Paul Unterhuber

Test of IEEE802.15.4 for Train-to-Train Short Range Communication and Relative Localization

Paul Unterhuber received the M.Sc. degree in electrical engineering and the M.Sc. degree in engineering and business from the Graz University of Technology, Graz, Austria in 2013 and 2014, respectively. In 2022 he received his Dr.-Ing. degree from Technische Universität Braunschweig, Germany. Since 2015, he has been with the Institute of Communications and Navigation at the German Aerospace Center (DLR) in Oberpfaffenhofen, Germany.

He has been participating in several national and international research projects, e.g. V2X-DuRail, X2-Rail, R2Dato and Pods4Rail. His research interests are on channel sounding, propagation and modeling with a focus on train-to-train communications, and joint communication and sensing for railway applications. He contributed to IEEE 802.11bd Enhancements for Next Generation V2X standard and the ETSI RT JTFIR standardization body.

Deutsches Zentrum für Luft- und Raumfahrt (DLR)

Münchener Straße 20
82234 Weßling
Germany

+49 8153 28-2291
paul.unterhuber@dlr.de

I. Introduction

The transportation sector is undergoing a transformation towards digitization, higher grades of automation, and lower emissions of carbon dioxide. In case of railway transportation innovative operational solutions like automatic train operation (ATO), remote train operation (RTO), self-driving freight wagons (SDFW) or virtually coupled train sets (VCTSs) have been investigated to foster this transformation. The wireless data exchange within the train, between train units or between different trains is enabling those innovative solutions and enhance the flexibility in operation [1].

When connecting multiple trains only by a wireless communication link we talk about VCTS. This wireless communication link needs to ensure highly reliable and low latency data exchange between all train units to control the platoon. Direct train-to-train (T2T) communication based on multiple and complimentary communication standards fulfill the stringent requirements. Different communication standards could be used based on the requirements in case of data rate, latency, frequency allocation and communication range as depicted in Figure 1. All train units, or at least the leading train within the VCTS, would be connected to a central coordination unit by a train-to-ground (T2G) communication like future railway mobile communication system (FRMCS).

In the last years, different tests and measurement campaigns were performed to test ETSI TETRA [2], ITS-G5 based on IEEE 802.11p [3] or 3GPP LTE V2X [4] for railway applications. With the focus on joint communication and sensing (JCAS), the latest communication standards like IEEE 802.11bd or 3GPP 5G NR, and standards offering high bandwidth like IEEE 802.15.4, gained on attraction. Large bandwidth for vehicular and railway applications can be either achieved by IEEE 802.15.4 below 10 GHz, or at frequencies above 20 GHz with 3GPP 5G NR and IEEE 802.11bd supporting mmWave communication. All approaches are limited in the communication range either due to the limited allowed transmit power or by the high propagation losses at mmWave bands. Hence, we limited the communication range up to 250 m for this kind of short-range communication (SRC) in combination with relative localization (RL) based on radio ranging (red part in Figure 1).

IEEE 802.15.4 offers on multiple channels 500 MHz or 1 GHz bandwidth, radio ranging capabilities and commercial off-the-shelf components. This standard was designed for indoor application or personal area networks with very limited communication range. Hence, a test campaign in a railway environment was planned and executed to test the SRC and RL capabilities of IEEE 802.15.4. The test system, the tests itself and a first summary of the achievements and outcomes of the tests are presented in the following sections.

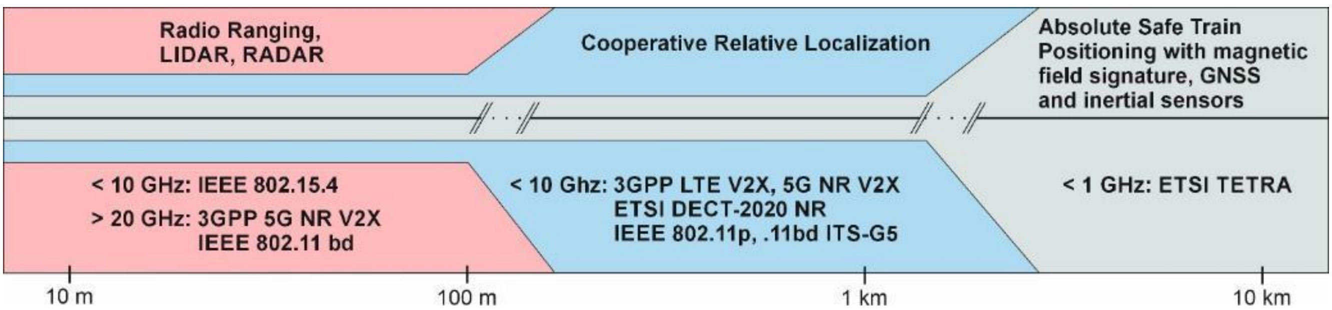

Figure 1: T2T communication and localization.

