Uplink Performance of LTE and NR with High-Speed Trains

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***Abstract*—Cellular network based connectivity for high speed trains (HSTs) is subject to large carrier frequency offset (CFO) due to high Doppler shifts. Large CFO will cause losing orthogonality between OFDM subcarriers which leads to significant performance loss. In this paper, we compare two Doppler estimation methods for HST links to compensate and remove CFO effect in the receiver in the context of 5G New Radio (NR) and long term evolution (LTE) systems. The first considered method to estimate Doppler shifts in LTE systems is based on the cyclic prefix (CP). The second method considered in NR system context is based on the phase tracking reference signal (PTRS). Simulation results shown that NR PTRS based method has higher estimation accuracy compared to LTE CP based method. Moreover, NR PTRS based method has higher signal to noise ratio (SNR) gain to achieve considered link performance target which is set to 70% of the maximum achievable throughput in this study. Additionally, the uplink data channel performance studies shown that, for systems using two demodulation reference signal (DMRS) per subframe for channel estimation, LTE CP based method can support only QPSK modulation scheme. In this case, a significant performance improvement is observed when the number of DMRS symbols per subframe is increased up to four, while almost the same performance is observed in NR systems for both slot patterns. Therefore, NR systems using PTRS based method with two DMRS configuration per subframe can be used with lower system overhead. In addition, block error rate (BLER) performance results show that NR PTRS based method has superior performance compared to LTE CP based method. Overall, these results demonstrate that NR PTRS based Doppler estimation method is more suitable in HST use cases.**

***Index Terms*—5G New Radio, 5G NR, Doppler estimation, reference signals, phase tracking reference signal, cyclic prefix.**

I. INTRODUCTION

The emerging 5G New Radio (NR) networks aim to provide ubiquitous everywhere radio connectivity for wide variety of use cases [1], [2]. High speed moving devices, especially high speed trains (HSTs), is a very important use case for 5G NR where the maximum user velocity can be up to 500 km/h [3]. However, HSTs suffer from carrier frequency offset (CFO) challenge due to high Doppler shifts, especially at the uplink receiver due to doubled frequency error, as illustrated in Fig. 1. In general, Doppler shift depends on the operating carrier frequency and user equipment (UE) speed.

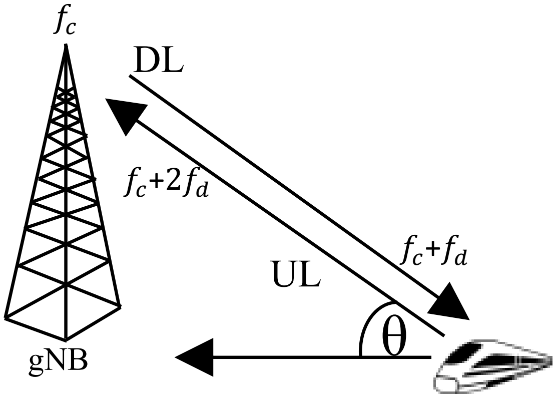


Fig. 1: Basic HST system model highlighting the CFO challenge.

Similar to long term evolution (LTE) networks, cyclic prefix orthogonal frequency division multiplexing (CP-OFDM) has been chosen as the 5G NR radio access waveform. CP-OFDM has a very high spectral efficiency and is robust against time and frequency selective channels by proper choice of subcarrier spacing (SCS) and CP length [4]. NR will support SCS values of $2^{\mu}\times$ 15 kHz, where $\mu = 0, 1, ..4$ [5]. This flexibility allows to support different use cases operating in different frequency bands, where higher SCS values are more robust to Doppler shifts and phase noise [6]. In this paper, however, we assume the LTE compatible SCS value of 15kHz, in order to enable LTE/NR spectrum coexistence [1]. This specific NR numerology has identical time and frequency resource grid to LTE that enables such coexistence. Therefore, NR performance evaluations with higher SCS values are not in the scope of this paper.

In general, large CFO will cause losing orthogonality between OFDM subcarriers, leading to significant performance losses – a phenomena commonly called inter-carrier-interference (ICI) [7]. Thus, the high Doppler shift must be efficiently estimated and compensated to remove the CFO effects. To this end, Doppler estimation methods have been widely studied in the literature, in general as well as in specific commercial system context, see e.g. [8]–[13].

