Measurement Efforts at mmWave Indoor and Outdoor environments

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TABLE I
CHANNEL MEASUREMENTS EFFORTS FOR THE VARIOUS INDOOR ENVIRONMENTS.

Frequency	**Experimental set-up**	**Remarks**
60 GHz	Office rooms having metal partitions and wooden doors, office corridors.	Narrowband propagation characteristics of the signal, received power and bit error rate (BER) measurements [1].
60 GHz	Empty square rooms, long narrow corridors with multiple doors.	Measurements of Fading characteristics and its distribution [2].
40 GHz, 60 GHz	-0.7cmSquare room with two long corridors.	-0.7cmEffects of frequency diversity on multi-path propagation are measured [3].
60 GHz	Bristol University's office and laboratory.	RMS delay spread measurement, results are compared with 1.7 GHz [4].
60 GHz	Indoor environment with mmWave BS mounted on the ceiling.	Effects of multiple reflections and transmissions between floors of building [5].
60 GHz	Smaller assembly hall, Bigger car manufacturing hall.	The RMS delay spread for the 60 GHz is less in comparison to 5 GHz [6].
60 GHz	Office with 4 windows and a steel door.	Effect of vertical, horizontal and right-handed circular polarisation on RMS delay spread [7].
60 GHz	Modern office building with 2 doors and 1 window.	Effects of antenna directivity on RMS delay spread is measured [8].
60 GHz	Different materials for walls, floors, windows and doors.	Measurement of transmission and isolation characteristics of building material [9].
60 GHz	Empty room with grid distribution of BSs and receivers.	Effects of space and frequency diversity in terms of correlation coefficient were studied [10].
60 GHz	Office environment with walking paths.	Human body shadowing effects based on the specific layout was studied [11].
60 GHz	Building hallways, conference room, classroom, laboratory with adjacent hallways, two rooms separated by plasterboard wall and parking lot with no car inside the Virginia Tech campus.	Extensive measurements were carried out to determine the direction of maximum multi-path power, maximum fading rate, RMS delay spread, received signal power, directional antenna effects, penetration losses through different building materials [12].
60 GHz	Residential house and laboratory.	Unavailability rate of the LOS link was evaluated due to natural human activity [13].
60 GHz	European residential house with wooden stairs, a fireplace, curtains, house plants.	Effects of furniture on received power, coherence bandwidth and the number of multi-path components were compared at the given locations [14].
60 GHz	Fourth floor of Durham Hall at Virginia Tech Campus	Local area RMS delay spread and partition losses due to the presence of drywalls, office whiteboards, glass, furniture were compared with that of 2.5 GHz [15].

TABLE II

CHANNEL MEASUREMENTS EFFORTS FOR THE VARIOUS INDOOR ENVIRONMENTS (CONTINUED).

