Location-Aware 5G Communications and Doppler Compensation for High-Speed Train Networks

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***Abstract*—We discuss methods to obtain high accuracy location information in high-speed train networks and way to use this information on the train and network side. First, the state-of-the-art train localization methods are reviewed and contributions of 5G new radio based localization to high-speed train systems are described. Then the location-awareness is discussed in the context of frequency domain Doppler distortion estimation and compensation in an example high-speed train system operating at 30 GHz carrier frequency. Finally, the benefits of location awareness from the communications network and train line operation point of view are discussed in general, including possibilities to improve the train track capacity and safety.**

***Keywords*—5G NR, location-awareness, Doppler, CFO, OFDM, ICI, transport systems, high-speed train, track capacity, safety**

I. Introduction

The high-speed train (HST) network is one of the most important use cases for the fifth generation (5G) new radio (NR), which defines the physical layer for mobile communications networks beyond the fourth generation (4G) technologies generally known also as long term evolution (LTE), LTE-Advanced, and LTE-Advanced Pro. 5G NR will bring several enhancements which will improve the system performance in HST networks, e.g., support for increased subcarrier spacings (SCSs), reduced slot durations, massive beamforming, and new reference signals that can be used for carrier frequency offset (CFO), phase noise (PN), and Doppler induced error estimation and compensation. All these enhancements are required as the wireless communications envisioned for HST shifts to higher carrier frequencies. In this paper, the baseline assumption for the operating carrier frequency is 30 GHz because higher carrier frequencies provide larger bandwidths which allow to provide sufficient throughput for each passenger.

In general, the requirements for the next generation access technologies regarding HST scenario are defined in [1][Section 6.1.5] and the link and system level simulation parametrizations are defined in [2]. The single frequency network (SFN) layout is seen as the most interesting and is the main focus in this paper.

The HST scenario has been extensively studied also in LTE context. In the technical report for study item on performance enhancements for high speed scenario in LTE [3], performance enhancements to radio resource management, and user equipment (UE) and base station (BS) demodulation were studied for velocities up to and above 350 km/h. Here the modeling assumption was that the train is equipped with a repeater connecting each UE to the network. This approach leads to significant signaling due to hand overs between cells. In this paper we do not consider this signaling load but consider the train relay as a single device in the network. The main benefit of using a sophisticated relay instead of UE wise connection is that the relay can incorporate larger antenna arrays and is not similarly power limited in the receiver (Rx) and transmitter (Tx) signal processing as individual UEs.

Two important concepts that were presented in [3] to improve the downlink performance are BS CFO/Doppler pre-compensation and unidirectional SFN scenario. Such BS pre-compensation allows pre-compensation of the Doppler frequency on the dominant line-of-sight (LOS) component which in turn allows legacy devices to operate well even in high speed scenarios. In unidirectional SFN scenario, each BS uses directional antennas to align the main beam of the Tx antenna radiation pattern with the train track. Both of these ideas are valid for 5G-NR based HST deployment, because the used beamforming concentrates the main lobe of the antenna radiation pattern towards the train Rx panel and CFO/Doppler pre-compensation allows to simplify the detection of signals from multiple radio remote heads (RRHs) connected to the same or different base band processing units (BBUs), as illustrated in Fig. 1.

In this paper, we concentrate on the high accuracy localization in 5G-NR systems with focus on HST networks and discuss the benefits of frequency domain intercarrier interference (ICI) compensation to further enhance the demodulation performance in high Doppler environments. Then, more general discussion on different benefits of high accuracy location information in HST networks is provided pointing out potential improvements in safety, train track capacity, network energy savings or resource sharing, and reliability.

This paper is organized as follows. In Section II the current status of train localization and views on positioning in 5G NR are given. Discussion on reference signal design for CFO and Doppler error mitigation and example performance comparison are provided in Section III. Then, in Section IV, a general view on the communication network and train line operation benefits with high accuracy location awareness are given. Finally, the conclusions are provided in Section V.

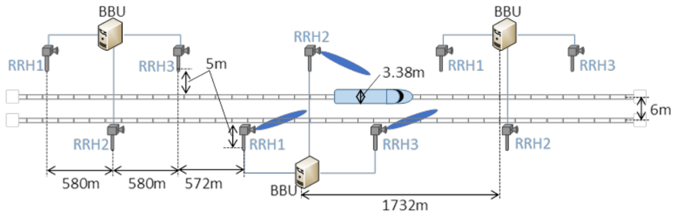

Fig. 1. Cell layout for high speed train scenario operating at 30 GHz carrier frequency in a single frequency network. Adopted from [2][Annex 2.1].

