Experimental Study of Doppler Shift in 5G NR based Non-Terrestrial Networks

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Abstract*—The 3GPP is currently exploring the evolution of 5G New Radio (NR) to support non-terrestrial networks (NTNs), particularly in the context of satellite communication networks. In NTNs, spaceborne platforms' movement can result in significant and varying Doppler shifts for devices located at different positions. In our experimental study focusing on the downlink channel and employing orthogonal frequency-division multiple access (OFDMA), we investigate the distinct behaviors of Flat fading and frequency-selective fading channels. This exploration involves systematic variations of multiple parameters to comprehensively assess their impact on system performance. Furthermore, we conduct an in-depth analysis of the channel impulse response, alongside other parameters, to gain a holistic understanding of the communication environment in NTN setups. In the downlink scenario, each device undergoes a unique frequency adjustment to counter Doppler shift effects. Our extended investigation of the channel impulse response enhances the granularity of our study, contributing valuable insights into the Doppler effect and its implications on communication channels within NTNs.

I. INTRODUCTION

New Radio (NR) is the fifth-generation (5G) wireless technology designed to cater to a wide range of use cases, including enhanced mobile broadband (eMBB), ultra-reliable low-latency communications (URLLC), and massive machine type communications (mMTC). Initially, 3GPP finalized the first 5G NR specifications in Release 15 and has since been continuously working on improving 5G NR performance and accommodating new use cases. One such area of exploration in 3GPP is the adaptation of 5G NR to support non-terrestrial networks (NTNs), encompassing networks involving non-terrestrial flying objects. The primary focus of 3GPP's NTN work centers on satellite communication networks that employ spaceborne platforms, including Low Earth Orbiting (LEO) satellites, Medium Earth Orbiting (MEO) satellites, and Geosynchronous Earth Orbiting (GEO) satellites.

The movement of these spaceborne platforms within NTNs introduces significant Doppler shifts. For instance, a high-speed LEO satellite at an altitude of 600 km can result in location-dependent and time-varying Doppler shifts as substantial as 24 ppm, which equates to 48 kHz at a 2 GHz carrier frequency. In order for user equipment (UE) to connect to an NR network, it must synchronize in terms of time and frequency using synchronization signals (SS) in the downlink (DL). Due to varying Doppler shifts, UEs within the same cell may need to tune to significantly different frequencies. If the DL signal frequency serves as the reference for the uplink (UL), the DL Doppler shift translates into a corresponding UL frequency shift at the UE. Additionally, UL signals are also subject to Doppler shifts, leading to frequency misalignments in UL transmissions, particularly in the context of NR's use of orthogonal frequency division multiplexing (OFDM) and orthogonal frequency division multiple access (OFDMA) in the UL transmissions. This misalignment challenges the orthogonality of OFDMA.

To address the frequency misalignment during transmissions or reception, each User Equipment (UE) must apply a distinct frequency adjustment in the uplink or downlink, tailored to compensate for its specific Doppler shift. The central challenge lies in the determination of the requisite frequency adjustments for each UE, considering the dynamic nature of Doppler shift in non-terrestrial networks (NTNs). Despite the implementation of measures such as Global Navigation Satellite System (GNSS) assistance and reference signals in multiple frequency positions, the Doppler shift continues to exhibit sensitivity to a myriad of parameters within the communication environment.

In response to this intricate challenge, our ongoing experimental analysis aims to delve deeper into understanding how various parameters influence the Doppler shift in NTNs. Atmospheric conditions, signal strength, and interference are among the key factors contributing to the variability of Doppler shift. By systematically varying these parameters in controlled experiments, we seek to quantify their individual and collective impacts on the Doppler shift. This meticulous investigation strives to provide valuable insights into the nuanced dynamics of Doppler shift, shedding light on the extent to which each environmental factor affects the frequency adjustments necessary for seamless communication in non-terrestrial scenarios. The outcomes of this research are anticipated to contribute significantly to the development of robust solutions for adaptive frequency adjustments in NTN setups, enhancing the reliability and performance of communication systems in dynamic and challenging environments.

In our comprehensive experimental study, we meticulously investigated the dynamic characteristics of two distinct communication channels – a flat fading narrowband channel and a frequency-selective fading Tapped Delay Line (TDL) channel. The primary focus of our analysis was on understanding the behavior of Doppler shift, received signal strength and the channel impulse response under varying atmospheric conditions, device mobility, sampling rate, and other pertinent parameters within these specific channel environments. The flat fading narrowband channel provided a simplified but crucial scenario, allowing us to isolate and examine the impact of individual parameters on Doppler shift and signal strength in a controlled setting. This controlled environment facilitated a detailed exploration of how atmospheric conditions, device mobility, and sampling rate alterations influence the communication performance in the presence of flat fading.

In contrast, the frequency-selective fading TDL channel introduced a more complex and realistic representation of the communication environment. This channel model incorporated multiple taps, simulating the multipath effects that are prevalent in real-world scenarios. By varying atmospheric conditions, device mobility, and sampling rates, we sought to understand the nuanced interactions between these parameters and the resulting Doppler shift and received signal strength in a frequency-selective fading context. The TDL channel analysis aimed to capture the intricate dynamics of communication channels in non-terrestrial networks, providing valuable insights into the challenges and opportunities associated with adaptive communication systems in dynamic and varying environments. The outcomes of these experiments contribute to the broader understanding of the doppler effect in NTN channel and its deviation due to various parameters.

II. SYSTEM MODEL

This illustration outlines the process of constructing a system model for New Radio (NR) non-terrestrial network (NTN) channels, focusing on two distinct types: a flat fading narrowband channel and a frequency-selective fading tapped delay line (TDL) channel. The characterization of these channels is based on 3GPP TR 38.811 Section 6.7.1 and Section 6.9.2, which encompass deployment scenarios involving both geo-synchronous orbit (GSO) satellites and non-geo-synchronous orbit (NGSO) satellites.

