Tampere University

RF Equipment for Wireless Networks

COMM.SYS.510

Project Work: Diversity Reception in Indoor Environment

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2026

Introduction

This project investigates the practical impact of uplink (UL) diversity reception on LTE data rates in an indoor environment. By performing field measurements in a 2100 MHz (Band 1) network using a OnePlus 9 Pro, we compared space and polarization diversity schemes against single-antenna reference cases

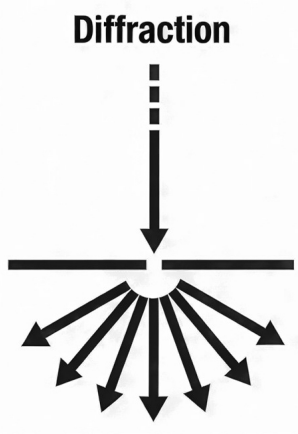
Before the Lab

Antenna Spacing is measured in Wavelengths

- Calculate how much 1λ is for 2 GHz (the network utilizes band 1, ~2100 MHz)
- λ = Wavelength (This is the length of one radio wave cycle)
- We will use this Wavelength value to measure distances between antennas

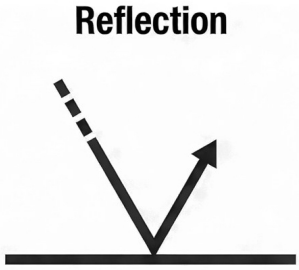
$$\lambda = \frac{c}{f} \rightarrow \lambda = \frac{3 \times 10^8}{2.1 \times 10^9} \rightarrow \lambda \approx 0.143 \text{ m} \rightarrow \lambda \approx 14.3 \text{ cm}$$

Where λ is wavelength, the f is frequency, the c is speed of light

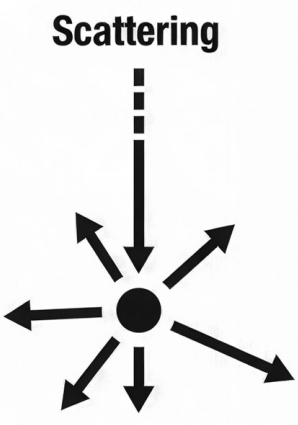


- 1λ Spacing → Signals are somewhat Correlated
- 5–10λ Spacing → Signals are largely Uncorrelated

Indoor environments create:



- Reflections (walls, doors, metal)
- Diffraction (corners)
- Scattering (people, furniture)



This causes:

- Deep fades at certain locations
- Rapid signal fluctuations over distances of ~λ/2
  λ/2 = 7.15 cm is where signal variations occur most rapidly

Multipath Fading:
Inside the corridor, the radio waves hit corners (diffraction) and objects (scattering). This means the signal strength changes rapidly every few centimeters.

Signal Correlation

When we say signals are correlated or uncorrelated, we're asking:
Do these two signals experience the same fading patterns at the same time?

Correlated Signals

Two signals are correlated when they:

- Experience fading at the same time
- Have similar Amplitude variations

We can think of two dancers performing in perfect sync.
No diversity benefit here. If both antennas are weak when you need them, you gain nothing by having two antennas.

Uncorrelated Signals

Two signals are uncorrelated when they:

- Experience fading independently
- Have different amplitude variations

We can think of two dancers performing completely different from each other.
When Antenna 1 experiences a fade, Antenna 2 is likely still receiving well, which in this case Diversity works.

Diversity Gain

When we look at Diversity from the receiver's perspective, the goal is to take multiple Faded versions of the same signal and process them to reconstruct a single high quality version

When multiple copies of the same signal arrive, they each have:

- Different delays
- Different phases
- Different amplitudes

Lower correlation between diversity branches generally increases the available diversity gain. Independent fading across branches improves the chance that at least one branch has a strong received signal.

Diversity Combining Techniques

It combines the signals from multiple receivers to improve overall signal quality.
In this example, the base station (eNB) must combine signals from both antennas.

- **MRC (Maximal Ratio Combining):**

It aligns the signals in phase and then gives more weight to the stronger, cleaner receivers before adding them together

- **EGC (Equal Gain Combining):**

It aligns all signals in phase, but then gives them equal strength when adding them

- **SC (Selection Combining):**

It doesn't combine anything.
It just picks the antenna that currently has the strongest signal and ignores the others

Note: MRC technique has been used in this experiment.

Signal Quality Metrics in Cellular Networks

- **RSRP (Reference Signal Received Power)**

Indicates the signal strength from a specific cell tower
We can think of it as How strong is the signal from this particular cell?

- **RSSI (Received Signal Strength Indicator)**

It is the Total received power in the channel, including signal, interference, and noise from all sources. Broader than RSRP, it captures everything the antenna picks up.
We can think of it as How much total RF energy is the device receiving?

- **RSRQ (Reference Signal Received Quality)**

A quality metric that combines both signal strength and interference (noise)
Helps distinguish between a weak signal vs. a strong but noisy signal
We can think of it as How clean or reliable is the signal, relative to the noise?

Calculated as $RSRQ = \frac{N \cdot RSRP}{RSSI}$

where N is the number of resource blocks

Measurement Reliability

- In the project work, we will be handling RF components (antennas, connectors, terminators and attenuators). We did handle them with great care, as they are expensive and fragile components.
- While connecting different components (a cable to an antenna or jumper cable), we didn't use force as this could damage it. However, we made sure that the connections were properly tightened.
- We make sure the cable (feeder cable or jumper cable) was not twisted.
- We ensured that feeder cable (both main and diversity branch) would not be left unconnected for long period of time (like half a minute) as this could cause the eNB to sense signal power bouncing back and it could have automatically shut down the transmission. So we always used a terminator if we were not using any of the cable for longer period (< than 30 sec).
- The measurements were performed in public areas so we did let other people pass without blocking the hallway or stopping in front of doors. Also, when we were reconfiguring the antennas, we did not place them in the middle of the corridor.
- After we finished the reference measurement (1a or 2a), we considered that it was very important not to move the antenna at all (we were careful not to accidentally hit antenna poles with our feet).
- We tried to ask the instructor if we would have any questions or faced any problem.

In this project work, we tested if using two antennas actually makes the internet faster (higher upload speed) compared to using just one.

Measurement Process

Two different diversity concepts, Space Diversity and Polarization Diversity, are studied with the measurements. First, reference measurements without diversity reception are conducted, and they are compared to different diversity schemes with equal and unequal input power between the reception branches.

Performance of different diversity reception schemes are studied by throughput values for uplink (UL) direction. Other parameters can be utilized to evaluate the differences in channel conditions between the measurements.

The measurement routes should be repeated the same way, that is, the same route with same speed etc. are utilized. Please note, that this does not guarantee that the measurements are the same for each measurement, but then you need to analyze the differences if those occur and how they can affect the results.

The measurement route is shown in Figure 1 below and an example image from the corridor in Figure 2. The actual measurement per use case (see next section) are performed by starting a measurement script that uploads a large file to an ftp server. We waited 5 seconds at the beginning and the end of the measurement route to let the script run a while before starting to move with the measurement equipment (used the same waiting time in all measurements).

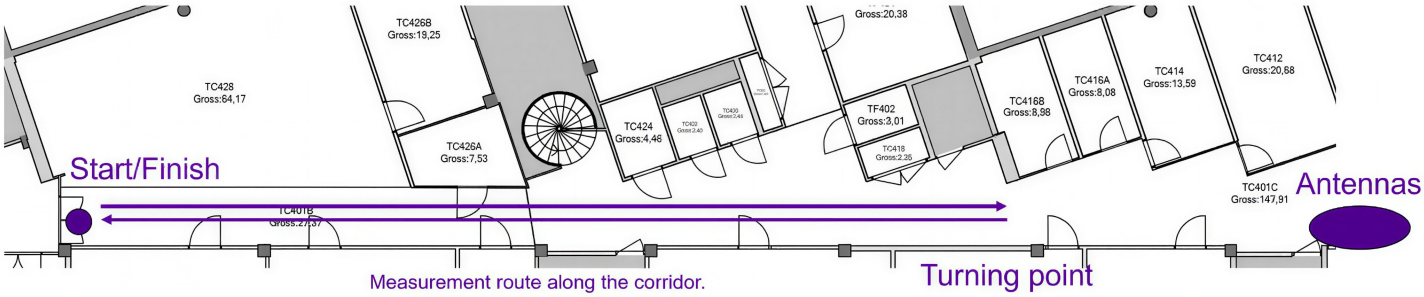


Figure 1. Measurement route on Tietotalo 4th floor, C-corridor

Receiver Diversity

Receiving the same signal through multiple independently faded paths

Types of Diversity we used here:

- Space Diversity → physically separated antennas
- Polarization Diversity → orthogonal polarizations (±45°)



Figure 2. Tietotalo 4th floor, C-corridor view

There are two different measurement configuration types that were measured: **Space Diversity** and **Polarization Diversity** configurations as shown in Figure 3 (showing the general idea of all measurements). The Space Diversity utilizes two separate antennas where the so-called main and diversity branch are attached. In the Polarization Diversity configuration these two different branches are connected to the one antenna that has two input ports.

