Wireless Networking Technologies Lab 4 Wi-Fi Link-Level Measurements over an NTN Link

Telecommunication Networks (TKN)

Begin: 27.05.2026, 08:00
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Introduction

In this lab you will investigate the link-level performance of the IEEE 802.11be (Wi-Fi 7) protocol. As indoor and outdoor terrestrial Wi-Fi links are already well understood, we will examine the feasibility of a direct low Earth orbit (LEO) non-terrestrial network (NTN) link, as shown in fig. 1. For this, you will get familiar with the 802.11 PHY for building a link-level simulation. Additionally, further corrections are needed in Wi-Fi to handle Doppler-induced carrier frequency offset (CFO). As a baseline for the scenario, we will use the MATLAB NTN example. Finally, you will learn about the channel frequency response (CFR) and its estimation in Wi-Fi.

Learning Objectives

After this lab you should be able to:

- quantify LEO Doppler as absolute and normalized CFO in an OFDM system,
- simulate packet error rate (PER) over signal-to-noise ratio (SNR) for Wi-Fi 7 over an NTN channel,
- explain how payload size, pilot tracking, carrier frequency, MCS, bandwidth, and NTN-TDL profile affect the link,
- interpret CFR magnitude plots and relate frequency selectivity to the selected channel profile and bandwidth.

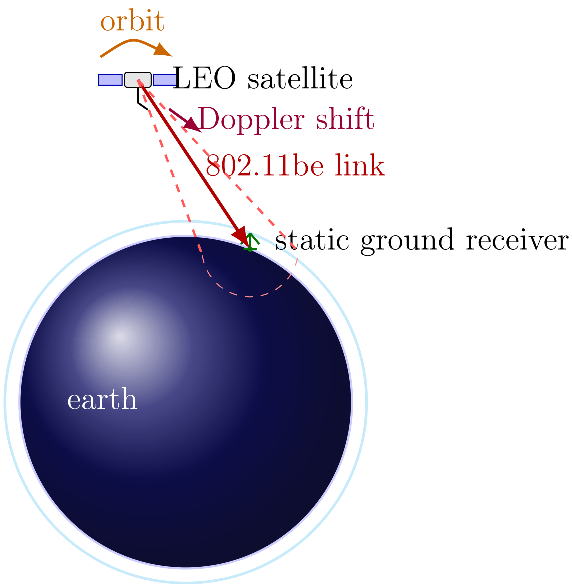

Figure 1: System model: LEO to ground receiver link

Common Simulation Parameters

Unless a task states otherwise, use the baseline configuration in table 1. Use the same random seed and stopping rule when comparing curves.

Parameter	Baseline value
NTN link	NTN-TDL-C channel, LEO altitude 600 km, carrier frequency 2.4 GHz
Wi-Fi link	SISO EHT-MU single-user packet, 20 MHz, MCS 2, APEP 1000 B, 1 TX and 1 RX antenna
Receiver	packet detection, coarse and fine CFO correction, EHT-LTF channel estimation, pilot tracking disabled
PER sweep	SNR vector 0:1:40 dB, at least 250 packets per SNR point, consistent `maxNumErrors` early stopping
Reproducibility	report MATLAB release, relevant toolboxes, random seed, SNR vector, packet budget, and `maxNumErrors`

Table 1: Baseline simulation parameters.

Background

LEO Doppler as Carrier Frequency Offset

For a carrier frequency f_c, a radial relative velocity v_r produces a Doppler shift

$$f_D \approx \frac{v_r}{c} f_c,$$

where c is the speed of light. In a LEO link, the satellite velocity is several km/s. Even for a static ground receiver, the projected radial velocity can therefore be large enough to create tens or hundreds of kHz of frequency offset. The Doppler shift scales linearly with carrier frequency. Therefore, a link that is manageable at S-band (2–4 GHz) can become much harder in higher bands (e.g., 6 GHz).

