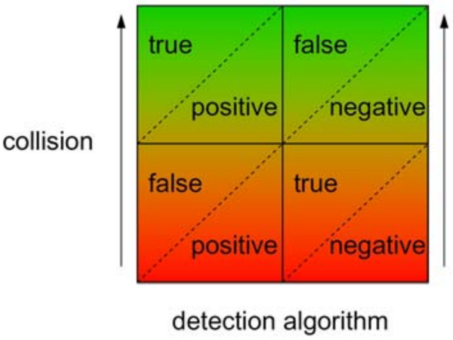

Figure 7: Contingency table for a collision detection algorithm

cause train drivers' to mistrust the system and eventually to ignore it. That means we have to minimize missed alarms (false positive) and minimize false alarms (true negative) as illustrated in the contingency table in **Figure 7**. This goal is particularly difficult to achieve in railway transportation. Imagine a single track line with a passing point at a small station, where two railcars are approaching, or one has already stopped in the station.

In order to distinguish collision scenarios from regular operation, it is very helpful to look at the estimated braking distances. In regular operation there is always enough margin to allow for a dosed braking. Thus, if the distance to another train on the same route approaches the sum of the braking capability limits of both trains, the RCAS system shall act.

Alert and advisory (command) concept

Because of the relatively high speeds of trains and the long braking distances, an alert and advisory (or command) concept, similar to the aeronautical TCAS, promises a major safety gain. In the first step a Traffic Alert (TA) signal shall warn the train driver in case of a detected close approach to another RCAS unit on a collision course. TA will be activated with a fixed time t_{Alert} prior to the time when the train has to start braking, given that it proceeds with the momentary speed. Thus, the train driver is prepared to receive a Braking Command (BC) in a second step, which is signaled after t_{Alert} seconds in order to avoid the collision. As an example **Figure 8** illustrates this concept for the front collision scenario.

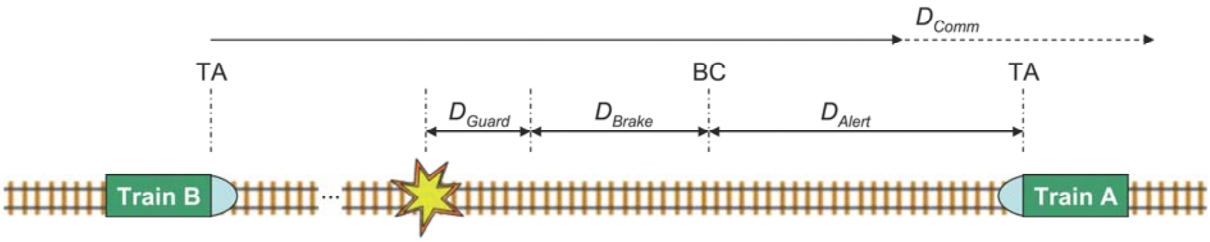

Figure 8: Illustration of Traffic Alert (TA) and Braking Command (BC) concept

The distance between TA and BC is given by $D_{Alert}(v) = v \cdot t_{Alert}$. To allow for a safe braking, a guard distance $D_{Guard}(v)$ is added to the braking distance $D_{Brake}(v)$ to assure that the trains come to a full stop under all environmental conditions.

A very similar situation is given, if a rear-end collision scenario is detected. In this case the length of the leading train has to be taken into account and only the following train will receive a braking command until its speed allows a safe follow up. To expand the TA-BC concept to fit flank collision scenarios, the following definitions are made:

- **Definition TA**
  - Current speeds of two trains lead to a collision or „close collision" (virtual lead-lag time t_l corresponding to a lead-lag range $D_l = v \cdot t_l$) on the planned route and
  - distance to BC point $\leq D_{Alert}(v)$

- **Definition BC**
  - TA active and
  - distance to (possible) collision point $\leq D_{Brake}(v) + D_{Guard}(v)$

The virtual lead-lag time t_l induces extra margins between trains that approach a crossing or a switch, even in the case that no flank collision would occur if they proceed with the same speed. But if one of the trains changes its speed this margin must allow the other one to react to the changed traffic situation. In this way safe and efficient transport can be achieved.

