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Positioning and Location-Aware Communications for Modern Railways with 5G New Radio

Jukka Talvitie, Toni Levanen, Mike Koivisto, Tero Ihalainen, Kari Pajukoski, and Mikko Valkama

Abstract—Providing high-capacity radio connectivity for high-speed trains (HSTs) is one of the most important use cases of emerging 5G New Radio (NR) networks. In this article, we show that 5G NR technology can also facilitate high-accuracy continuous localization and tracking of HSTs. Furthermore, we describe and demonstrate how the NR network can utilize the continuous location information for efficient beam-management and beamforming, as well as for downlink Doppler precompensation and cancellation, due to residual Doppler and oscillator phase noise, are described and demonstrated. The provided numerical results at 30 GHz operating band show that sub-meter positioning and sub-degree beam-direction accuracies can be obtained with very high probabilities in the order of 95-99%. The results also show that the described Doppler precompensation and ICI estimation and cancellation methods substantially improve the throughput of the single-frequency HST network.

Index Terms—5G New Radio (NR), high-speed trains, radio positioning, velocity estimation, tracking, beamforming, location-aware communications, Doppler compensation, phase noise compensation

I. INTRODUCTION

The upcoming 5G new radio (NR) networks have the potential to revolutionize the service and management opportunities of modern railway systems by introducing flexible and high-performance communications and positioning capabilities [1], [2]. Compared to previous mobile network generations, high-accuracy radio positioning is generally considered as one of the most exciting new key features of 5G NR networks, and it is expected that submeter or even centimeter-level positioning accuracy with high reliability can be provided, especially in the networks operating at the mmWave bands [3], [4]. Moreover, besides providing extreme broadband connectivity for increased data rates, 5G NR networks support mission-critical use cases with predefined requirements for the communications link performance, such as end-to-end latency, availability and reliability [5].

Whether the objective is to offer extremely high data rate mobile connections for passengers, or to support ultra-reliable and low-latency mission-critical railway management functionalities, 5G NR networks are able to provide diverse set of services via network slicing [1]. For each desired railway

system functionality, a unique network slice can be dedicated to support a specific set of required key performance indicators. Moreover, as 5G networks are able to offer multi-purpose services based on a single physical network, the implementation and maintenance cost of railway systems can be reduced compared to compound solutions where separate operations are distributed among multiple dedicated systems.

Due to the above-described great potential of 5G NR networks in modern railway systems, high-speed train (HST) aspects have been clearly recognized also in the 3rd generation partnership project (3GPP) standardization, see, e.g., [1], [6]. To this end, a baseline 5G NR network deployment and system parameterization for HST radio access research and performance evaluations, as illustrated at a conceptual level in Fig. 1, has been defined in [6]. Nonetheless, detailed requirements for railway communications, discussed, e.g., in [7], are still under the specification stage, but it is clear that both mission-critical use cases, as well as extreme broadband use cases with high data rates, are considered.

In this article, we describe a novel 5G positioning and communications concept for modern railway systems based on the 5G NR specification guidelines operating at the mmWave bands. The developed high-accuracy radio positioning scheme introduces considerable benefits for modern railway systems, especially including railway management functionalities and other mission critical services. As a standalone technology, 5G NR based positioning and tracking increase the diversity of the overall multitechnology train positioning solution, and thus improves the reliability and availability of the position information compared to current positioning solutions. It is generally known that, e.g., global navigation satellite systems (GNSS) alone are not able to provide the required positioning performance, and thus fusion over multiple positioning technologies, including the proposed standalone 5G positioning approach, is necessary to fulfill the required performance criteria [8], [9]. Besides describing and demonstrating the 5G NR based train positioning and tracking, we also discuss the utilization of the continuous position information in the NR data channel. Specifically, we demonstrate the feasibility of the location-based beamforming at the network side to enhance the efficiency of beam-alignment and beam-tracking in the mmWave HST network via reduced overhead and latency compared to conventional beam training procedures. Furthermore, with HSTs, the signal degradation due to high Doppler shifts at the mmWave bands can significantly limit the system performance, particularly in the single-frequency network (SFN) context where signals from multiple transmission points or remote radio heads (RRH) are superimposed at the receiver. However, presuming