In complex baseband notation, a carrier frequency offset can be written as

$$r(t) = h(t)s(t)e^{j2\pi\Delta f t} + n(t).$$

For OFDM this has two consequences. First, it rotates all subcarriers by a common phase that changes from OFDM symbol to OFDM symbol. Second, if the offset is large enough relative to the OFDM subcarrier spacing, it destroys orthogonality and creates inter-carrier interference. In 802.11be the subcarrier spacing is

$$\Delta f_{\text{sub}} = 78.125\,\text{kHz}.$$

A useful metric is the normalized CFO

$$\epsilon = \frac{f_D}{\Delta f_{\text{sub}}}.$$

For a 600 km LEO satellite at 5.8 GHz, the Doppler shift can exceed one 802.11be subcarrier spacing at low to medium elevation angles, while it becomes much smaller near zenith.

Wi-Fi Receiver Architecture

A Wi-Fi receiver does not decode payload bits directly from the raw waveform. It first finds the packet timing, estimates impairments from the preamble, and then tracks residual phase and channel changes during the data field. In an NTN link, the CFO-related steps are especially important because residual Doppler can accumulate phase over long packets.

1. **Packet detection:** Locate the packet start using the repeated structure of the L-STF. Good timing is needed so that the later FFT windows fall inside the OFDM symbols.
2. **Coarse CFO correction (L-STF):** Estimate a first, possibly large, carrier frequency offset from the periodic short training symbols. This removes most of the CFO before the receiver processes the longer training fields.

3. **Fine CFO correction (L-LTF):** Refine the CFO estimate with the longer legacy training symbols. The goal is to reduce residual common phase rotation before channel estimation.

4. **EHT-LTF channel estimation:** Estimate the CFR on the active subcarriers from the known EHT-LTF sequence. This estimate is later used by the equalizer to undo frequency-selective channel distortion.

5. **Optional EHT-Data pilot tracking:** Use pilot subcarriers inside the data symbols to track residual common phase error and slow channel variation. This is particularly relevant when Doppler leaves a time-varying phase error over the packet duration.

6. **Equalization and bit recovery:** Equalize each data subcarrier, demap the constellation symbols, and decode the bits. If the decoded packet fails its error check, it contributes to the measured PER.

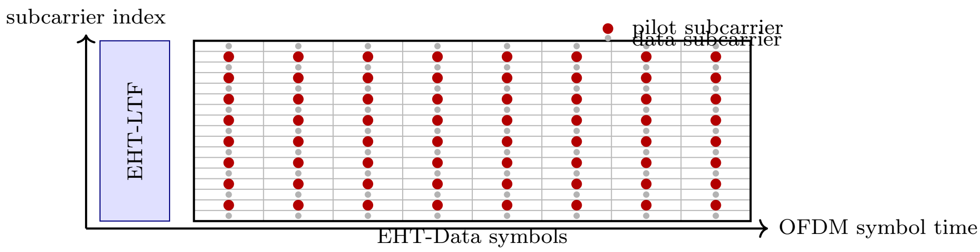

Figure 2: Simplified 802.11be EHT pilot structure in the EHT-Data field for the 20 MHz 242-tone RU used in this lab. The eight pilot subcarriers appear at known frequency positions in every OFDM data symbol and are used to track residual common phase error after preamble-based CFO correction.

Channel Frequency Response

In 802.11 OFDM systems, the wireless channel is usually described in the frequency domain by its channel frequency response (CFR). The CFR tells us how amplitude and phase change on each active subcarrier. For a transmitted symbol $X[k]$, the receiver observes:

$$Y[k] = H[k]X[k] + W[k],$$

where $Y[k]$ is the received symbol, $H[k]$ is the CFR, and $W[k]$ is noise. The magnitude $|H[k]|$ describes attenuation or amplification; the phase $\angle H[k]$ describes channel-induced phase rotation.