II. Short-range communication and relative localization system

A. Hardware

The hardware of the SRC and RL system is split in three similar nodes as shown in Figure 2: Train ATO (Node 1), Train X (Node 2) and Ground (Node 3).

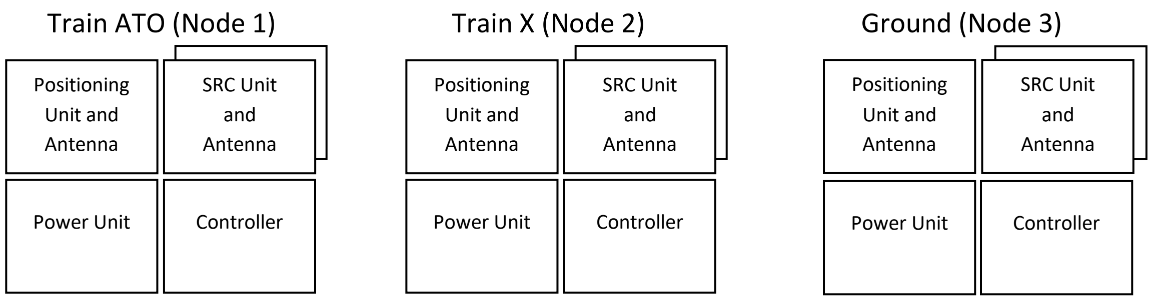

Figure 2: Schematic of the SRC and RL system

The SRC units are the heart of each node. The units are a DLR in house design and base on Qorvo DW1000 UWB chipsets. The SRC unit supports two independent communication threads and the possibility of connecting different antennas via the SMA connectors. This variable multi-unit installation has the benefit of acquiring more measurement data for each test run with the same conditions. Furthermore, different antenna settings can be installed and compared.

For accurate positioning global navigation satellite system (GNSS) receivers supporting multiple satellite constellation (GPS, Galileo, Beidou and GLONASS) and multi frequency positioning are used. These positioning units and the corresponding antennas deliver the GNSS position and store the data locally. Furthermore, the positioning units provide a network time protocol (NTP) server to all other units so that all data sets are recorded synchronously.

The control of the nodes can be done remotely via the built in controller unit. This unit consists of a Raspberry Pi 4 B computer and an LTE modem. The controller is also used to store the collected SRC data locally.

The power unit proves individual power supply to all units of the node. The power is provided by power banks supporting USB power delivery for different output voltages with a maximum output power of 140 W.

B. Software

The SRC communication exchange is implemented in two modes, an active and a passive mode. The active mode enables sending and receiving of packets between all active nodes. The node with the lowest ID is set as leader (see Figure 3, node 1) and initiates the data exchange. The other active nodes answer on this poll. For passive nodes like node 3, only receiving is enabled. The whole data exchange of active nodes can be received and evaluated.

Between the controller and the SRC unit different data and commands are exchanged. In the initialization phase, the controller forwards the RF settings, e.g. used UWB channel, power, etc., to the SRC unit. During the operation, the SRC unit forwards the collect channel state information (CSI) data and the estimated distance estimation to the controller. The CSI is stored locally on the controller for future JCAS applications or is used for displaying the CSI in combination with the estimated distance for the VCTS show case in real time.

Based on the data exchange provided by the SRC the RL, particularly the distance between the nodes is calculated. Two communication nodes (e.g. Train ATO and Train X in Figure 2) exchange multiple timestamped information packets in both communication directions and perform so called Round Trip Time (RTT) measurements. To minimize the influence of unknown processing time, the timing should be extracted in the physical layer of the SRC unit. With double sided RTT (DS-RTT) as shown in Figure 3 the accuracy can be increased. As stated in [5] the DS-RTT allows a compensation for linear clock drifts of the communication nodes.

