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***Abstract*— The use of Massive MIMO and Millimeter-wave (mmWave) networks can be beneficial for a number of Fixed Wireless Access use cases, such as Smart City (SC) Services, providing connectivity for SC infrastructure, and Fixed Wireless Access using street-level distribution and access via so-called "street furniture" equipment. In this paper, we present the findings from a mmWave channel measurement campaign performed in different indoor and outdoor scenarios as part of our contribution to the mmWave Network Project Group of the Telecom Infra Project see (https://telecominfraproject.com/mmwave/). Indoor scenarios included workspace environments such as office rooms, corridors, etc. whereas, outdoor scenarios included urban and suburban environments. A set of two 802.11ad Terragraph™ Channel Sounder nodes (provided by Facebook under TIP) equipped with massive MIMO antenna arrays were used as the transmitter and the receiver for the characterization of the 60GHz mmWave channel. The measurement results include path loss, received power, input and output SNR and delay spread values for each specified beam combination. Urban, suburban and indoor environments were tested in both Line of Sight (LoS) and Non-Line of Sight (N-LoS) configurations.**

Keywords*— Fifth Generation (5G), mmWave, massive MIMO, Fixed Wireless Access, smart city, wireless communications, channel modeling, phased arrays beamforming.

I. Introduction

The development of the 5th Generation networks aims at providing, among others, great capacity gains with significantly increased data rates. Millimeter-wave (mmWave) is considered a valuable asset to cater to the needs of 5G by taking advantage of wider spectrum. Several parts of the 6-300 GHz spectrum are targeted for broadband applications in the next few decades [1]. Several research efforts are being carried out to investigate the potential of mmWave communication. The suitability of mmWave frequencies is discussed in [2] for mobile communications, focusing on the propagation characteristics of mmWaves, penetration loss, doppler and multipath.

Note: All the authors were affiliated and working with Athens Information Technology (AIT) when the measurements were taken and AIT's premises were used for the indoor and indoor-to-outdoor measurements.

The easier deployment, increased data rates and high throughput for indoor and outdoor environments is investigated in [3]. In [4]-[8], authors have mostly discussed the utilization of mmWave spectrum in access networks for 5G communications and beyond.

The user demands have increased in terms of high-quality image/video transfers, ultrahigh definition video streaming and live video games, etc., because of the advancement of technologies. Users expect to have broadband internet anytime and everywhere. These trends will be further pronounced when 5G becomes available with all its capabilities and numerous features. It is expected that 5G will extend the wireless connectivity beyond the human users [9], including medical equipment, personal belongings, household appliances and smart cities. Outage studies have been conducted in [10] at 28GHz and 38GHz. Path loss, penetration losses and reflection coefficients were all measured to have higher values because of the dense urban environment. In spite of all these early measurements the modeling of channels at mmWave frequencies remains an ongoing challenge. This paper aims at contributing to future efforts in channel modeling at mmWave frequencies.

The rest of the paper is organized as follows: Section II introduces our measurement setup and considered scenarios. The results and findings are presented in Section III. To shed some light on the findings, an analysis is provided in the same Section. Section V contains the conclusions.

II. Measurements Setup and Scenarios

A set of two wireless 802.11ad Nodes (Terragraph Channel Sounders) were used as transmitter and receiver nodes for measuring and characterizing the 60GHz mmWave channel [11]. The nodes were provided by the Telecom Infra Project (TIP) community, along with the respective software and other peripherals. Each node has a Massive 288-element mmWave antenna array–whose beam width and beam direction can be controlled by phase shifters. By choosing different modes, the beamwidth of the nodes can be varied from 2.8° to 102° and the specific beam could be scanned from -45° to 45° in either elevation or azimuth planes. Path Loss, Received Power, Input and

Output SNR and Delay Spread values of the measurements is provided by the accompanied software.

The measurements were carried out in three different phases and in each phase, different scenarios were considered.