Wi-Fi estimates the CFR from known training fields in the packet preamble. For EHT data, the most relevant field is the EHT-LTF, which allows a per-subcarrier estimate:

$$\hat{H}[k] = \frac{Y_{\mathrm{LTF}}[k]}{X_{\mathrm{LTF}}[k]}.$$

This estimate is used for equalization of later data symbols. In this lab, the NTN-TDL profile and channel bandwidth determine whether the CFR looks almost flat or contains visible frequency-selective fades.

Task 1: Link-Level Simulation

In this task you will build the baseline packet-level LEO-NTN Wi-Fi simulation and collect the reference results used in the later sweeps.

1. Implement the NTN channel and Wi-Fi link using the baseline configuration in table 1. Use the MATLAB 5G-NTN example and the MATLAB 802.11be example as starting points.
2. Run the baseline PER-over-SNR sweep from table 1. Plot the PER-SNR curve and explain what PER measures at link level.
3. For the same run, report the mean elevation angle, mean slant range, mean satellite Doppler shift, and normalized CFO ϵ.
4. Pick a representative packet and plot the CFR magnitude. Explain whether the channel looks frequency-flat or frequency-selective.

Task 2: Payload Size Sweep

In this task, you will examine CFO tolerance. Pilot tracking is still disabled and you will examine how the residual CFO affects different payload sizes. Keep the Wi-Fi configuration from the previous task and only adjust the APEP length to the following values:

$$\text{APEP} \in \{250, 1000, 4000, 8000, 12000\}\,\text{B}.$$

1. For each payload size, run a PER-over-SNR simulation with 0:1:40 dB and plot all sizes in the same figure. Discuss how packet duration and residual CFO affect the result.
2. Determine a practical maximum payload size for which the receiver still reaches a target PER of $\leq 10^{-1}$ within the simulated SNR range. State which SNR you consider still reasonable and justify it.

Task 3: Pilot Tracking

In this task, you will examine the effects of pilot tracking.

1. Enable pilot tracking in the Wi-Fi receiver and run the same PER-over-SNR sweep using the same APEP lengths as in Task 2. Compare the results with pilot tracking disabled in one figure or table and discuss.

2. Set the APEP length to 8 kB. Run the same PER-over-SNR experiment and examine the following carrier frequencies: $f_c \in \{1, 2.4, 5, 5.8, 6, 12, 24, 60\}$ GHz. Report f_D and ϵ for each carrier frequency. The 12, 24, and 60 GHz cases are stress cases, not regular Wi-Fi 7 bands. What is the effect of pilot tracking?
3. Determine a practical carrier frequency where Wi-Fi 7 over NTN could be used and explain your decision.
4. Why can pilot tracking have little visible impact at very low SNR?
5. Why can pilot tracking have little visible impact at very high SNR?

Task 4: Impact of MCS and Channel Bandwidth

1. Keep the bandwidth set to 20 MHz and examine the following MCS:

$$\text{MCS} \in \{0, 2, 4, 8, 10, 12, 13\}.$$

Which MCS values are most sensitive to NTN Doppler and residual CFO?

2. Set the MCS to 3 and examine the impact of channel bandwidth on PER using

$$\text{CBW} \in \{20, 40, 80, 160, 320\}\,\text{MHz}.$$

Keep the remaining baseline parameters unchanged. Higher bandwidth may increase processing times. Does increasing bandwidth improve or degrade PER?

Task 5: Impact of NTN-Channel Model

1. Sweep only the channel profile with the baseline configuration. Compare the PER for `NTN-TDL-A` through `NTN-TDL-D`.
2. For the CFR comparison, change only the bandwidth to 320 MHz. Use the same SNR for all profiles and plot one packet per profile.

Submission

Your submission should be a zip file with the following:

1. A PDF report with all findings, figures, parameter settings, and answers to the tasks listed above. Every figure must have axis labels, units, legends where needed, and a short interpretation.
2. All code needed to reproduce your results.