Frequency	**Experimental set-up**	**Remarks**
60 GHz	Large room (working place) with desks, computers, chairs, a refrigerator, a microwave oven, walkways and windows	Effects of variation in the number of humans ranging from 1 -15 on the duration of the shadowing events and unavailability rate of the channel were measured [16].
60 GHz	Room with brick walls, wall-sized metal-framed window, metal cabinets, wooden tables	Effects of transmitter and receiver heights on normalised received power for LOS and NLOS regions were measured [17].
60 GHz	Long corridor with horizontally separated transmitter and receiver	Effects of the variations in the size of uniform rectangular array antenna on the channel data rate and capacity were measured [18].
60 GHz	Living room with 8 humans and office with 15 persons	Effects of static and moving blockages on the link-loss profile, connectivity consistency percentile at a various fixed location of receivers was studied and multi-hop relaying were studied to improve average network throughput improvement [19].
60 GHz	Conference room	Effects of co-polarised and cross-polarized transmit and receive antennas on the received SNR degradation were studied [20]
60 GHz	Hospital scenario, angiography and ultrasonic inspection rooms.	Angiography room consisting single X-ray machine with a movable screen and ultrasonic inspection room consisting 4 imaging machines with static display-screens and 4 beds separated by curtains. Radio channel responses between machines and screens in terms of path-loss and RMS delay spread were measured [21].
60 GHz, 300 GHz	-0.7cmRealistic office environment with rectangular shaped shelves, boxes, tables and cupboards	-0.7cm Furniture were approximated by edges, wedges and cylinders and diffraction characteristics of metal and wood furniture at two frequencies were compared [22]
60 GHz	T shaped intersections of two long corridors	Effects of the presence of deflecting/reflecting obstacles on the NLOS hostile channel were studied [23].
60 GHz, 70 GHz	-0.7cmOffice, shopping mall, railway station	-0.7cmEffects of transmitter– and receiver separations on power delay profile and delay spread were measured [24].
60 GHz, 70 GHz	-0.7cmAn empty office, an office in-use, open spaces in a shopping mall and a railway station platform	-0.7cmSpatio-temporal propagation characteristics of the two frequencies were compared and dominance of LOS and specular propagation over diffused scattering for the closed, semi-open and open environment were observed [25].
15 GHz, 28 GHz, 60 GHz	-0.9cmTerminal hall of Helsinki airport.	-0.9cmSpecular power ratio, specular and diffuse power decay, cross-polarisation, delay spread were measured based on the detected specular propagation paths for different frequencies [26].

TABLE III

CHANNEL MEASUREMENTS EFFORTS FOR THE VARIOUS INDOOR ENVIRONMENTS (CONTINUED).

Frequency	**Experimental set-up**	**Remarks**
60 GHz, 28 GHz	-0.7cmEmpty office.	-0.7cmEffects of transmitter and receiver separation on RMS delay spread were studied [27].
94 GHz	Laboratory room.	Effects of transmitter-receiver separation on the channel correlation and throughput for vertical and horizontally polarised antennas were studied [28].
28 GHz, 39 GHz, 60 GHz, 73 GHz	-1.1cmChesham building at the University of Bradford campus.	-1.1cmEffects of different building materials on signal reflections and diffraction and Effects of transmitter-receiver separation on delay spread, path-loss, variation of number of signal paths were observed [29].
28 GHz, 60 GHz	-0.7cmLight and heavy industry automation deployments.	-0.7cmDensity of LOS and NLOS path loss scatter points, RMS delay spread, Rician K-factor, AoA and AoD spreads based on the presence of machines, human bodies, and topology of the industrial sites were measured [30].
60 GHz	Gate and baggage areas of Boise airport and hallway of Boise State University campus.	Fitting parameters for the close-in free space reference distance path loss model and 3GPP floating-intercept path loss model were measured [31].
60 GHz	Indoor office building staircase environment with windows, guardrails, stair steps, and stair railings.	Effects of complex staircase environment on path loss exponent, delay spread, Ricean K -factor, angular spread were observed by simulation and correlations coefficients for these parameters were measured [32].

TABLE IV
CHANNEL MEASUREMENTS EFFORTS FOR THE OUTDOOR ENVIRONMENTS.

Frequency	**Experimental set-up**	**Remarks**
40 GHz, 60 GHz	-0.7cmNon-uniform road for the main entrance of University of Bath surrounded both sides by concrete buildings.	-0.7cmVertically polarised omnidirectional identical antennas for transmitter and receiver, Comparison of the propagation mechanisms and fading statistics of the received signals by slowly increasing (0.5 m/s) the receiver distance from the fixed transmitter [33].
60 GHz	Large rural area with a water canal, rows of trees, bushes, tall grass, grass-land, pebbles, hillocks, pits, trenches.	LOS links are obstructed by the natural environment, Tx-Rx separation ranges from 2 - 150m, Channel impulse response, CDFs of received signal envelope and RMS delay spread were measured [34].
60 GHz	Outdoor building environment with grass-field and footway, empty parking bordered by trees.	Flat omnidirectional transmit antenna with omnidirectional and patch directional receiver antennas, Ricean K-factors and path-loss exponents were measured for the LOS link [35].