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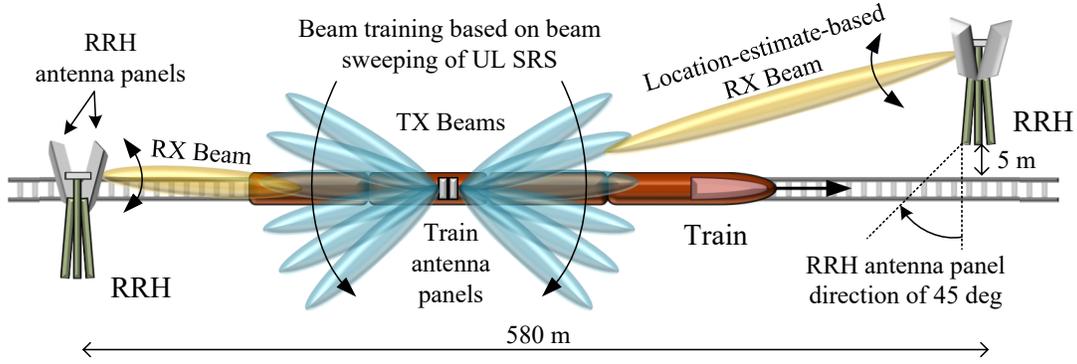


Fig. 1. Illustration of the considered railway scenario and the single-frequency mmWave radio network composing of multiple remote radio heads (RRHs).

access to real-time position and velocity information, we further demonstrate that appropriate Doppler pre-compensation methods can be introduced to alleviate the signal degradation due to high mobility. Finally, an important implementation challenge in the mmWave frequencies, namely the oscillator phase noise (PN), is considered by introducing novel signal processing solutions for mitigating the oscillator PN effects in the mmWave 5G NR networks.

II. 5G NR PROSPECTS FOR MODERN RAILWAYS: POSITIONING AND COMMUNICATIONS

A. System Description

Building on the 3GPP vision of 5G communications for HSTs presented in [6], the railway scenario considered in this article is illustrated in Fig. 1. The train is equipped with an external relay node including two antenna panels directed towards the nose and tail of the train. All communications between the network and the train is routed via the train relay, such as passenger communications and dedicated communication links of the underlying railway management system. Thus, instead of managing frequent and fast handovers for hundreds of passengers simultaneously, only a single relay node is utilized [6]. This reduces the network interference and increases the achieved data throughput due to reduced control signaling overhead. By following the 3GPP guidelines, the network consists of RRHs, whose locations are alternating between both sides of the track with inter-site distance of 580 m, and with 5 m distance to the track. Each RRH is equipped with two antenna panels, rotated by 45 degrees with respect to the track normal, covering both track directions.

The network is assumed to operate at 30 GHz mmWave band according to the SFN principle, where multiple RRHs transmit to or receive from the train relay using the same time-frequency resources. In downlink, network side time alignment is used to align the received signals in the train within the used cyclic prefix (CP) length. Since the RRH signals are mostly received from the angles corresponding approximately to the direction of the nose and tail of the train, separate antenna panels at the train observe significantly different Doppler shifts. This causes considerable degradation of the radio link quality, and therefore it is important to introduce appropriate Doppler shift

precompensation, as discussed and demonstrated later in this article.

B. 5G Positioning Prospects for Modern Railways

Positioning is, in general, considered as one of the key features in the upcoming 5G networks, and various positioning use cases with related performance requirements have been specified in detail by the 3GPP [10]. Besides focusing only on pursuing high positioning accuracy, also other performance indicators are considered including availability, latency, reliability, and integrity of the position estimates. In addition to actual positioning, estimation of velocity and device bearing are also addressed. Moreover, by exploiting the flexibility, versatility and configurability of the 5G-enabled positioning services, the positioning system can be customized for specific needs of modern railway systems. Thus, together with high-performance communications capability, 5G networks introduce a great asset for railway system management in terms of efficiency, affordability and safety.

Besides being an essential part of railway system management, positioning can benefit the performance of the 5G communications itself [11]. In location-aware communications, position information can be utilized for a vast set of location-aware radio resource management (RRM) functionalities, such as location-based beamforming and proactive resource allocation. In addition, position information can be used for reducing the overhead of beam training processes, and for mitigating the signal impairment due to Doppler phenomenon in high mobility use cases.

