Effect of Space Diversity for Fading Mitigation at 40 and 60 GHz Indoor Channels

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Abstract—**Measurements at 5G Frequency Range 2 (FR2) and beyond (41.5 GHz and 60.5 GHz) were carried out in order to study how space diversity can be applied to compensate for the challenging conditions at those frequencies. Several indoor scenarios were analyzed, including Line-Of-Sight (LOS) and Non-Line-Of-Sight (NLOS). When considering an outage of 1%, space diversity was found to be a suitable impairment mitigation technique. Improvements in signal signal levels with increments from 7.98 dB up to 15.18 dB, depending on the case study in question were observed.**

Index Terms—**propagation, measurements, 5G, space diversity.**

Fig. 1. Representation of the rail used to move the receiving antennas.

I. INTRODUCTION

With the recent release of 5G, more and more internet providers are switching to it in order to provide better data rates and thus, better service to their customers. Of the two Frequency Ranges (FR) under investigation, only one is currently in use: FR1, which goes from 450 MHz to 6 GHz. However, there are plans to implement the Frequency Range 2 (FR2) allocated between 24.25 and 52.6 GHz, and even beyond.

It is well-known that fadings at such frequencies are not negligible as not only the path losses are higher when compared with the frequencies on FR1, but also people crossing the radio link will affect it to a greater extent. All these impairments will challenge mobile network designers as they search for the optimal cellular coverage.

One of the possible solutions for this problem is the use of diversity. Having more than one signal path helps in raising the overall signal level when the conditions are not ideal. Polarization diversity with two antennas has already been considered in the past [1] at these frequencies, showing that it can be a good option to improve the signal's level.

Space diversity has also been studied at 40 GHz and 60 GHz in [2] and [3] respectively. However, the envelope of the signal to compute the diversity gain was not obtained simultaneously with several antennas, but in different measurements with the same antenna. This limits the validity of the study as coupling among antennas is not considered.

By using a setup with one transmitting antenna and three receiving ones, this work aims at filling the gaps left by those previous reasearchs and complement them in order to have a greater understanding of the radio channel at such frequencies. This pa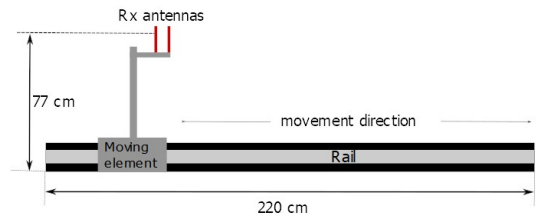per is structured as follows: An explanation of the measurement setup and environment is given in Section II. Diversity and processing procedure are explained in Section III and the results are presented in Section IV, while final conclusions are given in Section V.

II. MEASUREMENT SETUP AND ENVIRONMENT

In this section of the paper both the measurement setup and environment are discussed.

A. Measurement setup

In order to measure the channel response, a Rohde & Schwarz ZVA67 4-port Vector Network Analyzer (VNA) was used. As we wanted a three antenna system to observe the diversity, three S-parameters, to simulate three different branches, were simultaneously obtained: S_{21}, S_{31} and S_{41}; connecting the transmitting antenna to port 1 and the three receiving ones to ports 2, 3 and 4. The experiment was performed in wideband with two different central frequencies: 41.5 GHz and 60.5 GHz, both with a 3 GHz bandwidth and 1001 measured frequency points, which let us with a frequency resolution of 3 MHz.

Aside from the frequency, the setup was very similar for both experiments, having one directive antenna transmitting on the ceiling with a 3 dB beamwidth of 20º and three receiving ones on a moving rail on the floor (see Figure 1).

The antennas at the receiving end were omnidirectional for both cases and allocated on a plastic support with the shape of a triangle, so that the distances between the antennas centers were 3.75 cm and 2.5 cm for the 40 GHz and 60 GHz measurement respectively. This is five times their corresponding wavelengths. The parameters were measured according to the labels on Figure 2, being S_{21} the one corresponding to antenna number 2 and so on.
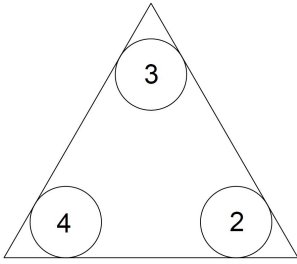
Fig. 2. Antenna allocation scheme.

Fig. 3. Antenna allocation.

TABLE I
DISTANCE OVER THE RAIL FOR EACH MEASUREMENT.

File	Distance (cm)	Step (cm)	no. measurements
40 GHz LOS	256	0.1875	1366
40 GHz NLOS	370	0.1875	1973
60 GHz LOS	350	0.125	2800
60 GHz NLOS	370	0.125	2960

The rail was 220 cm long and the distance moved over it varied from one experiment to another. By moving the rail backwards we were able to capture longer paths (see Table I). The antennas were moved in steps of $\frac{\lambda}{4}$ in both cases, which corresponds to 0.125 cm and 0.1875 cm for 60 and 40 GHz. As we processed the data by individual frequencies, this affects the number of samples available for every frequency step.

The measurements were automatized with the help of a Matlab's based software that controlled the movement over the rail using a step motor and captured the data from the VNA. This allowed the environment to remain static throughout all the experiment but for the position of the antennas relative to the transmitter.

B. Environment

Two different scenarios for both frequencies were considered: one with direct Line-Of-Sight (LOS) and another with Non-Line-Of-Sight (NLOS).

The environment was a corridor of 14.6 m in length, 2.2 m wide and 2.5 m in height. At the end there was a an extension to the left that we used to hide the transmitting antenna and create the NLOS conditions.

The position of the rail on the floor was slightly closer to the transmitting antenna at 60 GHz in LOS than it was at 40 GHz, so as to take advantage of the lower path losses of the latter. In the case of no LOS, the position of the rail was the same for both frequencies. At that location, it had approximately half of its length with direct vision of the transmitting antenna and the other half without it. In Figure 4, the floor plans for all experiments can be seen.

The transmitting antenna had an amplifier connected to compensate for the high propagation losses and was located right below the ceiling, at a height of 2.5 m, pointing directly at the frontal receiving antenna located on the floor (parameter S_{31}). Receiving ones, on the other hand, were situated over a stand in the rail to a total height of 77 cm to the antenna's

center of phase (located around the middle section of the antenna).

As it was a wideband measurement, we were able to compute the channel's Power Delay Profile (PDP). To have an idea of how the environment affects the radio waves, the PDP received from the antenna at the front (S_{31}) for the four case studies is ploted in Figure 5 . More information about that can be found in [4]. A couple of things can be pinpointed:

- As expected, at 40 GHz we have more echoes due to the lower path losses in both LOS and NLOS cases when compared to 60 GHz.
- In LOS, we have two clusters well differentiated: one on the left which comprises the main ray and the closest reflections, and one on the right which corresponds to a metal door at the end of the corridor.
- In NLOS, the part of the rail where the antenna was in LOS is well differentiated from where it was not (yellow fragment of the mesh).

III. PROCESSING

To process the wideband data, a single frequency from all measurements was selected, so we had a value per position of the antennas on the rail. Then, a signal was conformed for each S-parameter and the diversity algorithms were applied. After that, the level above which each signal was 99% of the time was computed. This operation was repeated for each available frequency, for a total of 1001 points. Figure 6 shows an example of how each S-parameter looks like after the conversion.

Three different spatial diversity methods were considered in this study: Selection Combining (SC)(Equation 1), Equal Gain Combining (EGC)(Equation 2) and Maximal Ratio Combining (MRC) (Equation 3).

In order to be able to compare the different methods, the concept of effective signal envelope introduced in [5] (Appendix D) was used. For this, equal noise power had to be assumed in each branch. This results in the following equations:

$$r_{SC}(t) = max\{r_k(t)\} = max\{r_2(t), r_3(t), r_4(t)\} \quad (1)$$

$$r_{EGC}(t) = \frac{1}{\sqrt{M}} \sum_{k=1}^{M} r_k(t) = \frac{r_2(t) + r_3(t) + r_4(t)}{\sqrt{3}} \quad (2)$$

$$r_{MRC}(t) = \sqrt{\sum_{k=1}^{M} r_k^2(t)} = \sqrt{r_2^2(t) + r_3^2(t) + r_4^2(t)} \quad (3)$$

where r_{SC}, r_{EGC}, and r_{MRC} are the signal envelopes for each combination method and r_2, r_3 and r_4 correspond to the signal envelopes of the different S-parameters or branches and M is the number of branches.

This results in data of the 99% availability of the channel for each S-parameter as well as the one corresponding to the different diversity methods per frequency step.
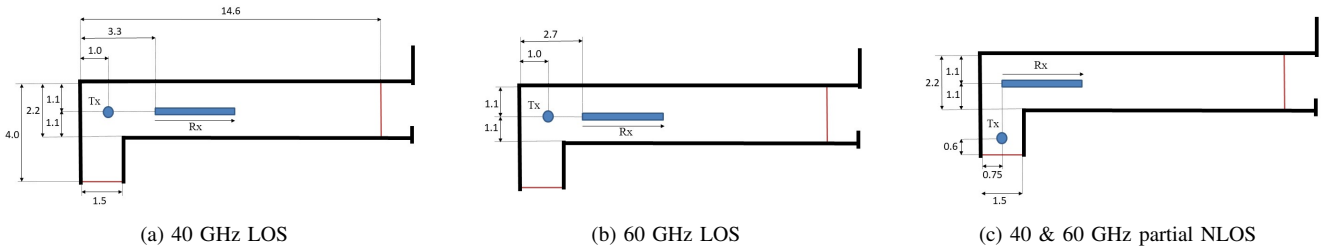
(a) 40 GHz LOS   (b) 60 GHz LOS   (c) 40 & 60 GHz partial NLOS

Fig. 4. Floor plan of the measurement's environment and setup.

(a) 41.5 GHz LOS   (b) 41.5 GHz NLOS   (c) 60.5 GHz LOS   (d) 60.5 GHz NLOS
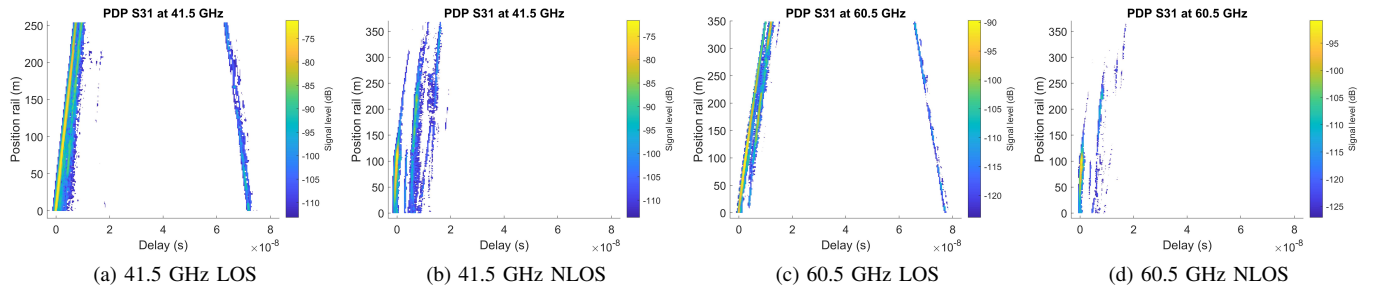
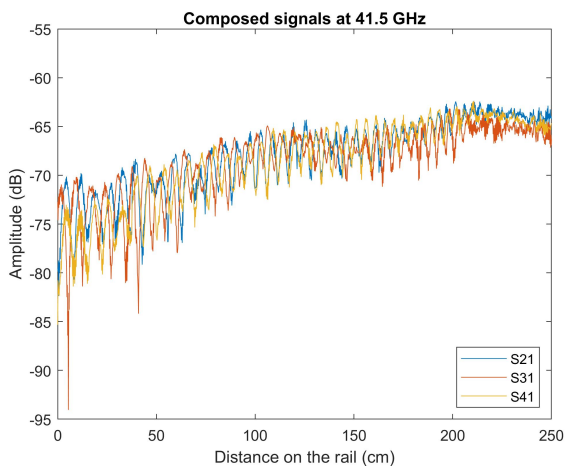Fig. 5. PDP of the different scenarios as received through parameter S31.

Fig. 6. Result of selecting one frequency point for each measured distance.

IV. RESULTS

A. 40 GHz

1) Line-Of-Sight: Figure 7 shows the results for the measurement at 40 GHz in LOS conditions. All three S-parameters are plotted along with the three diversity methods considered. Firstly, we can observe a clear decrease in the level of availability with the frequency increase affecting all the signals. Also, up to 42 GHz, the antennas have similar behaviors but then the parameter S_{31} decreases abruptly while the trend on others seems to be more or less stable. When compared with measurements done in another environment, this does not happen, so it can not be due to the antenna but to the environment itself. There may be a multipath component

that is affecting more the antenna at the front. Average 99% availability levels are -78.99 dB, -81.83 dB and -79.37 dB for S_{21}, S_{31} and S_{41} (see Table II).

With regard to the diversity method's performance, the best is clearly MRC closely followed by EGC and with MRC being the worst, with mean levels of -71.01 dB, -71.46 dB and -74.12 dB respectively. It is noticeable that diversity is working quite well. If we take a look at the drop in the signal level of S_{31} previously mentioned, we can see that it does not happen in neither of the diversity signals, so it is being compensated by the other two S-parameters.

This aligns with what is said in the literature [5]: MRC is slightly better than EGC and both of them outperform SS. It was consistently observed throughout all the experiment.

$$r_{MRC} > r_{EGC} >> r_{SC} \qquad (4)$$

2) Non-Line-Of-Sight: In the case of NLOS, there is more variation in the availability level of the signals, and while there is still a decreasing slope with frequency, it is less than in the LOS case, as seen in Figure 8.

Here it can be observed that the measured voltage levels for parameter S_{31} do not suffer a sudden drop at 42 GHz as they did before, which proves that the environment must be the one that causes it.

The values for the S-parameters can be observed in Table II and again, MRC is the best performer of the three, increasing the signal's level in 10.75 dB when compared to the best branch.

B. 60 GHz

1) Line-Of-Sight: Taking a look at Figure 9, it can be seen that parameter S_{31} has the highest level of the three, followed
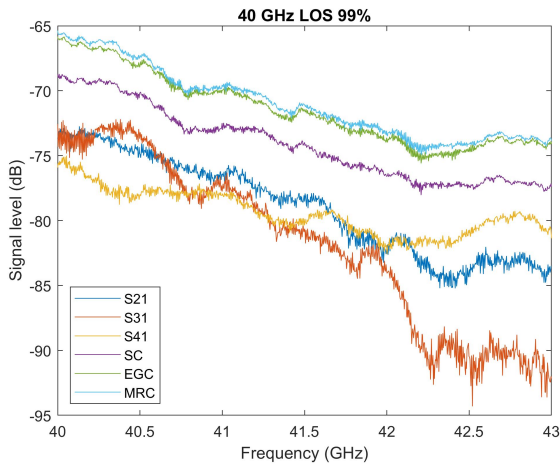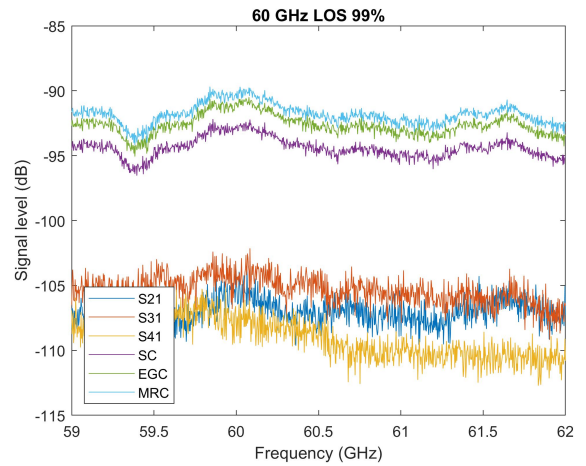
Fig. 7. 99% availability for 40 GHz LOS.

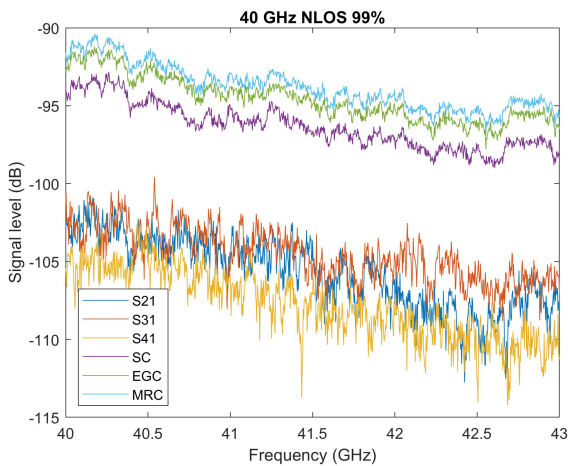Fig. 9. 99% availability for 60 GHz LOS
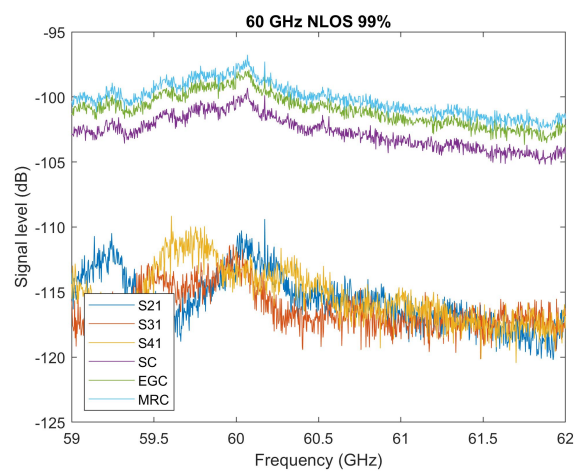

Fig. 8. 99% availability for 40 GHz NLOS.

Fig. 10. 99% availability for 60 GHz NLOS

by S_{21} and S_{41}. When compared with MRC, this method improves the signal level by 13.57 dB, while EGC and SS raise it by 12.74 dB and 10.99 dB respectively. The results are available in Table II.

2) Non-Line-Of-Sight: For the NLOS case (Figure 10), the three branches, the results are in line with what was previously exposed: Maximal Ratio Combining is the better performer of the three and, with a signal level of -100.17 improves the single best branch by a margin of 15.18 dB. Equal Gain Combining and Selection Combining raise the level by 14.37 dB and 12.65 dB respectively.

V. CONCLUSIONS

The 99% signal level availability was analyzed on several scenarios at two ranges of frequencies and three spatial diversity methods were studied to see their effect on the signals.

Spatial diversity is proven to work. Table III contains the improvement in dB of each method compared to the signal level captured by the best branch. It was observed that Maximal Ratio Combining was the one that gave the best

results. Its improvement with respect to the best single S-parameter captured increases with the frequency and when the conditions are not ideal (i.e. NLOS). Equal Gain Combining comes second and, in this case, the worst option is Selection Combining.

Furthermore, as explained by [5], the difference between Maximal Ratio Combining and Equal Gain Combining never exceeds 1.05 dB, which is the theoretical limit between them for an infinite number of branches.

TABLE II
MEAN LEVELS FOR AN AVAILABILITY OF 99 % (ALL UNITS IN DB)

Parameter	40 GHz		60 GHz	
	LOS	NLOS	LOS	NLOS
S21	-78.99	-105.72	-107.17	-115.67
S31	-81.83	-104.55	-105.37	-116.35
S41	-79.37	-107.76	-109.21	-115.35
MRC	-71.01	-93.80	-91.80	-100.17
EGC	-71.46	-94.59	-92.63	-100.98
SS	-74.12	-96.32	-94.38	-102.7

TABLE III
IMPROVEMENT OF EVERY DIVERSITY METHOD. ALL VALUES IN dB

File	Best S-Par	MRC	EGC	SS
40 GHz LOS	-78.99	7.98	7.53	4.87
40 GHz NLOS	-104.55	10.75	9.96	8.23
60 GHz LOS	-105.37	13.57	12.74	10.99
60 GHz NLOS	-115.35	15.18	14.37	12.65

ACKNOWLEDGMENT

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