2022 IEEE International Conference on Advanced Networks and Telecommunications Systems (ANTS) | 978-1-6654-7340-8/22/$31.00 ©2022 IEEE | DOI: 10.1109/ANTS56424.2022.10227793

Estimation and Compensation of Doppler in 5G NR Based Non-Terrestrial Networks

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Abstract*—With the increasing demand for global internet coverage, the Third-Generation Partnership Project (3GPP) has progressed in integrating the 5G New Radio technology with aerial or satellite access. 3GPP coined the term non-terrestrial networks (NTN) to refer to the aerial or satellite access activity. This integration of 5G with NTN has brought about new opportunities along with challenges to be addressed. The challenges arise due to the large propagation distance, different scattering environment, and the mobility of NTN terminals (satellites or high-altitude platform systems). The mobility of an NTN terminal causes a time-varying Doppler shift that must be accounted for. This Doppler shift significantly impacts the orthogonality of the 5G orthogonal frequency division multiplexing (OFDM) signals. In this paper, the throughput performance of 5G physical downlink shared channel (PDSCH) link is studied in NTN narrowband and NTN tapped delay line (TDL) channels for different satellite orbits. The analysis is carried out in two Doppler compensation scenarios. Firstly, the time-domain 5G OFDM signal is pre-compensated for the Doppler at transmitter before passing through the channel. Secondly, the received signal is compensated for the Doppler, then, passed through the general 5G terrestrial receiver. The paper outlines the estimation of overall Doppler offset at the receiver using a novel metric by using the repetitive portion of OFDM signal and the demodulation reference signal (DM-RS) of PDSCH. The results show that the Doppler compensation at the receiver provides almost similar performance as Doppler pre-compensation at the transmitter.

Keywords—5G, DM-RS, Doppler, NTN, New Radio, OFDM, PDSCH

I. INTRODUCTION

The 5G New Radio (NR) access technology targets a wide range of use cases broadly classified in to three groups; namely massive machine type communications, (mMTC), ultra-reliable low latency communications (URLLC), and enhanced mobile broadband (eMBB) [1]. The first 5G NR step of the Third-Generation Partnership Project (3GPP) focuses on the eMBB use case and rolled out a specification as part of the Release 15 version in 2018. Since then, 3GPP is continuously extending the 5G NR technology to cover the remaining use-cases and support new use-cases like integration of 5G NR with satellite or aerial access. The integration of satellite access with 5G NR is crucial for providing worldwide network connectivity. In older wireless generations like 4G, the integration of satellites was mainly to provide backhaul. The recent increase in space market and its opportunities has led to increased 3GPP participation from the satellite communications industry [2]. This collaboration of 5G technology with the satellite industry and the need for an integrated solution for terrestrial and radio access, has led to study and work items that provide enhancements to the baseline 5G NR for supporting satellite access [3] [4]. The 3GPP has defined the term "non-terrestrial networks (NTN)" for satellite and aerial access. The first specification impact to handle the NTN for 5G NR is part of Release 17 from early 2022.

5G NTN systems need to handle different satellite orbits from low Earth orbit (LEO) to medium Earth orbit (MEO) to geosynchronous Earth orbit (GEO). One of the major concerns in LEO NTN system is Doppler shift due to mobility of the satellites. The Doppler shift due to mobility of a LEO satellite is around +/- 48 kHz at carrier frequency of 2 GHz [4]. This large Doppler shift must be accounted for before passing the received signal through a general 5G terrestrial receiver. The Doppler shift results in a carrier frequency offset (CFO) and affects the orthogonality in the OFDM systems, thereby leading to significant performance degradation. The Doppler shift due to mobility of a GEO satellite is negligible or almost close to zero and is therefore not considered in this study.