In general, compared to previous mobile network generations, 5G networks benefit from the large signal bandwidths available at the mmWave bands, which enable very accurate ranging measurements for positioning systems [3]. In order to compensate for the increased path losses at the mmWave bands, large antenna arrays with effective beamforming capability are also introduced. From the positioning perspective, this means a potential access to high-accuracy angle measurements, and thus for improved positioning performance. Furthermore, line-of-sight (LOS) links are mostly available, which offers a straightforward utilization of both the ranging-based measurements and the angle-based measurements in various positioning algorithms, particularly in outdoor scenarios [3], [4].

Although 5G networks have evidently potential to reach submeter positioning accuracies, each positioning scenario has to be separately considered based on the given performance requirements [10]. In the studied railway scenario, there are several challenges, which have to be addressed in order to meet the given performance requirements. Firstly, the expected high velocities necessitate low latency and high positioning update rate in order to support mission critical railway management. Because of the expectedly large mass of a train, high-accuracy predictions of the train position and corresponding train dynamics are often feasible over a limited time period. However, with considerable track curvature and varying train acceleration, the prediction error can accumulate rapidly over given tolerable accuracy levels. Secondly, the specific access node geometry of the considered railway scenario is rather challenging, as the RRHs are aligned approximately on the same line with the train. This causes degraded geometric dilution of precision, which limits the achievable positioning performance. Finally, when considering ranging measurements attained by taking timing measurements of the radio wave propagation delays, the clock offsets between the train and the network nodes have to be taken into account. In the position approach described in Section III, these aspects are properly reflected.

C. 5G Communications Prospects for Modern Railways

Similar to the positioning, 5G communications at the mmWave bands benefits from the large available bandwidth, which increases the system capacity as well as provides means for enhanced transmission diversity and supplementary degrees of freedom in data scheduling. The role of beamforming has significantly increased in 5G NR, compared to Long Term Evolution based systems, and even the regularly broadcasted synchronization signals and fundamental system information are beamformed in the form of synchronization signal blocks [12]. Furthermore, diverse beamforming techniques provide effective utilization of spatial domain via large antenna arrays, and are considered as one the most promising techniques for reducing network interference, which is especially crucial in heterogeneous network deployments with highly dynamic time-division duplex transmissions. Another important feature of 5G NR is the flexibility and configurability of the air interface, particularly in the form of the scalable subcarrier spacing, which significantly increases the tolerance against substantial Doppler spreads in high mobility scenarios.

The SFN operating principle of the HST network provides good macro diversity, but has also certain technical challenges. Particularly, due to largely different Doppler shifts of the signals coming from different RRHs, there can be severe problems in channel estimation and received signal quality, especially if it is assumed that the received signals from the different panels are combined to be processed with a single baseband to reduce the cost of the implementation. Therefore, a network side Doppler precompensation technique is proposed in this article. The idea is to estimate the Doppler shift per communications link based on the estimated train position and velocity and known RRH positions. With this information, the network can calculate estimates of link-wise Doppler shifts

and thereon pre-compensate the transmit signals per RRH. This leads to more stable LOS channel experienced through separate communication links and allows to combine signals in the radio frequency system before analog-to-digital conversion and baseband processing in the train receiver. This technique and its benefits are evaluated and demonstrated in Section IV.

Another potentially significant error source in a SFN is the timing alignment of the downlink signals. By timing alignment we refer to the relative timing of the received signals. When the train is receiving signals from two or more RRHs, time difference of the arriving waveforms is defined by the difference in distance to the serving RRHs. For this reason, so called network timing alignment is also proposed and considered for high speed single frequency networks, where the estimated train position and known RRH positions are used to calculate the time it takes for the transmitted signals to reach the receiver.

In mmWave communications, PN is typically more pronounced limiting the use of smaller subcarrier spacings and/or higher-order modulation and coding schemes (MCSs). With CP orthogonal frequency division multiplexing (CP-OFDM), PN causes common phase error (CPE) and inter-carrier interference (ICI). The CPE is observed as a common phase rotation over all active subcarriers and can be relatively easily estimated and compensated. For this reason, in 5G NR Rel-15, a new reference signal type called phase tracking reference signal (PTRS) was introduced to allow estimation and compensation of CPE in mmWave communications. The ICI, in turn, typically impairs the performance with higher MCSs. The current PTRS design of 5G NR Rel-15 does not support estimating or compensating the ICI. In Section IV, we will demonstrate a novel block based PTRS design [11], [13] and show its benefits on the link throughput in the considered mmWave HST scenario.