II. High Speed Train Positioning

A. State-of-the-art solutions

Detection of the position of trains, control signalling, and traffic management are safety critical applications in railroads. European rail traffic management system (ERTMS) [4] and European train control system (ETCS) [5] initiated by European Union aim to unify the requirements and ensure interoperability of railway systems between European countries. The detection of trains according to ETCS is based on a balise, a radio frequency tag installed on the track roughly 1 km apart from each other, and an on-board balise reader. Between the balises, the ETCS specification requires the on-board odometry system to maintain a position accuracy no worse than $\pm$(5 m + 5% of the distance travelled) since the passing of a balise group [5]. Odometry is based on wheel angular speed sensors providing a reliable estimate of the train speed unless wheel-rail adhesion conditions degrade and the wheels are sliding. The accuracy of dead reckoning by odometry can be improved by fusing odometer with measurements from other sensors; Doppler radar, accelometers, gyroscopes, and magnetometers. In particular, inertial measurement units (IMU) are becoming attractive due to the rapid evolution of micro electro-mechanical systems (MEMS).

Together with the balise, a global navigation satellite system (GNSS) receiver is able to provide absolute positioning information, while the accuracy of odometer and inertial navigation suffer from cumulative errors over time. As for GNSS, its accuracy degrades in urban and forest environments when the signal is subject to high attenuation and multipath propagation. Nevertheless, it is useful to fuse GNSS measurements at low sampling frequency with odometer and inertial navigation measurements at high sampling frequency. Wide-area differential information, (European Geostationary Navigation Overlay System (EGNOS) in Europe, and Wide-Area Augmentation System (WAAS) in the USA) can be used to further improve the accuracy of GNSS. In addition, trains move on predetermined tracks, so localization is improved by casting the three-dimensional positioning problem into one dimension by using the information from digital track maps. After all these efforts, i.e. fusing odometer, IMU, GNSS, and track maps, INTEGRAIL prototype [6] reached $0.8 - 1.3$ m accuracy (standard deviation) when multipath and shadowing do not obstruct GNSS signals. In case of incomplete map data and severe multipath, the accuracy was degraded to 1.8 m.

Therefore, a modern railway control system would be able to provide sufficient means for time alignment in nanosecond scale for an on-board wireless communication system. On the other hand, the vendor of the wireless communication system may not have access to the railway control system, and its specifications are determined by a different standard organization. A complementary 5G-NR positioning system is still needed, while the railway control system provides a good benchmark for 5G NR.

Studies on railway control systems have shown that GNSS or dead reckoning alone are not enough, and sensor fusion is required to fulfill ETCS requirements in any case [7]. Like GNSS, localization based on 5G-NR positioning signals does not suffer from cumulative errors and provides an alternative to GNSS for sensor fusion. The 5G-NR signals are subject to similar shadowing and multipath effects as GNSS, therefore having the same drawbacks. On the other hand, the received 5G-NR signal has better SINR and wider bandwidth than GNSS facilitating better accuracy. Furthermore, with proper network planning and deployment, there is a very high probability for line-of-sight (LoS) between the train and the network elements/RRHs. Therefore, hybrid 5G-NR positioning and on-board sensing has a lot of potential and may result in a useful combination for train localization. This in turn facilitates timing alignment and compensation of Doppler shift in communication systems for HST.

B. Positioning in 5G NR

Compared to many common mobility scenarios, such as pedestrian and vehicular, the train mobility is substantially more constrained. Besides the fact that the train movement is limited to the coordinates of the track, the maximum acceleration and braking capabilities are strongly dictated by the large mass of the train. This relieves the requirement of considering very fast changes in the train velocity, and thus, facilitates the use of effective tracking algorithms for estimating the train position and velocity. Without taking a stand on which specific position and velocity estimation approaches are used, it is possible to study the train position and velocity estimation errors by using a conventional Kalman filter to fuse the position and velocity estimates. Now, assuming that the track coordinates are known, the train position can be determined with a single coordinate, and therefore, the state of the train position and velocity at time step n, denoted here by $\mathbf{x}(n)$, can be written as

$$\mathbf{x}(n) = [p(n), v(n)]^T, \tag{1}$$

where $p(n)$ is the (1D) train coordinate on the track and $v(n)$ is the corresponding velocity.