TABLE V
CHANNEL MEASUREMENTS EFFORTS FOR THE OUTDOOR ENVIRONMENTS (CONTINUED).

Frequency	**Experimental set-up**	**Remarks**
28 GHz	Transmitter was mounted on the top of a 95m tall apartment building in Brighton Beach, Brooklyn with 77 measurement location within 6km, the receivers antenna height ranges from 3.4-11.3 m.	Performance of Local Multipoint Distribution Service (LMDS) was investigated based on the path-loss characteristics and presence of specular reflections by the varying height of receiving antenna [36].
62 GHz	Transmitter fixed at one end of the road while receiver mounted on the moving van (4.47 m/s) over a 57m distance, both ends of the road was surrounded by buildings.	The effect of multi-path component reflected from building walls on LOS links was observed, variation in the mean signal level was explained based on signal reflection only [37].
38 GHz	Three cross-campus LMDS links of lengths 605 m (LOS), 262 m (obstructed) and 262 m (partially obstructed) were observed for 3 months under different weather conditions at Virginia Tech campus. A sector horn transmitting antenna and a parabolic reflector receiving antenna was used.	Severe weather conditions and vegetation cause multi-path and increase in RMS delay spread. Wet brick and glass walls provide more specular reflections more power than the dry ones. Rician-K factor: $K = 16.88 - 0.04 \times (\text{Rain-rate})$ dB. Incoherent scattered power increase with rain-rate [38].
27.4 GHz	Transmitter was located on the rooftop of a building on a hill while 73 receiving sites were placed on the rooftop of 13-25 tall building in Singapore. Blockage from adjacent buildings and vegetations was observed.	Excess path losses were observed due to blockages and a linear relation between delay spread and environmental loss was obtained. For LOS channel, 0-12 dB loss and 15-20 ns delay spread were observed while in heavy blockage scenario, 26-40 dB loss and 1240 ns delay spread was observed [39].
35 GHz	Red pine trees with two different needle cluster structures; end-cluster and stem-cluster.	Effects of multi-path scattering over foliage attenuation, mean and standard deviation of the path-loss were measured [40].
60 GHz	Urban environment with 20m wide street bordered by 5 to 6 stories buildings made with concrete and bricks.	Effects of two antenna configurations, uniform linear array and uniform rectangular array on the channel capacity performance of the WPAN were observed [41].
60 GHz	Soldier-to-soldier communication to relay information on situations, tactical instructions and surveillance during covert battlefield operations. Each soldier is equipped with light-weighted body-worn wireless systems.	Overall combat operation was divided into 3 stages having outdoor, outdoor-to-indoor and indoor environment. CDFs of RMS angular spread and RMS delay spread were simulated [42].
60 GHz	Nodes were deployed on lamp-posts of straight streets, two ends of street bordered by buildings.	CDFs of received signal power for different antenna heights and building wall distances from lamp-posts for SISO were simulated. Effect of diversity gain (2×2 MIMO channel) on channel capacity was observed [43].

TABLE VI
CHANNEL MEASUREMENTS EFFORTS FOR THE OUTDOOR ENVIRONMENTS (CONTINUED).