There has been an extensive study on the time-frequency synchronization for OFDM systems to address the unknown timing delay and frequency offset, which considers the terrestrial systems [5]-[7]. In a recent study [8], there is a proposal for time-frequency synchronization of 5G NTN using synchronization signals. The study considers only the AWGN and Rayleigh channels, but not the NTN channel mentioned in TR 38.811. A similar study is performed in [9], which estimates the Doppler shift and carrier frequency offset in case of no Global Navigation Satellite System (GNSS) receiver or weak GNSS signals using two synchronization bursts at different frequency bands. In [10], performance analysis of a data channel is carried out using slot aggregation in a GEO scenario. An enhanced synchronization is proposed in [11] for a 5G-like system in multipath channels. A fine frequency offset estimation along with Doppler rate estimation using Kalman filter is proposed in [12] using synchronization signals for LEO satellite networks. All the above-mentioned studies for 5G NTN consider the usage of synchronization signals for initial synchronization to get connected to the network. To the best of our knowledge, there is no study related to physical downlink shared channel (PDSCH) link level simulations that use the Doppler compensation using the reference signals of PDSCH for different satellite orbits. This study helps in understanding how the reference signals of PDSCH can be used to correct the

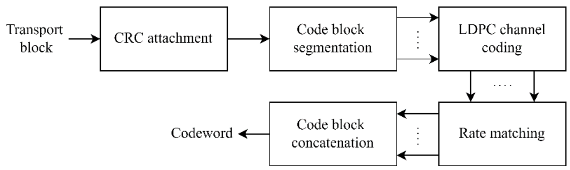

Fig. 1. 5G NR DL-SCH processing chain

Doppler in the slots where synchronization signals are not present.

In this paper, performance analysis in terms of throughput of 5G NR PDSCH link is studied for an NTN narrowband channel and an NTN tapped delay line (TDL) channel, using a novel Doppler estimation algorithm at the receiver. The impact of the proposed algorithm is compared with the link performance when using the Doppler pre-compensation at the transmitter, and it is observed that the link performance matches that of Doppler pre-compensation.

The remainder of the paper is organized as follows. The system and signal model are described in Section II. The Doppler estimation and compensation algorithm is provided in Section III, followed by link-level simulation results in Section IV. Lastly, the conclusions are presented in Section V.

II. System Model

In 5G NR, a frame contains 10 subframes with each subframe having a duration of 1 millisecond. Each subframe contains multiple slots based on the carrier numerology (or subcarrier spacing). For a carrier subcarrier spacing of 15 kHz, 30 kHz, 60 kHz, and 120 kHz, the number of slots in a subframe are 1, 2, 4, and 8, respectively. A slot contains either 14 or 12 OFDM symbols depending on the normal cyclic prefix or extended cyclic prefix of the carrier, respectively. For a carrier with normal cyclic prefix, the starting OFDM symbol of every half-subframe has larger cyclic prefix length compared to the other OFDM symbols in the subframe [13].

The PDSCH carries the encoded user data along with some system information. The transport block contains user data or system information; and undergoes downlink shared channel (DL-SCH) coding. The DL-SCH coding for one transport block as shown in Fig. 1 involves cyclic redundancy check addition, code block segmentation, low-density parity check (LDPC) coding, rate matching, and code block concatenation. These encoded, rate-matched, and concatenated code blocks are referred to as codewords. They are passed to PDSCH, which converts the coded bits to the symbols that are used for transmission. The PDSCH processing as shown in Fig. 2., includes scrambling, symbol modulation, layer mapping, and antenna port mapping. The antenna port symbol is mapped to

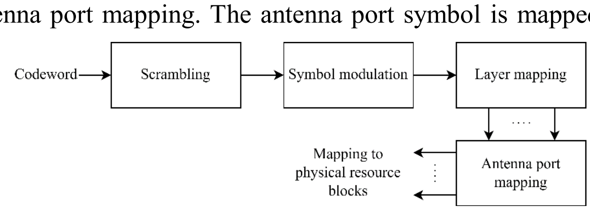

Fig. 2. 5G NR PDSCH processing chain

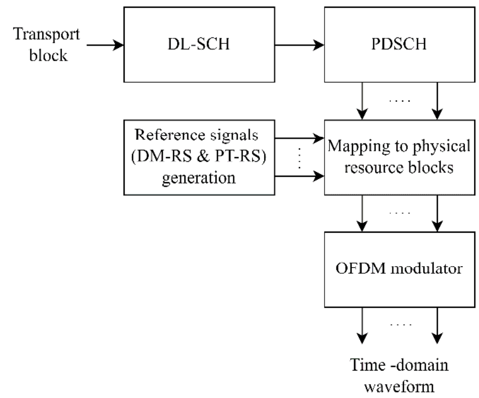

Fig. 3. 5G NR PDSCH transmitter chain

physical resource block (PRB) in the resource grid. Along with the PDSCH symbols, the reference signal symbols are also mapped to the resource grid. The resource grid from multiple antennas is passed to an OFDM modulator to get the time-domain waveform as shown in Fig. 3.