TABLE I. CONSOLIDATES DIFFERENT PHASES/SCENARIOS

Scenario	Tx /Rx location	Tx-Rx distance (m)	Tx/Rx height (m)	Setup
S1	AIT corridor/ AIT corridor	20	1.5	Indoor-Urban
S2	Pole/Pole	55	3.5/3.5	Outdoor-Urban
S3	Pole/Lamp-pole-I	10	2.7/2.7	Outdoor-Urban
S4	Pole/Lamp-pole-II	15	2.7/2.7	Outdoor-Urban
S5	Pole/Lamp-pole-III	22	2.7/2.7	Outdoor-Urban
S6	Pole/Lamp-pole-IV	30	2.7/2.7	Outdoor-Urban
S7	Pole/Lamp-pole-V	40	2.7/2.7	Outdoor-Urban
S8, S9	Left side of the fountain/ Right side of the fountain	24	3/3	Outdoor-Urban
S10	Ground/ First Floor	10	2/6	Outdoor-Urban
S11	Car/ Radio Tower	30-90	2/20	Outdoor-Suburban

A. *Phase -1*

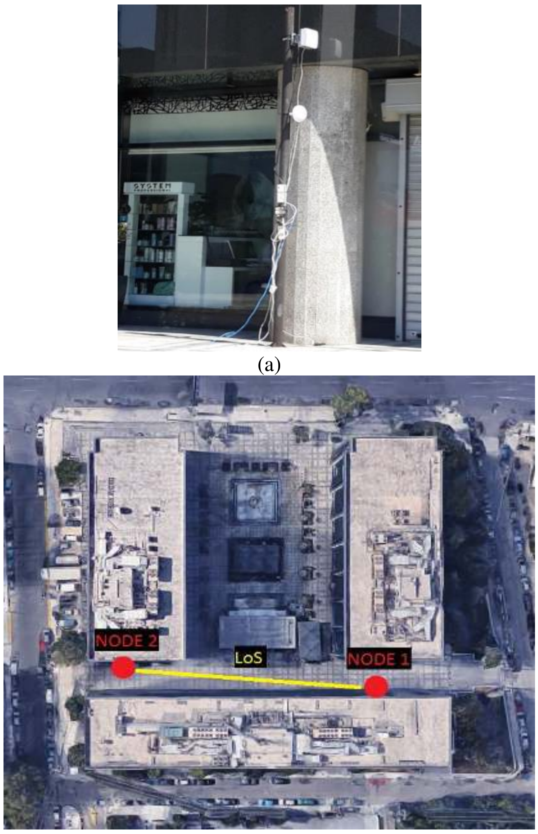
The first phase of the measurement was performed in an indoor office environment over an office corridor and meeting room, with the transmitter and receiver nodes separated by a distance of 20m from each other. It is clear from Fig.1. that a strong LoS link is guaranteed between the transmitter and the receiver nodes, with the possibility of additional N-LoS links from the surrounding reflecting glass and floor surfaces.

(a) (b)

Fig. 1. Indoor LoS measurements setup at (a) a conference room setup with a distance of 2-6m between Tx and Rx (b) Measurements in the corridor where the distance between Tx and Rx is 20m.

B. *Phase -II*

The second phase of measurements consists of several outdoor scenarios. To emulate the mmWave communication in an urban environment, the measurements were conducted at the busy square of Monumental Plaza in Maroussi, Athens, Greece, which is a typical (U-Shaped) corporate office plaza surrounded by office buildings.



(a)

(b)

Fig. 2. Outdoor LoS measurements setup at Monumental Plaza (a) Node-I mounted on a pole at height of 3.5m (b) Measurements setup for Urban corporate environment scenario where the distance between nodes is 55m.

(a) (b)

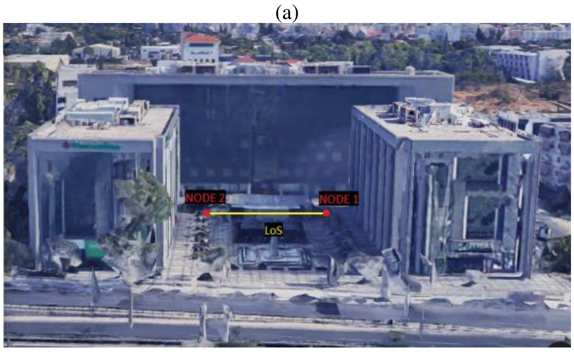
Fig. 3. Outdoor LoS measurements setup at Monumental Plaza (a) Node-I mounted on a tripod and is placed inside an office facing outside through a glass window, the height of the node from the ground is 6m (b) Node-II is placed outside the building and mounted on a tripod at a height of 2m.

The goal was to study the effect of the reflections from the materials/surfaces such as (marble columns and walls) glass windows and glass doors, water fountain, moving pedestrians, etc, on the millimeter-wave channel features. Most of the measurements were conducted using the narrowest beamwidth of 2.8° at transmitter with a Tx gain of 20dB. This urban environment consisted of granite pavement (dry, smooth level), glass windows, glass doors, marble columns and walls and metallic poles. whereas the obstructions were faced by light pedestrian traffic below the scanning level. The scenarios implemented are listed in Table. I and shown in Fig. 2, 3, 4 and 5 followed by detailed descriptions for each one.

(a) (b)

Fig. 4. Outdoor LoS measurements setup at Monumental Plaza (a) Node-II mounted on a lamp pole at a height of 3m (b) Node-I is fixed and mounted on a pole in the alley of monumental plaza whereas Node-II is mounted on poles at different distances from Node-I.

(a)

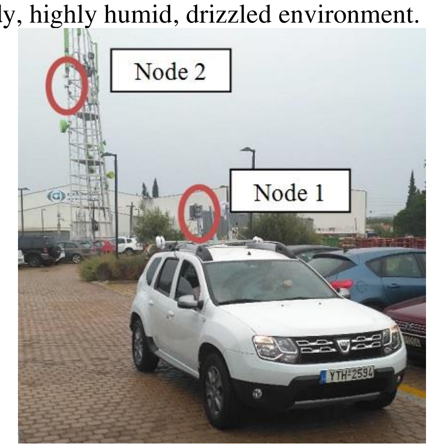


(b)

Fig. 5. Outdoor measurements setup across the water to see the direct path and the reflected path, distance between the nodes is 24m (a) Node-I mounted on a pole at a height of 3m (b) Node-II is placed outside the building and mounted on a tripod at a height of 3m.

C. Phase -III

The third phase of measurements involved outdoor scenarios in a suburban environment, specifically a parking lot at Cosmote's facilities in the area of Peania, close to Athens International Airport. Node 2, used as the Tx was placed at a height of 15m, on Cosmote's must. Node 1, the Rx was mounted on an SUV's roof. Measurements were conducted over a range of 40-100m. The Tx gain was set at 20 dB for all the measurements. Those were the only outdoor measurements in our campaign that were conducted in a cloudy, highly humid, drizzled environment.



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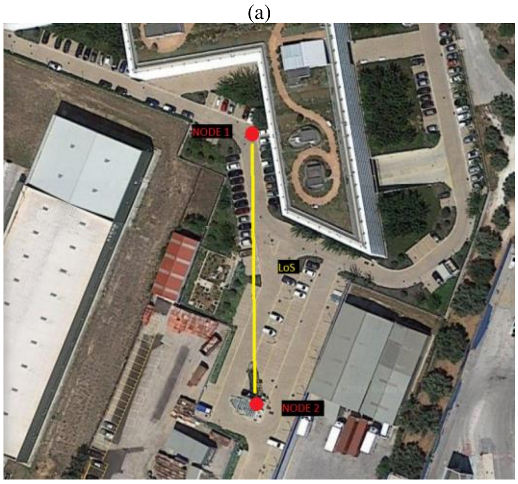


(b)

Fig. 6. Outdoor measurements setup in a suburban environment, at Cosmote's parking lot, the distance between the nodes is approx. 84m (a) Node-I mounted on the roof of SUV car (b) Node-II is placed on a tower at a height of 15m.

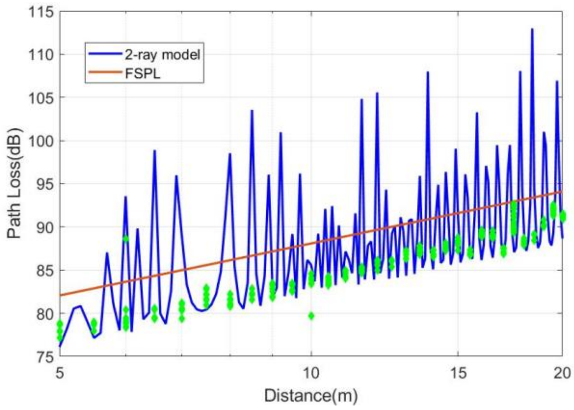
III. Results and Analysis

From the available measurement data, we use the data corresponding to the parameters mentioned in Table-II.

TABLE II. TIP NODE PARAMETERS

Parameter	Value
Tx Beamwidth	2.8° (Narrowest)
Rx Beamwidth	8.5° (Wide)
Tx Gain	20dB
Rx Gain	30dB
Frequency	60GHz

The narrowest beam at the transmitter is selected because it provides the maximum horizontal range for the measurement and the wider beam at the receiver node is selected as it could receive all the multipath components from the transmitter node. From Fig. 7 (a), we can see that the measured pathloss closely follows a 2-ray ground reflection model with a strong LoS component and multipath components from the reflectors. The pathloss for outdoor scenarios seems to follow the FSPL pattern for both urban and suburban environments.