The braking distance of each train mainly depends on the following parameters: Speed, slope of the track, brake type, brake configuration, number of axels, and ratio braking weight to train weight. While the track slope is provided by the electronic map, all other parameters are train or vehicle specific parameters which are either pre-assigned or they can be determined by sensors.
An estimate of the braking distance s_B can be calculated with e.g. the Mindener equation [7]

$$s_B = \frac{3{,}85 v_0^{\;2}}{6{,}1\psi(1 + c_1\lambda/10) + c_2 i_m}, \tag{1}$$

where v_0 is the speed at the start of braking, ψ, c_1 and c_2 are higher order function of v_0 which depend on the brake type, brake configuration and number of axels, i_m is the mean slope of the track, and λ is the ratio braking weight to train weight. Equation (1) is valid for passenger trains only. For a modified version of (1) addressing freight trains and for more details on the parameters we refer to [7]. To calculate the total braking distance D_{Brake} we need to add the distance depending on the reaction time t_{React} of the train driver

$$D_{Brake} = v \cdot t_{React} + s_B\,. \tag{2}$$

Although such calculations can provide good estimates and one can even think of expanding the model to take e.g. aging of brakes into account, the real braking distance might vary due to the fact that adhesion and friction between wheels and rails are changing depending on the environmental conditions, which are difficult to be quantified. In order to minimize false alarms in regular operation conditions and to efficiently use the track infrastructure, the braking distance shall not be overestimated. On the other hand, an underestimation of the braking distance would cause collisions at low speed. Therefore we propose to add a guard distance D_{Guard} as depicted in **Figure 8**, which is a second order function of the momentary speed

$$D_{Guard} = k_0 + k_1 v + k_2 v^2\,. \tag{3}$$

This provides enough margin at high speeds but also allows short distances between trains at low speed. In the RCAS algorithm the traffic situation will be assessed repeatedly, thereby taking velocity changes into account. In the future, if we think of an RCAS controlled brake, this would also enable to specify the distance between vehicles when they come to a stop. In the case that we set $k_0 = 0$, this would allow for automatic coupling.

Under the assumption, that all involved vehicles are aware of the critical situation, that means we can guarantee that the communication range D_{Comm} is larger than the sum of the total braking distances (see **Figure 8**), we can further assume, that all train drivers will follow a BC. That means each involved vehicle is able to determine a common point on the track (crash symbol in **Figure 8**), where it must come to a full stop. This finally leads to the absolute points on the track for TA and BC signaling.

Besides the alert and advisory/command concept which is apparent to the train drivers, the RCAS collision detection algorithm internally uses a 5 step classification process to improve performance:

1. **"listening"** – as long as there are no messages received,
2. **"awareness"** – if another RCAS unit is within the communication range on a route that does not cause a conflict,
3. **"surveillance" –** if the possible routes of the trains and their speeds lead to a contact or close contact, i.e. they might pass the same switch or track, or they pass on a parallel track,
4. **"warning" –** when TA is active,
5. **"braking" –** when BC is active.

Depending on the status, distance and speed of the other user, the conflict potential is assessed at different rates.

Adaptive message broadcast rate

Similar to the adaptive internal processing rate, the broadcast rate of messages is adapted to efficiently use the allocated frequency band. This is especially important in dense areas near large shunting yards, where we meet hard limits on the total system data rate. It is not only required to guarantee the necessary data throughput on the communications channel. Most important is to minimize the latency times for receiving updated information from other trains.

In the following we will derive a formula for the necessary message broadcast rate, which is once more dependent on the actual speed and the braking distance and which takes worst case assumptions for a train just entering the communications range in a front collision scenario into account. According to **Figure 8** the total distance between the hypothetical collision point and the TA point for train A is given by

$$D_{Total,A} = D_{Guard,A} + D_{Brake,A} + D_{Alert,A} \, , \tag{4}$$

where $D_{Brake,A}$ and $D_{Guard,A}$ are calculated from (2) and (3) using the momentary speed v_A of train A. In the second section of this chapter on page 4, where we investigated the different topological scenarios, we concluded that the required communication range D_{Comm} = 5 km. Under worst case assumptions a train B travels at the maximum speed $v_{B,\max}$ = 160 km/h in the regional network and requires a maximum braking distance because adhesion is reduced and the slope is negative. In fact this would mean the driver is going faster than allowed. Adding some minimum alert margin to the braking distance, this should never exceed half the communication range. Thus the total distance between the hypothetical collision point and the TA point for train B is maximal