The time-frequency resource allocation of PDSCH in a slot is scheduled by the downlink control information. PDSCH is associated with two reference signals, namely a demodulation reference signal (DM-RS) and a phase tracking reference signal (PT-RS) [13]. DM-RS is used to estimate the radio channel, whereas PT-RS is used to combat the common phase error (CPE) due to phase noise in frequency range 2 (FR2). DM-RS is a mandatory reference signal and is always present in any PDSCH transmission, whereas PT-RS is an optional signal. The time-frequency pattern of DM-RS depends on the number of OFDM symbols allocated for PDSCH, mapping type of PDSCH, number of consecutive OFDM symbols allocated for DM-RS, additional positions assigned for DM-RS, configuration type of DM-RS, and the antenna port used for transmission.

In this study, no implementation-specific pre-coding is considered, and two NTN channel models as mentioned in [3] are used. The first one is NTN narrowband channel which is a single-input-single-output (SISO) flat-fading channel. The other

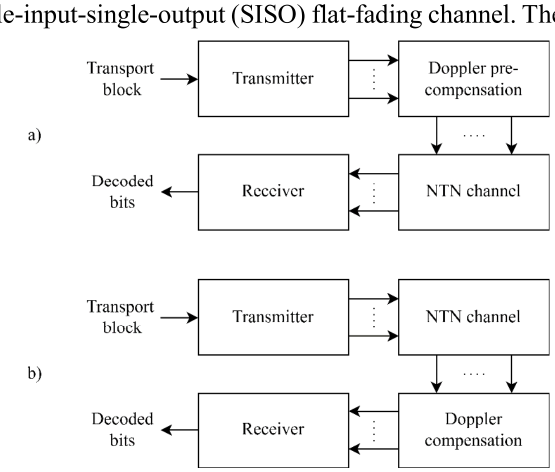

Fig. 4. a) 5G PDSCH link with Doppler pre-compensation; b) 5G PDSCH link with receiver Doppler compensation

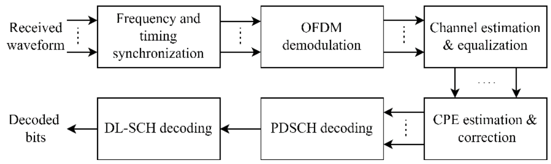

Fig. 5. 5G NR PDSCH receiver chain

one is NTN TDL channel which is a multiple-input-multiple-output (MIMO) frequency selective fading channel. Fig. 4 shows the two approaches that are considered in this NR PDSCH link study. The first approach applies a Doppler pre-compensation to the time-domain OFDM waveform before passing it on to the channel. The channel introduces a Doppler shift based on the scenario that is analyzed. The link performance is subsequently evaluated. The second approach passes the 5G PDSCH time-domain waveform directly to the channel and performs Doppler compensation at the receiver and then passing it on to the nominal 5G PDSCH terrestrial receiver. Fig. 5 shows the nominal 5G terrestrial receiver that performs frequency and timing synchronization, OFDM demodulation, channel estimation, equalization, CPE correction in presence of PT-RS, PDSCH decoding, and DL-SCH decoding. The PDSCH and DL-SCH decoding is performed by carrying out the inverse operations of the processing from Fig. 2 and Fig. 1 respectively. The decoded transport block and the CRC detection helps in determining the throughput and the block error rate.

To make the disposition simple, we start by considering a time-varying Doppler shift introduced by the SISO channel with no multi-tap and an additive white Gaussian noise (AWGN). The algorithm in Section III is subsequently described for a MIMO system. The received time-domain analog OFDM signal [3], is:

$$y(t) = x(t)\ exp(j\ 2\pi \int_0^t f_{Doppler}(\tau) d\tau) + w(t) \tag{1}$$

where, $y(t)$, $x(t)$, and $w(t)$ represent the received signal, the transmitted signal, and the noise signal, respectively. The transmitted signal contains information from PDSCH data and reference signals and is of a 1 slot duration. $f_{Doppler}(\tau)$ is the time-varying Doppler shift. Expanding the time-varying Doppler shift function using the Maclaurin series, it can be seen as per [14] that:

$$f_{Doppler}(\tau) = \alpha + \beta\tau + \gamma\tau^2 + O(\tau^3) \tag{2}$$

where, α is the Doppler shift with the value of $f_{Doppler}(0)$, β is the Doppler rate with the value of $f'_{Doppler}(0)$, γ is the variation of Doppler rate with the value of $\frac{f''_{Doppler}(0)}{2}$, and $O(\tau^3)$ contains the higher order terms. Assuming the Doppler shift has linear variation within one slot, the terms greater than the first degree can be ignored. After an analog-to-digital conversion with a sampling interval T_s, the received discrete signal can be written as:

$$y(n) \cong x(n)\ \exp(j\ 2\pi \textstyle\sum_{p=0}^{n} f_{Doppler}(p)\ T_s) + w(n) \tag{3}$$

where $T_s = \frac{1}{N\,\Delta f}$, p is an integer, N is the number of samples in one OFDM symbol (or the fast Fourier transform (FFT) size), and Δf is the subcarrier spacing. Substituting (2) in (3) leads to:

$$y(n) \cong x(n)\ exp(j\ 2\pi \sum_{p=0}^{n} (\alpha + \beta p T_s)\ T_s) + w(n) \tag{4}$$

Applying the summation of n terms in an arithmetic progression and upon further simplification, (4) can be rewritten as

$$y(n) \cong x(n)\ exp\left(j\ 2\pi \left(\left(\alpha + \frac{\beta\ T_s}{2}\right) nT_s + \left(\frac{\beta\ T_s}{2}\right) n^2 T_s\right)\right) + w(n) \tag{5}$$

Substituting the value of sample time T_s, the received signal can further be represented as:

$$y(n) \cong x(n)\ exp\left(j \frac{2\pi}{N} \left(\left(\alpha' + \frac{\beta'}{2}\right) n + \frac{\beta'}{2} n^2\right)\right) + w(n) \tag{6}$$

where, α' is the normalized Doppler shift with value equal to $\frac{\alpha}{\Delta f}$ and $\beta'$is the normalized Doppler rate with value equal to $\frac{\beta}{N\,\Delta f^2}$. It can be observed from (6) that the Doppler shift impacts the signal in the same way as a carrier frequency offset, thereby, significantly impacting the orthogonality. The overall Doppler offset is $\left(\alpha' + \frac{\beta'}{2}\right)$, having the contribution from both Doppler shift and Doppler rate. Extending (6) for an M multi-tap SISO channel with each tap experiencing the same Doppler variation, the resultant received signal would lead to,

$$y(n) \cong exp\left(j \frac{2\pi}{N} \left(\left(\alpha' + \frac{\beta'}{2}\right) n + \frac{\beta'}{2} n^2\right)\right) \left(\sum_{l=0}^{M-1} h(l)\ x(n-l)\right) + w(n) \tag{7}$$

The channels used in this study are the NTN narrowband and NTN TDL channels from [3]. Using (5), even the Doppler rate can be modeled. Simulation results are presented for one such scenario. The Doppler shift due to satellite motion is considered using the formula from [3]:

$$f_{Doppler,sat} = f_c \left(\frac{v_{sat}}{c}\right)\left(\frac{R}{R+h}\right) cos\alpha_{model} \tag{8}$$

where, f_c is the carrier frequency, c is the speed of light, R is the radius of earth, h is the altitude of the satellite, v_{sat} is the speed of the satellite, and α_{model} is the elevation angle.

III. Doppler Estimation And Compensation

Doppler estimation is divided into two steps: fractional Doppler offset estimation and integer Doppler offset estimation. Simulation results show that even in the presence of Doppler rate, compensation of Doppler offset for the received signal and passing it to the 5G terrestrial receiver exhibits similar link performance with minimal degradation. This section provides some details about the Doppler offset estimation for a high

Doppler, multi-tap channel, and MIMO system. The fractional Doppler offset estimation uses the repetitive nature of OFDM signal using the cyclic prefix. The integer Doppler offset uses the DM-RS signal associated with PDSCH.

A. Fractional Doppler Offset Estimation

A 5G slot can have different cyclic prefix lengths based on the carrier numerology for each OFDM symbol. Using maximum likelihood estimation [7] and valid detection [15], a new metric proposed in (9) is used to provide fractional frequency offset.

$$NCC_r(m) = \sum_{i=m}^{m+L-1} \frac{y_r(i)y_r^*(i+N)}{sqrt(|y_r(i)|^2|y_r(i+N)|^2)} \tag{9}$$

where, $y_r^*(i+N)$ is the conjugate of received sample delayed by N, N is the FFT length, L is the lowest cyclic prefix length in the slot, and $m \in \{1 \ldots N_{samples} - L + 1\}$. The lowest cyclic prefix length is used as the majority of the OFDM symbols in a slot have that redundancy length.

The fractional Doppler offset is estimated by finding the normalized correlation metric value of an OFDM sample with delayed samples of length N. A moving sum is calculated with a window length equal to the lowest cyclic prefix length in the slot. The angle of peak location(s) of this moving sum gives the fractional Doppler offset. Note that the metric (9) proposed in this paper is different from the one used in [7], as (9) considers the energy of received signal. This proposed metric is useful for considering the peak values that are part of a valid OFDM symbol.

The fractional Doppler offset is estimated using these steps:

1. For each received signal y_r from different antennas, append zeros of length N, where N is the FFT length. The resultant signal for one receive antenna is of length $N_{samples}$.
2. For the appended signal, compute the normalized correlation value for each sample with the sample delayed by N. Then, find the moving sum $NCC_r(m)$ of all the samples considering a window of length L, as given in (9).
3. Compute the absolute values of $NCC_r(m)$
$$absNCC_r(m) = |NCC_r(m)| \tag{10}$$
4. Compute $absNCC_r(m)$ for all the received signals from different antennas and choose the antenna index that has the maximum value across all the receive antennas for further processing.
$$bestAntIdx = \max_r(absNCC_r) \tag{11}$$
5. Find the peak values of $absNCC(m)$ corresponding to the $bestAntIdx$ in a sliding window length of N, and compare the peak values against a threshold, as mentioned in [15], to decide if it is a valid peak detection. The choice and value of the threshold is mentioned in simulation results.
6. Store the valid peak locations, $validLoc$, and use them to find out the moving sum values in NCC corresponding to $bestAntIdx$. The fractional Doppler offset ($\widehat{f_{DO}}$) is estimated using:
$$\widehat{f_{DO}} = -\frac{\Delta f}{2\pi} \arg\{ mean\left(NCC_{bestAntIdx}(validLoc)\right)\} \tag{12}$$

From (12), the estimation range of Doppler offset is $[\frac{-\Delta f}{2}, \frac{\Delta f}{2})$. The received signal is compensated with the estimated fractional Doppler offset for each receive antenna as:

$$y_{c,r}(n) = y_r(n) \exp\left(-j\frac{2\pi}{N} n\widehat{f_{DO}}\right) \tag{13}$$

B. Integer Doppler Offset Estimation

The integer Doppler offset is estimated by using the DM-RS of PDSCH. For a given PDSCH resource allocation, the DM-RS sequence is known in any slot, and this information can be used at the receiver. For integer Doppler offset estimation, the compensated signal from (13) is used.

The properties of FFT are used to estimate the integer Doppler offset and these are the main steps:

1. With the known DM-RS symbols $R(k)$ for different layers, generate a time-domain reference waveform $Ref(n)$ across all the layers. In Fig. 3., map zeros at the locations of PDSCH data, and pass the resource grid containing only the DM-RS signal for the OFDM modulator, to get the time-domain waveform. Note, the transmitter might apply some windowing, but the reference signal must be generated with no windowing. This is because receiver is not aware of the nature of windowing applied (e.g., roll-off factor in case of root raised cosine windowing).
2. For each receive antenna, compute the correlation of compensated signal with the reference signal $Ref_i(n)$ across all layers and sum the correlated signal across all layers.
$$S_r(n) = \sum_{i=1}^{v} y_{c,r}(n)Ref_i^*(n) \tag{14}$$
where, $Ref_i^*(n)$ is the conjugate of time-domain reference signal and v is the number of layers.
3. Find the energy of the resultant signals across all the receive antennas and select the receive antenna signal that has maximum correlation energy value for further processing.
$$bestIdx = \max_r |S_r(n)|^2 \tag{15}$$
4. Perform FFT for $S_{bestIdx}(n)$, which is of length N_l. Store the maximum value of FFT waveform and its corresponding FFT bin value.
$$S_{FFT}(k) = \sum_{n=-N_l/2}^{\frac{N_l}{2}-1} S_{bestIdx}(n) \exp(j\frac{2\pi}{N_l} n\, k) \tag{16}$$