Within this demonstration, the NTN channel model is generated by deriving path gains from a foundational channel model and subsequently introducing the Doppler shift resulting from satellite movement; we took this reference Model of NTN from[4]. The base channel model for the NTN flat fading narrowband channel adheres to ITU-R P.681-11, outlining propagation data for a land mobile-satellite (LMS) channel. For the NTN frequency-selective TDL channel, the base channel model follows the specifications of 3GPP TR 38.901, defining the terrestrial TDL channel.

A. Doppler Shift Calculation:

The Doppler shift induced by satellite motion is contingent on parameters such as satellite speed, orbit, elevation angle, and carrier frequency. As articulated in 3GPP TR 38.811 Section 6.7.1 and Section 6.9.2, the Doppler shift fd,sat is computed as follows:

$$f_{d,\mathrm{sat}} = \left(\frac{\nu_{\mathrm{sat}}}{c}\right) * \left(\frac{R}{R+h}\cos(\alpha_{\mathrm{model}})\right) * f_c \tag{1}$$

where, Vsat denotes the satellite speed, c represents the speed of light, R stands for the earth radius, h indicates the satellite altitude, αmodel corresponds to the satellite elevation angle, and fc represents the carrier frequency.

B. Modeling Process:

To emulate an NTN narrowband or TDL channel, it is imperative to configure all requisite channel parameters alongside those utilized in the base channel model. Following the definition of these parameters, a suitable base channel is constructed for the flat fading narrowband channel or frequency-selective TDL channel. Path gains are generated from this base channel, and subsequently, a Doppler shift due to satellite movement is applied to obtain the path gains of the NTN channel. The input signal is then filtered with the resultant path gains. The workflow for generating the NTN channel is illustrated in the accompanying Fig. 1.

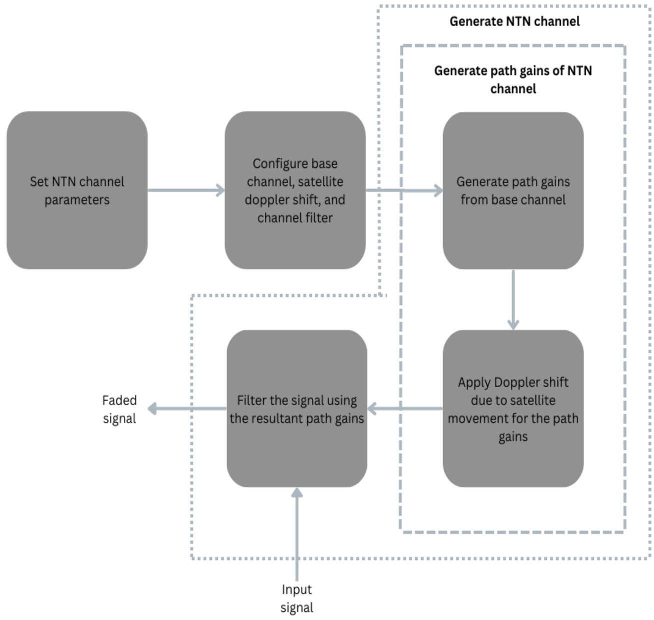

Fig. 1. 5G NTN model generation flow

To establish a comprehensive system model for both the New Radio (NR) non-terrestrial network (NTN) narrowband flat fading channel and the NTN TDL channel, it is essential to define common parameters that govern the behavior of the channels. The parameters include those related to the satellite, the environment, and the communication setup. In this example, we'll consider a low Earth orbit (LEO) satellite operating in the S-band, moving at a speed of 7.5622 km/s, and positioned at an altitude of 600 km. Additionally, we'll assume a mobile or user equipment (UE) speed of 3 km/hr. These default parameters are derived from 3GPP TR 38.821 Table 6.1.2-4.

1. Satellite Speed: The speed of the satellite, which influences the Doppler shift. In this experiment the initial reference speed is ,(7.5622) km/s.

2. Satellite Altitude: The height of the satellite above Earth's surface. In this scenario, (h = 600) km.

3. Elevation Angle: The angle between the satellite and the line of sight from the receiver. It is a critical parameter for Doppler shift calculations.

4. Sample Rate: The rate at which the signal is sampled, impacting the accuracy of the channel model. This is a crucial parameter in the simulation.

5. Carrier Frequency (fc): The frequency at which the carrier signal operates. For this example, the satellite operates in the S-band.

6. Mobile Speed: The speed of the mobile or user equipment (UE) in the terrestrial network. In this case, the assumed mobile speed is (3) km/hr.

By defining these common parameters, the NTN channel model can accurately represent the dynamic interplay between the satellite and the terrestrial environment. The specified values, sourced from 3GPP TR 38.821 Table 6.1.2-4, provide a baseline for modeling scenarios involving low Earth orbit (LEO) satellites in the S-band. The inclusion of mobile speed ensures a comprehensive depiction of the NTN channel, considering both satellite and user equipment dynamics. These parameters are foundational to the subsequent steps in constructing the NTN channel model, encompassing both narrowband flat fading and TDL channel configurations.

TABLE I .NTN CHANNEL COMMON PARAMS

Parameter	***Value***
Carrier Frequency	2GHz
Elevation Angle	50 deg
Satellite Altitude	600000 m
Satellite Speed	7562 m/s
Mobile Speed	3 km/hr
Sample Rate	7.68 MHz

C. NTN Frequency-Selective Fading TDL channel:

The NTN frequency-selective fading tapped delay line (TDL) channel, as standardized by 3GPP, replicates authentic communication scenarios within non-terrestrial networks. Utilizing a tapped delay line structure featuring diverse delay paths and attenuations, this model faithfully reproduces frequency-selective fading effects induced by reflections and scattering. It stands as a pivotal instrument for assessing communication system performance in varied and demanding NTN environments.