Based on a continuous white noise acceleration model [8] we assume that the velocity between two consecutive time steps is nearly constant, but affected by a slight random variation. Thus, the linear model for the state transition can be described as

$$\mathbf{x}(n) = \begin{bmatrix} 1 & \Delta t \\ 0 & 1 \end{bmatrix} \mathbf{x}(n-1) + \mathbf{q}(n), \tag{2}$$

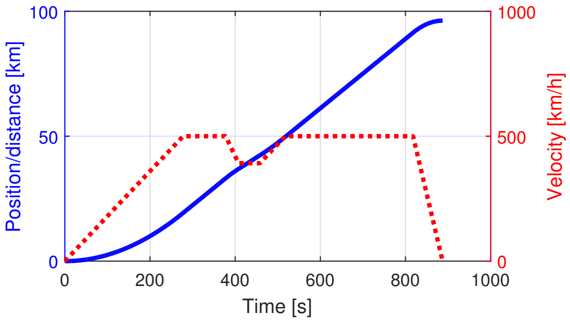

Fig. 2. Assumed example behavior of the position and velocity of a high-speed train in the considered simulation scenario.

where Δt is the time difference between two consecutive time steps, and $\mathbf{q}(n) \sim \mathcal{N}(0, \mathbf{Q})$ is process noise with a covariance matrix

$$\mathbf{Q} = \sigma_q^2 \begin{bmatrix} \frac{\Delta t^3}{3} & \frac{\Delta t^2}{2} \\ \frac{\Delta t^2}{2} & \Delta t \end{bmatrix}, \quad (3)$$

where σ_q^2 is the variance of the velocity fluctuation. Furthermore, by assuming a linear additive white Gaussian noise observation model, estimates of position and velocity at a single time step can be described as

$$\mathbf{y}(n) = \mathbf{x}(n) + \mathbf{w}(n), \quad (4)$$

where $\mathbf{w}(n) \sim \mathcal{N}(0, \mathbf{\Sigma})$ is the estimation error with the covariance matrix

$$\mathbf{\Sigma} = \begin{bmatrix} \sigma_p^2 & 0 \\ 0 & \sigma_v^2 \end{bmatrix}. \quad (5)$$

Here σ_p^2 and σ_v^2 are the variances of the position and velocity measurement errors at a single time step n. Now, by using the Kalman filter based tracking approach with the above defined state transition model in (2) and the observation model in (4), it is possible to evaluate the train tracking accuracy over various position and velocity measurement error variances σ_p^2 and σ_v^2.

Based on the indicative acceleration and braking capabilities given for a high-speed train in [9], and assuming some performance increase for the future trains, we have created a synthetic train movement scenario as shown in Fig. 2. Here, by starting at rest, the train accelerates with the acceleration of 0.5 m/s^2 up to the maximum velocity of 500 km/h. Approximately after 380 s from the beginning, the train begins to brake by rate of 2 m/s^2 until reaching the velocity of 400 km/h. After a while, the maximum speed is again obtained until the train stops at the final destination approximately 96 km away from the start location. In addition, we have simulated random position and velocity estimates at intervals of 100 ms with specific error variances as given in (5). In Fig. 3, the average position tracking accuracy for the train is shown as a function of measurement error variances σ_p^2 and σ_v^2 over 1000 Monte Carlo realizations. The results show that in order to achieve low position tracking errors, either high-accuracy position measurements or high-accuracy velocity measurements are required. The asymptotes of the provided 1 m, 3 m, and 5 m threshold

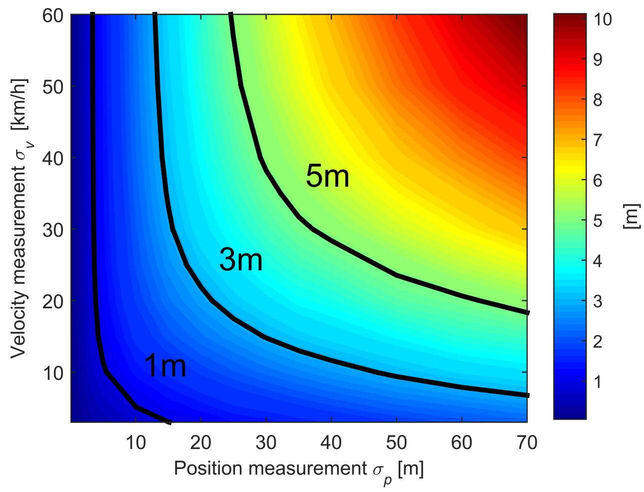

Fig. 3. Average position tracking accuracy of the train as a function of position and velocity measurement error standard deviations σ_p and σ_v

lines in Fig. 3 can be considered as scenarios where only position or velocity measurements are available. For example, a sub-meter positioning accuracy can be always obtained with the position measurement error $\sigma_p < 3$ m regardless of the existence (or quality) of velocity measurements. Therefore, 3 m position measurement error standard deviation should be used as minimum accuracy for 5G-NR based positioning in HST networks.

III. Location-Aware Doppler Compensation

A. Relation between Velocity and Doppler Estimation

If we assume that the coordinates of the track and RRHs are known, the resulting Doppler shift due to the train movement can be estimated based on the train position and velocity information. The Doppler shift of the observed LOS signal component is defined as

$$\Delta f = \frac{v}{\lambda} \cos(\theta), \quad (6)$$

where v is the train velocity, λ is the signal wavelength (approx. 1 cm with the 30 GHz carrier frequency), and θ is the angle between the train and the RRH with respect to the train direction. The maximum Doppler shifts are observed based on the furthest heard RRHs, in which case the cosine term in (6) can be approximated as $\cos(\theta) \approx 1$. Consequently, by estimating the Doppler shift directly from the train velocity and position estimates (and assuming known RRH positions), the maximum Doppler shift estimation error can be determined as

$$\varepsilon_{\Delta f} = \frac{\varepsilon_v}{\lambda}, \quad (7)$$

where ε_v is the error of the velocity estimate. For instance, in the considered example positioning scenario studied earlier in Section II-B, the average velocity estimation errors over the considered parameter space of σ_p (< 70 m) and σ_v ($<$ 60 km/h) were always below 3 m/s. Consequently, based on

(7), this results in average Doppler shift estimation error of around 300 Hz for the furthest heard RRHs.

B. Residual Doppler

In [3][Section 6.4.3.2], it was shown that BS side Doppler frequency pre-compensation allows legacy devices to perform well even at 350 km/h velocities. Here the assumption was that the DL Doppler frequency is perfectly obtained from the UL Doppler frequency estimate. This assumption can be used in a SFN network with beamforming, as long as there are no moving obstacles between the train and a connected RRH. When there is, e.g., another train traveling to the opposite direction on a second aligned track, the UL Doppler frequency estimate can be significantly biased due to the strong reflection from the approaching train. Therefore, by knowing accurately the location and velocity of the desired train, the Doppler frequency estimate for DL pre-compensation can be accurately bounded or even solved without UL measurements from the network geometry. DL pre-compensation will in any case ease the Rx processing even with advanced Rx compensation algorithms and should be considered as a solution for HST connectivity in 5G NR.

Even in the case of perfectly cancelling the Doppler frequency shift of the relatively strong line-of-sight (LOS) component, there exists time variation of the LOS component amplitude and phase within a OFDM symbol period with high speeds due to vibrations in the RRH and train antenna arrays. When targeting high modulation and coding scheme (MCS) for DL and UL between the train and network, e.g. using 256-QAM modulation, the inter-carrier-interference (ICI) induced by LOS component time variation and the Doppler shift of all low power non-line-of-sight (NLOS) components starts to affect the link performance.

Currently in 5G standardization, there is an ongoing discussion related to phase tracking reference signals (PTRSs) which are mainly used for phase noise (PN) and CFO estimation and compensation, but which can also be used to mitigate the Doppler induced ICI. Currently there are two different PTRS designs under evaluation, distributed PTRS with frequency-distributed pilots and PTRS block with frequency-localized pilot block based designs [10]. In distributed PTRS, a single resource element (RE) within a group of physical resource blocks (PRBs) is allocated for PTRS in every OFDM symbol. The distributed PTRS allows to estimate the common phase error (CPE) over all subcarriers (SCs) in an OFDM symbol. This is sufficient to track slowly changing PN response and small residual CFO errors. It can also track the average phase rotation of a time varying channel in a moderate Doppler environment. The main benefits are very low overhead and good performance in moderate MCS and Doppler scenarios. The downside is that distributed PTRS does not allow to estimate and compensate ICI from the Rx signal.