III. 5G NR BASED POSITIONING OF HIGH-SPEED TRAINS IN MODERN RAILWAYS

To benefit from the large bandwidths of 5G NR, and to avoid tight requirements on the clock synchronization between the train and the network, the considered positioning approach relies on uplink time-difference-of-arrival (TDOA) measurements at the RRHs. Since the measurements and the related positioning algorithms are managed at the network side, the network possesses always the most recent position information, which is crucial for the operation of location-aware RRM and low-latency railway management systems. The used TDOA measurements are based on the uplink sounding reference signal (SRS), specified for the 5G NR in [12]. According to the TDOA-based positioning principle, the RRHs are assumed mutually time-synchronized, which is well justified especially when the RRHs are under the same baseband unit. However, clock synchronization between the network and the train is not required, as the TDOA processing effectively removes any clock offsets between the transmit and receive nodes.

A. TDOA/EKF based Positioning Engine

In order to alleviate the complexity of the beam training procedure in the considered railway scenario, location-based

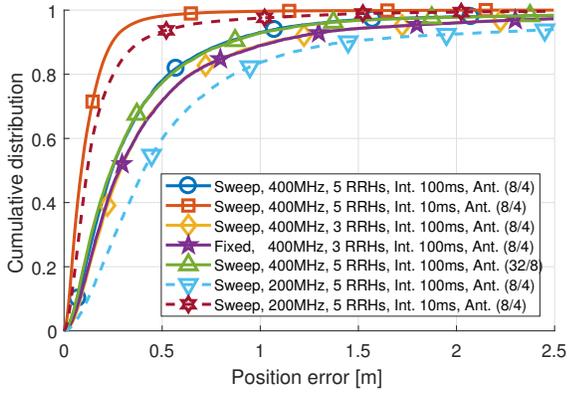


Fig. 2. Cumulative distributions of the train position estimation error.

beamforming is assumed at the RRH beamformers. Thus, each RRH adjusts the transmit and receive beams towards the estimated train position, which requires accurate and real-time train tracking capability in order to maintain the link connection in the considered high mobility scenario. Furthermore, it should be emphasized that the location-based beamformers in the RRHs are utilized for both the communications and positioning purposes. However, at the train side, where real-time position information is not directly accessible, the optimum beam selection is based on a conventional beam-sweeping-based training, where the train transmits a time-multiplexed set of SRSs over a predefined set of beams. The SRSs with different transmit beams are then received by the RRHs, which are able to collect the positioning measurements and choose the best train-side beam for subsequent transmissions until the next set of SRSs are transmitted and the beams are updated.

The processing of the TDOA estimates from multiple RRHs builds on the extended Kalman filter (EKF), which includes joint tracking of the train position and velocity. For the sake of simplicity, the position and velocity in the considered scenario are defined in 2D coordinates, but the extension for supporting 3D coordinates, or including other tracked parameters, such as train acceleration, is straightforward. Furthermore, although acceleration estimates would not be explicitly exploited for any purpose in the system, including acceleration in the EKF can sometimes improve the overall performance. However, for the studied HST scenario in this article, we did not observe any significant performance improvement by considering acceleration in the EKF, and thus excluded it from the model.

The fundamental operating principle of the EKF consists of two distinct steps, namely the prediction step and the measurement update step. In the EKF processing, the state of the train, including the train position and velocity, is assumed to evolve based on a constant velocity model, where the train is assumed to travel with a constant velocity between two consecutive time steps. Moreover, the covariance of the corresponding state evolution process is based on a continuous white noise acceleration model.

At predefined intervals, the train transmits uplink SRSs, which are time-multiplexed over the available beams. The SRSs are observed at multiple RRHs with different relative delays.