In our investigation, we deliberately chose the NTN-TDL-A profile, specifically designed for non-line-of-sight (NLOS) conditions, in alignment with the communication scenarios prevalent in NTN deployments. Given that NTN communication frequently involves satellite links where direct line-of-sight isn't guaranteed, selecting the NTN-TDL-A profile enables us to precisely characterize and tackle challenges inherent to NLOS environments. This purposeful choice amplifies the applicability of our study to real-world NTN communication scenarios, offering insights that hold greater relevance for practical deployment considerations. Our experimental study adhered to the parameters specified in the TABLE II below, enabling a thorough examination of the NTN-TDL-A profile's performance under diverse conditions and variables.

TABLE II .NTN TDL PARAMS

Parameter	***Value***
Channel Type	TDL frequency selective
Delay Profile	NTN-TDL-A
Delay Spread	30ns
Transmission Direction	Downlink
MIMO correlation	Low
Polarization	Co-Polar
Path Delays	0
Average Path Gains	0
Fading Distribution	Rayleigh
TX antennas	1
RX antennas	2

D. NTN Flat Fading Narrowband Channel:

The NTN flat fading narrowband channel, integral to our experimental study, is characterized by consistent channel response over a narrow frequency range in non-terrestrial networks. This flat fading nature simplifies the analysis of Doppler shift effects caused by relative motion. Our investigation focuses on understanding how atmospheric conditions, device mobility, and other parameters influence communication in this specific NTN channel.

In our experimental setup, we meticulously followed the procedural guidelines specified in Section 6.7.1 of 3GPP TR 38.811 to model the NTN flat fading narrowband channel. This involved the systematic configuration of channel parameters tailored to the NTN flat fading narrowband channel, with a particular focus on utilizing the parameters outlined in the accompanying table. Subsequently, we generated the NTN flat fading narrowband channel and proceeded to visualize the spectrum of the resulting faded or filtered signal. This channel model was specifically employed for narrowband single-input-single-output (SISO) simulations, providing insights into the performance characteristics under various conditions.

TABLE III .NTN NARROWBAND PARAMS

Parameter	***Value***
Channel Type	Narrowband Flat Fading
Environment	Urban
Fading Technique	Sum of Sinusoids
Azimuth Orientation	0
Path Delay	0
Channel Filter Delay	0
Channel Filter Coefficients	1

III. SIMULATION RESULTS

In the initial phase of our experiment, we employed the NTN frequency-selective fading TDL channel model, a crucial component for emulating realistic non-terrestrial network (NTN) communication scenarios. To comprehensively assess the behavior of the communication system, we deliberately varied key parameters such as satellite mobility, mobile speed, and sample rate. These variations allowed us to scrutinize the impact on critical performance metrics, including Doppler shift, received signal strength, and channel impulse response. Through this systematic exploration, we gained valuable insights into how the NTN communication system responds to changes in environmental and operational factors, providing a nuanced understanding of its dynamic behavior under diverse conditions.

In our simulation, we ran the NTN frequency-selective fading TDL channel model with parameters set as follows: ChannelFilterDelay of 7, MaximumChannelDelay of 8, PathDelays [0 3.2433e-08 8.5248e-08], AveragePathGains [0 -4.6750 -6.4820], KFactorFirstTap set to -Inf, NumTransmitAntennas of 1, NumReceiveAntennas of 2, and SpatialCorrelationMatrix as [2×2 double]. The estimated Doppler Shift in this reference scenario was found to be 50409.1111 Hz.

Following are the plots depicting the received signal strength Fig. 2 and channel impulse response Fig. 3 for the reference model.

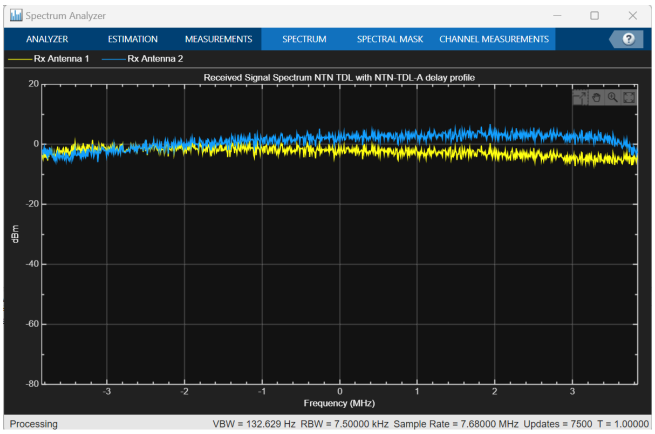

Fig. 2. Received Signal Spectrum NTN frequency selective fading TDL channel with NTN-TDL-A delay profile with TABLE I and II data (Reference Signal)

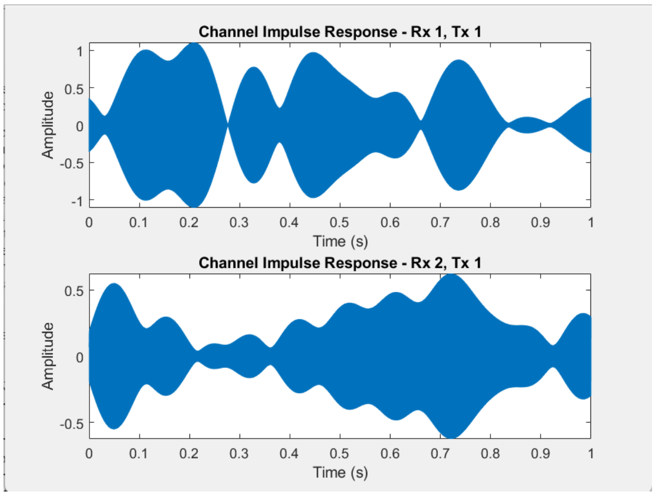

Fig. 3. Received Signal Impulse response for NTN frequency selective fading TDL channel with TABLE I and II data (Reference Signal)