Frequency	**Experimental set-up**	**Remarks**
26 GHz	Under the influence of rain.	Impacts of rain attenuation on the link availability and signal depolarization were measured [44].
60 GHz	Urban streets environment bordered with buildings with rough wall-surfaces.	Variations of roughness reflection factors for roughness height of building walls were simulated. Ray-tracing and street canyon model were used to observe the variation of received power with distance for different roughness heights [45].
60 GHz	Outdoor courtyard of the University of Texas campus with a pedestrian walkway, plants and lamp-posts between several 6 to 10 stories tall buildings and an urban parking lot.	For courtyard measurement, the path loss exponents and mean RMS delay spread of LOS and NLOS paths were $\{2.23,\ 0.9\ \text{ns}\}$ and $\{4.19,\ 7.39\ \text{ns}\}$, respectively. For vehicular measurement, the path loss exponents and mean RMS delay spread of LOS and NLOS paths were $\{2.66,\ 0.9\ \text{ns}\}$ and $\{7.11,\ 12.3\ \text{ns}\}$, respectively [46].
70-100 GHz, 146-154 GHz	-0.7cmPassive mmWave imagers were developed for terrestrial remote sensing of a red car parked beside two blue dumpsters.	-0.7cmThe resolution of 146-154 GHz radiometer was higher than that of dual-polarised 70-100 GHz because of their smaller wavelengths [47].
38 GHz	Rooftop-to-ground channel measurements at The University of Texas campus by using 13.3 dBi and 25 dBi horn antennas.	731 measurements were taken. Antenna with lower gain capture less multipath components resulting in lower RMS delay and path-loss exponents for NLOS scenario. RMS delay spread increases with off-boresight angle of antenna and decreases with Tx-Rx separation [48], [49].
120 GHz	Outdoor measurement over a distance of 5.8 km by Tokyo Institute of Technology and Nippon Telegraph and Telephone Corporation, Japan	Antenna gain criteria for outdoor, indoor and on-chip communications were defined and 3 types of antennas were developed each of which succeeded in transmitting at 10 Gbps data-rate which is suitable to transmit uncompressed HDTV and Super Hi-Vision signals [50].
38 GHz	Two adjacent buildings; the Engineering Science Building (ENS) and W. R. Woolrich Laboratories (WRW) on The University of Texas at Austin campus, respectively.	Two transmitters with heights 36 m and 18 m, are located at the rooftops ENS and WRW buildings, respectively. Outage characteristics for 53 blindly chosen receiver locations were observed. Reasonable selection of power levels and directional antenna had 0 % outage within 200 m [51].
60 GHz	Medium (NLOS) and short (LOS) distance measurements were performed at the 2 semi-open corridors intersecting at the right angle.	A cylindrical reflector was used for NLOS measurements. The Measured RMS delay spread for NLOS case shown a substantial difference in the absence of reflector (from 18 ns to 82 ns) [52].

TABLE VII

CHANNEL MEASUREMENTS EFFORTS FOR THE OUTDOOR ENVIRONMENTS (CONTINUED).

Frequency	**Experimental set-up**	**Remarks**
28 GHz, 40 GHz	-0.7cmSamsung Telecommunications campus in America. The transmitter was placed at the rooftop of the building of while the receiver was placed at the parking lot for LOS measurement and the garage for NLOS measurements.	-0.7cmPenetration losses and reflectivity testing were performed for metal objects and water inside the lab with Tx-Rx separation of 30 cm and 10 cm, respectively. Receiver with wide beamwidth captured more reflected energy thus received power was more in comparison to that of conventional narrow beamwidth antennas at mmWave [53].
28 GHz	Urban environments with parks, commercial districts, high-rise buildings, dense pedestrian and vehicular traffic at NYU campus in Manhattan.	Mean path-loss exponents for LOS and NLOS was 2.55 and 5.73, respectively. Only 16% outage rate was observed for receivers within 200 m while the overall rate was 57%. The shorter range of mmWave links signifies that rain attenuation will not be a major issue in future networks [54].
28 GHz	NYU campuses in Manhattan and Brooklyn. The tenth floor of 2 MetroTech Center in Brooklyn, Warren Weaver Hall in Manhattan, and Othmer Residence Hall in Brooklyn.	Penetration and reflection losses for different building materials such as concrete, brick, clear and tinted glass, drywall are measured. Indoor-to-outdoor propagation losses were very high however highly reflective building materials helped in better indoor-to-indoor and outdoor-to-outdoor communication [55].
28 GHz	NYU campus in Manhattan. Transmitters were located on the rooftops of Rogers Hall in Brooklyn, Coles Sports Center and Kaufman building in Manhattan.	RMS lobe angle spread and the number of lobes can be modelled by the exponential random variable with mean 7.8° and 2.5, respectively. while CDFs of the angle of arrival and shadow fading fitted well with the uniform and lognormal distribution, respectively [56].
28 GHz, 38 GHz	-0.7cmMeasurements were performed on the rooftops of different buildings around the campuses of NYU-Brooklyn, NYU-Manhattan and the University of Texas.	-0.7cmPath-loos models were developed by from the multiple measurements performed at different microcellular scenarios around the campuses based on the linear regression fit of parameters like floating intercepts, average path-loss exponents and standard deviation of shadow fading having log-normal distribution [57].
73 GHz	Backhaul and mobile mmWave communication channel measurements were performed at the campus of New York University, Manhattan within the range of 30-200 m.	The path-loss exponents in the backhaul scenario were 2.58 and 4.44 while that in the mobile scenario were 2.58 and 4.29 for LOS and NLOS case, respectively. Time and angular delay spreads were measured and measurement results are compared with the simulated scenario of ray-tracing method [58], [59].
28 GHz	Small scale fading measurements in an outdoor street canyon scenario at the campus of NYU, Brooklyn.	Rician distribution provided the best fit to the path amplitudes data over the lognormal and Rayleigh distributions for both, the co-polarised and cross-polarised antenna configurations [60].