In block-based PTRS design, the PTRS is a contiguous block of REs in the frequency domain. Typically block sizes which are multiples of PRBs are assumed. The PTRS overhead is typically slightly increased compared to distributed PTRS to allow estimation of a few dominant ICI components in the Rx signal. The ICI components may be caused by PN or by highly time varying channel experienced in high velocities. An example of the pilot block based PTRS design and its performance is given in [11]. The pilot block based PTRS is used with a mitigation algorithm derived from [12]. By estimating the most dominant ICI bins in the frequency domain, the effect of these can be mitigated by deconvolution.

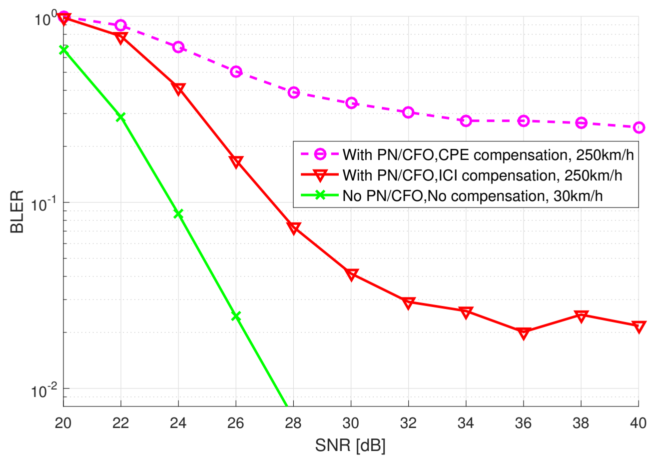

Fig. 4. Performance example of ICI compensation vs. CPE compensation in a TLD-D 10 ns channel at 30 GHz carrier frequency using 256-QAM and coding rate R=3/4.

In Fig. 4, an example of the performance gain achieved by ICI compensation versus CPE compensation is given for a TLD-D 10 ns delay spread channel [13] with device velocity 250 km/h. The used MCS is 256-QAM with coding rate R=3/4, assuming an LTE compliant turbo code. The carrier frequency is 30 GHz, and the evaluated SCS is 60 kHz with FFT size of 2048 designed to support 80 MHz channel bandwidth. The desired signal is assumed to have allocation of 10 PRBs from which 12 SCs are reserved for PTRS. For CPE compensation the PTRS is evenly distributed over the whole allocation. With ICI compensation, 1 PRB PTRS block is used to solve CPE and ICI components. The PN model is defined in [14] and the CFO is assumed to be uniformly distributed on the interval [-1500,1500] Hz.

In Fig. 4, the simulated BLER performance with 30 km/h velocity and without PN, CFO, or any compensation algorithm is given as a reference. With CPE compensation, the BLER performance does not even achieve the 10% BLER target. On the other hand, the ICI compensation algorithm can significantly reduce the BLER and allows to use high MCS even at 250 km/h velocity achieving 10% BLER target with 3 dB SNR loss compared to the low mobility, distortion free reference case. Thus, the PTRS block design should be supported in 5G NR to enable high data rates in HST networks.

IV. Discussion on Location-Awareness for High Speed Train Networks

An important side product of high accuracy localization is the capability to synchronize the device clocks in the network [15]. Similar to using position and velocity estimates to pre-compensate Doppler frequency of the dominant LOS component in the network side, improved time synchronization among RRHs and high accuracy position information allows the network to do network side timing alignment. This improves the time alignment of the DL signals in the train Rx effectively reducing the delay spread experienced by multipoint transmission in a SFN. This may allow to use higher SCS with shorter CP duration in the network to alleviate the effects of high PN, CFO, and Doppler distortion. For example, assuming a Gaussian location error with 1 m standard deviation in the final tracking estimate would indicate that with network side time alignment the signals from different RRHs would be received in the Rx with timing accuracy of ± 10 ns with probability of 99.7%. On the contrary, the maximum propagation delay difference in the HST network illustrated in Fig. 1 corresponds to 1.9 μs which exceeds the CP lengths assumed for SCSs 60 kHz and above [2].

If we assume that the used network is dedicated only for serving train commuters, accurate location estimation allows to optimize the sleeping times of network nodes. Because the network has accurate knowledge of moving trains within the network, unused BBUs and RRHs can be ordered to sleep and wake-up only when there are trains nearby. For example, based on [9], we can make a conservative estimate that a modern HST railway could support 13 trains per hour capacity. Now taking the total distance in which the middle BBU participates on transmission to be 2304 m, as shown in Fig. 1 and estimating the maximum average speed of a HST to be 500 km/h, we can approximate that each train spends approximately 16.6 s under one BBU when traveling with the maximum speed. Including the number of trains per hour, each BBU may be active only 6% of time. This indicates that in a dedicated train network, significant power savings can be achieved with the help of accurate train location information.

On the other hand, if the network is not dedicated to HST, it can be used to provide extra capacity, e.g., for a nearby highway (which are typically aligned with the HST rails) or habitation nearby the train tracks. The numerical example above indicates that the train network could be used up to 94% of the time as a secondary carrier for improved capacity. Now, because the HST network is already designed to support devices moving with high velocities, it is perfectly matched to support vehicle-to-network (V2N) communications for the highway commuters.

Reliability of communications has been noted in the earlier discussion, but the effect of high accuracy tracking of location and velocity should be emphasized in this context. As the network knows where the train is and how fast it is moving, tight bounds on Doppler frequency, Tx/Rx beam alignment, expected pathloss, and active BBUs and RRHs can be given. This bounds different estimation algorithms used in the physical layer giving an extra boost to the reliability of the communications by reducing the effect of occasional large estimation errors in the frequency or timing synchronization, beam selection and MCS adaptation. Especially in beam finding and beam tracking, only a reduced synchronization signal (SS) burst set [2] needs to be transmitted which reduces the overhead and reduces the latency when the Tx and Rx are looking for best beam orientations while moving from one RRH to another. Altogether, it allows to improve the average spectral efficiency, quality-of-service, and user experience of the train commuters.

With high accuracy tracking the efficiency of the rail way tracks can also be improved. The benefits are two fold. First of all, we can reduce the minimum train separation time or the operation margin time used to define the number of trains per hour [16]. This is enabled by the high accuracy location information and modern train automation. The second benefit is that we can reduce the stopping times of passing trains in a single rail system, where one train has to slow down or stop to a side track to allow second train to pass. As seen from Fig. 2, the acceleration and de-acceleration take significant amount of time, and the further we can reduce the required variations from the nominal traveling speed the shorter are the transitions between stations. This allows to increase the rail capacity and to reduce the traveling time, providing the rail companies better income and better quality of experience for train travelers. Furthermore, as a side product of accurate localization, the system can update and improve its knowledge of the accurate location of the train tracks and RRHs installed in the HST network. This allows to improve the performance of all systems relying on accurate digital maps of the train tracks or RRH locations.

The last, but not the least important aspect, is the safety impacts of high accuracy localization. Safety is the main concern in HST railways. With high accuracy localization, location information of de-railed of stopped trains is instantaneously available and this allows to send immediate help to correct location in the case of accident and allows to stop nearby trains and possibly to reroute them. Losing a connection or detecting a de-acceleration corresponding to emergency breaking or derailing gives an immediate indicator of significant problems in the train or track.

V. CONCLUSION

In this paper, the current state-of-the-art of HST localization was discussed and extended with performance bounds on location and velocity tracking accuracy based on Kalman filter fusion. It was shown that with positioning system providing a standard deviation of 3 m we can achieve sub-meter position tracking accuracy even with high velocity estimation errors. Therefore, this standard deviation can be considered as the upper limit of position error standard deviation for 5G-NR based positioning. With sub-meter positioning, a high accuracy Doppler frequency estimate can be obtained for Doppler frequency pre-compensation allowing significantly improved Rx demodulation performance in the train relay.

The effects of the residual Doppler interference were also discussed and example results on ICI compensation gains over CPE compensation were provided. Therefore it is proposed that 5G NR should support frequency localized RS patterns to allow ICI estimation and mitigation in the train and network side Rx processing.

The benefits of high accuracy localization for HST networks and train line operation were discussed and several important potential benefits were noted. High accuracy position estimation allows to improve demodulation performance, energy efficiency, resource sharing, quality-of-service, train line efficiency and safety. Thus, given all the benefits potentially achieved by high accuracy localization, the need for further research on the location-aware 5G communications to fully harness the potential of a 5G-NR HST network is required and can benefit the network operators, train commuters, and the train line operators.

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