TABLE I
CONSIDERED 5G NR PHYSICAL LAYER PARAMETERIZATION

Parameter	Value
Carrier frequency	30 GHz
Channel bandwidth	[200,400] MHz
Subcarrier spacing	120 kHz
Allocation size	[132,264] PRBs
Transmission rank	2 (polarization based)
Channel model	CDL-D 100 ns
K-factor	13.3 dB
RRH antenna array size	8 x 4 or 32 x 4 (hor. x ver.)
Train antenna array size	4 x 4 or 8 x 4 (hor. x ver.)
Transmission power	+30 dBm
Train velocity (max.)	500 km/h
Inter-RRH distance	580 m
Uplink SRS Tx interval	[10,100] ms
Evaluated MCS indices	18 (64-QAM, R=822/1024) 24 (256-QAM, R=841/1024)

Based on the cross-correlation between the received signal and the known SRS, timing measurements are obtained and compared with each other in order to assemble a set of TDOA measurements. The covariance of the TDOA measurements can, in turn, be estimated based on analytic Fisher information according to coarsely estimated signal-to-noise ratio (SNR) levels of each measurement. According to the TDOA principle, at least three RRHs are needed in order to obtain an unambiguous position estimate.

For obtaining each measurement, the beam direction is defined according to the predicted train position based on the previously updated position estimate and the included prediction model of the EKF. Nevertheless, it should be noted that since obtaining high-quality positioning measurements and accomplishing accurately directed beams are interdependent, there is a possibility for error accumulation, especially if potential measurement outliers are not properly handled.

B. Positioning and Beam Alignment Performance

The positioning performance is evaluated by using a simulated 100 km long train track identical to the one considered in [14], but with slight additional curvatures along the route. In the beginning, the train is standing still and begins to accelerate with full power. After reaching the maximum velocity of 500 km/h the train maintains its velocity for about 4 minutes. After this, the train slows down to around 290 km/h velocity, but re-accelerates again, until stopping in the end. The number of RRHs taking simultaneous timing measurements is considered to be either three or five. Detailed parameterization of the underlying 5G NR physical layer is shown in Table I, where the signal bandwidth and the number of antenna elements are varied between different positioning performance results. Similar to the modeling in [14], the radio propagation related path loss model and the corresponding spatially correlated shadowing model are determined according to the 3GPP-specified urban micro model characteristics. As shown in Table I, the considered fast fading channel model in this article is the 3GPP-specified time varying Clustered Delay Line D (CDL-D) with a dominating LOS path. Moreover, since the utilized

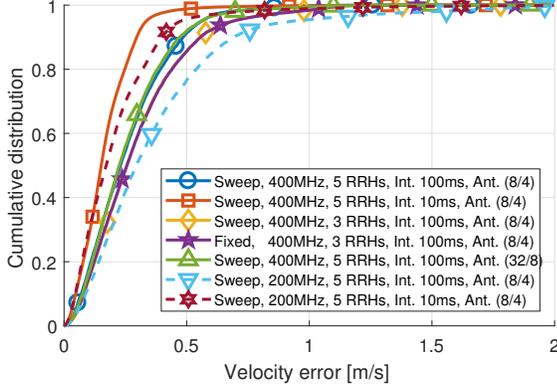


Fig. 3. Cumulative distributions of the train velocity estimation error.

TDOA-based positioning approach presumes ranging via LOS paths, the obtained performance results are highly dependent on the LOS path availability. However, when the LOS path availability is compromised, for example, when another train is blocking the signal, appropriate LOS detection methods and measurement outlier detection methods, such as the ones presented in [14], can be used to mitigate positioning errors due to reflected paths. Nevertheless, in the considered scenario, where multiple RRHs are assumed to be located within the TDOA measurement range, the performance degradation due to occasional LOS signal blocking is expected to be minor.

In Fig. 2, the cumulative distribution of the train position estimation error is shown with variable measurement and EKF update intervals, antenna configurations, bandwidths, and uplink beamforming strategies. Regarding the latter one, besides the earlier described beam sweeping based SRS transmissions at the train side, we consider as an alternative using also fixed beams at the train as a reference [14]. In the case of fixed beams, the train transmits only a single SRS with the beams pointing towards the nose and the tail of the train. Depending on the beamwidth, the link quality in proximity of a RRH might suffer due to the poor beam alignment. Furthermore, the antenna panels at the RRHs and the train comprise a uniform rectangular array, where the number of vertical direction antenna elements is fixed to 4. However, the number of horizontal direction antenna elements is varied in the evaluations, and it is either 4 or 8 at the train side, and either 8 or 32 at the RRH side. Moreover, it should be noticed that the required angular resolution of the uplink beam sweeping procedure depends on the considered beamwidth, and thus, the number of antenna elements at the train side.