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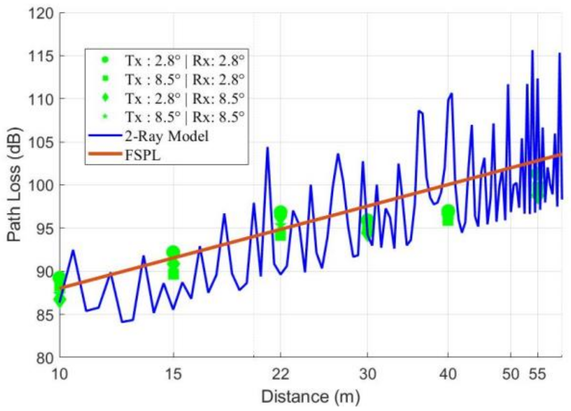

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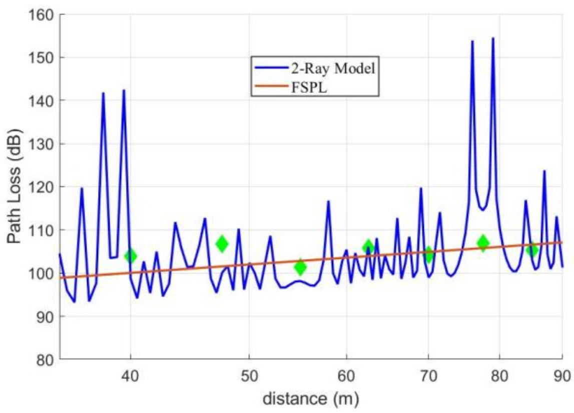
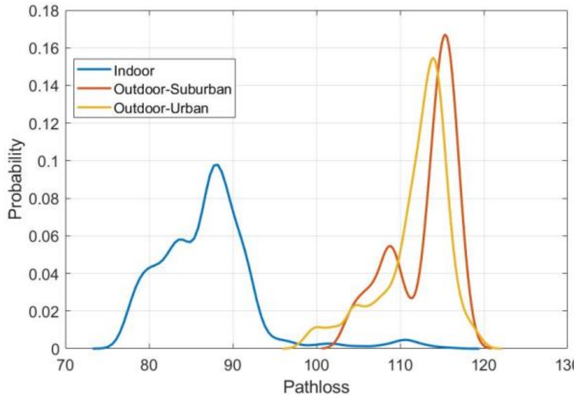


(c)

Fig. 7. Measured Pathloss between Tx and Rx over different distances, compared with FSPL and 2-Ray Pathloss models for; (a) Indoor (b) Urban-Pole to lamp-poles (c) Suburban

As seen in Fig. 8, the PDF of pathloss of all the three measurement phases is close to a Gaussian distribution. The graph corresponding to the urban scenario is from the data of *pole to pole (S7)* outdoor urban measurement. The distance between the transmitter and receiver nodes is 20m, 55m and 84m in the respective indoor, outdoor-urban and outdoor-suburban scenarios. The larger Tx-Rx separation is the reason for higher mean path loss for suburban environment than urban.



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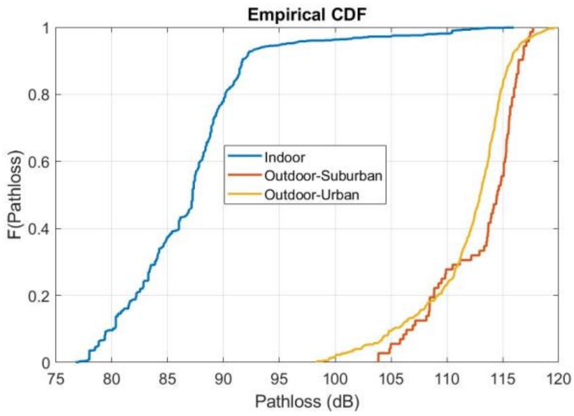


(b)

Fig. 8. (a) The probability density function (PDF) of pathloss for indoor, outdoor urban and suburban scenarios (b) The cumulative distribution function (CDF) of pathloss for indoor, outdoor urban and suburban scenarios.