In this paper, we study the Doppler shift estimation capabilities and performance in the base station (gNB, eNB) side using cyclic prefix (CP) based method [12] and reference signal based method [13], with specific emphasis on the HST use case. In CP based method, the basic concept to estimate Doppler shifts is to exploit the cyclic nature of received signal samples enabled by OFDM symbol cyclic prefix through the auto-correlation function [14]. In the reference signal based approach, the cross-correlation between two reference symbols adjacent in time domain can be used to estimate the Doppler shift. Specifically, in this paper, we compare the performance of the physical uplink shared channel (PUSCH) in LTE and NR systems, in the HST use case, while utilizing the above mentioned Doppler shift estimation methods.

The novelty of this paper is to show that the phase tracking reference signal (PTRS) can be used for high accuracy estimation of large frequency offsets at relatively low frequency bands. PTRS is originally introduced in NR to compensation for oscillator phase noise when operating in higher frequency bands associated with NR, particularly the millimeter wave (mmWave) bands [2]. Additionally, it is shown that demodulation reference symbol (DMRS) based channel estimation performance is not sufficient for HST scenarios, even with four DMRS symbols per subframe, and therefore Doppler shift estimation solutions, such as the PTRS based one, need to be adopted for HST use case. Moreover, we also show that using PTRS allows to utilize a lower number of DMRS symbols in time domain for channel estimation and equalization which implies higher spectral efficiency.

The rest of this paper is organized as follows: Section II describes the considered system model, Doppler induced CFO phenomenon, DMRS based CFO compensation and two considered Doppler estimation methods used in the performance evaluations. In Section III, performance comparison between the discussed methods are provided and analyzed. Finally, the conclusions of this study are drawn in Section IV.

II. HST SYSTEM MODEL AND DOPPLER INDUCED CFO ESTIMATION

A. Basic Assumptions

The considered system model resembles the ones in [3], [6], [15], implying that the line of sight (LOS) component of the HST propagation channel is dominant and can be modeled as a constant frequency shift in the received signal. In Fig. 1, the gNB is transmitting the downlink signal at a carrier frequency f_c to HST with velocity v. Since the HST is moving towards the gNB, the transmitted signal is effectively received with carrier frequency of f_c + f_d. Assuming ideal automatic frequency control (AFC) operation in the UE receiver, the uplink transmission is performed with carrier frequency equal to the output of the AFC: f_c + f_d. Due to the Doppler shift, the gNB then eventually receives the uplink signal at effective carrier frequency of f_c + $2f_\text{d}$.

In this paper, it is assumed that the HST is travelling with a speed of 500km/h and the carrier frequency is 3.5GHz, which correspond to an effective maximum Doppler shift of ($2f_\text{d}$ = 3240Hz) at gNB. In high-mobility scenarios, radio propagation and the received signal are generally subject to fast time-varying fading. To this end, the corresponding coherence time (T_c), which is inversely proportional to the Doppler shift f_d is commonly defined as [16]:

$$T_\text{c} = \sqrt{\frac{9}{16.\pi.f_\text{d}^2}} = \frac{0.423}{f_\text{d}} \tag{1}$$

where f_d is the Doppler shift expressed as

$$f_\text{d} = f_\text{max} cos(\theta) \tag{2}$$

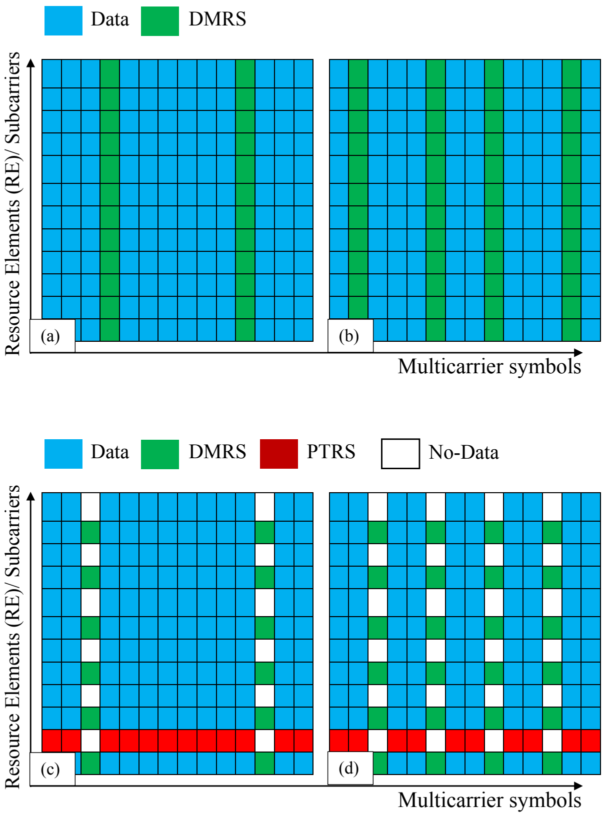


Fig. 2: Top: LTE subframe configurations where two or four DMRS symbols are used for channel estimation and equalization. Bottom: NR subframe configuration with PTRS resources scheduled every two PRBs.

with θ denoting the angle between the moving train direction and the LOS component while f_max is the maximum Doppler shift. Therefore, in the considered HST system, T_c is approximately equal to 130.5 μs when effective maximum Doppler shift is $2f_\text{d}$ = 3240Hz at gNB.

As one of the fundamental effects, the CFO due to LOS Doppler causes fixed phase rotation for all subcarriers per OFDM symbol, but varies from symbol to another. This allows to estimate the CFO as a phase rotation between two adjacent reference OFDM symbols. However, due to the phase ambiguity problem, the phase rotation estimation provides a unique estimate only if the phase estimate range is limited to the interval (-π, π). Keeping this in mind, the maximum Doppler frequency range that can be estimated can be defined as

$$f_d^\text{max} = \pm \frac{N_\text{FFT}}{(m_2 - m_1)(N_\text{FFT} + N_\text{CP})} \frac{\Delta f}{2} \tag{3}$$

where m_1 and m_2 are the indices of adjacent reference symbols, Δf is the subcarrier spacing in Hz and N_FFT and N_CP correspond to the FFT length and the number of CP samples, respectively.

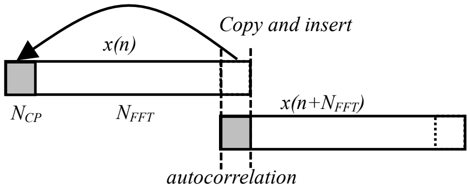


Fig. 3: CP based Doppler estimation concept

B. DMRS based Channel Estimation and Maximum Doppler Shift Support

Next, we discuss and address the ability of the gNB channel estimator to mitigate Doppler shifts, without using separate Doppler estimation algorithm in the gNB receiver. Channel estimation is performed using DMRS symbols to track channel variations both in time and frequency domains. In time domain, the distance between adjacent DMRS symbols should be less than channel coherence time to enable successful tracking of channel variations.

In LTE PUSCH transmission, only two DMRS symbols per subframe are supported [17]. In Fig. 2 (a), two DMRS symbols are allocated per subframe. Therefore using (3) and (1), channel estimation can support Doppler shifts up to 1000 Hz (T_c = 423 μs). However, to improve gNB demodulation performance for high speed use cases, 3GPP has specified the use of DMRS configuration of PUCCH format 2 as an option [18]. In this configuration, four DMRS symbols are used per subframe as shown in Fig. 2 (b). The corresponding maximum Doppler shift supported by the DMRS based channel estimation algorithm is 1750 Hz (T_c = 241.7 μs).

In NR PUSCH transmission, both two and four DMRS configurations are supported as shown in Fig. 2 (c) and (d), corresponding to maximum Doppler shift support of 779 Hz (T_c = 543 μs) and 2336 Hz (T_c = 181 μs), respectively. This shows that neither LTE nor NR systems can support HSTs with 500km/h ($2f_\text{d}$ = 3240 Hz), and thus it is required to *estimate and compensate Doppler shift before performing channel estimation*. Two alternative methods for Doppler estimation are therefore described next.

C. PTRS based Doppler Shift Estimation

The bottom part of Fig. 2 shows PTRS distribution in NR subframe where PTRS symbols are occupying one resource element per physical resource block (PRB). According to NR Rel-15, PTRS symbols can be scheduled every second or fourth PRB in frequency domain. In time domain, PTRS symbols can be allocated every n^{th} OFDM symbol, where $n \in 1, 2, 4$. In this work, we consider PTRS allocation in every second PRB and in every OFDM symbol in frequency and time domains, respectively. This allows for better tracking of the rapidly varying channel in high mobility cases. Furthermore, using PTRS based method to estimate Doppler shift comes with very low system overhead, that is 1/(2 x 12) = 4.17%.

TABLE I: CONSIDERED PHYSICAL LAYER PARAMETERIZATION

Parameter	LTE/5G NR
Carrier frequency [GHz]	3.5
Channel model	CDL-E-100ns
K-factor [dB]	13.3
User equipment mobility [km/h]	500
Maximum Doppler shift at gNB ($2f_\text{d}$) [Hz]	3240
Sub-carrier spacing [kHz]	15
Bandwidth [MHz / PRBs]	20 / 100 (LTE), 106 (5G NR)
Transmission mode	Single-layer-two-antenna ports
FFT size	2048
CP length	144
Modulation	QPSK, 16QAM and 64QAM
Code rate	1/3 and 2/3
Channel code	Turbo, LDPC
Antenna configuration	1 Tx × 2 Rx
Waveform	DFT-s-OFDM, CP-OFDM
OFDM symbols per slot	14
Number of subcarriers per PRB	12
DMRS allocation density	two and four OFDM symbols
Channel and SINR estimation	DMRS-based
Receiver algorithm	MRC

In the PTRS based method, the cross-correlation is performed between two adjacent reference symbols in time domain to obtain an estimate of the phase rotation. To this end, the Doppler shift at the gNB can be estimated as follows

$$\hat{f}_\text{d} = \frac{1}{2\pi T_\text{s}(||\tau_{Rs}||-1)||\Phi_{Rs}||}\arg\left(\sum_{i,i+1}\sum_{k} x_i^*(k)x_{i+1}(k)\right) \tag{4}$$

where $||\Phi_{Rs}||$ is the number of resource elements carrying RS, $||\tau_{Rs}||$ is the size of the RS time domain index set. $k \in \Phi_{Rs}$ and $i \in \tau_{Rs}$ are the frequency and time domain indices of the allocated RS, respectively.

It should be noted that in practical deployments, perfect and fixed LOS condition is obviously not guaranteed. Moreover, there is always residual Doppler estimation error, due to noise already, which will lead to residual ICI in the receiver. Residual ICI estimation and compensation is, however, not in the scope of this paper.

D. CP based Doppler Shift Estimation

In the CP based method, autocorrelation is calculated between CP samples and the corresponding original samples within one OFDM symbol. In particular, the CP samples at the beginning of one OFDM symbol are correlated against CP samples located at the end [12], as illustrated in Fig. 3. The Doppler shift at the gNB can thereon be estimated as

$$\hat{f}_\text{d} = \frac{1}{2\pi T_\text{s} N_\text{slot} N_\text{CP}}\arg\left(\sum_{s}^{N_\text{slot}-1}\sum_{n=0}^{N_\text{CP}-1} x_s^*(n)x_s(n+N_\text{FFT})\right) \tag{5}$$

where $x_s(n)$ denotes the nth sample of a given OFDM symbol with length ($N_\text{FFT} + N_\text{CP}$), T_s is the sample duration and N_slot is the number of OFDM symbols per slot. Ideally, this method can estimate Doppler shifts up to 1/T_s, which corresponds to 14 kHz in our system model. However, these estimates are very noisy, and include, e.g., inter-symbol-interference induced by the time dispersive channel.

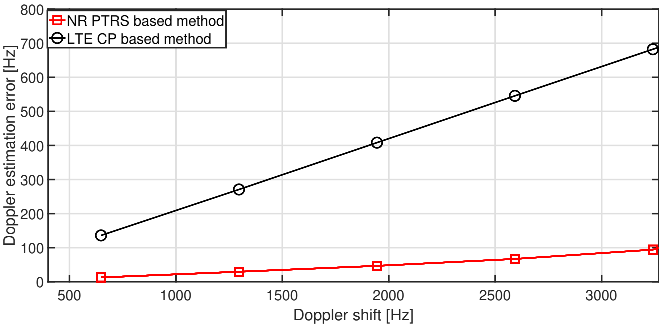


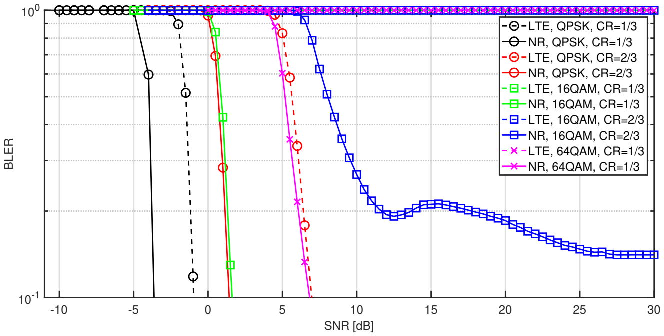
Fig. 4: Doppler estimation error for both LTE-CP and NR-PTRS based methods. Doppler estimation error is calculated at train speeds of 100, 200, 300, 400, 500 km/h.