As seen in Fig. 2, the positioning accuracy is considerably improved when using 10 ms ("Int. 10 ms") measurement update interval compared to the 100 ms ("Int. 100 ms") interval. However, neither the number of antenna elements ("Ant., number of horizontal elements at RRH / at train") nor the beamforming strategy (i.e. "Fixed" or "Sweep" beamformer at the train side) have a considerable effect on the positioning accuracy. On the contrary, the performance with the 400 MHz bandwidth (i.e. 264 physical resource blocks, PRBs) is considerably better compared to the 200 MHz bandwidth (i.e. 132 PRBs), stemming

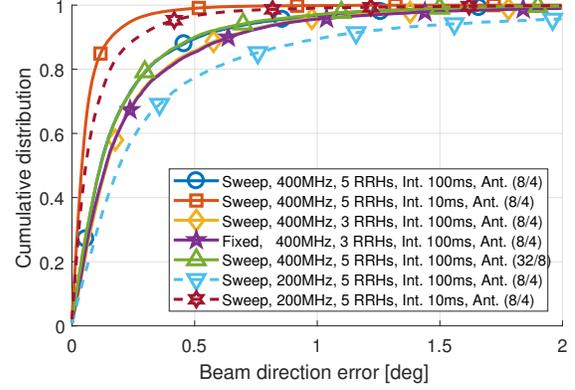


Fig. 4. Cumulative distributions of the RRH beam direction error with the location-based beamforming, when obtaining the position measurements.

from the increased TDOA ranging resolution. In addition, as expected, the position estimation accuracy is improved, when using measurements from 5 RRHs instead of only 3 RRHs. Similar observations can be done, when considering the train velocity estimation error, whose cumulative distributions are shown in Fig. 3.

With location-based beamforming, the beam direction error is a crucial performance indicator, as it determines the achievable beam gains, but also the possible beam losses in case of substantial beam misalignment. In Fig. 4, the cumulative distributions of the RRH beam direction error are shown at the time instants where the positioning measurements are taken. In these error curves, only the beam error of the closest RRH is considered at the time, since due to the specific system geometry, RRHs further away have generally smaller beam direction errors. As the beam direction accuracy depends on the positioning accuracy, the results are consistent with the results shown in Fig. 2.

IV. 5G NR COMMUNICATIONS FOR MODERN RAILWAYS

In this section, the throughput performance of the 5G NR based HST radio link, building on the technical enablers described in Section II, is demonstrated. The main evaluation parameters are similar to the positioning evaluations, shown in Table I, and follow the general high speed train scenario evaluation assumptions defined in [15]. The 400 MHz channel bandwidth case is assumed, while the antenna array sizes are 8x4 (RRHs) and 4x4 (train). Specifically, we assume that the network uses the position and velocity estimates to calculate the Doppler frequency and timing alignment precompensation factors as described in Section II-C.

In addition to the advanced Tx processing in the form of precompensation, a novel block PTRS is used to allow PN or residual Doppler induced ICI compensation. As described earlier, the NR Rel-15 PTRS is designed to only allow for the estimation and compensation of the CPE introduced by PN and modest frequency offset. The more elaborate contiguous block PTRS structure allows for the estimation of the ICI components by solving a set of linear equations limited by the number of reference symbols in the block PTRS as described in [13]. In

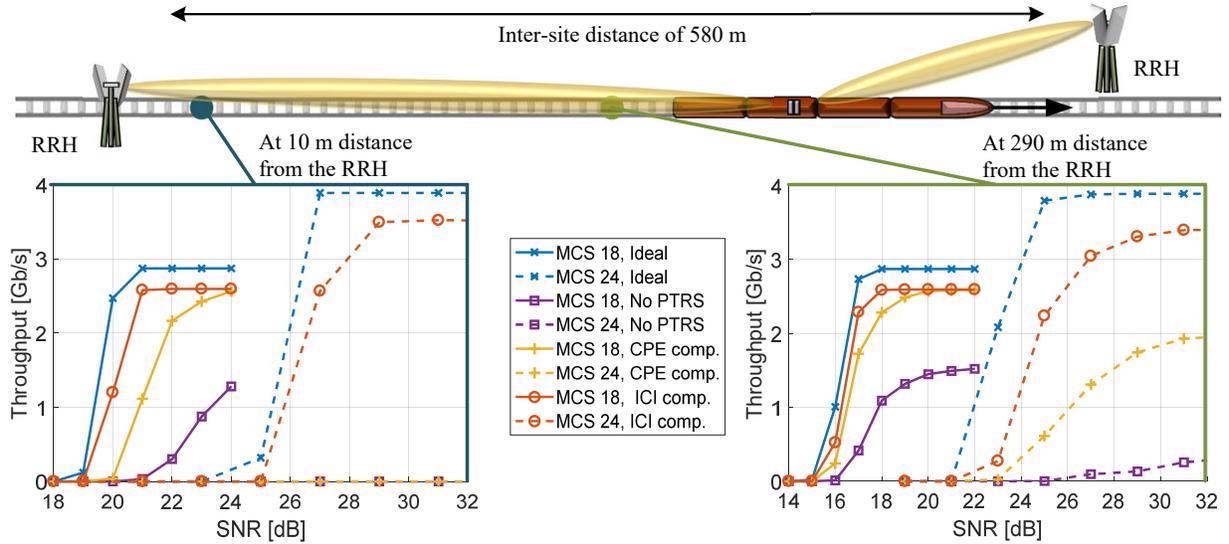


Fig. 5. Throughput of the HST communications link as a function of the SNR with different parameterizations at example distances of 10 m and 290 m from a RRH.

the presented results, we have assumed a block PTRS of size 4 PRBs to be transmitted in both spatial layers and we have configured the 5G NR Rel-15 compliant PTRS structure to use similar amount of subcarriers to provide equal overhead for the two reference signals structures. Additionally, a 3GPP compliant PN model is assumed.

As shown in Fig. 5, the downlink throughput performance of the radio link is evaluated at two different distances from the closest RRH, namely 10 m and 290 m distance, for varying SNR levels such that different MCSs can be show-cased. Regarding the communications link, it is here assumed that the train is always connected to two RRHs in a single frequency network. The "Ideal" reference curves demonstrate the link performance without PN, position or velocity estimation errors, or beam alignment errors. All other cases include these non-idealities, and it is assumed that the errors follow the statistics presented in Section III-B. The "No PTRS" case corresponds to performance without PTRS and the "CPE comp." case corresponds to 5G NR Rel-15 compliant distributed PTRS structure which allows to estimate and compensate only the CPE in the received signal. Finally, the "ICI comp." case refers to the scenario where the block PTRS structure is enabled allowing the receiver to estimate and compensate also for the ICI induced by the PN and residual Doppler error effects.

We can observe that with 64-QAM modulation (MCS 18) the distributed PTRS provides clear performance improvement in the throughput performance compared to the "No PTRS" case, while block PTRS is able to achieve the maximal throughput at lower SNR. In the case of 256-QAM modulated data signal (MCS 24), the block PTRS shows significant gain over the distributed PTRS allowing to achieve 3.5 Gbps throughput at both the 10 m and 290 m distances, whereas with the distributed PTRS the radio link does not work at the 10 m distance. This highlights the benefits of block PTRS, not only for PN distortion compensation, but also for residual Doppler error compensation. Without any kind of PTRS, the radio

link does not work with 256-QAM modulation. It can be concluded that the considered transmitter pre-compensation and receiver processing techniques significantly improve the link performance and allow to obtain ultra high throughput in the HST scenario.

V. CONCLUSION

The emerging 5G networks with flexible radio interface design open new opportunities for modern railway systems, including both extreme broadband communication links and various mission critical railway management services. It was shown that with 3GPP-specified 5G NR parametrization, when using the 400 MHz bandwidth and TDOA measurements processed through an EKF with 10ms interval, it is possible to achieve submeter positioning accuracy over 99% of the time. Moreover, by exploiting the obtained position information in the underlying 5G NR communications system for precompensating the Doppler shift and timing alignment, combined with novel block PTRS based receiver algorithms, up to 3.5 Gbps throughput can be supported throughout the track. Besides the Doppler shift precompensation and timing alignment, position information was used for location-based beamforming at the RRHs to simplify the beam training processes. Hence, with the proposed high-efficiency positioning approach and the related utilization of location-awareness in the physical layer processing methods and location-aware RRM, 5G networks have the potential to revolutionize the communications and management systems for modern railways.

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