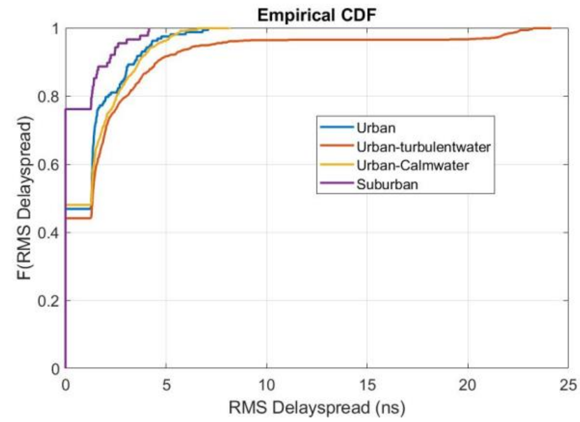
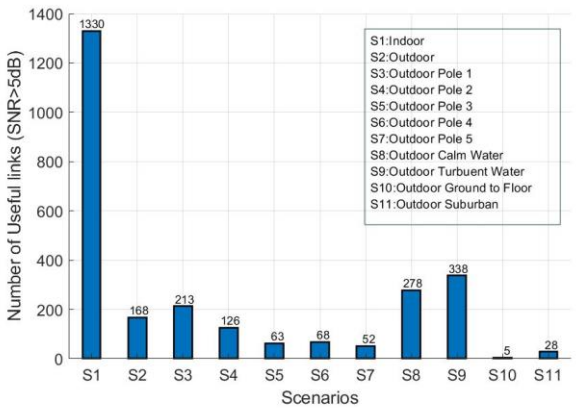


Fig. 9. CDF of the root mean square (RMS) delay spread of the received signal.

As per Fig. 9, around 90% of the RMS delay spread occurs below 5ns. The positive values of the RMS delay spread confirm the presence of multipath components at the receiver. As we can see, the delay spread corresponding to suburban has fewer multipath components, due to fewer reflections from the surroundings. In the urban environment, the maximum delay spread occurs, when the measurement is done in the presence of turbulent water from the fountain. Because of the turbulent nature, more reflections, hence more delay spread is observed at the receiver.



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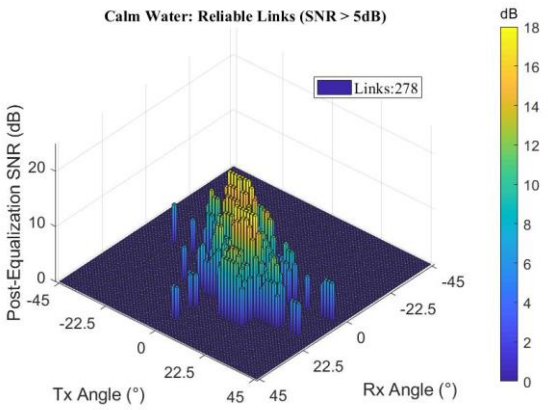

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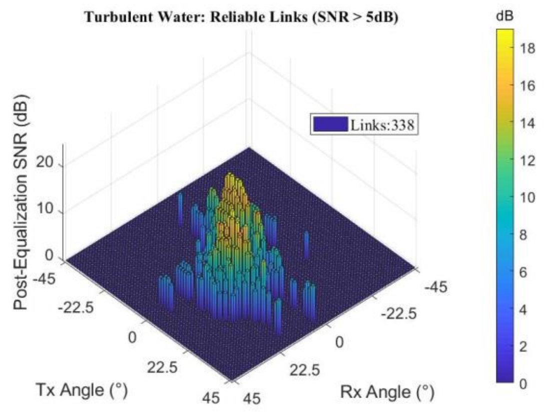
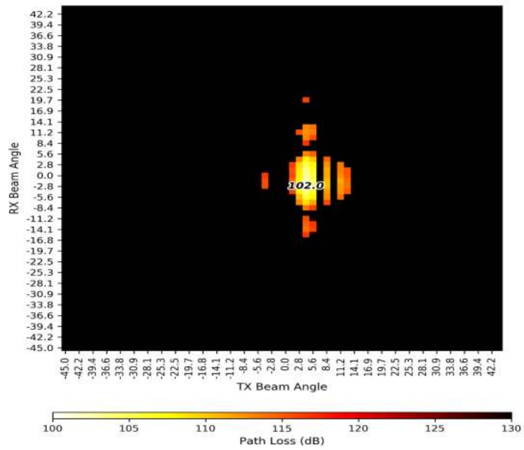


(c)

Fig. 10. (a) The number of useful links in different scenarios (b) SNR values at the receiver in the presence of calm water; (c) SNR values at the receiver in the presence of turbulent water.

The number of successful links available in each scenario is plotted in Fig. 10. A communication link from the transmitter to the receiver is considered as a successful link if the signal to noise ratio (SNR) at the receiver corresponding to that link is greater than a threshold value (depending upon the chosen Multiplication Coding Scheme (MCS)). Because of the least Tx -Rx separation, the maximum number of useful links is obtained for the indoor scenario as shown in Fig. 10 (a). The number of useful links decreases, with an increase in distance in the pole to lamp-pole scenario (S3 to S7). Even though the Tx-Rx separation is more in S2 compared to S7, the number of useful links in the former scenario is more because of the greater number of multipath links from the surrounding marble wall/glass window reflectors.



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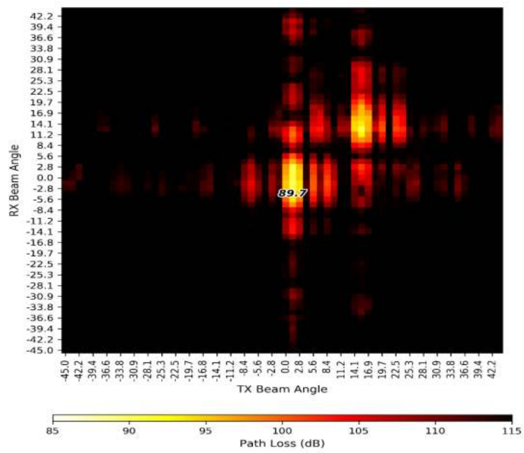

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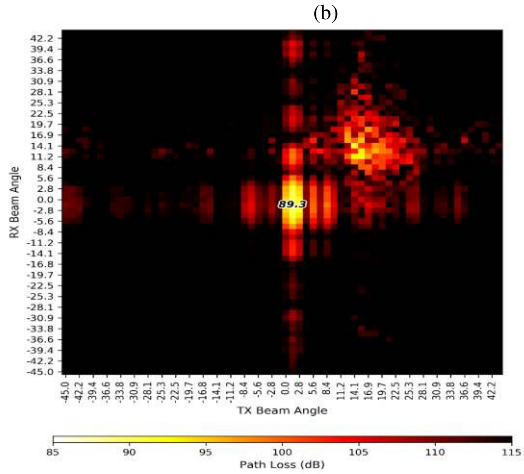

(c)

Fig. 11. Sample heat maps (a) S10: Outdoor urban ground to the floor (b) S8: Outdoor urban calm water (c) S9: Outdoor urban turbulent water.

The maximum number of useful links in the outdoor scenario is obtained when the measurement is done in the presence of turbulent water. More reflections from the moving water lead to more successful links, the above observation can also be seen from the heat maps given in Fig. 11. For S10, the number of useful links is the least. Unequal Tx-Rx heights are the main reason for the least number of successful links in the ground to floor transmission. To achieve the maximum number of successful links between the transmitter and the receiver, the Tx should be close to Rx and the heights of Tx and Rx should be equal. The presence of reflectors can increase the number of useful links with the penalty of more RMS delay spread.

CONCLUSION

The data collected throughout these measurement campaigns can assists the development of statistical channel models for urban environments which will be highly valuable for the development of broadband fixed wireless access using mm-wave bands in the coming years. The key takeaways from the measurements in the considered setups are summarized below;

1) Corporate urban plaza:

- There is a 34dB loss over the Free Space Path Loss (FSPL) due to the window attenuation (Ground-to-Floor).
- The Rx Angle Spread is on the order of 15°-25° (Ground-to-Floor).
- In 80% of reliable established links, the angle spread is below 10° (Pole-to-pole).
- The reflection link established shows 6.1 dB lower received power (Ground-to-Floor).
- Overall, the Rx is served reliably from all 5 positions by a fixed Tx (Poles, LoS).
- RMS delay spread can be up to 8 ns.
- Path loss from 20-60m seems better than FSPL.
- Turbulent water reflection helps the establishment of more links.

2) Suburban parking lot:

- Path loss from 60-90m seems to be consistent with free space transmission.
- RMS delay spread does not exceed 3.5 ns
- Thick tree foliage made it impossible to establish a link.

3) Office corridor:

- Path loss values approach the 2-ray model due to the density of the established links.
- CDF nicely fits the Rician distribution.
- There is a spike over the Rician distribution on the PDF plot (@86-93 dB) due to saturation (indoor propagation).

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