A. Satellite Mobility

After adjusting the SatelliteSpeed Vsat(1) in our simulation to 7562.2 m/s, 5562.2 m/s, and 9562.2 m/s, we observed changes in the Doppler shifts. The updated results from the final project with Doppler shift estimation include ChannelFilterDelay of 7, MaximumChannelDelay of 8, PathDelays [0 3.2433e-08 8.5248e-08], AveragePathGains [0 -4.6750 -6.4820], KFactorFirstTap of -Inf, NumTransmitAntennas of 1, NumReceiveAntennas of 2, and SpatialCorrelationMatrix [2×2 double].

The estimated Doppler shifts are as follows:

- Estimated Doppler Shift 1: 50409.1111 Hz
- Estimated Doppler Shift 2: 37075.7778 Hz
- Estimated Doppler Shift 3: 63742.4444 Hz

These results indicate that variations in satellite speed have a direct impact on the Doppler shift in the NTN frequency-selective fading TDL channel model. Specifically, as we reduce the satellite speed, the Doppler shift decreases, and conversely, an increase in speed results in a higher Doppler shift. This observation provides valuable insights into the dynamic relationship between satellite mobility and Doppler effects in non-terrestrial communication scenarios.

Below are the received signal strength Fig. 4 and channel impulse response Fig. 5 plots for the NTN frequency-selective fading TDL channel, with varying SatelliteSpeed Vsat(1) set to 5562.2 m/s.

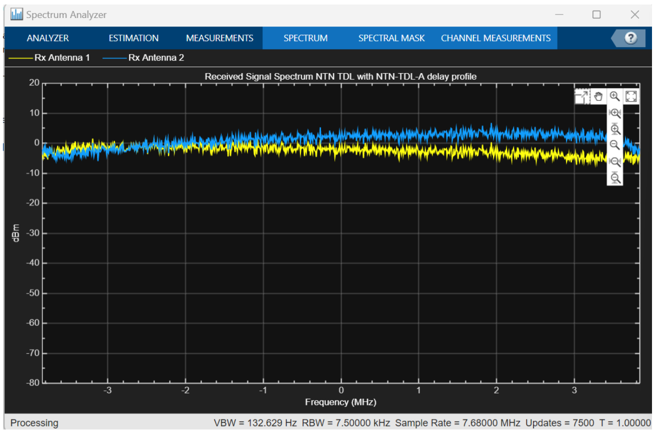

Fig. 4. Received Signal Spectrum for NTN frequency selective fading TDL channel with NTN-TDL-A delay profile along with TABLE I and II data with modified Satellite mobility

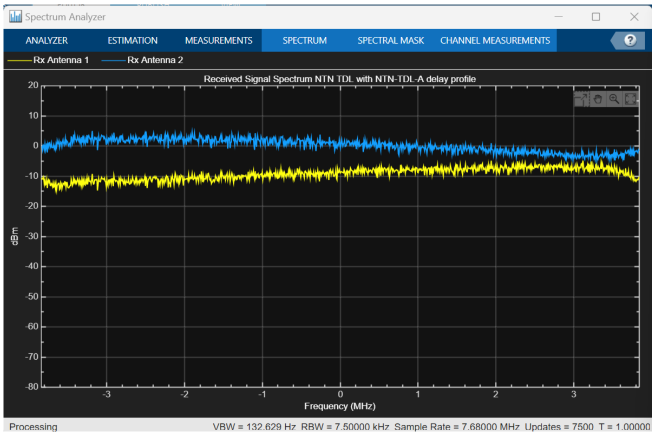

Fig. 6. Received Signal Spectrum for NTN frequency selective fading TDL channel with NTN-TDL-A delay profile along with TABLE I and II data with modified mobile speed

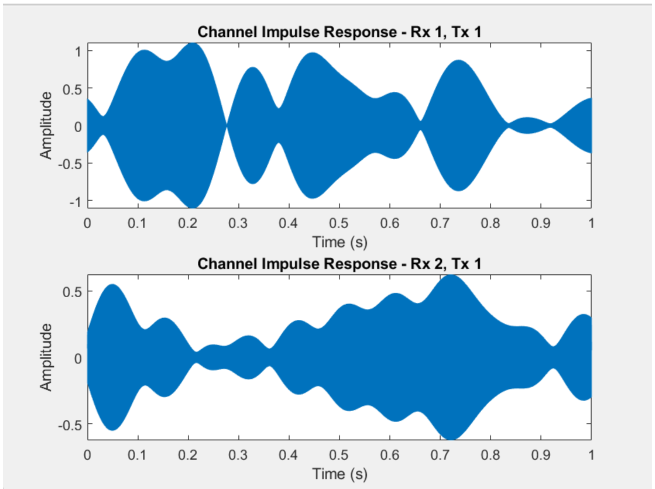

Fig. 5. Received Signal Impulse response for NTN frequency selective fading TDL channel with TABLE I and II data with modified Satellite mobility

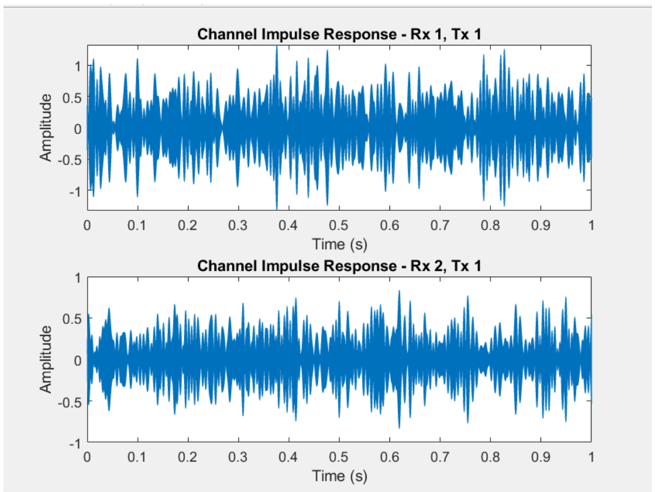

Fig. 7. Received Signal Impulse response for NTN frequency selective fading TDL channel with TABLE I and II data with modified mobile speed

B. Mobile Speed

After changing the mobile speed parameter commonParams.MobileSpeed to 10*1000/3600 m/s, 50*1000/3600 m/s, and 1*1000/3600 m/s, the simulation results showed that altering the mobile speed had minimal impact on the Doppler shift.

The estimated Doppler shifts are reported as follows:

- Estimated Doppler Shift 1: 50396.1481 Hz

- Estimated Doppler Shift 2: 50322.0741 Hz

- Estimated Doppler Shift 3: 50412.8148 Hz

However, significant variations were observed in the received signal strength and channel impulse response, highlighting the sensitivity of these parameters to changes in mobile speed.

Here are the plots depicting received signal strength Fig. 6 and channel impulse response Fig. 7 for the NTN frequency-selective fading TDL channel, where the mobile speed was adjusted to 50*1000/3600 m/s.

C. Sample Rate

Following the adjustment of the sampling rate from 7.68MHz to both 3MHz and 15MHz, our experimental findings indicated consistent values for Doppler shift and channel impulse response. Throughout these modifications, Doppler shift and channel impulse response remained stable, underlining their resilience to changes in the sample rate. However, a noteworthy observation was the variations in received signal strength, suggesting its sensitivity to alterations in the sampling rate. This underscores the robustness of Doppler shift and channel impulse response, while highlighting the more nuanced impact on received signal strength.

The estimated Doppler shifts are as follows:

- Estimated Doppler Shift 1: 50409.1111 Hz

Here are the plots illustrating the received signal strength Fig. 8 and channel impulse response Fig. 9 for the NTN frequency-selective fading TDL channel, with the sample speed adjusted from 7.68 MHz to 15 MHz.

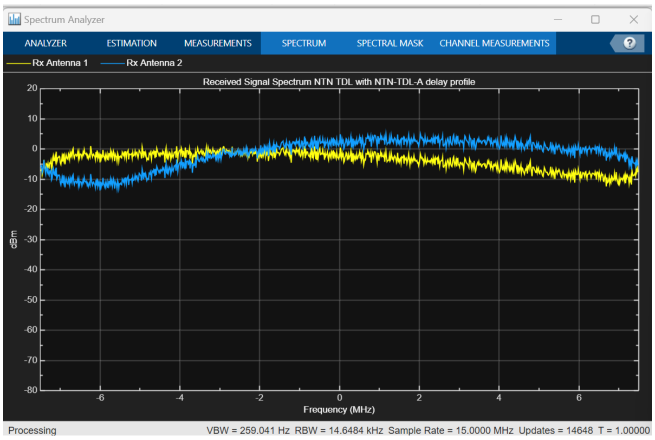

Fig. 8. Received Signal Spectrum for NTN frequency selective fading TDL channel with NTN-TDL-A delay profile along with TABLE I and II data with modified sample rate

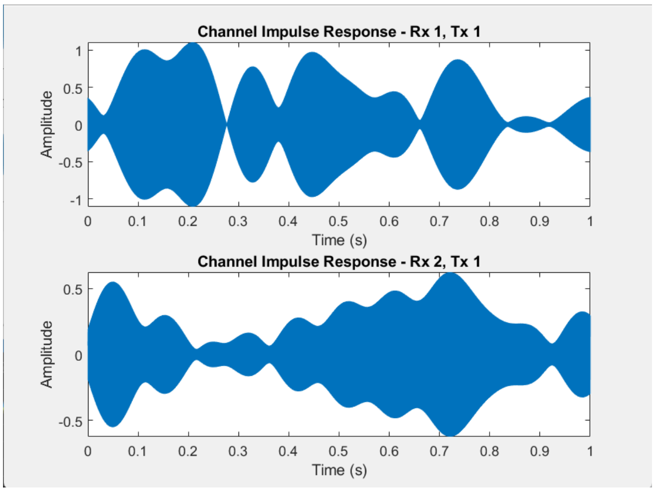

Fig. 9. Received Signal Impulse response for NTN frequency selective fading TDL channel with TABLE I and II data with modified sample rate

In the second phase of our experimentation, our focus is on the NTN Narrowband Flat Fading Channel model, where we aim to gain a comprehensive understanding of its behavior under various conditions. Our primary objective is to carefully observe and analyze simulation outcomes by intentionally manipulating crucial parameters, specifically satellite mobility, mobile speed, and sample rate. This systematic variation of parameters serves as an in-depth exploration into the intricacies of the channel model, providing valuable insights into its performance characteristics.

In our reference simulation, we utilized common channel parameters for NTN channels and ran the NTN flat fading TDL channel model with the following settings: ChannelFilterDelay of 0, PathDelays 0, Mobile Doppler Spread of 5.559, NumTransmitAntennas of 1, NumReceiveAntennas of 1, and a satellite Doppler shift of 2.9637e+04. The estimated Doppler Shift in this reference scenario was determined to be 50409.1111 Hz.

The subsequent plot showcase the received signal strength Fig. 10 for the reference model, providing a visual representation of the simulation outcomes.