The antennas used in the measurements are typical omni-directional and directional indoor antennas (or micro cell antennas used outdoors). Space diversity measurements utilize two omni-directional antennas (2 dBi gain) and polarization diversity measurement utilize one directional indoor panel antenna (7 dBi gain).

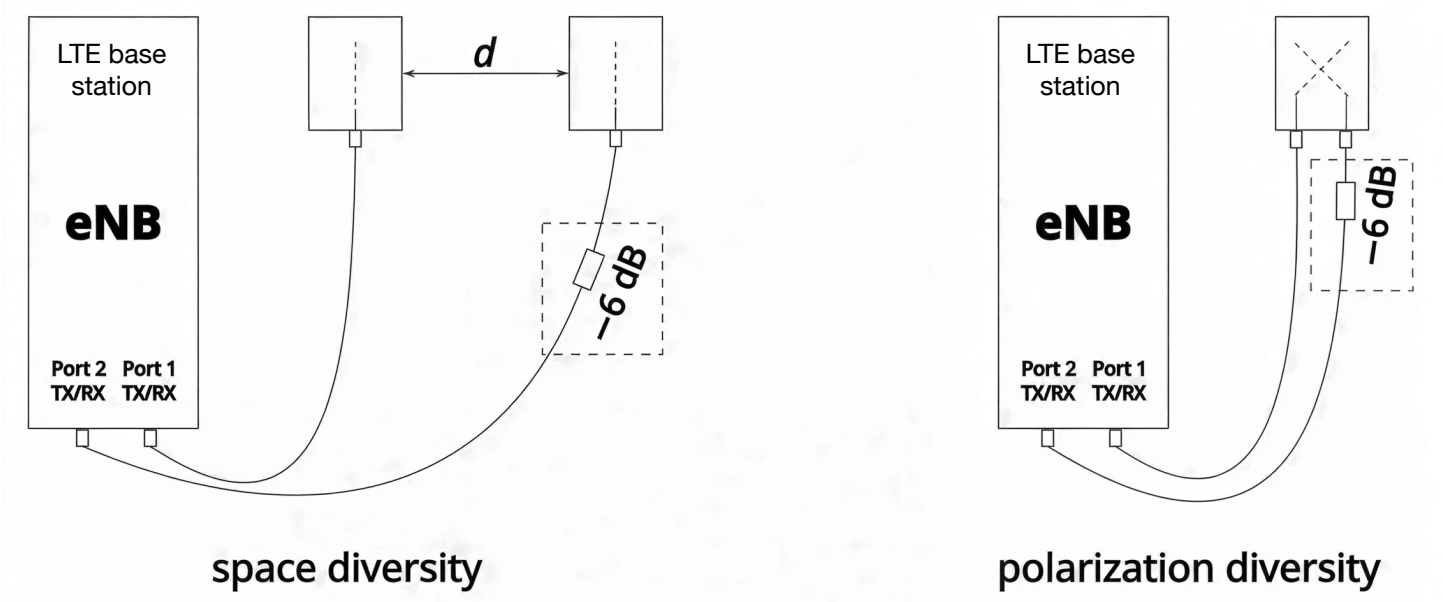


Figure 3. Two different diversity reception types

MEASUREMENT SETTING 1 – Space Diversity

In Space Diversity measurements, one and two omni-directional antennas are utilized. All four Space Diversity related measurement configurations are presented in Figure 4. We used two antennas separated by a physical distance. If they are far enough apart, they both won't experience a bad signal at the same time.

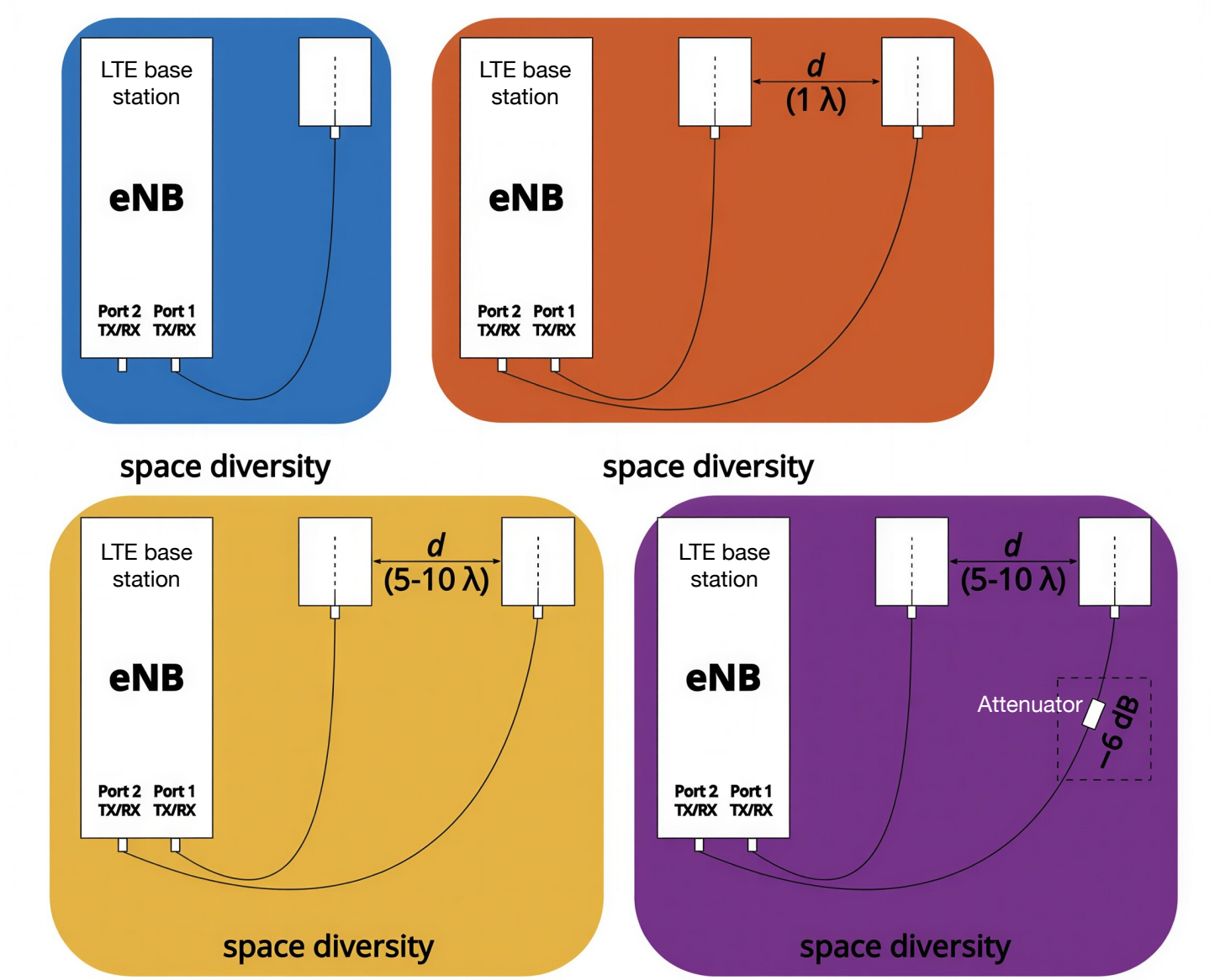


Figure 4. All different space diversity cases (1a to 1d).

Below is a list of these different measurement cases:

1a Reference measurement without space diversity (only one antenna)

1b Measurement with Rx space diversity (small d: 1 λ)

1c Measurement with Rx space diversity (large d: 5-10 λ)

1d Measurement with Rx space diversity (large d: 5-10 λ)
Unequal Branches, (other antenna line has an additional 6 dB attenuator)

We have to walk the same route in a corridor multiple times.
For each walk, we need to change the antenna setup.

The Routine:

1. Started the file upload script on the phone.
2. Waited 5 to 10 seconds (stationary).
3. Walked the corridor route at a steady speed.
4. Stopped the script.

- **Case 1a (The Baseline):**
  We used only one antenna. This is our control group. It represents a bad scenario with no diversity.
- **Case 1b (Close Antennas):**
  We used two antennas spaced very close together (1λ or ~14 cm).

- **Case 1c (Far Antennas):**
  We moved the antennas far apart (5–10λ or ~70-140 cm). This usually gives the best results because the signals are totally different (uncorrelated).
- **Case 1d (Unbalanced Antennas):**
  We kept them far apart, but we add the Attenuator to one cable. This simulates a real world situation where one antenna is blocked or weaker than the other.
  We want to see if diversity still helps even if one side is weak.

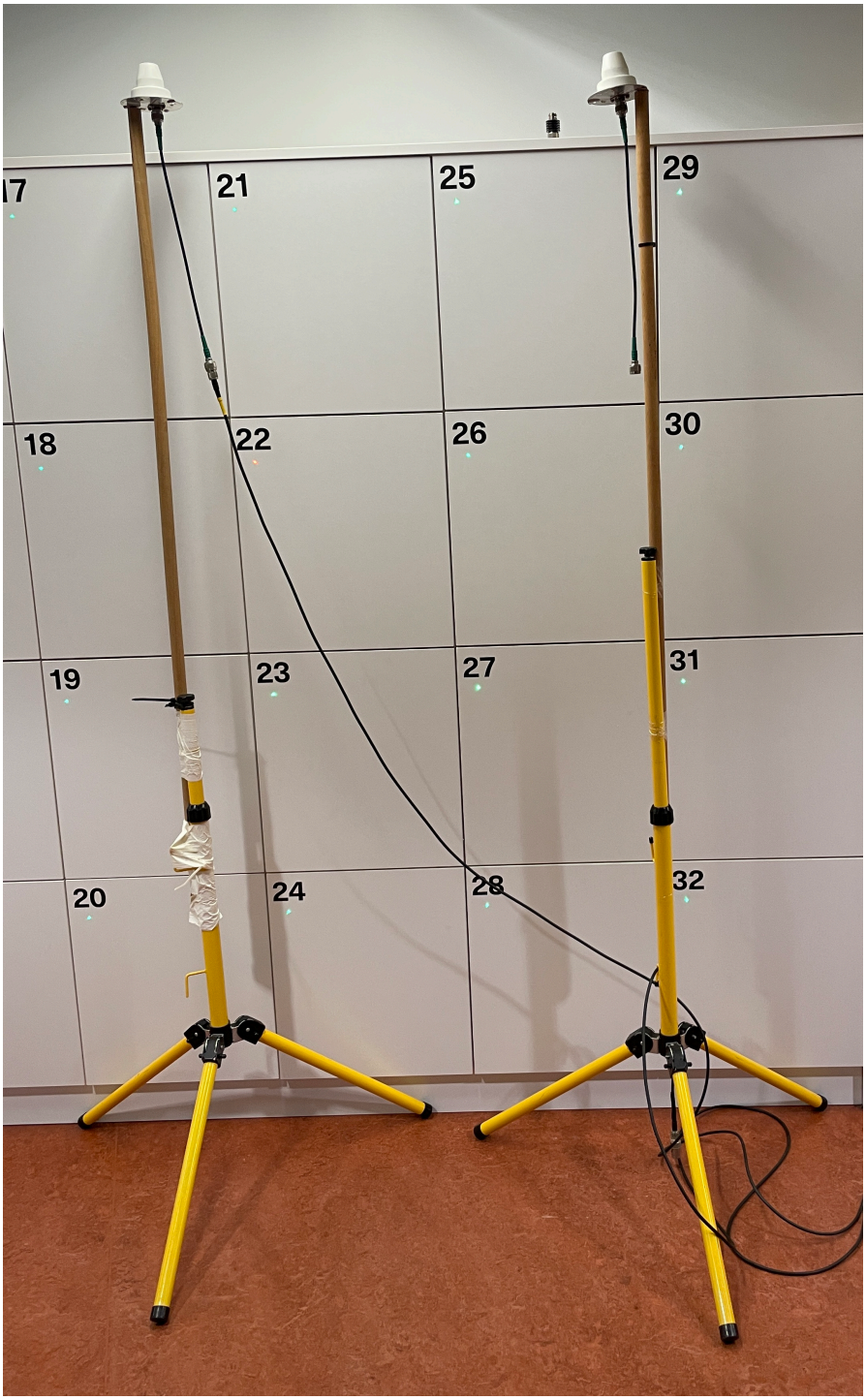


Figure 5. Case 1a (The Baseline)



Figure 6. Case 1b (Close Antennas)

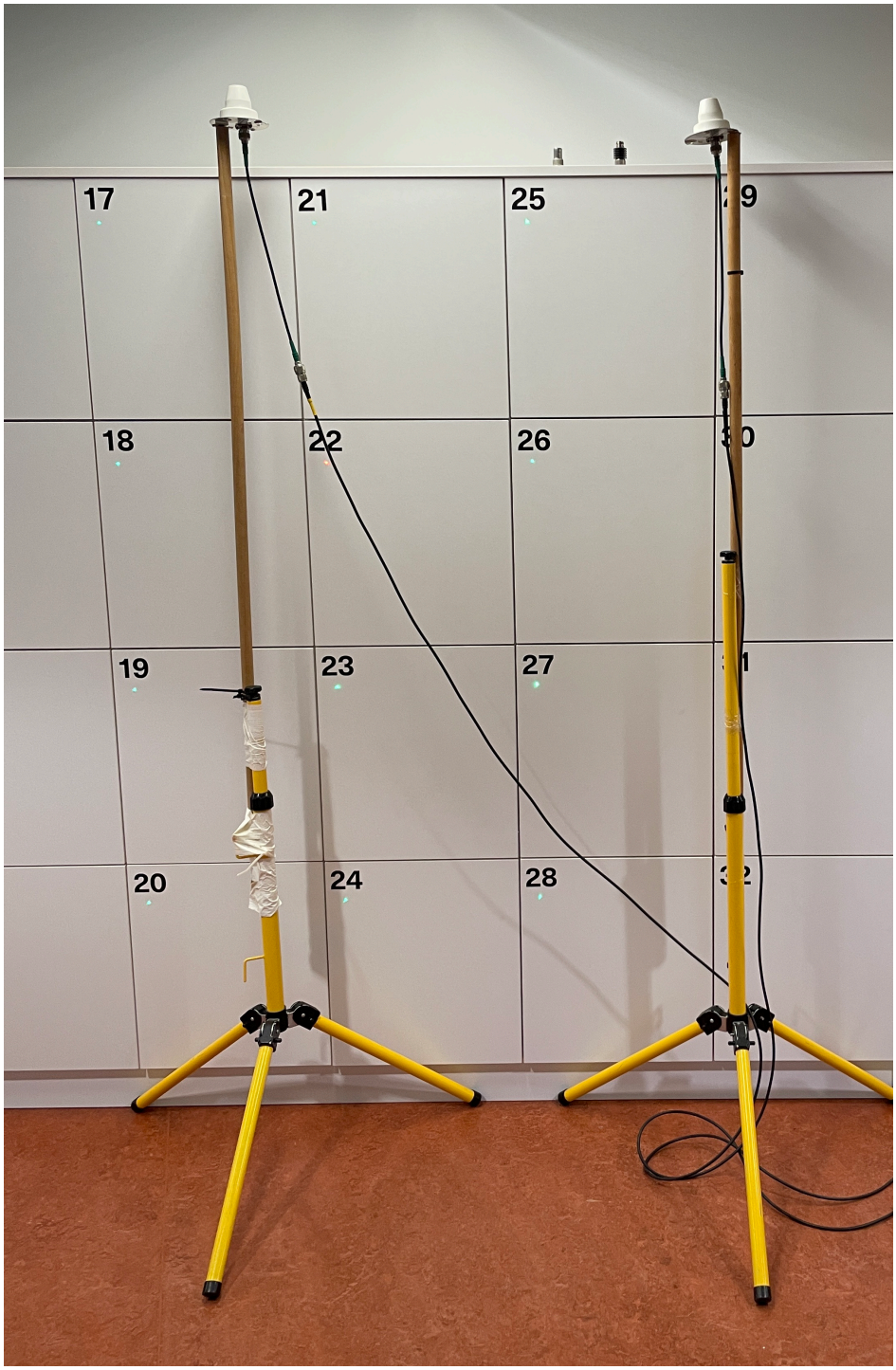


Figure 7. Case 1c (Far Antennas)

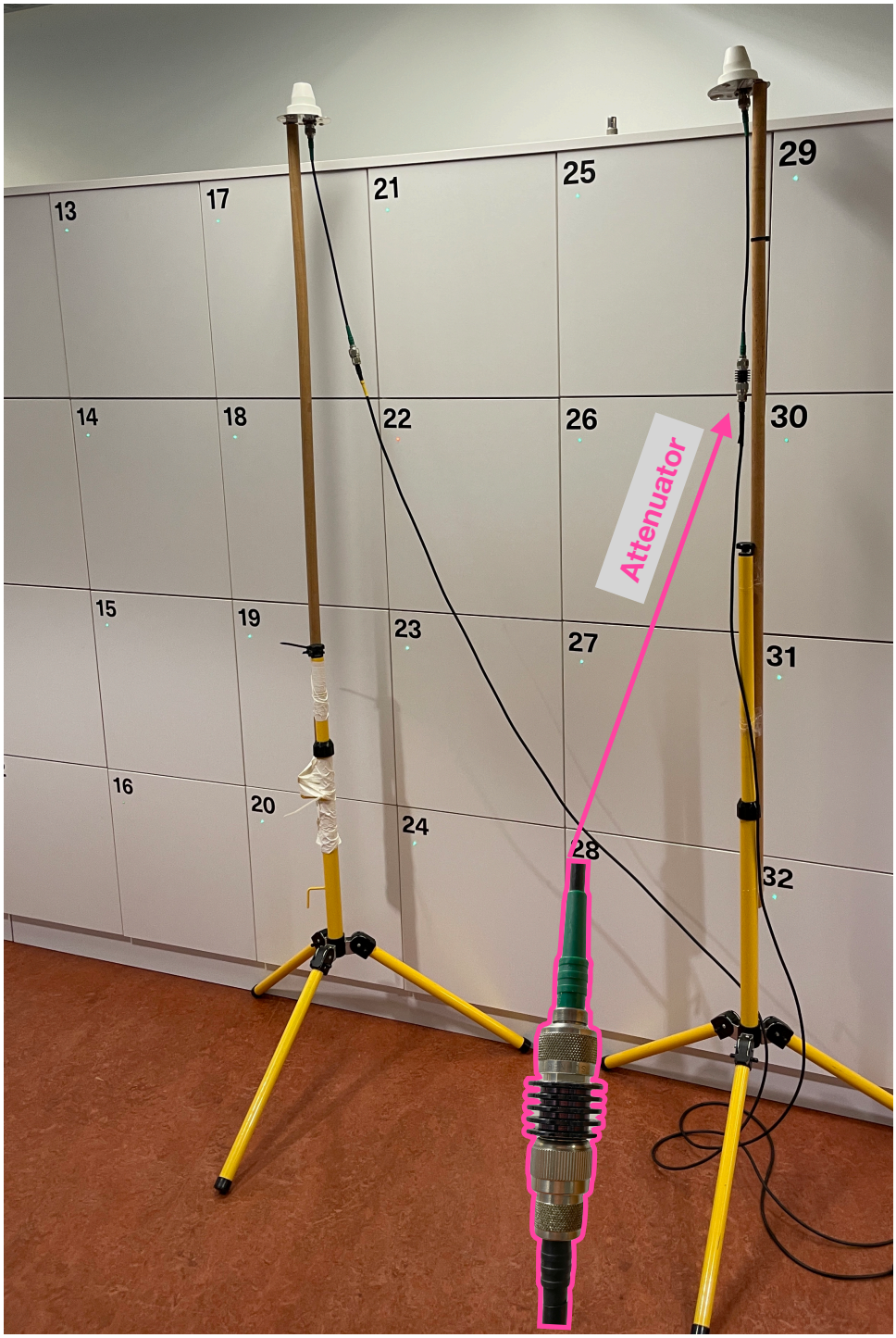


Figure 8. Case 1d (Unbalanced Antennas)

MEASUREMENT SETTING 2 – Polarization Diversity

In Polarization Diversity measurements, an outdoor XPol (Cross polarization with ±45° slanted polarization) antenna is used.

All three Polarization Diversity measurement configurations are presented in Figure 9.

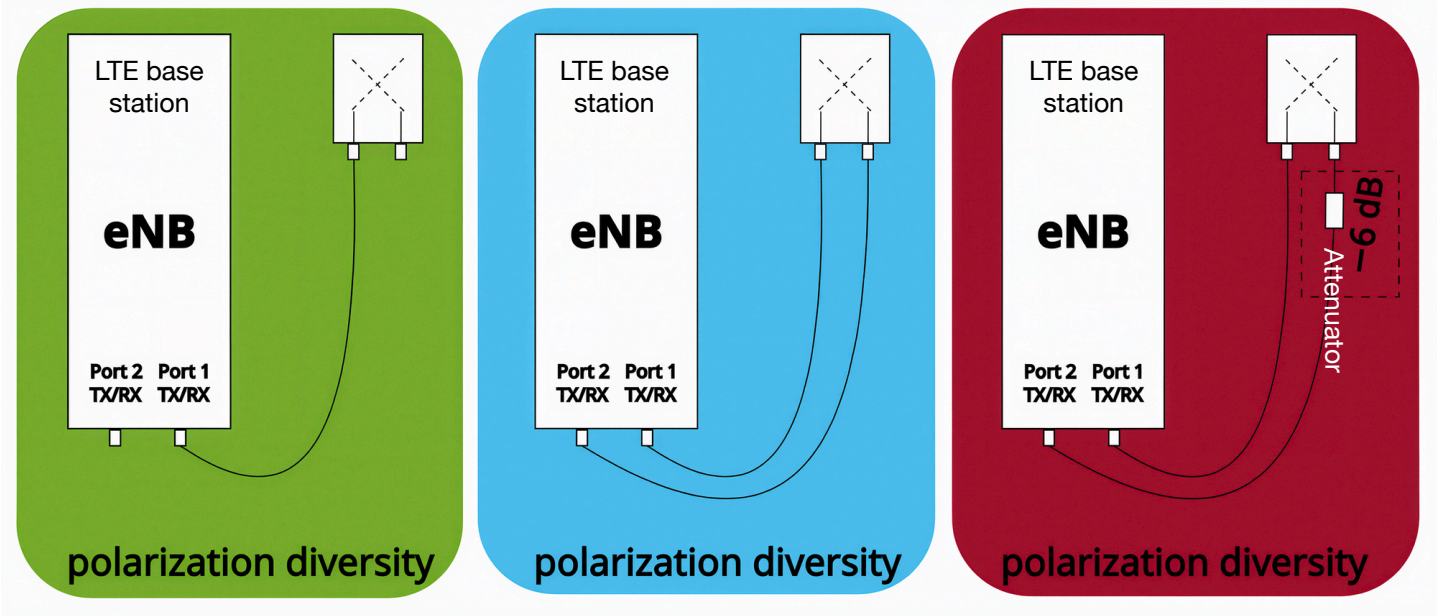


Figure 9. All different polarization diversity cases (2a to 2c).

Below is a list of these different measurement cases:

- **2a** Reference measurement without Rx diversity
- **2b** Measurement with polarization diversity
- **2c** Measurement with polarization diversity
  (Unequal Branches, other antenna line has an additional 6 dB attenuator)

We used one physical antenna unit that listens to waves vibrating in two different directions. It saves space because we don't need to separate antennas by meters.

Attenuator: A small component that lowers the signal strength by 6 decibels (dB) to simulate a weaker connection.

- **Case 2a (Baseline):**
  Reference measurement with no diversity.
- **Case 2b (Polarized):**
  We used a special XPol antenna.
  It looks like one box, but inside it receives signals at ±45° angles.
  This tests if changing angles works as well as separating antennas by distance.
- **Case 2c (Unbalanced Polarized):**
  Same as previous 2b, but we added the Attenuator to one branch to weaken it.



Figure 10. Case 2a (Baseline)



Figure 11. Case 2b (Polarized)

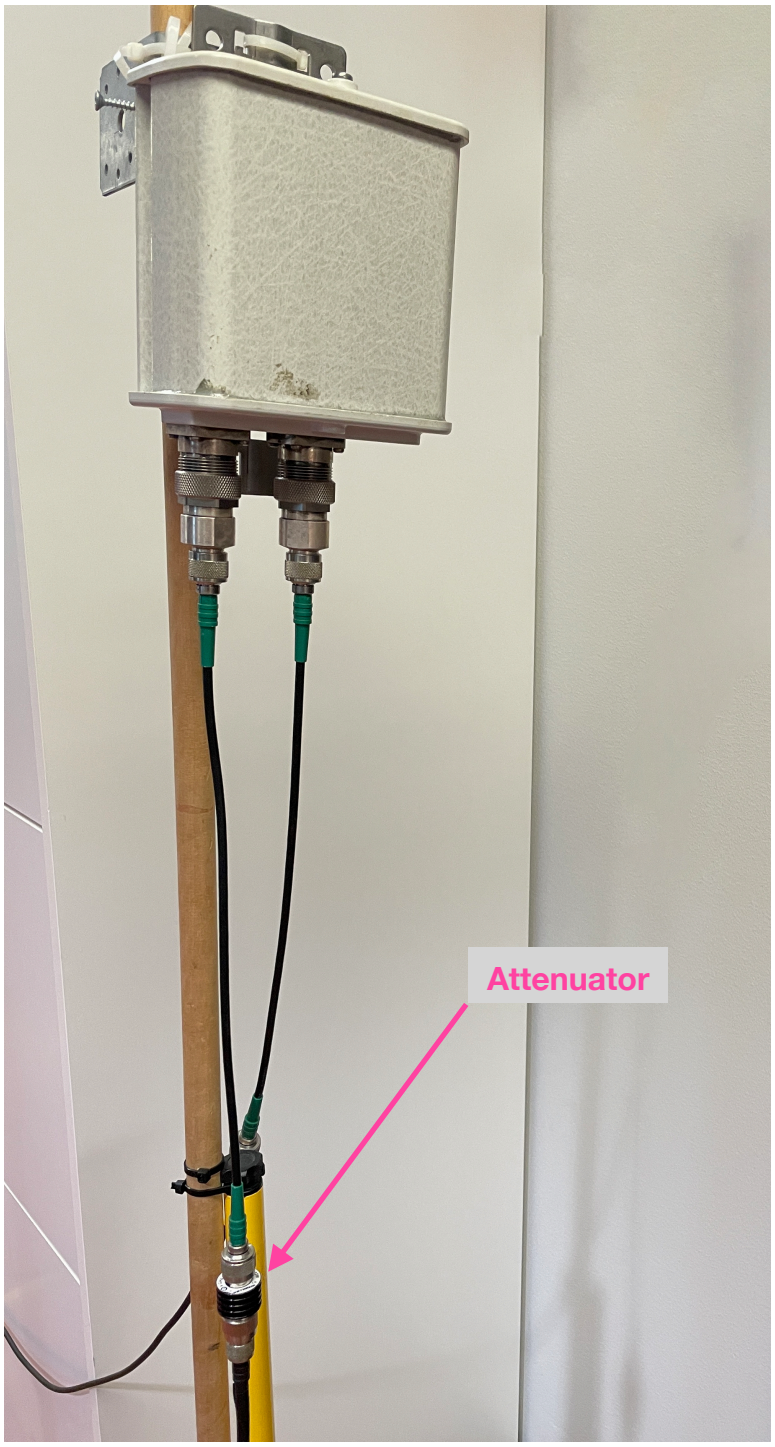


Figure 12. Case 2c (Unbalanced Polarized)

Measurement Data

The *.csv* file includes the following data (we did not need everything; It has been listed carefully the ones we might need, the most important is the uplink data rate):

- Header Line: Time, RSRP (LTE pcell), RSRQ (LTE pcell), E-UTRAN carrier RSSI (LTE pcell), PCell bandwidth, Band (LTE pcell), Timing advance ,PRB utilization DL, PDSCH throughput, PDSCH BLER, PDSCH MCS index for codeword 0, PDSCH MCS index for codeword 1, PDSCH modulation for codeword 0, PDSCH modulation for codeword 1, PDSCH modulation percentage,
  PUSCH modulation for codeword 0, PUSCH modulation percentage, PUSCH throughput, TX power PUSCH
  - Rows with comma separated values for each header row variable
    - Time = Time stamp of the measurement in yyyy-MM-dd HH:mm:ss.SSS
      - yyyy – year with 4 digits
      - MM – month with 2 digits
      - dd – day with 2 digits
      - HH – hours in 24 h format with 2 digits
      - mm – minutes with 2 digits
      - ss – seconds with 2 digits
      - SSS – milliseconds
    - RSRP = Reference Signal Received Power (dBm)
    - RSRQ = Reference Signal Received Quality (dB)
    - E-UTRAN carrier RSSI = Received Signal Strength Indicator (dBm)
    - PCell bandwidth = Channel bandwidth in use for the primary cell
    - Band (LTE pcell) = Utilized frequency band
    - PDSCH throughput = Physical Downlink Shared Channel Throughput (Mbps)
    - PDSCH BLER = Physical Downlink Shared Channel Block Error Rate (%)
    - PUSCH throughput = Physical Uplink Shared Channel Throughput (Mbps)
    - TX power PUSCH = Tx power for Physical Uplink Shared Channel (dBm)
    - (LTE pcell) = Primary Cell (indication that this value is from the serving cell)
- Next values correspond in the order of the header values.
  - Note! There can be some NaN values along with the measurement data, so we took those into account. These means cases where, for some reason, the value was not saved into the measurement file. This affects our mean calculations and/or the visualization functions we have. We dealt with these properly (Nemo Handy can separate some values with same time stamp into several rows)

An example of a .csv file is shown in Figure 13.

```
Time,RSRP (LTE pcell),RSRQ (LTE pcell),E-UTRAN carrier RSSI (LTE pcell),PCell bandwidth,Band (LTE pcell),Timing advance,PRB utilization DL,PDSCH throughput,PDSCH BLER,PDSCH MCS index for codeword 0,PDSCH MCS index for codeword 1,PDSCH modulation for codeword 0,PDSCH modulation for codeword 1,PDSCH modulation percentage,PUSCH modulation for codeword 0,PUSCH modulation percentage,PUSCH throughput,TX power PUSCH
15:26:37.063,,,,5 MHz,,,,,,,,,,,,
15:26:37.063,-90.2,-8.9,-67.4,,LTE FDD 2100 band 1,,,,,,,,,,,,
15:26:37.063,,,,,,2,,,,,,,,,,,
15:26:37.371,,,,5 MHz,,,,,,,,,,,,
15:26:37.371,-90.5,-8.1,-68.3,,LTE FDD 2100 band 1,,,,,,,,,,,,
15:26:37.371,,,,,,,,0.0,2.5,,,,,,,,
15:26:37.371,,,,,,,,,,,,,,,,,0.4,
15:26:37.371,,,,,,1,,,,,,,,,,,
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15:26:37.371,,,,,,,0.2,,,"n/a, 0, 0, 1, 3, 14, 15, 16, 20, 27, 3","n/a, n/a, n/a, n/a, n/a, n/a, n/a, n/a, n/a, n/a, 1","n/a, QPSK, QPSK, QPSK, QPSK, QPSK, 16QAM, 16QAM, 16QAM, 64QAM, 64QAM, QPSK","n/a, n/a, n/a, n/a, n/a, n/a, n/a, n/a, n/a, n/a, QPSK","97.4, 0.0, 0.0, 0.0, 0.0, 2.1, 0.1, 0.0, 0.0, 0.3, 0.0",,,,
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15:26:37.871,-89.6,-7.9,-66.9,,LTE FDD 2100 band 1,,,,,,,,,,,,
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15:26:37.871,,,,,,,,,,,,,,,,,14.1,
15:26:37.871,,,,,,,,,,,,,,,,,,20.0
15:26:37.871,,,,,,5.6,,,"n/a, 1, 14, 15, 19, 23, 25, 27","n/a, n/a, n/a, n/a, n/a, n/a, n/a, n/a","n/a, QPSK, 16QAM, 16QAM, 64QAM, 64QAM, 64QAM, 64QAM","n/a, n/a, n/a, n/a, n/a, n/a, n/a, n/a","30.7, 0.4, 58.8, 1.0, 0.2, 1.4, 0.2, 7.2",,,,
15:26:37.871,,,,,,,,,,,,,,,"64QAM, 64QAM, 64QAM, 64QAM, 64QAM, 64QAM, 64QAM, 64QAM","0.2, 0.8, 0.4, 4.7, 0.6, 4.5, 8.8, 79.9",,
15:26:38.389,-93.4,-7.9,-71.5,,LTE FDD 2100 band 1,,,,,,,,,,,,
```

Figure 13. An example of a .csv file

Post-lab Assignment: Written Report

In the report, first we listed and explained the benefits of utilizing different diversity schemes, explained the measurement procedure, showed measurement results including values for Diversity Gains in different scenarios (how do they compare with the reference case and between different use cases), discussed the observations, and compared the results with the theory presented in our lectures. Also, included plots for all measured values (listed in the following). We used the RSRP, RSRQ and RRSI values in comparing the channel conditions between the measurements to analyze how similar they were between the measurements as well.

We showed a cumulative distribution function (CDF) plot that compares cases 1a–1d and 2a–2c and show the mean values of each case comparing again different diversity techniques with the help of histograms as also shown in the following comparison figures for application throughput.

Space Diversity Analysis

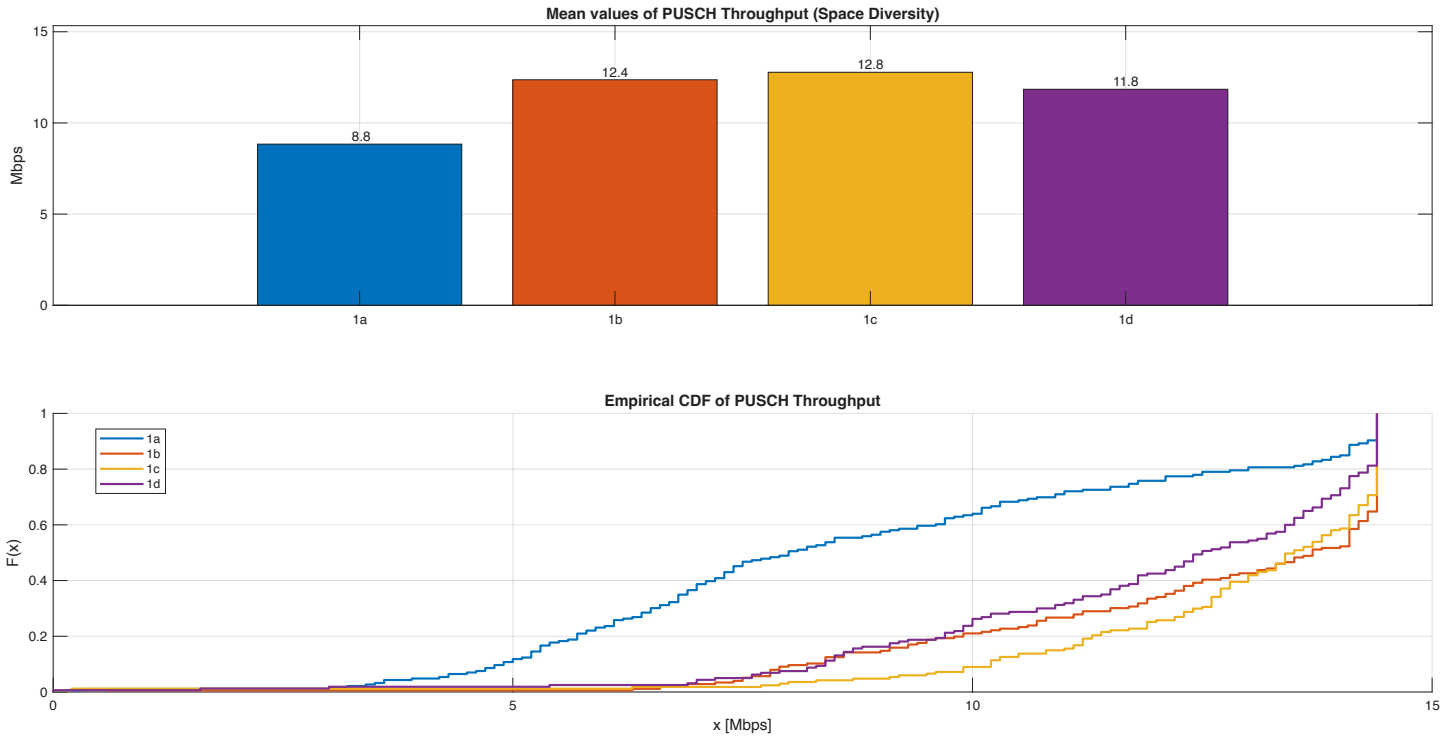


Figure 14. Uplink Throughput: Space Diversity

Space Diversity Results

The mean PUSCH throughput values and empirical CDFs for the space diversity cases (1a–1d) are shown in Figure 14. The reference case 1a, using a single antenna with no diversity, yielded a mean throughput of 8.8 Mbps. When space diversity was introduced with close antenna spacing (1λ ≈ 14.3 cm, case 1b), the mean throughput increased to 12.4 Mbps, representing a diversity gain of approximately 41% relative to the reference. With larger antenna separation (5–10λ, case 1c), throughput further improved to 12.8 Mbps, a gain of approximately 45% over 1a. This result is consistent with theory: at 5–10λ spacing, the received signals at the two antennas experience largely uncorrelated fading, allowing the combining algorithm at the eNB to more effectively reconstruct the uplink signal. Case 1b at 1λ spacing provides some gain, but since the signals remain somewhat correlated at this spacing, the diversity benefit is slightly lower than in 1c.

Case 1d (5–10λ spacing with a 6 dB attenuator on one branch) yielded a mean throughput of 11.8 Mbps, which is still a 34% gain over the reference but lower than 1c. The 6 dB power imbalance between branches reduces the effectiveness of the combining, the attenuated branch contributes less useful signal energy, degrading the quality of the combined output. This is expected behavior because diversity combining works best when both branches deliver comparable signal power.

The CDF curves in Figure 14 further confirm these trends. The 1a curve is shifted significantly to the left compared to all diversity cases, indicating consistently lower throughput across all measured points. The 1b and 1d curves overlap considerably, and 1c sits furthest right, reflecting its highest throughput distribution. Notably, the CDF of 1a shows the steepest slope in a narrow range, suggesting little variation, the single-antenna case suffers from persistent, consistent fading rather than occasional deep fades.

Table 1: Space Diversity - Mean PUSCH Throughput and Diversity Gain (Cases 1a–1d)

Case	Mean Throughput	Diversity Gain vs. 1a
1a (reference)	8.8 Mbps	—
1b (1λ spacing)	12.4 Mbps	+3.6 Mbps (+41%)
1c (5–10λ spacing)	12.8 Mbps	+4.0 Mbps (+45%)
1d (5–10λ, unequal)	11.8 Mbps	+3.0 Mbps (+34%)

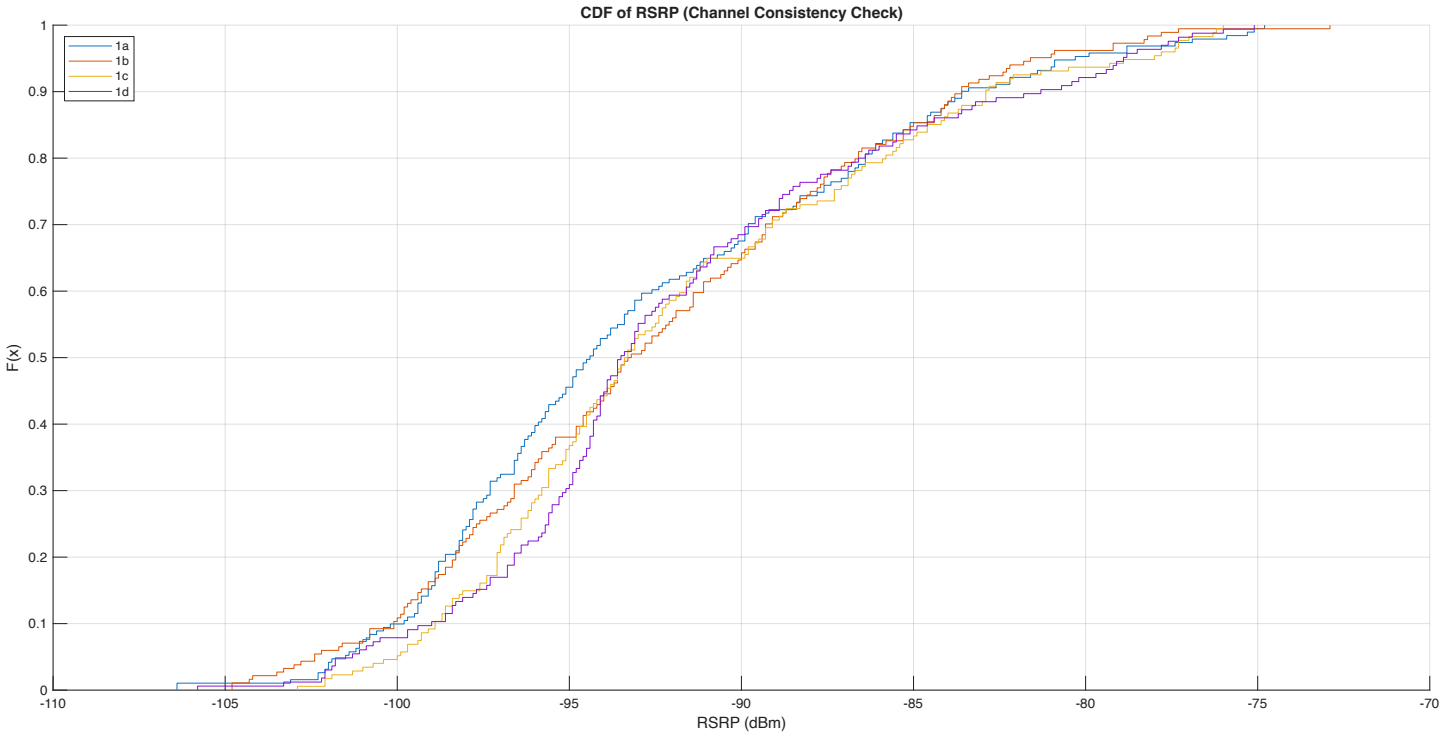


Figure 15. RSRP CDF Comparison: Space Diversity

Channel Condition Consistency (RSRP)

Figure 15 shows the CDFs of RSRP for space diversity cases 1a–1d. The four curves are closely grouped, spanning approximately −110 to −70 dBm with similar median values around −92 to −90 dBm. This indicates that the channel conditions were broadly similar across all four space diversity measurements, which supports the validity of the throughput comparisons, differences in throughput can be attributed to the antenna configurations rather than to substantially different propagation environments during the walks.

Some spread between curves is visible, most noticeably that 1a's RSRP curve is slightly different from the others. This may reflect minor variations in walking speed, people in the corridor, or small environmental changes between the measurement rounds. Since the deviations are small, the comparisons remain meaningful.

Polarization Diversity Analysis

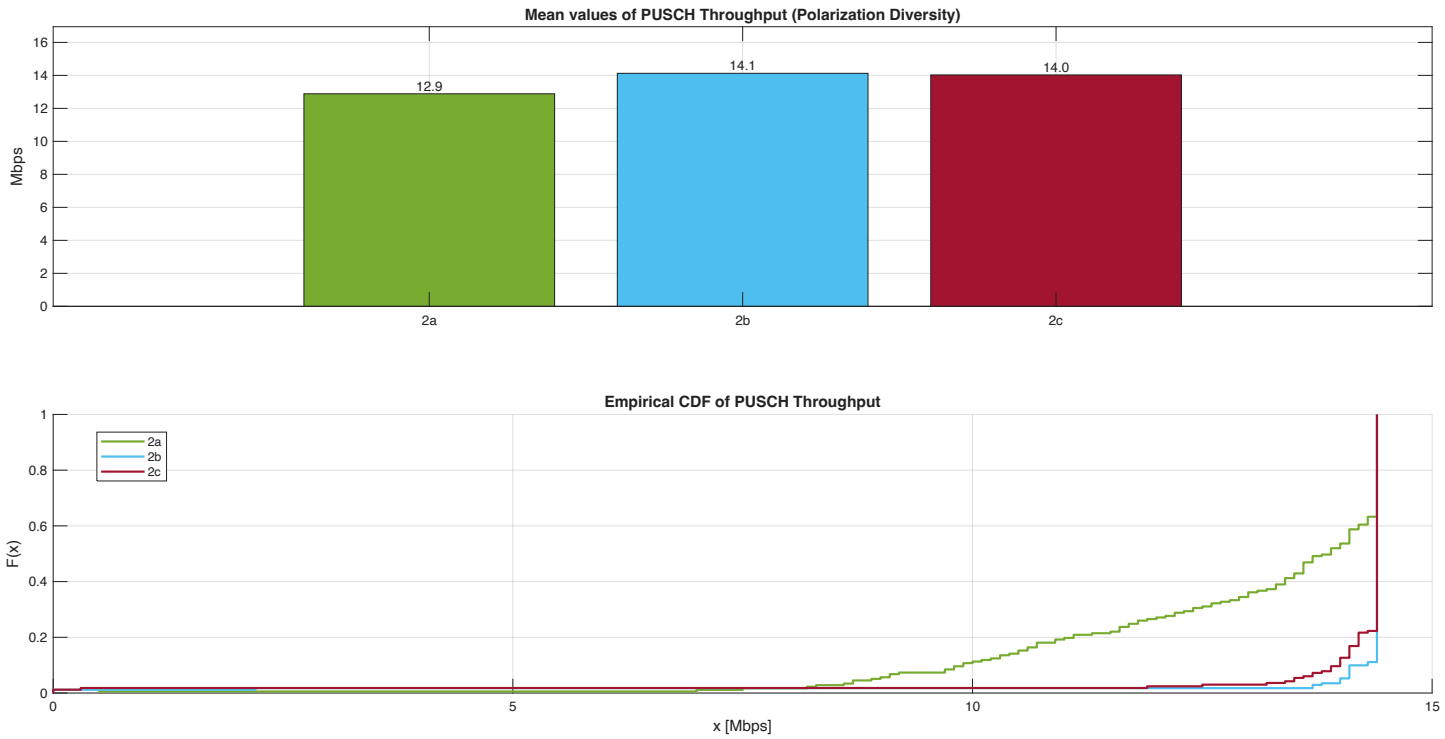


Figure 16. Uplink Throughput: Polarization Diversity

Polarization Diversity Results

The mean PUSCH throughput values and empirical CDFs for the polarization diversity cases (2a–2c) are presented in Figure 16. The reference case 2a, using the XPol antenna with only one port active (no diversity), produced a mean throughput of 12.9 Mbps. Enabling polarization diversity (case 2b, both ±45° ports active) increased this to 14.1 Mbps, a gain of approximately 9% over the reference. Case 2c, which introduced a 6 dB attenuator on one polarization branch, yielded 14.0 Mbps, nearly identical to 2b, suggesting the combining algorithm was still able to effectively exploit the available diversity even with the imbalanced branches.

Table 2: Polarization Diversity - Mean PUSCH Throughput and Diversity Gain (Cases 2a–2c)

Case	Mean Throughput	Diversity Gain vs. 2a
2a (reference)	12.9 Mbps	—
2b (polarization diversity)	14.1 Mbps	+1.2 Mbps (+9%)
2c (unequal branches)	14.0 Mbps	+1.1 Mbps (+9%)

The smaller relative gain of polarization diversity compared to space diversity (9% vs. 41–45%) is partly explained by the already high baseline throughput in the polarization measurement set (12.9 Mbps vs. 8.8 Mbps for space). This suggests the channel conditions during the polarization measurements were more favorable. Additionally, the 7 dBi directional XPol antenna provides higher gain than the 2 dBi omnidirectional antennas used in the space diversity setup, which likely elevates the baseline throughput for all polarization cases.

Polarization Diversity is particularly effective in indoor environments due to multipath scattering which rotates the signal's polarization, making the orthogonal branches (±45◦) highly uncorrelated even when the antennas are in the same physical box.

The CDFs in Figure 16 show very tight clustering between 2a, 2b, and 2c compared to the space diversity cases, which also reflects the narrower performance spread.

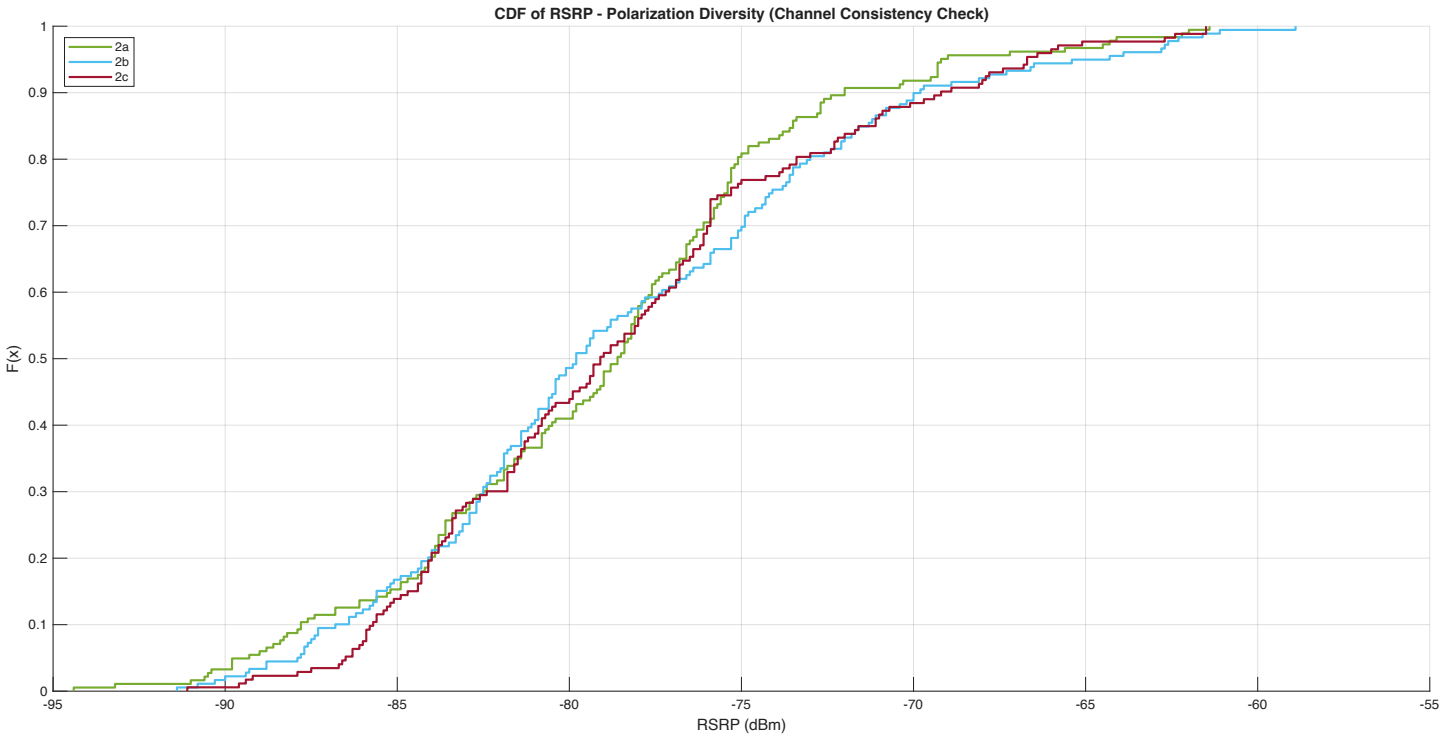


Figure 17. RSRP CDF Comparison: Polarization Diversity

The consistency of the channel during these measurements is confirmed by the Figure 17, which shows the RSRP CDFs for cases 2a–2c. The tight grouping of these curves around –90 to –60 dBm indicates that the signal environment remained stable, ensuring the throughput gains observed were due to the diversity configuration rather than external changes

Channel Quality Metrics (RSRQ)

Figure 18 shows the RSRQ CDFs for both diversity measurement sets. For space diversity (1a–1d), the curves span approximately –25 to 0 dB, with broadly similar distributions indicating comparable signal quality conditions across the four measurements. The slight variations reflect the expected channel fluctuations during different walks. For polarization diversity (2a–2c), the RSRQ curves show tighter clustering around –12 to 0 dB, consistent with the more favorable channel conditions observed in the RSRP analysis. The higher RSRQ values confirm better overall signal quality during the polarization diversity measurements.

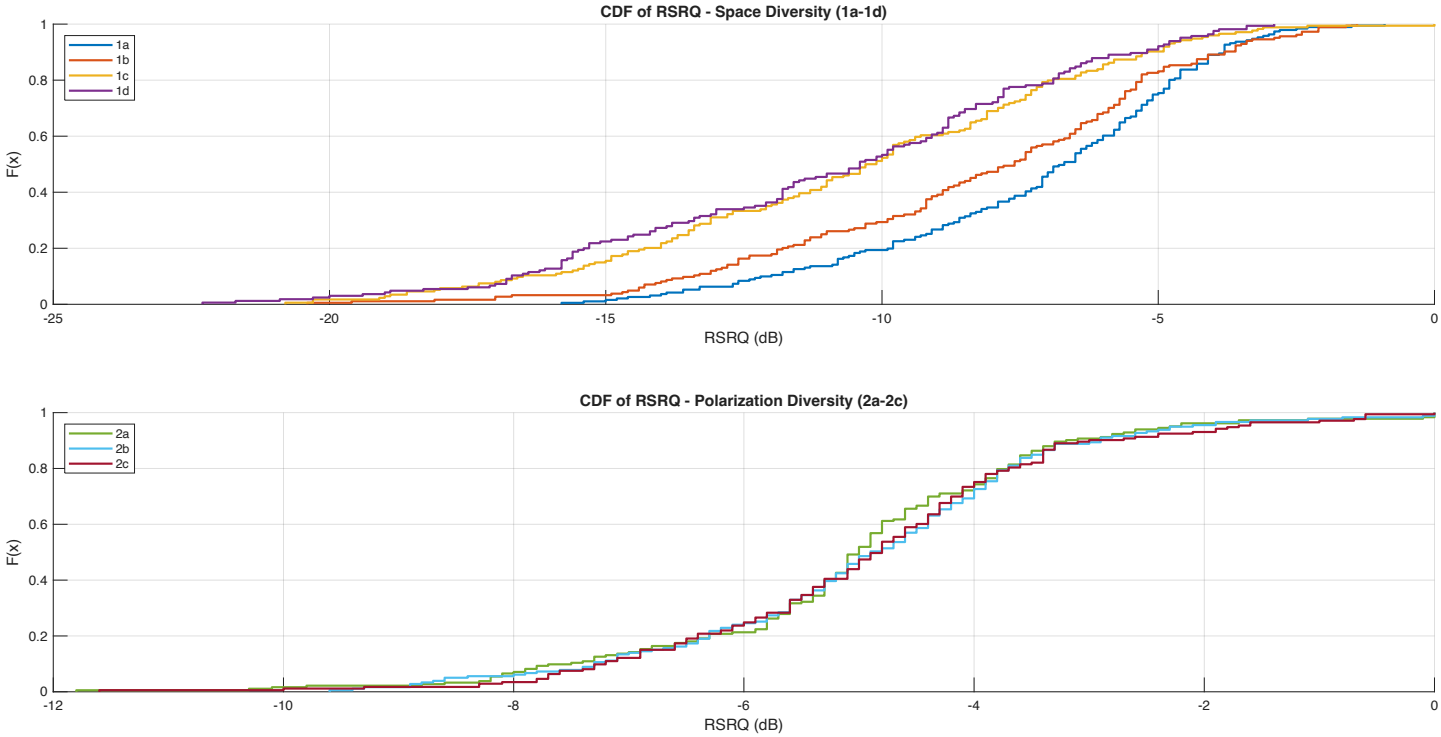


Figure 18. RSRQ CDF Comparison: Space Diversity vs. Polarization Diversity

Channel Quality Metrics (RSRQ and RSSI)

Figure 19 presents RSSI CDFs for both measurement sets. The space diversity cases show RSSI values between −85 and −55 dBm with consistent distributions, while polarization diversity cases exhibit higher RSSI (−80 to −40 dBm), confirming greater total received power due to the 7 dBi directional antenna compared to the 2 dBi omnidirectional antennas. The close grouping of curves within each measurement set validates that the total interference and noise levels remained relatively stable across the measurement runs.

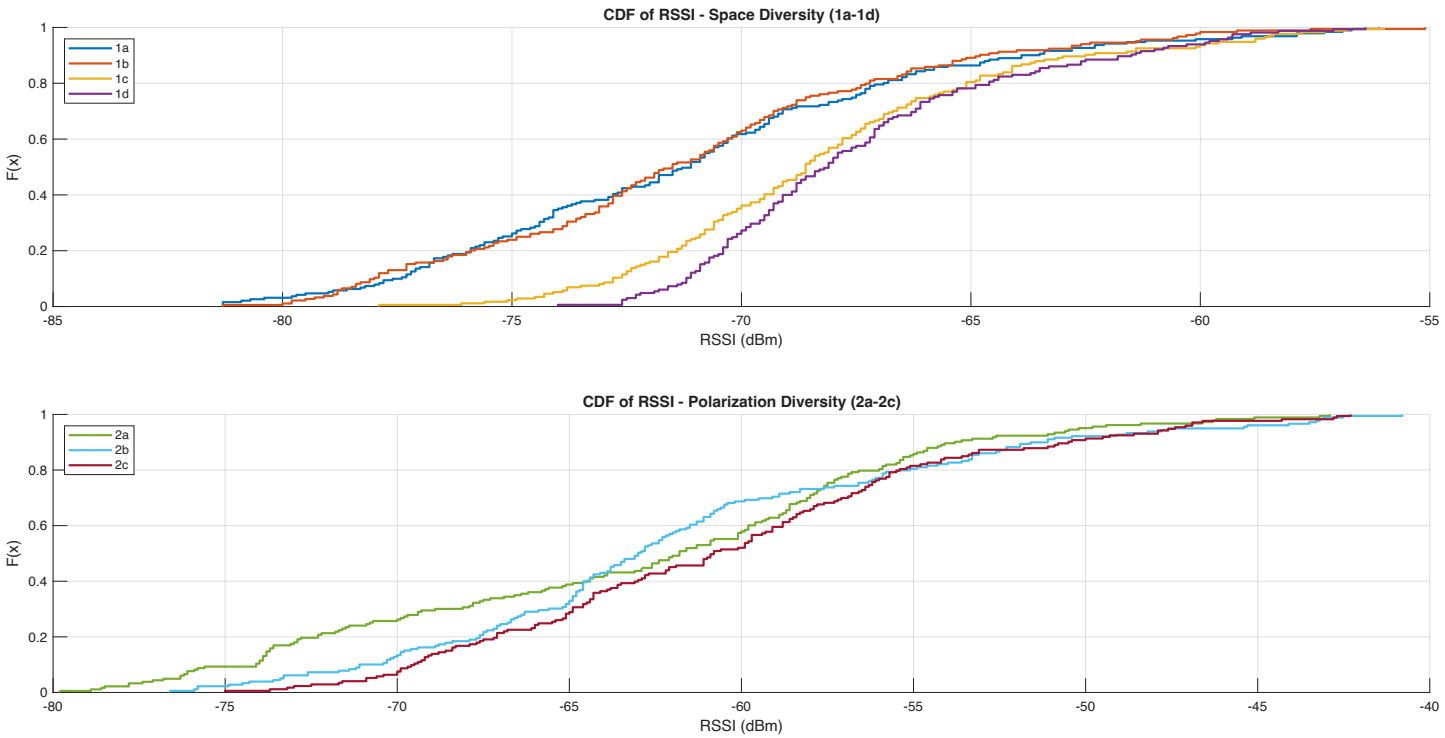


Figure 19. RSSI CDF Comparison: Space Diversity vs. Polarization Diversity

Conclusion

This project measured the effect of uplink diversity reception on PUSCH throughput in an indoor LTE corridor environment. Both space diversity and polarization diversity were tested under equal and unequal branch power conditions.

Space diversity produced the largest absolute throughput gains, with 5–10λ antenna separation (case 1c) delivering a 45% improvement over the single-antenna reference (1a). Even with a 6 dB attenuator degrading one branch (case 1d), a 34% gain was retained, confirming that diversity remains beneficial even in imbalanced conditions. Close spacing at 1λ (case 1b) also improved performance but slightly less so, consistent with the higher signal correlation expected at that distance.

Polarization diversity showed a more modest gain of approximately 9%, though this is partly because the XPol antenna's higher gain elevated the baseline throughput. The near-identical performance of cases 2b and 2c shows that polarization diversity is robust to power imbalance between branches.

Both results align well with theory: diversity gain is maximized when the signal branches are uncorrelated, and is reduced, but not eliminated by power imbalance. The RSRP channel consistency check confirmed that the measurement conditions were sufficiently stable across all runs to make the comparisons valid.

References

These references support the technical background, standards, and tools used in this report.

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