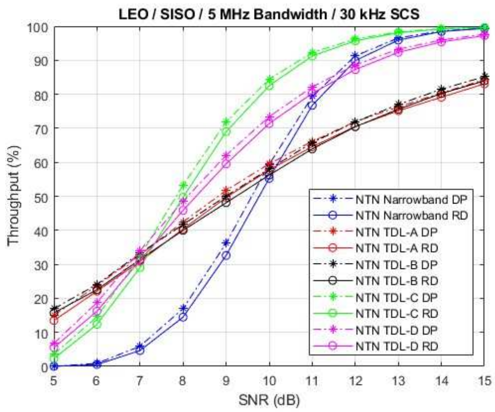

Fig. 7. Throughput performance of 5G PDSCH link for SISO in LEO @ 600 km in presence of Doppler shift (DP: Doppler pre-compensation, RD: Receiver Doppler compensation)

When there is no multi-tap channel, the FFT bin value is the estimated integer Doppler offset ($\widehat{f_{IO}}$). In case of a multi-tap channel, steps 2 to 5 must be performed for each sample offset; and the FFT bin value corresponding to the maximum FFT value among all the shift offsets is the estimated integer Doppler offset. The range of sample offsets must be such that it covers the whole cyclic prefix length of the first OFDM symbol in the slot. With this estimated integer Doppler offset ($\widehat{f_{IO}}$), the signal in (13) is compensated by replacing y_r with $y_{c,r}$ and $\widehat{f_{DO}}$ with $\widehat{f_{IO}}$ in the right-hand side of (13). The estimation range of integer Doppler offset is dependent on the length of the signal in a slot and the resolution is given by the ratio of sample rate to that of the length of signal. The estimated integer Doppler offset is in the range $[\frac{-sampleRate}{2}, \frac{sampleRate}{2})$, where $sampleRate$ is the sampling rate of the signal.

IV. Simulation Results

The performance results of a 5G PDSCH link are presented for a sub-GHz frequency range (FR1) with carrier frequency of 2 GHz and subcarrier spacing of 15 kHz. The channel models used for link-level simulations are NTN narrowband channel with urban environment and NTN TDL channel with four delay profiles, namely, NTN-TDL-A, NTN-TDL-B, NTN-TDL-C, and NTN-TDL-D [3]. The simulation setup is provided in Table I showing the different parameters used in the evaluation. The simulations are acquired using 5G Toolbox™ [16], Satellite Communications Toolbox [17], and MATLAB® [18]. The metric in (9) is computed for long-running simulations with only Gaussian noise as mentioned in [15] and the threshold chosen is 0.48 which gives the probability of false detection around 0.01.

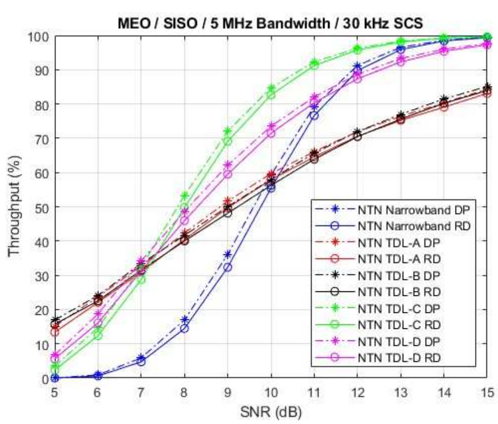

Fig. 8. Throughput performance of 5G PDSCH link for SISO in MEO @ 10000 km in presence of Doppler shift (DP: Doppler pre-compensation, RD: Receiver Doppler compensation)

TABLE I. Parameter Setup [4]

Parameter	Value
Frequency range	FR1 (S-band)
Carrier frequency	2 GHz
Channel bandwidth	5 MHz
Subcarrier spacing (SCS)	30 kHz
Channel model	NTN narrowband urban and NTN TDL at elevation angle of 50 degrees
Number of transmit antennas	1
Number of receive antennas	1 (for narrowband / TDL profiles), 2 (only for TDL profiles)
PDSCH symbol allocation	[0 13]
PDSCH resource block allocation	0 to the largest PRB index in carrier
PDSCH mapping type	A
DM-RS configuration	Single-symbol DM-RS, 2 DM-RS additional positions, DM-RS configuration type 1, number of CDM groups without data 2
Mobile speed	3 km/h
Satellite orbit	LEO @ 600 km, MEO @ 10000 km
Satellite speed	7562.2 m/s (LEO 600 km), 4930.1 m/s (MEO 10000 km)
Channel estimation	Least squares
Equalization	Minimum mean square error
LDPC decoding algorithm	Normalized min-sum
Modulation	16QAM
Target code rate	490/1024