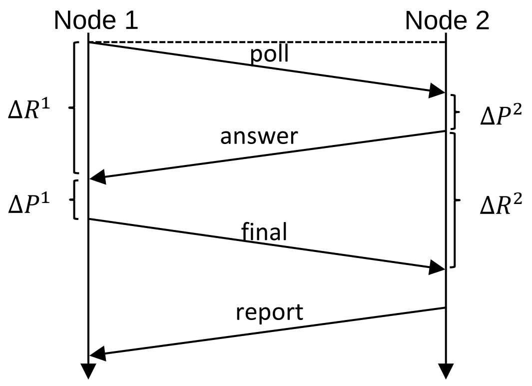

Figure 3: DS-RTT measurements

With the data exchange indicated as final, node 2 is able to calculate the distance to node 1. To allow node 1 derive a distance estimation as well, the recorded time stamps are transmitted from node 2 to node 1 in the additional data exchange called report [5], [6]. The distance can be calculated as

$$d = c\ \frac{(\Delta R^1 \cdot \Delta R^2) - (\Delta P^1 \cdot \Delta P^2)}{\Delta R^1 + \Delta P^1 + \Delta R^2 + \Delta P^2} \quad (1)$$

where c denotes the speed of light. The ground unit is implemented as passive communication node and only receives the communication packets from node 1 and 2.

III. Tests

The tests were conducted in a railway environment with two commuter trains to evaluate the potential of broadband communication for T2T SRC and RL up to a distance of 250 m. The tests were performed on the shunting yard of Nederlandse Spoorwegen (NS) in Amersfoort, Netherlands, end of April 2025.

A. Test cases and environments

Five different test cases (number 1 to 5) were planed representing VCTS and SDFW operation as listed in Table 1. The test case 5, coupled mode for VCTS, is shown in Figure 4 with two trains driving in short distance on the same track. Six runs of test case 5 were set up as VCTS show case. During this show case, the estimated distance between the trains and the CSI was displayed to the train drivers in real time.