$$D_{Total,B,\max} = \frac{D_{Comm}}{2} = 2500 \text{ m.} \tag{5}$$

Now, if we assume that train B is unknown and just enters the communication range, we can calculate the minimal required message broadcast rate $R_{A,\min}$ for train A to notify train B in time with a specified probability P_t:

$$R_{A,\min} = \frac{n_{P_t}(v_{B,\max} + v_A)}{D_{Comm} - D_{Total,A} - D_{Total,B,\max}} \quad . \tag{6}$$

The denominator in (6) is the sum of the remaining distances which A and B are in front of their TA points. Multiplied by $(v_{B,\max} + v_A)$ this gives the reciprocal value of the time left to reach these points. Neglecting the propagation delay this is finally multiplied by the number of repeated transmissions n_{P_t}, which are necessary to ensure the reception of at least one message with a probability P_t.

The number of necessary repeated transmissions n_{P_t} mainly depends on the propagation conditions and on the user density, respectively on the implemented MAC protocol as explicated in [6]. First analysis of promising new MAC protocols for high dynamic Mobile Ad-hoc NETworks (MANETs) in dense user areas using the channel model presented in [8] indicate, that a probability in the order of $P_t = 1 - 10^{-5}$ is achievable with $n_{1-10^{-5}} < 10$ transmissions even under such demanding conditions. The details of this analysis would by far exceed the content of this paper and will be published separately in the near future.

For the next step let us assume that $P_t = 1 - 10^{-5}$ under such extreme conditions is sufficient for the overall performance of the system and that $n_{1-10^{-5}} = 7$. In case that train A is at a stop, (6) allows us to calculate the minimal required message broadcast rate of the complete system

$$R_{\min} = \frac{7 \cdot (44.4\,\text{m/s} + 0\,\text{m/s})}{5000\,\text{m} - 0\,\text{m} - 2500\,\text{m}} = 0.125\,\text{Hz}\,. \tag{7}$$

On the other hand, we need to set an upper limit due to communication channel resource limitations. A reasonable value is $R_{\max} = 2\,\text{Hz}$. This meets the processing performance limits of the collision detection algorithm in first tests and leads to acceptable short delays in updating the changes in the traffic situation.

Equation (6) allows us to calculate the required broadcast rate depending on the momentary speed. Advantages for the investigated MAC protocols is a stepwise change like $R = 0.125/0.25/0.5/1/2\,\text{Hz}$. Thus the result of (6) must be rounded to the next higher of these values. In this way slot reservation is possible (see message format details in **Figure 6**), which reduces message collisions.

If another train C is detected to cause a conflict, i.e. the status is **"surveillance"**, **"warning"** or **"braking"**, the rate will be further increased step by step.

SUMMARY AND OUTLOOK

In this paper we presented a reliable surveillance strategy concept for an efficient and robust train control overlay system exploiting direct train-to-train communications. The content of the broadcasted messages allows each railway vehicle to assess the traffic situation in its vicinity. The variable broadcast rate of messages enables to get by with the limited communication channel resources in the envisaged internationally available frequency band under all operational conditions and in the different railway scenarios like regional networks or large shunt yards.

The presented surveillance strategy provides instant information to train engine drivers in case of imminent collisions and many other threats on railroads that cause most of the accidents today. At the same time it allows for a more efficient use of rail infrastructure in the future. The advantages of this infrastructure-less approach are fast and relatively cheap deployment. Moreover a continuous roll-out is possible without the need to take a hand in existing train control mechanisms.

One of the next steps in our research is the verification of the propagation channel model through measurements. Together with real network and train schedule data this will allow us to perform detailed simulations of the new MAC layer approaches. Especially the distribution of latency times in receiving updated traffic information is important to evaluate the reliability of the direct train-to-train communication link.

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