III. PERFORMANCE RESULTS AND ANALYSIS

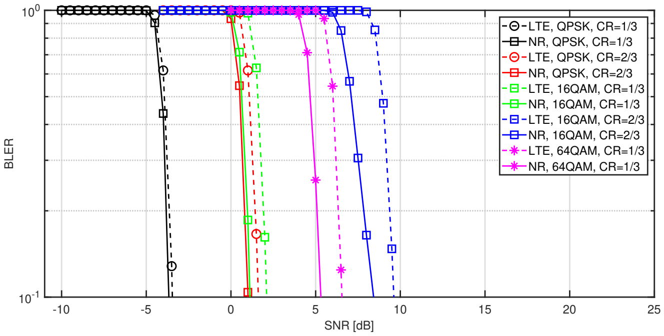
To assess and compare the performance of the different methods, a 3GPP standardization compliant radio link simulator is used to carry out realistic evaluations where CP-OFDM and DFT-s-OFDM uplink waveforms are used for NR and LTE systems, respectively. Performance of DFT-s-OFDM waveform with PTRS based Doppler shift estimation method in NR system context is left for future studies. The main physical layer parameters used in the evaluations are defined and shown in Table I.

The performance of the considered Doppler estimation methods is analyzed by assessing and comparing the achievable PUSCH data throughput and block error rate (BLER), while considering also the effects of different modulation and coding schemes, specially QPSK, 16QAM and 64QAM with code rates: 1/3 and 2/3. The propagation channel model is 3GPP CDL-E with K-factor of 13.3 dB that reflects relatively strong LOS component while covers also multipath propagation [19].

First, Fig. 4 illustrates and compares example Doppler shift estimation errors, starting from relatively low mobility case, with a train speed of 100 km/h (f_d = 648 Hz), going then gradually up to the final high mobility case with a train speed of 500 km/h (f_d = 3240 Hz). It is shown that for CP based method, the Doppler estimation error increases linearly as Doppler shift increases. Moreover, Doppler estimation errors are 136 Hz and 683 Hz for 100km/h and 500 km/h, respectively, reflecting essentially constant relative error of around 21% of the prevailing Doppler shift. While for NR PTRS based method, estimation errors are 12.49 Hz and 94 Hz for 100km/h and 500 km/h, respectively. These correspond only to some 1.9% and 3% relative estimation error values. Fig. 4 clearly shows and demonstrates that NR PTRS based method has a significantly higher Doppler estimation accuracy compared to LTE CP based method.



(a) 2-DMRS configuration per subframe



(b) 4-DMRS configuration per subframe

Fig. 5: PUSCH BLER performance for NR PTRS and LTE CP based methods. QPSK, 16QAM and 64QAM modulation schemes are considered with code rates of 1/3 and 2/3 code at 500km/h ($2f_\mathrm{d}$ = 3240 Hz).

Table II shows the required SNR values to achieve 70% of the maximum PUSCH throughput for two and four DMRS configurations when Doppler shift equals 3240 Hz. For *two DMRS configuration*, the NR system using PTRS based method has 2.26 dB and 5.14 dB gain over LTE system using CP based method, when QPSK modulation scheme and code rate of 1/3 and 2/3 are used, respectively. When 16QAM and 64QAM are used, only NR PTRS based method can achieve 70% of the maximum throughput. For 16QAM modulation scheme, 70% of the maximum throughput is achieved at SNR values of 1.21 dB and 9.59 dB when code rates are 1/3 and 2/3, respectively. For 64QAM modulation scheme, only code rate of 1/3 can achieve 70% of the maximum throughput, in this case at SNR of 5.7 dB. These results shows that for HST use cases, LTE operation with two DMRS configuration per subframe only supports QPSK modulation scheme. Thus LTE can only support some baseline system coverage requirements, while clearly failing to support higher data rates.