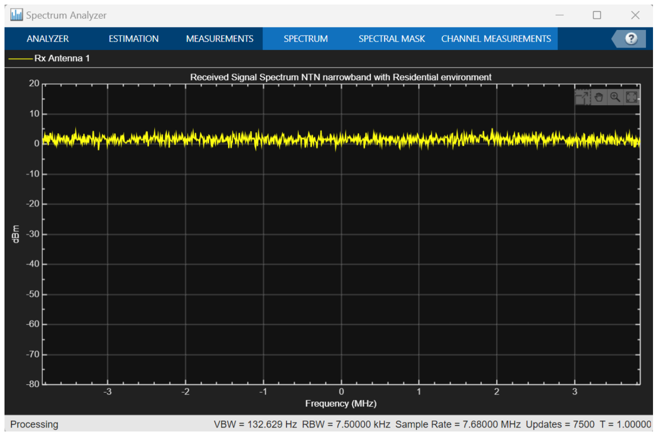

Fig. 10. Received Signal Spectrum for NTN flat fading narrowband channel in Residential Environment with TABLE I and III data (Reference Signal)

A. Satellite Mobility

Upon adjusting the SatelliteSpeed Vsat(1) parameter in our simulation from its initial value of 7562.2 m/s to 5562.2 m/s for the NTN Narrowband Flat Fading Channel model, we conducted an analysis of the resulting changes. Specifically, we observed variations in the estimated Doppler shifts, with the first shift recorded at 37075.7778 Hz. Despite these changes in the Doppler shifts, there was no noticeable impact on the received signal strength, indicating that alterations in the satellite speed within this range did not significantly affect the Doppler shift of this communication model.

Moreover, we have included the received signal strength plot for the NTN Narrowband Flat Fading Channel, showcasing variations in satellite speed. Notably, the observed behavior aligns consistently with the reference model, indicating minimal change in the channel's characteristics under these adjustments.

The analysis of the NTN Flat Fading channel model reveals interesting insights into the impact of changing satellite speed on Doppler shift and received signal spectrum. Despite observing a considerable change in Doppler shift with varying satellite speeds, there is a notable resilience in the received signal spectrum. This phenomenon can be attributed to the robust nature of the Flat Fading Narrowband channel model.

The robustness of the Flat Fading Narrowband channel model suggests that, while Doppler shift values may change significantly, the overall characteristics of the received signal spectrum remain relatively constant. This stability is advantageous in scenarios where the channel's response needs to be predictable and less susceptible to dynamic environmental changes, such as fluctuations in satellite speed.

This finding emphasizes the importance of considering the inherent characteristics of the channel model when interpreting simulation results. In applications where maintaining a consistent received signal spectrum is crucial, the NTN Flat Fading Narrowband channel model proves to be a reliable choice, showcasing its resilience in the face of varying satellite speeds.

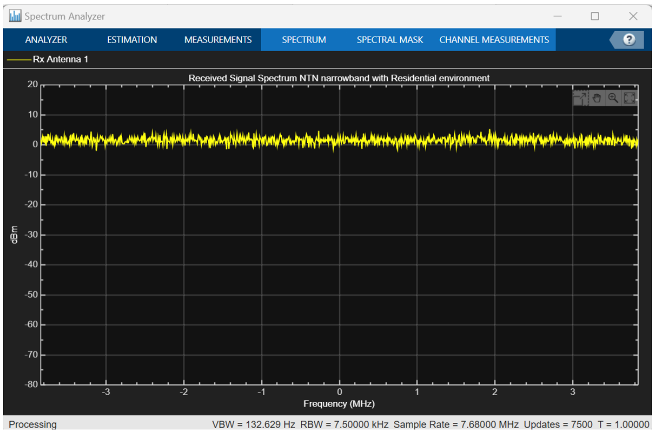

Fig. 11. Received Signal Spectrum for NTN flat fading narrowband channel in Residential Environment with TABLE I and III data with modified satellite mobility

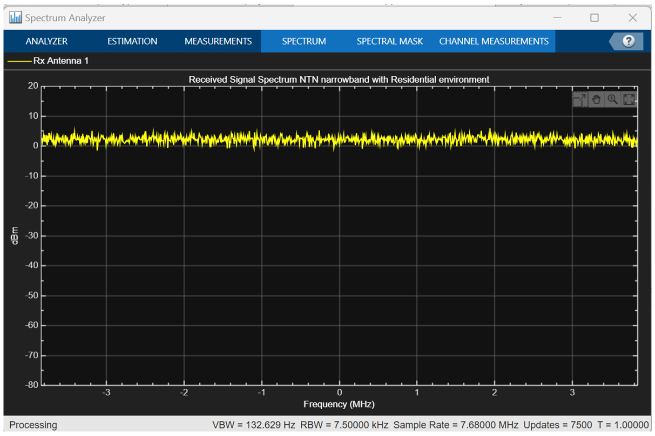

Fig. 12. Received Signal Spectrum for NTN flat fading narrowband channel in Residential Environment with TABLE I and III data with modified mobile speed

B. Mobile Speed

While modifying the mobile speed parameter, specifically setting commonParams.MobileSpeed to 10*1000/3600 m/s, 50*1000/3600 m/s, and 1*1000/3600 m/s, our simulation results revealed that variations in mobile speed had minimal impact on the Doppler shift. The estimated Doppler shifts were recorded as follows:

- Estimated Doppler Shift 1: 50396.1481 Hz
- Estimated Doppler Shift 2: 50322.0741 Hz
- Estimated Doppler Shift 3: 50412.8148 Hz

However, despite variations in mobile speed, the received signal strength for the NTN flat fading narrowband channel remained consistent, indicating stability in this parameter.

The analysis of the NTN Flat Fading channel model, with a change in mobile speed, reveals an interesting characteristic of the channel's response. Despite the variation in mobile speed, there is a limited impact on the Doppler shift, indicating a degree of robustness in the channel model.