The Doppler pre-compensation is performed at the transmitter by using the known Doppler shift with (8). In the simulations with Doppler rate, it is assumed that Doppler rate is known at the transmitter and pre-compensation includes even the Doppler rate in that case. Fig. 7 and Fig. 8 show the throughput percentage as a variation of signal-to-noise ratio (SNR) for a SISO channel with different channel conditions for LEO and MEO respectively. The receiver Doppler compensation exhibits similar performance as the Doppler pre-compensation. A similar behavior with diversity gain is observed in Fig. 9 for a single-input-multiple-output (SIMO) system having 1 transmit antenna and 2 receive antennas. The

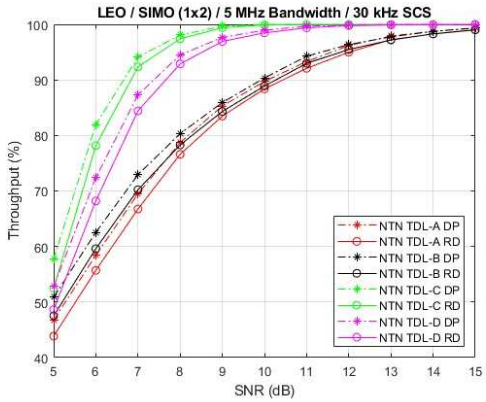

Fig. 9. Throughput performance of 5G PDSCH link for SIMO in LEO @ 600 km in presence of Doppler shift (DP: Doppler pre-compensation, RD: Receiver Doppler compensation)

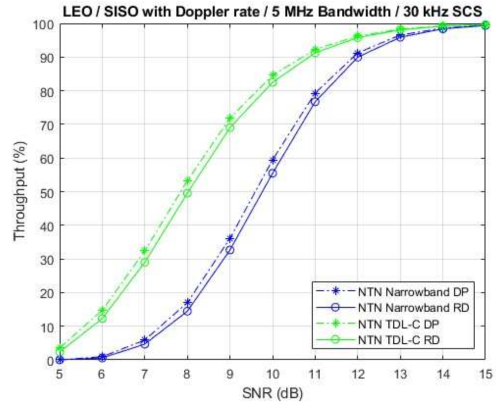

Fig. 10. Throughput performance of 5G PDSCH link for SISO in LEO @ 600 km in presence of Doppler shift and Doppler rate (DP: Doppler pre-compensation, RD: Receiver Doppler compensation)

maximum SNR variation is calculated as the maximum difference between the throughput curves of Doppler pre-compensation and receiver Doppler compensation for a particular throughput percentage. The maximum SNR variation for different scenarios is tabulated in Table II. Fig. 10 shows the throughput percentage as a variation of SNR using the maximum Doppler shift of 48 kHz and maximum Doppler rate of -544 Hz for a LEO satellite at 600 km.

TABLE II. RESULTS SUMMARY

Antenna configuration	Satellite orbit	Doppler configuration	Maximum SNR variation (dB)
SISO	LEO @ 600 km	Doppler shift	0.26
SISO	MEO @ 10000 km	Doppler shift	0.21
SIMO	LEO @ 600 km	Doppler shift	0.25
SISO	LEO @ 600 km	Doppler shift with Doppler rate	0.22

V. CONCLUSION

Performance analysis of a 5G NR PDSCH link for 5G NTN networks is presented. An algorithm is proposed for Doppler offset compensation at receiver to handle the high Doppler due to satellite movement (in LEO), multi-tap channel, and multiple antenna system. The algorithm uses redundancy in the OFDM signal for fractional offset estimation and DM-RS for integer offset estimation. Simulation results show that the proposed Doppler offset compensation achieves a similar link performance as Doppler pre-compensation at transmitter for different satellite orbits in different NTN channel conditions. The proposed algorithm can be applied to a multiple-antenna system and can work with a 5G terrestrial receiver.

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