TABLE VIII
CHANNEL MEASUREMENTS EFFORTS FOR THE OUTDOOR ENVIRONMENTS (CONTINUED).

Frequency	**Experimental set-up**	**Remarks**
60 GHz	The Potsdamer Straße in Berlin, a 51.5 m wide, busy street canyon bordered by high-rise buildings. Omnidirectional antennas were used.	Effects of ground reflections and human shadowing on LOS path-loss measurements was observed. The path-loss exponent was 2.41 at 5 m which reduced to 1.68 at 15 m due to the presence of ground reflection. Human shadowing can causes more than 40 dB attenuation for a LOS link while multi-path components os signal remain unaffected [61], [62].
60 GHz	The Berlin-Gatow (former) airport with 800 m long asphalt's apron and runway surrounded by, grass, weeds, metal fencing and forest.	Effects of ground reflections and fading on path-loss for distance ranging from 40 to 1000 m were analysed and compared with the two-ray model. The key observation was the absence of fading effect at distance greater that 700 m [63].
73 GHz	MetroTech Commons Courtyard consisting open sidewalk and cherry trees at the New York University', Brooklyn.	Free space, foliage and ground reflections measurements were performed by using co-polarized vertical-vertical and cross-polarized vertical-horizontal transmit and receive antennas. A high cross polarisation discrimination was observed in the foliage scenario which is good for the orthogonal frequency reuse. Also 10 to 34 dB ground reflection losses were observed [64].
60 GHz	Two car-parking areas in the campus of the University of L'Aquila, Italy with one side, surrounded by buildings while another side, by lawn and metal fencing.	Path-loss and time-dispersion characteristics of the channel were analysed in the with cars and without cars cases. An improvement in average RMS delay was observed due to the presence of cars in the parking areas [65].
26 GHz	Three-year trials of 11.1 km long radio link path in Bergen, Norway and Four-year trials of 5.5 km long radio link path in Prague, Czech Republic.	Attenuation effects of rain, hail and wet snow were measured by using co and cross polarised transmit and receive antennas and results were compared with the models given by the International Telecommunication Union (ITU) [66], [67].
28 GHz	Low-rise urban environment at Gwanpyung and very high-rise urban area of Gangnam in South Korea.	Measurements were conducted in the daytime during working hours. Effects of antenna beamwidth on RMS delay and angular spread were observed and corresponding fitting models were proposed [68].
28 GHz	A biathlon stadium having 21 LOS location and An Alpensia ski resort having 15 NLOS location in Pyeongchang, south Korea.	Spatio-temporal characteristics of were analysed through excess delay, sub-path delays, RMS delay and angular delay spread for the clustered multi-path scenario and effects of blockers such as human bodies and vehicles were observed [69].
32 GHz	A single lane pedestrian and two-lane streets of North China Electric Power University campus.	Directional scan sounding channel measurement with 1 GHz bandwidth were conducted. