Fixed Wireless Access Propagation Challenges

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1. Introduction

5G Fixed Wireless Access targets ‘cable like’ services taking advantage of the newly allocated mid and milimmiter wave (mmwave) band spectra, supporting channel bandwidth of 100MHz (sub 7GHz) or up to 400MHz (24-52.4GHz), particularly for locations where the mobile wireless spectrum is under-utilized. While the user outdoor antennas provide superior coverage and eventually user throughput rates, they may not be economically efficient, due to the required professional installation required.

The performance of cost effective FWA solutions target indoor CPEs, not dependent on field technician services, is critically determined by the Outdoor to Indoor (O2I) and indoor propagation. In this paper, we analyze how the related key performance propagation parameters shape up the FWA performance.

This paper is based on the statistically processed results coming out of 3 indoor and O2I measurement campaigns, whose results were summarized in 5 conference papers, as listed in the Reference section. Without losing the generality, the test campaigns were centered on the unlicensed/shared 6 and 37GHz bands, being considered suitable candidates for future FWA applications.

The MIMO capacity analysis for FWA O2I environments is presented separstely in the companion paper [9].

1.1. Key Findings

We discuss the following key performance parameters, affecting FWA O2I/Indoor propagation performance:

- Indoor path loss model in an office environment
  - The measured NLOS indoor path model (irregular office geometry) has significant variations vs. the similar 3GPP model (large conference room with symmetrical geometry).
  - The large amount of measurements (2x76 Test Positions – TPs), for 6 and 37GHz, made possible to derive an indoor channel model.
- O2I path loss for an FWA small cell scenario in a typical North American residential neighborhood, compared with 3GPP model prediction. FWA O2I network planning should:
  - Limit pass-through tree links due to the increased link budget uncertainty additionally augmented by rain/snow potentially present on the trees’ foliage.
  - The propagation through wet foliage is out of scope for this analysis
  - Target CPE locations 1m behind the outer wall closest to the BS. Any other deep inside the house CPE locations may attract larger than expected link budget variations.
- Root-Mean-Square (RMS) Delay Spread (RMS-DS)
  - RMS-DS increases over LOS, NLOS, and deep NLOS conditions.
  - RMS-DS decreases with frequency
- RMS-Angular Spread (RMS-AS)
  - 3GPP provides a more optimistic estimate (lower standard deviation) for the AS distribution vs. our findings.
  - 3GPP AS model doesn’t differentiate between NLOS and deep NLOS propagation.
- Angle of Arrival (AoA)

- The ocurence of NLOS links affected by Rayleigh fading is higher for sub 6GHz O2I links. This is translated having O2I mmW links operating with a lower number of MPCs vs. sub 6 GHz one, however under a more challenging link budget (more MPC fall under the detection theshold.

- Synthetic beamwidth and number of Multi-Path Components (MPC)
  - The impact of small scale fading is mitigated by reducing the antenna HPBW.
  - The qualitative and quantitative analysis, suggests that using a directive antenna in a multipath environment could increase the SNR and ultimately the user throughput.
- Ricean *K*-factor
  - The K-factor could vary significantly between -5 up to 12 dB for different links dependent on the amount of multipath, the link budget being affected accordingly.
  - The negative K factor for Deep NLOS and some NLOS links indicate that the Rayleigh fading should be used when modeling these links (a reduced link budget could be expected).
- Number of Multi Path Components (MPCc) and their relationship with the frequency bands.
  - The amount of MPCs decreases progressively with the decrease of the HPBW angle (when a Synthetic Beamwidth analysis is considered) for all 10 TPs under consideration [1], for both 6 and 37GHz, indicating the impact of small scale fading is mitigated by reducing the antenna HPBW [1].
  - The same MPC reduction trend is also reflected into the RMS-DS and RMS-AS trend.
  - The qualitative analysis coupled with the quantitative one, suggests that using a directive antenna in a multipath environment could increase the SNR and ultimately the user throughput.
- Frequency Domain Analysis
  - A fixed FWA 5G sector involving pass through tree links may require a higher NR DM-RS symbol density per slot, to correct the increased path induced phase-amplitude impairments, trading-off user throughput against better phase-amplitude impairment correction capability (outside the scope of this paper).

2. Test Setup

2.1. Measurement campaigns

This paper summarizes statistically processed test results pertaining to O2I and indoor propagation measurement campaigns as follows:

1. Indoor (office) propagation environment covering 11 links (6 and 37 GHz), [1]
2. O2I suburban residential scenario covering 216 links (6 and 37 GHz), 7 outdoor BS locations and 17 indoor CPE locations [2]
3. Indoor office environment covering 2x76 links (6 and 37GHz) with NLOS distances (straight line) up to 85m [3].

2.2. Channel measurement system design

The setup block diagram, key setup parameters and the VCA device are presented in Figure 1 and Figure 2.

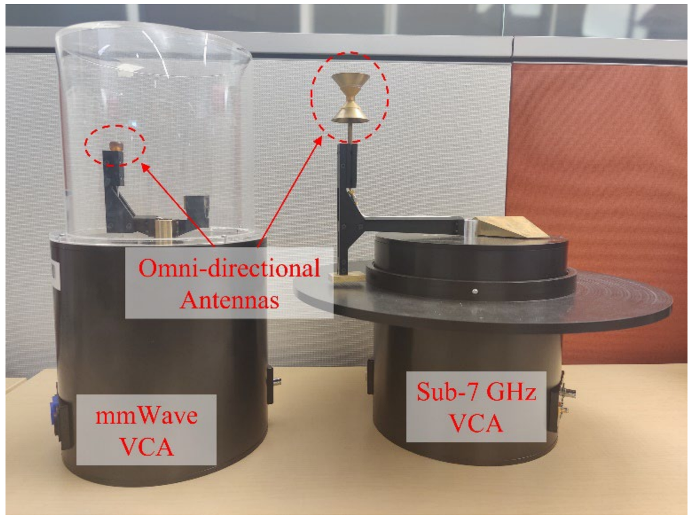
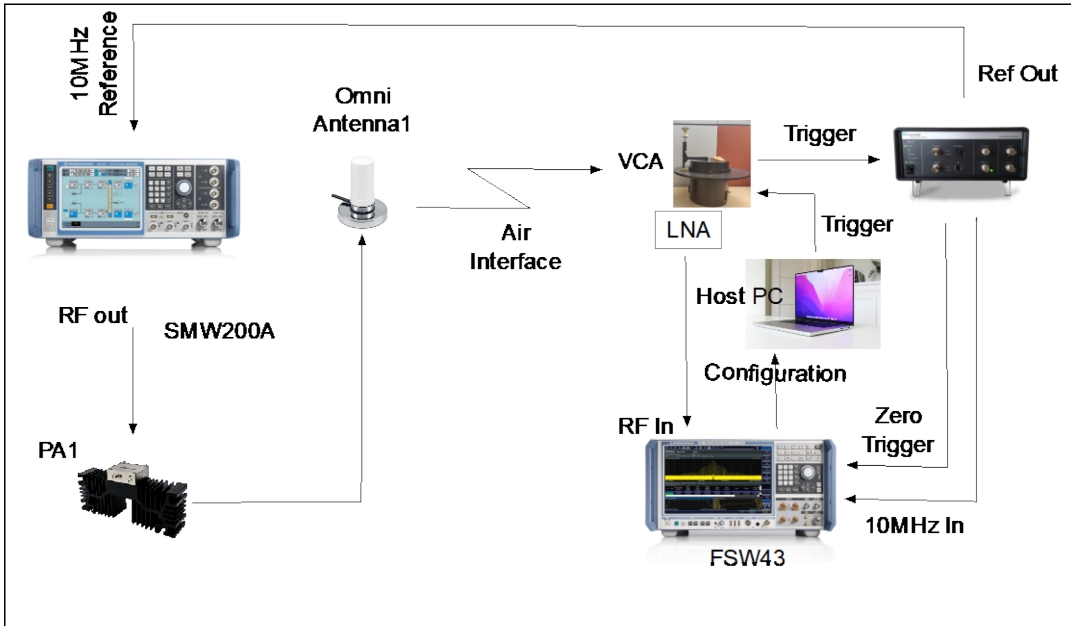


Figure 1 - 6 GHz (left) and 37GHz Virtual Circular Arrays (VCA) used during testing [5].

The VCA is a key component of the test setup, supporting 1000 measurements during one rotation of the single omni antenna along the circumference, though being able to measure the small scale fading impact parameters (RMS-DS, RMS-AS, AoA etc). The VCA consists of an omnidirectional antenna that rotates on a circular path [5], collecting 1000 sampled measurements, being equivalent to a 1000 antenna elements distributed evenly across the circumference (circular array). It allows acquiring propagation channel information when subject to small scale fading, which is critical for OLOS or NLOS environments.

The setup block diagram and the key setup parameters are presented in Figure 2.



a. SISO Measurement Setup

Parameter Name	Value
Carrier central frequency [GHz]	6.175/37.3
Ch Measurement BW [MHz]	500
Time resolution [ns]	2
Sequence time duration [µs]	500
Maximum excess delay [µs]	250
Sequence Length [kHz]	250
Frequency resolution	24
Virtual Antennas Number	1000
One measurement duration [ms]	500
Tx power 6.175GHz [dBm]	30
Tx power 37.3GHz [dBm]	28
Antenna Half Power Bmwdh [^{0}]	40

b. Setup parameters

Figure 2 - a. Channel Propagation measurement setup. b.Setup parameters.

The setup is time domain controlled. On the transmitter (TX) side, a 40GHz vector signal generator (Rohde&Schwarz SMW200A), an optional (setup dependent) power amplifier (PA), and an omnidirectional antenna are used. The receiver (RX) side employs a virtual circular array (VCA) following multiple measurements within one snapshot. The receiver side also consists of an optional low noise amplifier (LNA) and a vector signal analyzer (Rohde & Schwarz FSW43). A timing and triggering device (Synchronomat) generates a common 10 MHz reference signal for the TX and RX as well as a trigger signal for the VSA. This enables phase-coherent measurements and the acquisition of absolute time of flight and AoA information.

The transmitter generates a periodic correlation sequence (Frank-Zadoff-Chu sequence) with 500 µs length and 500 MHz bandwidth. At the receiver, 1000 repetitions of the correlation sequence are recorded, which are associated with 1000 subsequent antenna positions evenly distributed on the complete circumference of the VCA. Both VSG and VCA are controlled by the laptop computer. From each measurement, 1000 channel impulse responses (CIR) were recorded, tracking absolute time and amplitude information, accounting for the calibrated over the air calibration.

The measurement campaign used two different central frequencies: 6.175 GHz and 37.3 GHz.

3. Propagation Environment

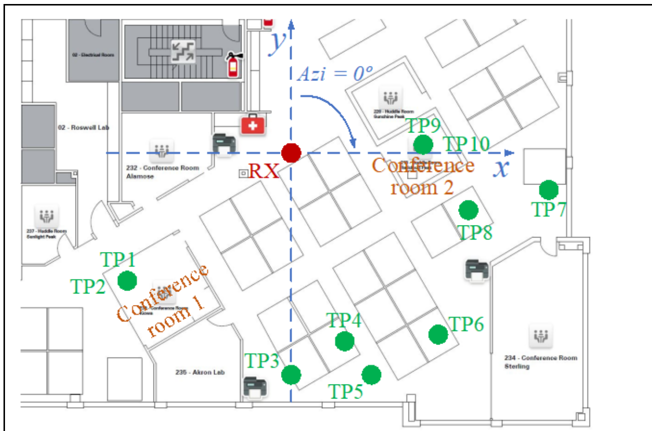
There have been used two propagation environments for both frequency bands of interest, targeting different goals:

a. Indoor propagation environment:
   - Number of MPCs
   - RMS-DS, RMS-AS vs. Synthetic beamwidth
   - Spatial Correlation

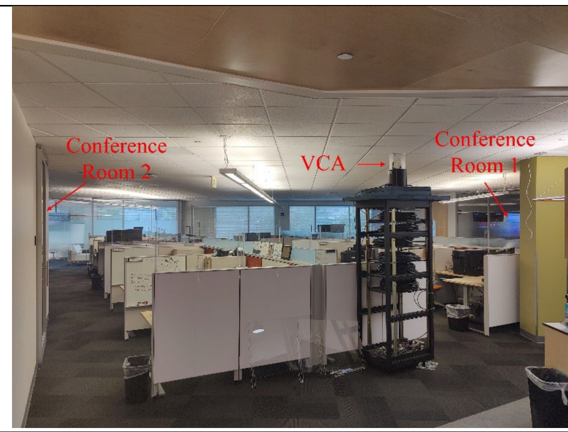
b. O2I propagation environment:
   - Path Loss
   - Small Scale fading parameters
   - Azimuth Angle Of Arrival (AoA)
   - Power variation across subcarrier

3.1. CableLabs office indoor environment

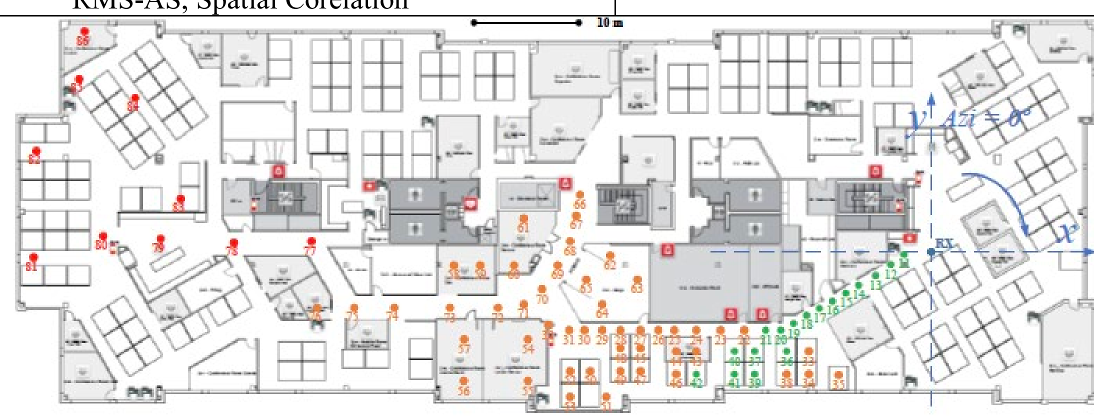
Map/floorplan with TX and RX positions, material of wall, ceiling, and floor, etc.



a. Indoor test area layout used for Synthetic Beamwidth, number of MPC, RMS-DS and RMS-AS, Spatial Corelation



b. Picture of the test area under consideration (a)



c. Indoor test layout used for indoor path loss models, small scale fading analysis

Figure 3 - Indoor test propagation environments used for the test campaign.

3.2. CableLabs test house O2I environment

CableLabs Test House was selected as the test area for O2I propagation. There were:

- 6 outdoor test points (BS locations), numbered from 0 to 6, 4 providing LOS/OLOS propagation and 2 providing NLOS (behind trees).
- 18 indoor TP (CPE locations) spread across two floors providing a mix of LOS and NLOS (behind one indoor wall or multiple walls).
- All outdoor-indoor combination resulted into 216 link (6 and 37 GHz). [3]

d. TP5 (first floor) view

e. TP1 (towards the house view)

Figure 4 - O2I test environment used for testing.

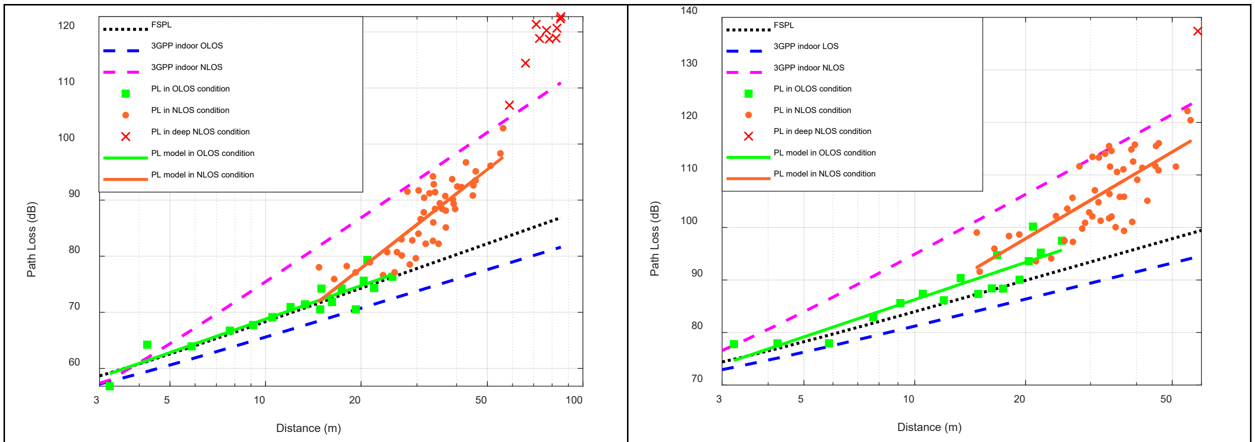
4. Summary of Test Results

4.1. Indoor Path Loss Model

The measurements environment presented in Figure 3c was used for this analysis [3]. The measured path losses for the TPs under consideration were compared with the Free Space Loss (FSPL) and 3GPP indoor LOS and NLOS.

We divided the 86 TPs and related links into 3 categories, dependent on the environment propagation particularities:

- LOS conditions: 3-25m path (TPs 12-21, 36-42, 37, 39-42)
- NLOS conditions: 15-56m (TPs 22-32, 33-35, 43-76)
- Deep NLOS 59-85m (TPs 76-89)



a. 6GHz indoor path loss model

b. 37GHz indoor path loss model

Figure 5 - Indoor path model (6 and 37 GHz)

The above figure plots the measured OLOS/NLOS Path Losses against FSPL and 3GPP indoor LOS/NLOS for 6 and 37GHz.

The measured OLOS PL (6GHz):

- Is above FSPL by 0.6-1.1dB, due to the the rich indoor scaterring propagation environment.
- Varies between 2.5dB lower (TP35 – path length 3.2m) to -4.4dB (TP 42 – Path Length 25.1m), when compared with the 3GPP LOS indoor model.

The measured NLOS PL (6GHz):

- Varies between 11.5dB lower (TP35 – Path Length 14.7m) and -6.2dB (TP 76 – Path Length 56m) when compared with the 3GPP LOS indoor model.

Based on the 86 Path Losses measured across all 86TPs, the 6GHz PL model presented in Table 1 was derived.

The generic Path Loss formula is presented below

$L(d) = L_{ref}(dmin) + n * 10 * log10(d) + \delta$ *Equation 1*

Table 1 - Key path loss model parameters (6GHz)

	Exponent n	Reference PL L_{ref} at min distance (dB)	Min distance d_{min} (m)	σ (dB)
OLOS	2.1	61.7	3.2	1.7
NLOS	4.4	73.3	14.7	3.7

The 3GPP indoor model [6] was developed for a generic indoor environment (large conference room), over estimating the NLOS PL by 6.2 – 11.5 dB.

The measured OLOS PL (37GHz):

- Is 0…-3.5dB vs. FSPL, due to the the rich indoor scaterring propagation environment.
- Varies between 1.5dB (TP11) to -7.3dB (TP 42 Path Length 56m) vs. 3GPP LOS indoor model.

The measured NLOS PL (37GHz):

- Varies between 9.7dB (TP35 – Path Length 14.7m) and -7.2dB (TP 76 – Path Length 56m) when compared with the 3GPP LOS indoor model.

The 37GHz PL model, based on 76 TPs measured was derived (see Table 1).

Table 2 - Key path loss model parameters (37GHz)

	Exponent n	Reference PL L_{ref} at min distance (dB)	Min distance d_{min} (m)	σ (dB)
OLOS	2.4	77.5	3.2	2.7
NLOS	4.1	92.4	14.7	4.9

More details could be found in [3].

4.2. O2I Loss

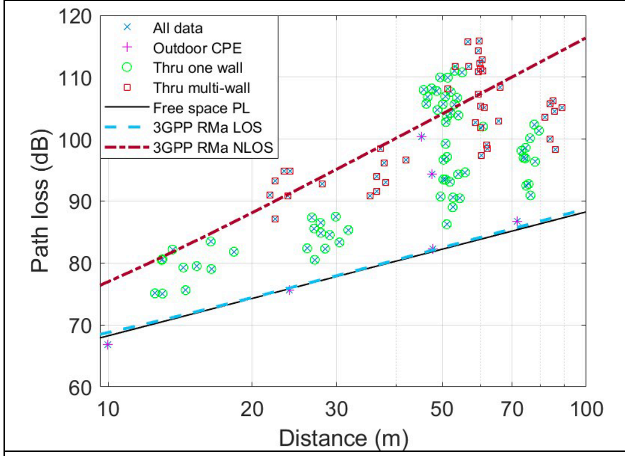
The Path Losses for different O2I propagation scenarios [2] were measured, based on 2x108 measured links (6 and 37 GHz). The Path Loss determines the Link Budget, RX SNR, coverage and ultimately the User Throughput for FWA links. This highlights the priority to properly estimate O2I path losses and compare our measured results with 3GPP path loss estimates [6].

The measurements couldn’t be extended over 80m O2I path lenth, since the test equipment based link budget reached its limits, particularly for the pass through trees and deep NLOS combinations. This precluded further efforts to derive a O2I path loss model.

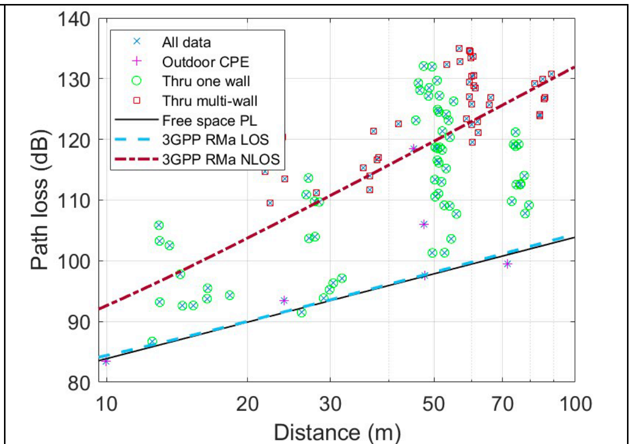
The O2I Path Loss (6 and 37 GHz) measurements were grouped :

- Indoor CPE links positioned behind one wall and behind multiple walls.
- Outdoor BS locations (LOS using an outdoor CPE) behind one or multiple trees.

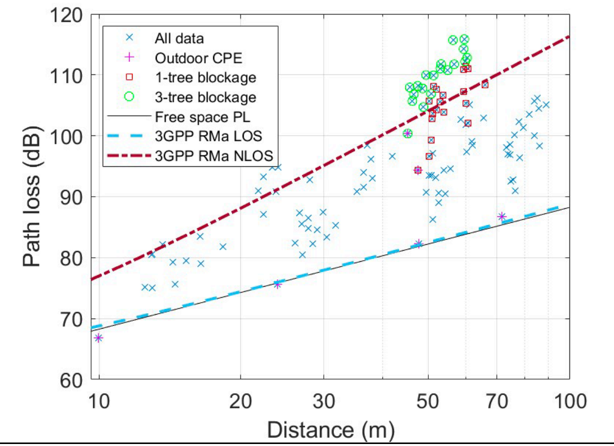
The Path Loss results were reported as excess path loss vs. the similar 3GPP estimates.



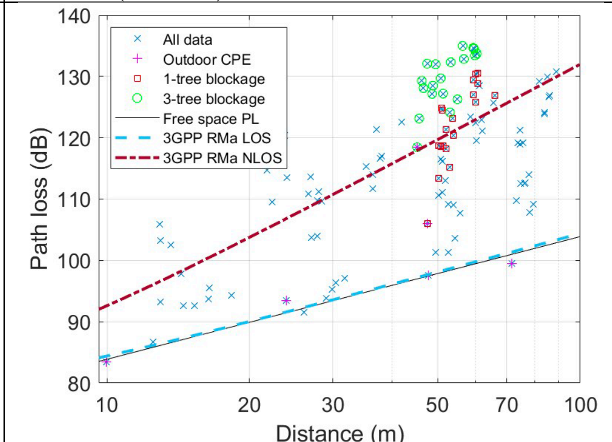
a. Path Loss impact of indoor CPE locations (6 GHz)



b. Path Loss impact of indoor CPE locations (37 GHz)



c. Path Loss impact of outdoor BS locations (6 GHz)



d. Path Loss impact of outdoor BS locations (37 GHz)

Figure 6 - CPE (indoor) and BS (outdoor) path loss (6 and 37 GHz).

The O2I Excess Path Loss, for 6 and 37 GHz vs. 3GPP LOS and NLOS O2I path loss models are presented in the below table.

Table 3 - Excess path Loss (Measured LOS and NLOS (grouped against the outdoor BS locations) vs. 3GPP LOS and NLOS Path Loss) for 6 and 37GHz.

RX \ TX	TX1	TX2	TX3	TX4	TX5 (1 tree)	TX6 (3 trees)
Outdoor	-1.1	-0.2	0.2	1.0	12.4	18.8
Indoor avg	11.3	10.1	12.2	12.8	22.2	27.3
One wall	8.0	7.2	9.3	10.8	20.5	25.8
Multi-wall	16.4	14.5	16.8	16.0	24.9	29.7

a. Excess Path Loss (6GHz)

RX \ TX	TX1	TX2	TX3	TX4	TX5 (1 tree)	TX6 (3 trees)
Outdoor	-0.2	2.0	-0.1	-1.8	8.4	21.3
Indoor avg	15.1	14.1	15.6	17.1	24.1	31.7
One wall	9.3	9.4	10.6	12.4	21.3	30.0
Multi-wall	24.2	21.5	23.4	24.4	28.5	34.4

b. Excess Path Loss (37GHz)

Notes:

- The one wall O2I losses fall between 3GPP LOS and NLOS models, except the multiple trees outdoor propagation cases.

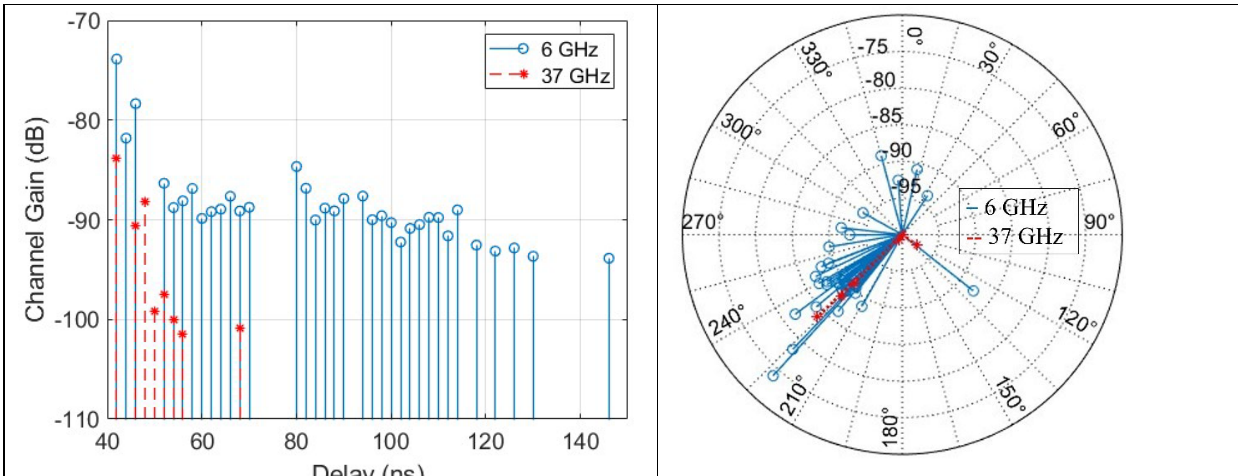
- The multiple trees outdoor links exceed the 3GPP NLOS model by up to 5-8dB (6GHz) and up to 12-15dB (37GHz).
- The pass through tree links were measured during sunny days (dry foliage). It is expected that similar wet foliage measurements to return higher excess path loss.
- FWA O2I planning should avoid pass through multiple (e.g.) tree links due to the increased link budget uncertainty.
- FWA O2I planning should be based on a CPE location positioned 1m behind the outer wall closest to the BS. Any other deep inside the house CPE location may attract larger than expected link budget variationsand decreased service (link) availability, resulting into degraded user Quality of Service (QoS).

More details on our test setup and procedure are provided by [2].

4.3. Power Delay Profile (PDP)

PDP provides the amplitude of a received multipath signal receive vs. time delay. PDP is crucial for estimating the Cyclic Prefix (CP) for OFDM transmissions. It also provides information about the amount of Multi Path Components.

The Power Angular Profile (PAP) provides a graphical representation of the LOS/OLOS/NLOS type of propagation. It also helps the antenna designer to design an antenna array suitable for the respective propagation environment.



a. Averaged PDP (TP1)

b. PAP (TP1)

Figure 7 - Sample of (a) PDP and (b) PAP profiles measured in an indoor environment [1].

The examples above relates to TP1 (Figure 3 - Indoor test propagation environments used for the test campaign. This example [1] points to:

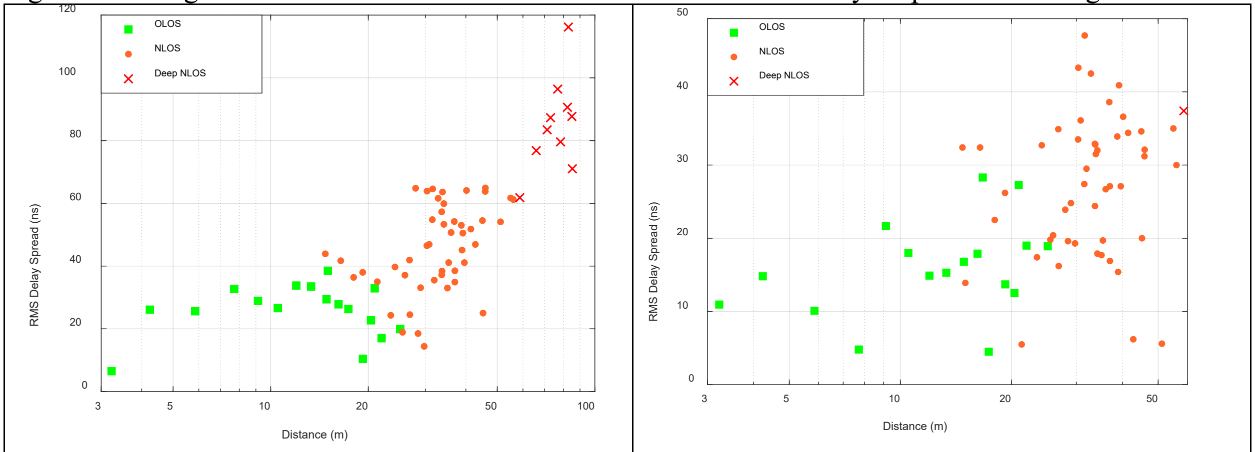
- Even if TP1 path (Figure 3a) relates to a relatively short OLOS path, the link is subject to a large amount of multipath components (MPCs) due to the large amount of relevant amplitude reflections incurred in that specific indoor office environment, particularly for the 6GHz propagation.
- A reduced MPC amount for the 37 GHz link (the larger path attenuation causes a faster MPC decay vs. 6 GHz), caused by the rapid MPC attenuation (higher path losss vs. 6GHz case).

More details are provided in [1].

4.4. Delay Spread (DS)

DS represents the time delay spread vs. Path length. It is reported for LOS, NLOS and Deep NLOS.

Figure 7 and Figure 8 summarizes the RMS-DS and RMS-AS for the layout presented in Figure 3c



a. RMS-DS 6 GHz. Indoor environment [4]

b. RMS-DS 37 GHz. Indoor environment [4]

Figure 8 - RMS-DS, 6GHz (a), 37 GHz (b) distributions for the indoor environment.

Notes:

- RMS-DS increases over LOS, NLOS, and deep NLOS conditions
- RMS-DS decreases with frequency
    - MPCs at high-frequency decay (power reduction relative to the strongest MPC) faster than MPCs at low-frequency
    - The number of MPCs above the 20 dB MPC threshold at high-frequency is smaller than that at low-frequency.

We divided the 86 TPs into 3 categories, dependent on the environment propagation particularities (see Figure 3c):

- LOS conditions: 3-25m path (TPs 12-21, 36-42, 37, 39-42)
- NLOS conditions: 15-56m (TPs 22-32, 33-35, 43-76)
- Deep NLOS 59-85m (TPs 76-89)

We compare the measured average RMS-DS (across the 3 categories mentioned above) with 3GPP RMS-DS specifications [6], the results being presented in the table below:

- The measured RMS-DS results are more conservative for NLOS and Deep NLOS environments than the 3GPP ones for both 6 and 37GHz frequencies.
- The measured OLOS RMS-DS is more optimistic vs. 3GPP RMS-DS specifications.

Table 4 - Comparative summaries of the measured RMS-DS vs. 3GPP RMS-DS for an indoor environment (3)

Measured RMS-DS (ns)		Max	Min	Mean	Standard deviation
6 GHz	OLOS	39	7	25	9
	NLOS	65	14	46	14
	Deep NLOS	116	62	85	15
37 GHz	OLOS	28	5	16	6
	NLOS	48	6	27	10
	Deep NLOS	37	37	37	0

a. Summary of measured RMS-DS 6 and 37GHz, indoor environment

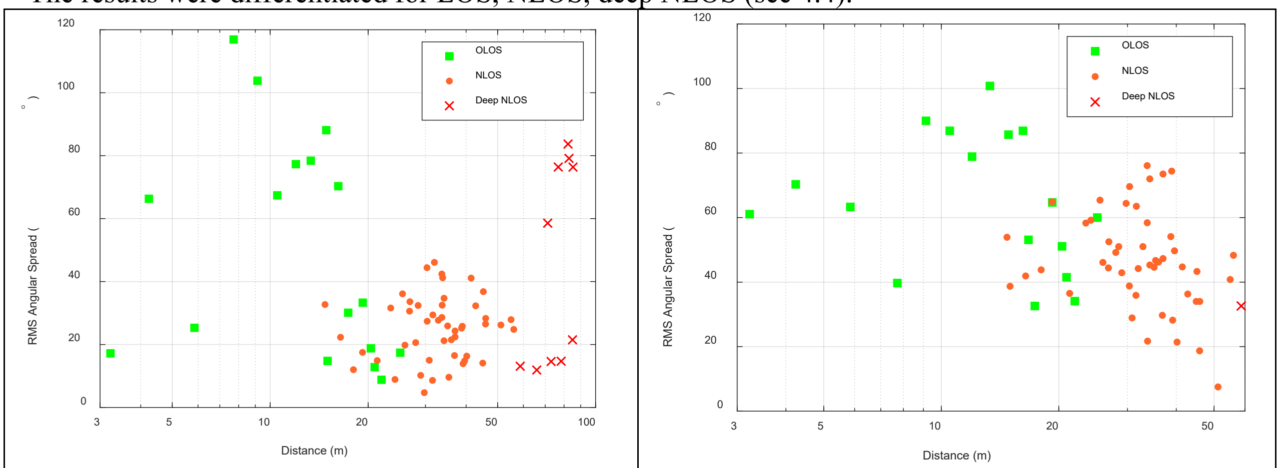
3GPP model RMS-DS (ns)		Mean	Standard deviation
6 GHz	LOS	20	1.5
	NLOS	39	1.4
37 GHz	LOS	20	1.5
	NLOS	24	1.6

b. Summary of 3GPP RMS-DS indoor model specifications

4.5. Angular Spread (AS)

The Angular Spread highlights the angular spread distribution against path length. It shows how the relevant MPCs are distributed angle wise (vs. the highest power MPC component). It is useful for the indoor CPE antenna designer.

We calculated the RMS-AS distribution vs. distance for the same propagation environment (Figure 3c). The results were differentiated for LOS, NLOS, deep NLOS (see 4.4).



a. RMS-AS 6 GHz. Indoor environment [4]

b. RMS-AS 37 GHz. Indoor environment [4]

Figure 9 - RMS-AS vs. Distance for (a) 6 GHz and (b) 37GHz [3]

Notes:

- The amount of OLOS reflections exceeds the relevant NLOS reflections (due to the faster amplitude decay of the latter).
- The amount of Deep NLOS reflections exceeds the relevant NLOS reflections.

The average measured RMS-AS is further compared with 3GPP RMS-AS specifications ([6].

Table 5 - Comparison between measured average RMS-AS and relt4ed 3GPP specifications [6]

Measured RMS-AS (°)		Max	Min	Mean	Standard deviation
6 GHz	OLOS	105	9	45	33
	NLOS	37	5	20	7
	Deep NLOS	98	12	44	34
37 GHz	OLOS	122	23	63	35
	NLOS	71	7	37	13
	Deep NLOS	23	23	23	0

a. Average of the measured RMS-AS for the environment presented in Figure 3c

3GPP model RMS-AS (°)		Mean	Standard deviation
6 GHz	LOS	42	1.7
	NLOS	59	1.5
37 GHz	LOS	30	2.0
	NLOS	49	1.8

b. RMS-AS 3GPP specifications [6]

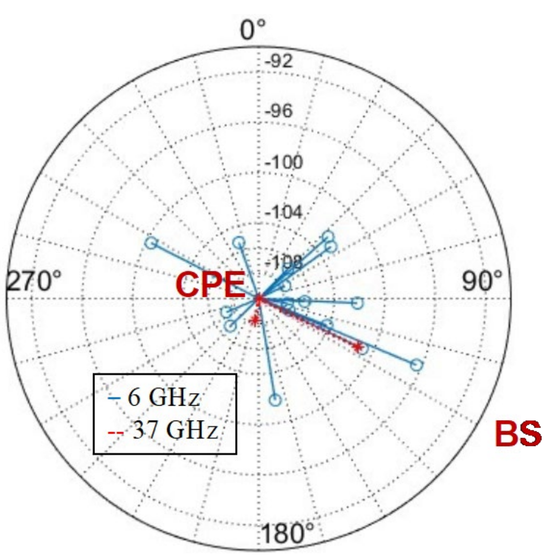
Notes:

- 3GPP provides a more optimistic estimate in terms of lower standard deviation for the AS distribution.
- 3GPP AS model doesn't differentiate between NLOS and Deep NLOS propagation.

More details are provided in [3].

4.6. Angle of Arrival (AoA)

The Angle of Arrival (AoA) provides information about the type of fading a CPE operates in. It represents the MPC azimuth directions.



a. Example of Power Angular Profile (6 and 37 GHz) for Tx2/Rx2 (Figure 4)

	$\Delta\varphi>30^o$	$\Delta\varphi>45^o$	$\Delta\varphi>60^o$
6 GHz	47%	35%	26%
37 GHz	36%	25%	15%

b. Excess AOA of the strongest MPC

Figure 10 - a. Example of Power Angular Profile; b. Summary of Excess AoA (6/37GHz) [2]

The O2I propagation is characterized by two types of fading (associated with different path loss distributions).

- For a Rician type of fading, the strongest MPC direction coincides with the LOS direction (above figure is representative for a Rician type of fading).
- For a Rayleigh type of fading, the strongest MPC direction is not aligned with BS-CPE LOS.

We defined the Excess AoA as the difference between measured azimuth of the strongest MPC and geometrical BS-CPE (LOS) direction. The Excess AoA was calculated for all 2x108 links (6 and 37GHz) defined by Figure 4 geometry. Ther results are summarized by table presented in Figure 10b:

- The percentage of Ryaleigh fading (NLOS) is higher for 6GHz. This means that the mmW O2I environment operates more on direct links than a sub 6 GHz one. This could be probably explained by the rapid decay of reflection paths for mmW links.
- Given the percentage of pure O2I NLOS links, a case could be made for using directive antennas in O2I environments.

More details could be found in [2].

4.7. Synthetic Beamwidth and Number of Multi-Path Components (MPC)

The Synthetic Beawidth represents the Half Power Beamwidth of a directive antenna with the bore sight aligned with the strongest MPC.

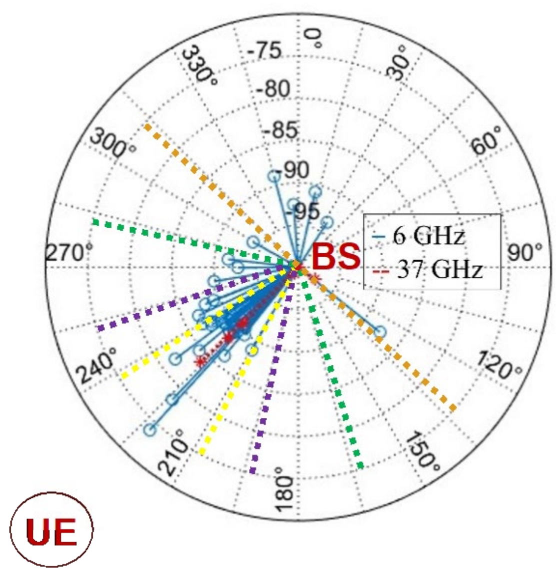


Figure 11 - Example of Synthetic Beamwidth alternatives vs. RMS-AP [1].

The example above projects the 10, 30, 60 and 90 deg sectorial antenna structures over the AoA corresponding to TP1 (Figure 3a, [1]).

Based on the plot above, it loos like if a directive antenna is aligned with the highest power MPC received in a NLOS environment, it could reduce the amount of MPC components and eventually reduce the small scale fading impact.

Table 6 - Summary of Synthetic Beamwidth performance (Number of MPCs, RMS-DS, RMS-AS) for 6GHz (a) and 37GHz (b) [1].

TP index	Synthetic beamwidth (°)						Synthetic beamwidth (°)						Synthetic beamwidth (°)					
	360	180	120	60	30	10	360	180	120	60	30	10	360	180	120	60	30	10
	Number of MPCs						RMS-DS (ns)						RMS-AS azimuth (°)					
1	35	30	29	26	21	8	24	22	21	21	21	14	46	21	9	7	5	1
2	64	47	42	36	24	11	35	34	33	31	31	31	72	30	15	11	5	2
3	43	39	29	25	20	12	21	20	16	15	14	12	78	77	56	20	4	2
4	34	32	27	20	16	9	18	17	16	14	12	8	110	108	105	92	94	45
5	35	33	28	15	13	6	22	21	20	16	14	12	132	132	127	87	91	1
6	63	47	43	35	20	5	33	33	33	30	27	23	116	93	59	10	6	1
7	41	31	25	22	16	9	25	22	17	16	17	13	44	18	13	9	4	1
8	77	54	48	35	17	10	48	41	38	34	28	24	121	124	126	132	100	2
9	28	20	17	15	8	4	21	15	13	13	10	7	134	137	137	112	4	1
10	65	46	30	26	15	8	32	27	20	19	17	17	49	28	14	11	7	2
Average	72	38	32	26	17	8	30	25	23	21	19	16	90	77	66	49	32	6

a. Synthetic beanwidth performance (Number of MPCs, RMS-DS, RMS-AS) 6GHz

TP index	Synthetic beamwidth (°)						Synthetic beamwidth (°)						Synthetic beamwidth (°)					
	360	180	120	60	30	10	360	180	120	60	30	10	360	180	120	60	30	10
	Number of MPCs						RMS-DS (ns)						RMS-AS azimuth (°)					
1	8	6	6	6	4	3	4	3	3	3	3	3	23	4	4	4	1	0
2	6	3	3	3	2	2	5	3	3	3	2	2	34	4	4	4	1	1
3	22	21	18	15	13	4	9	8	8	7	5	3	21	20	11	6	5	0
4	18	18	18	15	13	8	12	12	12	11	10	7	11	11	11	5	3	1
5	39	26	22	13	8	5	18	15	15	12	10	11	52	27	20	16	5	1
6	9	7	7	7	7	1	8	7	7	7	7	0	22	4	4	4	4	0
7	42	36	25	10	8	4	21	21	19	10	8	6	60	40	31	9	3	1
8	46	30	25	15	12	7	26	27	25	17	15	10	49	21	18	6	4	1
9	53	33	27	13	8	4	26	26	25	13	11	8	70	25	21	11	6	1
10	53	32	26	19	16	6	31	31	25	21	19	10	65	28	14	9	7	2
Average	30	21	18	12	9	4	16	15	14	10	9	6	41	18	14	7	4	1

b. Synthetic beamwidth performance (Number of MPCs, RMS-DS, RMS-AS) 37GHz

A quantitative analysis is presented in Table 6 The amount of MPCs, RMS-DS and RMS-AS were calculated for an synthetic (artificial) beamwidth emulating a directive antenna aligned on the strongest MCP component (either LOS or NLOS), for a selection of Half Power Beamwidth angles (10deg 30deg, 60deg, 120deg and 180deg) for both 6 and 37GHz. This analysis indicate that:

- The amount of MPCs decreases progressively with the decrease of the HPBW angle (when a Synthetic Beamwidth analysis is considered) for all 10 TPs under consideration (6 and 37GHz). This indicates the impact of small scale fading is mitigated by reducing the antenna HPBW [1].
- The same MPC reduction trend is also reflected into the RMS-DS and RMS-AS trend.
- The qualitative analysis coupled with the quantitative one, suggests that using a directive antenna in a multipath environment could increase the SNR, the user throughput and ultimately user QoS.

More details are provided in [1].

4.8. K factor [8]

Rician fading describes the radio multipath interference, caused by the partial cancellation of the radio waveform itself when transmitted over a multipath propagation environment. It is described by a stochastic model, the Rician fading being modeled by the Rician distributed [8]. The Rician fading is characterized by a main (typically) LOS component. A particular case of the Rician fading is the Rayleigh fading (no LOS component).

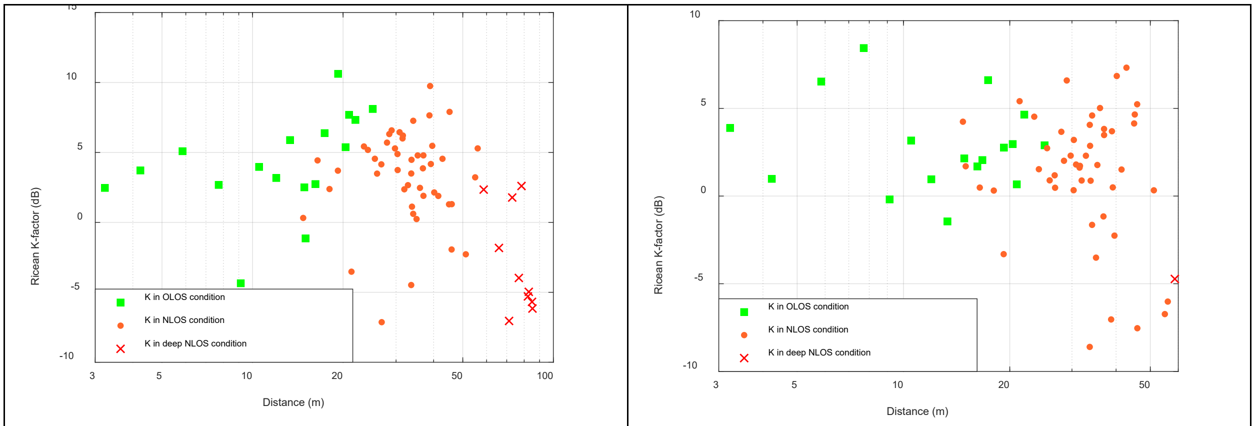
The Rician fading channel is described by two parameters [8]:

- K is the ratio between the direct path power and the sum of all other non-LOS received powers
- Ω is the total received power from all paths.

Any O2I propagation and related link budget is determined by either a Rician or a Rayleigh type of distribution. However the Rician fading and the related K parameters are specific to different type of O2I propagation. For an accurate O2I link budget/coverage estimate, the network planner must use proper K factor concerning the specific propagation scenario under consideration.

We derived K factor for O2I, OLOS and NLOS conditions based on two different propagation environments:

- A heavy multipath indoor (office) environment (3)
- A residential O2I environment (2)
- In both cases, there was introduced a 20dB discrimination threshold against non-relevant MPC components.



a. K factor 6 GHz

b. K factor 37 GHz

Figure 12 - Comparative Ricean-K factor (6 and 37GHz) for an indoor environment (3)

The comparative measured K results for the O2I environment [2] are summarized below.

Table 7 - Summary of the measured Rician K-factor(6 and 6 GHz) for an O2I environment [2]

RX \ TX	TX1	TX2	TX3	TX4	TX5 (1 tree)	TX6 (3 trees)	Mean
Outdoor	6.5	9.1	8.7	8.8	-0.2	-3.0	5.0
Indoor avg	1.8	2.4	3.1	1.9	2.3	0.3	2.0
One wall	2.0	3.5	4.1	2.0	2.8	1.2	2.6
Multi-wall	1.6	0.6	1.5	1.9	1.5	-1.2	1.0
1st-fl avg	1.5	1.8	2.7	0.7	1.8	0.9	1.6
2nd-fl avg	2.2	3.0	3.5	3.5	2.9	-0.5	2.4

a. Summary of K-factor (6GHz)

RX \ TX	TX1	TX2	TX3	TX4	TX5 (1 tree)	TX6 (3 trees)	Mean
Outdoor	11.5	12.5	10.4	9.2	8.9	-6.6	7.6
Indoor avg	3.4	1.2	0.5	-0.3	0.4	-4.9	0.1
One wall	4.4	2.3	2.8	0.4	1.0	-2.9	1.3
Multi-wall	1.8	-0.4	-3.2	-1.5	-0.6	-8.0	-1.9
1st-fl avg	4.4	2.5	0.2	0.3	0.2	-3.5	0.7
2nd-fl avg	2.2	-0.3	0.8	-1.1	0.6	-6.6	-0.7

b. Summary of K-factor (37GHz)

3GPP [6] specifies for LOS:

- K (mean)=7dB

- Rician fading standard deviation: 7 dB.