In contrast to certain channel models that undergo substantial Doppler shift changes with fluctuations in mobile speed, the NTN Flat Fading model demonstrates a notable degree of stability in this regard. The constrained variation in Doppler shift implies that the channel's reaction to alterations in mobile speed is less pronounced compared to other scenarios. Additionally, the absence of significant fluctuations in the received signal spectrum, as observed in the NTN TDL channel model, underscores the robust nature of the flat fading NTN model. This suggests that the NTN Flat Fading model exhibits greater resilience, making it a more stable and reliable choice in varying operational conditions.

Below is the plot illustrating the received signal strength Fig. 12 for the NTN flat fading narrowband channel, with adjustments made to the mobile speed set to 50*1000/3600 m/s.

C. Sample Rate

Following the adjustment of the sampling rate from 7.68MHz to both 3MHz and 15MHz, our experimental findings indicated consistent values for Doppler shift. Throughout these modifications, Doppler shift remained stable, underlining its resilience to changes in the sample rate.

It is observed that upon manipulating the sample rate in the NTN Flat Fading Narrowband channel model, it is discerned that the channel's response exhibits limited variation. This suggests that altering the sample rate does not significantly impact the characteristics of the received signal spectrum or Doppler shift estimation.

The lack of substantial changes in the channel response under different sample rates implies a certain robustness in the NTN Flat Fading Narrowband model. The channel appears to maintain stability across a range of sample rates, indicating that its performance may not be overly sensitive to variations in this particular parameter.

This observation can be crucial in practical applications, where maintaining a consistent channel response despite fluctuations in sample rate is desirable. The NTN Flat Fading Narrowband model's resilience to changes in sample rate enhances its versatility and reliability in various communication scenarios.

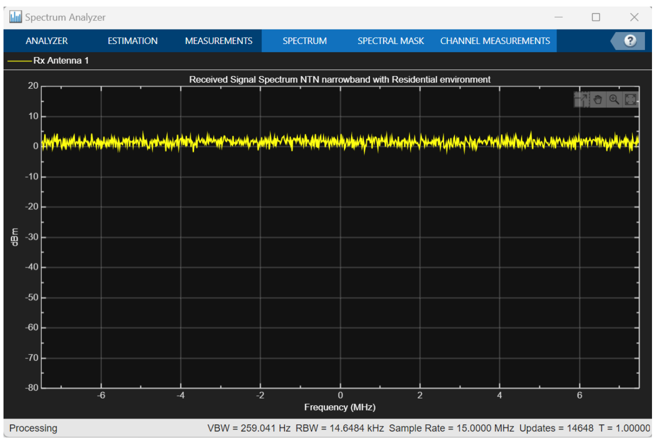

Fig. 13. Received Signal Spectrum for NTN flat fading narrowband channel in Residential Environment with TABLE I and III data with modified sample rate

IV. CONCLUSION

In delving deeper into the simulation outcomes, it becomes evident that the NTN TDL Frequency Selective Channel model introduces a layer of complexity stemming from its frequency-selective nature. This complexity contributes to a more dynamic behavior in the received signals, potentially leading to varied and pronounced Doppler shifts. This increased dynamism is notably contrasted with the NTN Flat Fading Narrowband Channel model, which, by design, exhibits a narrower frequency response.

The inherent narrowband characteristics of the NTN Flat Fading Narrowband Channel model translate to a more stable received signal, marked by a restricted range of Doppler shifts. This stability is a consequence of the channel's limited frequency variation, resulting in a more predictable response to the dynamic interplay between the satellite and the mobile unit.

In conclusion, our experimental study involving the NTN Flat Fading Narrowband Channel model revealed its remarkable robustness to variations in parameters such as sampling rate and mobile speed. On the other hand, the NTN Frequency Selective Fading TDL Channel model exhibited characteristics more akin to real-world environments, demonstrating the importance of considering these intricate channel behaviors in non-terrestrial networks. Notably, our findings underscored that the satellite speed exerted the most significant influence on Doppler shift. As a practical implication, ensuring connectivity with satellites characterized by lower mobility relative to the User Equipment (UE) becomes crucial for maintaining stable communication in non-terrestrial network scenarios. These insights contribute to the ongoing efforts to enhance the design and deployment of NTN communication systems, striking a balance between robustness and fidelity to real-world conditions.

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4. https://www.mathworks.com/help/satcom/ug/model-nr-ntn-channel.html