Figure 4: Test case 5, coupled mode for VCTS

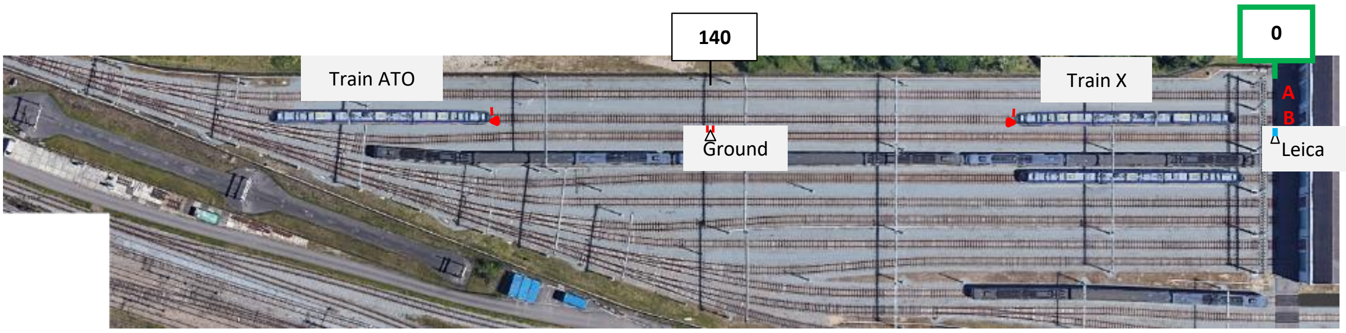

Figure 5: Test environment and tracks

Table 1: Test cases and environments

Test case				Train ATO – Node 1				Train X – Node 2				Ground – Node 3	
#	Name	Maneuver	Environment	Start	Stop	Speed	Track	Start	Stop	Speed	Track	Track	Position
1	VCTS coupling	Approaching on same track	Clear A	300	0	15-25	B	0	0	0	A or B	0-A or B-C	140
			Clear B	300	0	15-25	A	0	0	0	A or A	0-A or B-C	120
2	VCTS de-coupling	Departing on same track	Clear A	0	300	15-25	B	0	0	0	A or B	0-A or B-C	140
			Clear B	0	300	15-25	A	0	0	0	A or B	0-A or B-C	120
3	Fixed distance	Static, multi positions	Clear A	300	0	0-10	B	0	0	0	B	B-C	140
4	Passing	On parallel tracks	Clear A	0	300	15-25	B	60	60	0	A	B-C	140
			Clear A	260	0	15-25	B	60	60	0	A	B-C	140
5	Coupled mode	A platoon driving	Clear A	300	20	5-15	B	260	0	5-15	A or A-B	B-C	140
6	Sensing	Static and moving train, passive moving objects	Clear A	100	100	0 or 20	B	0	0	0	B	B-C	80
7	Sensing	Static Trains, active moving object (track worker)	Clear A	100	100	0	B	0	0	0	B	0-A	80

Test case 6 and 7 representing future JCAS applications for obstacle detection and track worker localization were conducted in addition to the planned tests. Due to track occupation, the test environment was limited to Track A and B as shown in Figure 5. Track A and B were used for driving and parking of trains, or kept empty (clear A or clear B) depending on the test case.

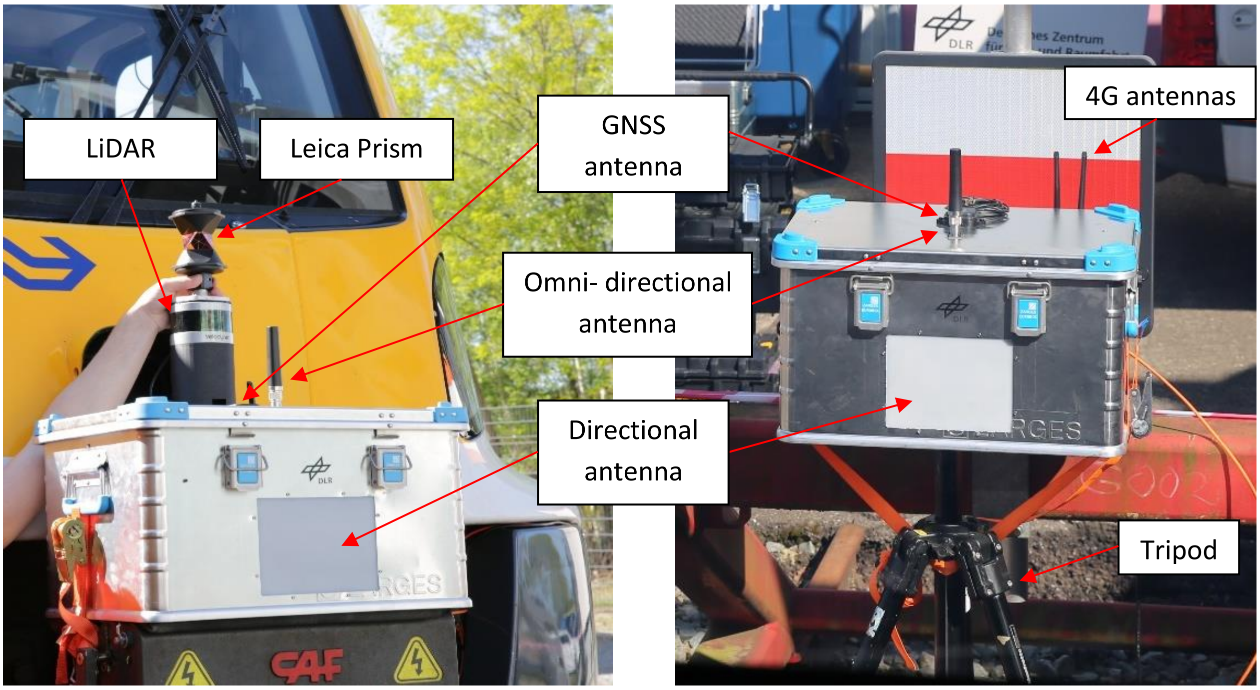

Figure 6: Test equipment for Train ATO (Node 1, left) and Train X (Node 2, right)

B. Test equipment and implementation

Based on the schematic shown in Figure 2 three nodes were designed. The SRC multi-unit installation enables for node 1 and 2 simultaneous tests on two communication links. One link was using a directive antenna and the other link was using an omni-directive antenna as shown in Figure 6. Node 1 and 2 were assembled as stand-alone nodes with all related test units, power and controller in one casing. This approach reduced the effort of installation, mounting and cabling on the train. Furthermore, the necessary flexibility was given to change the position of node 2 from the train coupler to the tripod in front of the buffer stop. In Figure 5 both trains are shown and the nodes indicated in red mounted on the coupler facing each other. Train ATO was a CAF SNG ATO test train. For Train X either a second CAF SNG train was used (in case of test case 4 and 5), or the node 2 was mounted on a tripod in front of the buffer stop (in case of test case 1-3) with the position indication (start and stop) 0 m.

Node 3, the ground station, was installed in an additional casing, externally powered and placed at 140 m distance. The SRC multi-unit installation at node 3 was used to install two omni-directional antennas in a distance of 2 λ on a ground plane, mounted on a tripod. Node 3 was not actively exchanging data with node 1 and 2 but received on both antennas the data exchange between node 1 and 2.

As a position reference system, a Leica total station (TS) was used. The TS was used to measure the positions of fixed points, such as overhead line masts, building walls, and parked trains, with high accuracy. It was also used to measure the position of the static Train X. During driving of the Train ATO, the TS tracked the Train ATO and recorded its position. Based on the millimeter accuracy of the Leica TS system, the RL tests can be evaluated. Nevertheless, the TS is limited to measure or track one object at the time.

For the test case 5 with two trains driving, a light detection and ranging (LiDAR) system was used to record the environment in front of Train ATO. In addition to the absolute position of the Train ATO tracked by the TS, the collected data of the LiDAR is used to estimate the distance between the Train ATO and the Train X. The estimated distance from the LiDAR data set will be compared to the UWB based RL test data and is seen as distance reference system in test case 5.

In addition to the SRC and RL test equipment, inertial measurement units (IMUs) and magnetic field sensors were installed in node 1 for safe train absolute positing tests. For the sake of completeness, these sensors are mentioned, but further details are beyond the scope of this contribution.

IV. Achievements and Conclusion

The tests were performed on 3 days, ½ day installation and 2 days testing. Within the two days, 12 tests were performed; in detail 11 test cases and 1 VCTS show case as shown in Figure 4. In total 103 runs back and forth on the roughly 400 m track were done and a total distance of more than 35 km were driven. During the tests 1 TByte data for the data exchange by UWB SRC nodes, localization by GNSS receivers, IMU and magnetic field sensors, point clouds from LiDAR, ground truth by Leica tracking and videos were recorded.

The tests were accompanied by extensive public relations work. The tests were documented by a video team and a promotion video with expert interviews was produced [7]. A press release [8] and multiple LinkedIn posts were released. Articles about the tests were published in several news channels and magazines.

Based on our observations we can conclude the following:

We observed different influences of the railway environment and the trains on the SRC and RL performance. First, due to curved track segments, objects along the track can obstruct the communication link. An object like a fence next to the curved railway track is clearly influencing the SRC in terms of packet drops and RL in case of accuracy. Second, with the installation of the communication nodes in the coupling area of the train obstructions by the train bodies itself occur when both trains passing each other on parallel tracks. A significant difference between the one link using a directional antenna and the other link using an omni-directional antenna could be observed. A reception of the direct signal or reflections of the signal can be observed partially with the omni-directional antenna, but not with the directional antenna. Third, the use of a directive antennas increased the SRC performance but misalignment of the directive antennas in a curved track section clearly degrades the SRC.

A successful data exchange between the SRC units based on UWB communication could be established up to a range of 340 m. The tested maximum range was bounded by the length of the track within the yard and not by the communication system. The RL algorithms could be successfully tested, DS-RTT packets were exchanged and the distance could be estimated from 2 to 340 m. The test results can be interpreted as proof of concept and show the suitability of broadband systems supporting communication and distance estimation for railway applications. A detailed analysis will clarify the suitability of such an UWB based system for SRC and RL.

At the VCTS showcase, the positive response from train drivers and attendees regarding the availability of real-time estimated distances between trains highlighted the potential of such a system for accurately controlling the distance between rail vehicles for applications such as VCTS, SDFW, shunting, and stabling.

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