We observe that:

- The measured K-factor results are different than the similar 3GPP predictions.
- The measured (indoor and O2I) K-factors are based on a large amount of measured links
- The measured K-Factor are different for 6GHz and 37GHz. 3GPP doesn't provide different K-factor values for different frequencies.
- Excepting the Outdoor case, the measured O2I 37GHz K-factor is lower than the 6GHz for the same link.
- The OLOS K-factor could vary significantly between 2 up to 12 dB for different links dependent on the amount of multipath, the link budget being affected accordingly. The outliers are caused by severely obstructed links along relatively narrow halls, causing large amounts of MPC.
- The negative K factor for Deep NLOS and some NLOS links indicate that the Rayleigh fading should be used for these links.

More details concerning the Rician K-factor analysis are provided by [2] and [3].

4.9. Frequency Domain Analysis

The following in-band fading example relates to the 6GHz, Tx6 (behind one tree) → Rx0 (outdoor patio). See the O2I geometry presented in Figure 4. The data was aquired from VCA antenna (Figure 2).

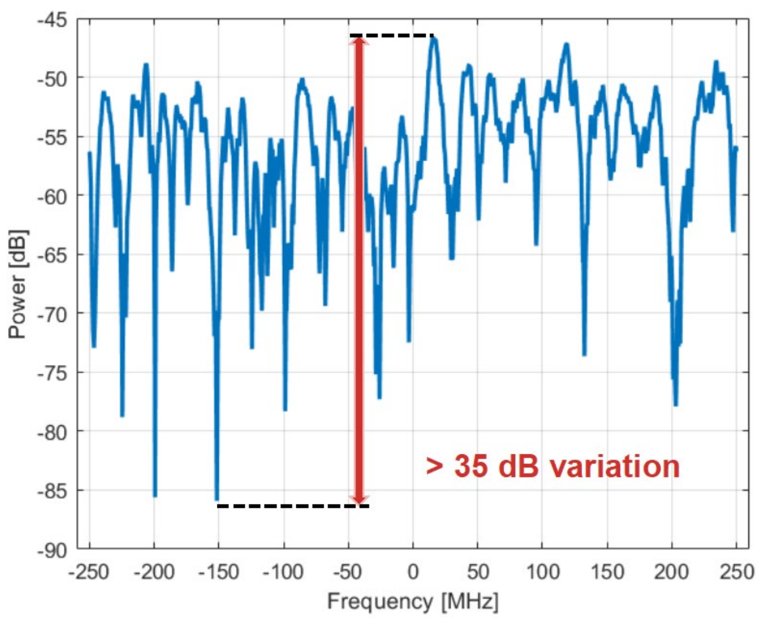


Figure 13 - Sample of in-band fading

Consider a 5G mid band analogy (ChBW=100BW), it appears that the max power variation in the -250…-150MHz frequency domain exceeds 30dB. While not a mobile wireless propagation environment, this particular fixed O2I environment may require:

- Either a higher NR DM-RS symbol density per slot to correct, which trades-off user throughput with better phase-amplitude impairment capability.

- Or avoid pass through multiple (e.g.) tree links, though optimizing the user throughout vs. a reduced 5G DM-RS symbol density.
- Randomly spread the subcarriers across the entire band (known as randomization for LTE and 5G).

5. Conclusions

In this paper we discussed specific indoor and O2I propagation challenges, impacting FWA network planning. The companion paper [9] discusses MIMO challenges related to FWA O2I/Indoor links.

The user throughput is directly impacted by link budget and related SNR. All these parameters under consideration in this paper, impact directly or indirectly the link budget and SNR. A proper FWA network planning should consider propagation parameters based on relevant field measurements.

- Indoor path loss model in an office environment
  - The measured NLOS indoor path model (irregular office geometry) has significant variations vs. the similar 3GPP model (large conference room with symmetrical geometry). 3GPP indoor model should be used with caution.
- O2I path loss for an FWA small cell scenario in a typical North American residential neighborhood, compared with 3GPP model prediction. FWA O2I network planning should:
  - Avoid pass through tree links due to the unknown link budget uncertainty.
  - The network planner should target CPE locations positioned 1m behind the outer wall (geometrically closest to the BS). Deep inside the house CPE locations may attract larger than expected link budget variations and potentially a higher CPE equipment churn rate.
- RMS-Delay Spread (RMS-DS)
  - RMS-DS increases over LOS, NLOS, and deep NLOS conditions.
  - RMS-DS decreases with frequency.
- RMS-Angular Spread (RMS-AS)
  - 3GPP provides a more optimistic estimate (lower standard deviation) for the AS distribution.
  - 3GPP AS model doesn't differentiate between NLOS and Deep NLOS propagation.
- Angle of Arrival (AoA)
  - The percentage of Rayleigh fading (NLOS) is higher for sub 6GHz O2I links. This means that the mmW O2I environment operates with a higher probability on direct links vs. sub 6 GHz one.
- Synthetic beamwidth and Number of Multi-Path Components (MPC).
  - The impact of small scale fading is mitigated by reducing the antenna HPBW, when aligned with the strongest MPC.
  - The qualitative and quantitative analysis, suggests that using a directive antenna in a multipath environment could increase the SNR and ultimately the user throughput.
- Ricean *K*-factor

- The LOS K-factor could vary significantly (2…12dB), dependent on the amount of multipath, the link budget being affected accordingly.
- The negative K factor measured for Deep NLOS and some NLOS links indicate these links are modeled by a Rayleigh fading rather than a Rician one.

- Number of Multi Path Components (MPC) and their relationship with the frequency bands.

  - The amount of MPCs decreases progressively with the decrease of the HPBW angle(when a Synthetic Beamwidth analysis is considered) for all 10 TPs under consideration, for both 6 and 37GHz. This indicates the impact of small scale fading is mitigated by reducing the antenna HPBW [1].
  - The same MPC reduction trend is also reflected into the RMS-DS and RMS-AS trend.

- Frequency Domain Analysis

  - A fixed FWA 5G sector/cell involving pass through pass-through tree links may require a higher NR DM-RS symbol density per slot, to correct the increased path induced phase-amplitude impairments, trading-off user throughput against a reduced phase-amplitude impairment correction capability.

Abbreviations

ADP	Angular Delay Profile
AoA	Angle of Arrival
AS	Angular Spread
BS	Base Station
CIR	Channel Impulse Response
CPE	Customer Premises Equipment
FSPL	Free Space Path Loss
FWA	Fixed Wireless Access
HPBW	Half Power Beamwidth
LOS	Line-Of-Sight
MIMO	Multiple Inputs Multiple Outputs
mmW	Millimeter wave
MPC	Multi Path Components
NLOS	Non Line Of Sight
O2I	Outdoor to Indoor
OFDM	Orthogonal Frequency Division Multiplex
OLOS	Obstructed Line of Sight
PAP	Power Angular Profile
PDP	Power Delay Profile
PL	Path Loss
QoS	Quality of Service
RMS-AS	rms Angular Spread
RMS-DS	rms Delay Spread
Rx	Receive
SCS	Subcarrier Spacing
SNR	Signal to Noise Ratio
TP	Test Point
Tx	Transmission
VCA	Virtual Circular Antenna
VSA	Vector Signal Analyzer
VSG	Vector Signal Generator

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