V. APPENDIX

(i) NTN Frequency Selective Fading TDL Channel model MATLAB Code:

```
clear all
commonParams = struct;
commonParams.CarrierFrequency = 2e9;
commonParams.ElevationAngle = 50;
commonParams.SatelliteAltitude = 600000;
commonParams.SatelliteSpeed = 7562.2;
commonParams.MobileSpeed = 3 * 1000 / 3600;
commonParams.SampleRate = 15000000;
commonParams.RandomStream = "mt19937ar with seed";
commonParams.Seed = 73;
commonParams.NumSinusoids = 48;
ntnTDLParams = commonParams;
ntnTDLParams.NTNChannelType = "TDL";
ntnTDLParams.DelayProfile = "NTN-TDL-A";
ntnTDLParams.DelaySpread = 30e-9;
ntnTDLParams.TransmissionDirection = "Downlink";
ntnTDLParams.MIMOCorrelation = "Low";
ntnTDLParams.Polarization = "Co-Polar";
ntnTDLParams.NumTransmitAntennas = 1;
ntnTDLParams.NumReceiveAntennas = 2;
ntnTDLParams.TransmitCorrelationMatrix = 1;
ntnTDLParams.ReceiveCorrelationMatrix = [1 0; 0 1];
ntnTDLParams.TransmitPolarizationAngles = [45 -45];
ntnTDLParams.ReceivePolarizationAngles = [90 0];
ntnTDLParams.XPR = 10;
ntnTDLParams.SpatialCorrelationMatrix = [1 0; 0 1];
ntnTDLChan = HelperSetupNTNChannel(ntnTDLParams);
tdlChanInfo = info(ntnTDLChan.BaseChannel);
disp(tdlChanInfo);
speedOfLight = 3e8;
satelliteRelativeVelocity =
commonParams.SatelliteSpeed -
commonParams.MobileSpeed;
dopplerShift = commonParams.CarrierFrequency *
satelliteRelativeVelocity / speedOfLight;
disp("Estimated Doppler Shift: " + dopplerShift + "
Hz");
rng(commonParams.Seed);
in = complex(randn(commonParams.SampleRate,
tdlChanInfo.NumTransmitAntennas), ...
randn(commonParams.SampleRate,
tdlChanInfo.NumTransmitAntennas));
[tdlOut, tdlPathGains, tdlSampleTimes] =
HelperGenerateNTNChannel(ntnTDLChan, in);
% Plot the channel impulse response manually
figure;
for nRx = 1:ntnTDLParams.NumReceiveAntennas
for nTx = 1:ntnTDLParams.NumTransmitAntennas
subplot(ntnTDLParams.NumReceiveAntennas,
ntnTDLParams.NumTransmitAntennas,
(nRx-1)*ntnTDLParams.NumTransmitAntennas + nTx);
plot(tdlSampleTimes, squeeze(tdlPathGains(:, nRx,
nTx)));
title(['Channel Impulse Response - Rx ' num2str(nRx)
', Tx ' num2str(nTx)]);
xlabel('Time (s)');
ylabel('Amplitude');
end
end
% Plot the received signal spectrum
ntnTDLAnalyzer = spectrumAnalyzer(SampleRate =
ntnTDLParams.SampleRate);
ntnTDLAnalyzer.Title = "Received Signal Spectrum " +
ntnTDLChan.ChannelName;
ntnTDLAnalyzer.ShowLegend = true;
for nRx = 1:size(tdlOut,2)
ntnTDLAnalyzer.ChannelNames{nRx} = "Rx Antenna " +
nRx;
end
ntnTDLAnalyzer(tdlOut);
```

(ii) NTN Flat Fading Narrowband Channel model MATLAB Code:

```
commonParams = struct;
commonParams.CarrierFrequency = 2e9; % In Hz
commonParams.ElevationAngle = 50; % In degrees
commonParams.SatelliteAltitude = 600000; % In m
commonParams.SatelliteSpeed = 7562.2; % In m/s
commonParams.MobileSpeed = 3*1000/3600; % In m/s
commonParams.SampleRate = 15000000; % In Hz
% Set the random stream and seed, for reproducibility
commonParams.RandomStream = "mt19937ar with seed";
commonParams.Seed = 73;
% Set the number of sinusoids used in generation of
Doppler spread
commonParams.NumSinusoids = 48;
% Initialize the NTN flat fading narrowband channel
parameters in a
% structure
ntnNarrowbandParams = commonParams;
ntnNarrowbandParams.NTNChannelType = "Narrowband";
ntnNarrowbandParams.Environment = "Residential";
ntnNarrowbandParams.AzimuthOrientation = 0;
ntnNarrowbandParams.FadingTechnique = "Sum of
sinusoids";
% Set the below parameters when Environment is set to
Custom
ntnNarrowbandParams.StateDistribution = [3.0639
2.9108; 1.6980 1.2602];
ntnNarrowbandParams.MinStateDuration = [10 6];
ntnNarrowbandParams.DirectPathDistribution = [-1.8225
-15.4844; 1.1317 3.3245];
ntnNarrowbandParams.MultipathPowerCoefficients =
[-0.0481 0.9434; -14.7450 -1.7555];
ntnNarrowbandParams.StandardDeviationCoefficients =
[-0.4643 -0.0798; 0.3334 2.8101];
ntnNarrowbandParams.DirectPathCorrelationDistance =
[1.7910 1.7910];
ntnNarrowbandParams.TransitionLengthCoefficients =
[0.0744; 2.1423];
ntnNarrowbandParams.StateProbabilityRange = [0.05
0.1; 0.95 0.9];
% Setup NTN channel and get channel information
ntnNarrowbandChan =
HelperSetupNTNChannel(ntnNarrowbandParams);
p681ChannelInfo =
info(ntnNarrowbandChan.BaseChannel);
% Estimate Doppler shift
speedOfLight = 3e8; % Speed of light in meters per
second
satelliteRelativeVelocity =
commonParams.SatelliteSpeed -
commonParams.MobileSpeed;
dopplerShift = commonParams.CarrierFrequency *
satelliteRelativeVelocity / speedOfLight;
disp("Estimated Doppler Shift: " + dopplerShift + "
Hz");
% Generate a random input
rng(commonParams.Seed);
in = complex(randn(commonParams.SampleRate,1), ...
```

```
randn(commonParams.SampleRate,1));
% Generate the faded waveform for NTN narrowband
channel
[narrowbandOut,~,~] =
HelperGenerateNTNChannel(ntnNarrowbandChan,in);
% Plot the received signal spectrum
ntnNarrowbandAnalyzer = spectrumAnalyzer( ...
SampleRate = ntnNarrowbandParams.SampleRate);
ntnNarrowbandAnalyzer.Title = "Received Signal
Spectrum " ...
+ ntnNarrowbandChan.ChannelName;
ntnNarrowbandAnalyzer.ShowLegend = true;
ntnNarrowbandAnalyzer.ChannelNames = "Rx Antenna 1";
ntnNarrowbandAnalyzer(narrowbandOut);
```