Then, to increase channel estimation capabilities, the *four DMRS configuration* per subframe is next considered. To this end, the results in Table II show that increasing the number of DMRS symbols per subframe to four, significantly improves LTE performance with low-order modulation (QPSK), while the NR system performance is similar to the two DMRS configuration. In this case, NR system has still a small SNR gain over LTE, i.e., 0.32 dB and 0.45 dB with code rates of 1/3 and 2/3, respectively. The NR SNR gain is further increased to 0.83 and 1.64 dB when 16QAM with code rates of 1/3 and 2/3 are used, respectively. At 64QAM and code rate of 1/3, the NR gain is 1.37 dB. Both systems fail to reach 70% of the maximum achievable throughput when code rate is increased to 2/3. Overall, NR system using PTRS based Doppler estimation clearly outperforms the LTE system using CP based method.

The corresponding BLER performance for PUSCH is shown in Fig. 5. For two DMRS configuration, QPSK modulation

TABLE II: PERFORMANCE COMPARISON BETWEEN LTE CP BASED AND NR PTRS BASED DOPPLER ESTIMATION METHODS, WHERE TWO OR FOUR DMRS CONFIGURATIONS PER SUBFRAME ARE USED FOR CHANNEL ESTIMATION. THE SHOWN VALUES REPRESENT THE SNR VALUES REQUIRED TO REACH 70% OF THE MAXIMUM THROUGHPUT AT 500KM/H ($2f_D = 3240$ HZ).

Modulation	QPSK				16 QAM				64 QAM			
Number of DMRS symbols per subframe	2 DMRS		4 DMRS		2 DMRS		4 DMRS		2 DMRS		4 DMRS	
Code Rate	CR=1/3	CR=2/3	CR=1/3	CR=2/3	CR=1/3	CR=2/3	CR=1/3	CR=2/3	CR=1/3	CR=2/3	CR=1/3	CR=2/3
NR	-3.49	0.98	-3.91	0.73	1.21	9.59	0.86	7.45	5.7	N/A	4.91	N/A
LTE	-1.23	6.12	-3.59	1.18	N/A	N/A	1.69	9.09	N/A	N/A	6.28	N/A
NR gain	2.26	5.14	0.32	0.45	N/A	N/A	0.83	1.64	N/A	N/A	1.37	N/A

scheme can achieve 10% BLER at -3.63 dB and 1.42 dB for code rates of 1/3 and 2/3, respectively, using NR PTRS based approach. The LTE CP based method can, in turn, achieve 10% BLER at -0.97 dB and 6.98 dB. For higher modulation orders, i.e., 16QAM and 64QAM, LTE fails to reach 10% BLER. In addition, for four DMRS symbol configuration, we can observe BLER performance improvement due to the increased estimation performance especially in case of LTE. To this end, for LTE CP based method, QPSK modulation scheme can achieve 10% BLER at -3.46 dB and 1.67 dB SNRs with code rates of 1/3 and 2/3, respectively. For NR system, the corresponding BLER performance improvement is clearly smaller. Specifically, we can observe that the NR system with two DMRS configuration per subframe provides similar performance compared to LTE system with four DMRS configuration per subframe with lower system overhead assuming QPSK modulation scheme. Results with higher modulation orders show that NR PTRS based method has superior performance compared to LTE CP based method. For 16QAM modulation scheme, NR PTRS based method can achieve 10% BLER at SNRs of 1.11 dB and 8.378 dB with code rates of 1/3 and 2/3, respectively, while the corresponding numbers for LTE CP based method are 2.1 dB and 9.6 dB. Finally, for 64QAM and code rate of 1/3, 10% BLER is achieved at 5.29 dB and 6.54 dB for NR PTRS and LTE CP based methods, respectively.

IV. CONCLUSIONS

In this paper, we described and analyzed two alternative methodologies for Doppler estimation in NR and LTE system context, namely the PTRS based and the CP based approaches, with specific emphasis on high-speed trains type of high-mobility use cases. Overall, the NR PTRS based Doppler estimation method was shown to outperform the LTE CP based method. Specifically, using two DMRS symbols configuration per subframe, the NR PTRS based method was shown to allow reaching the 70% target of the maximum throughput with QPSK modulation at clearly lower SNRs. Additionally, it was shown that the LTE CP based method fails to support higher modulation schemes, i.e., 16QAM and 64QAM. Increasing the number of DMRS symbols per subframe to four, was shown to improve LTE system performance significantly, specially with QPSK modulation. Moreover, the provided BLER performance results show that PTRS based method has superior performance compared to CP based method. Furthermore, the results show that the NR PTRS allows to reduce the reference signal overhead in high mobility scenarios, thus making the 5G NR radio interface more suitable for the high speed use cases.

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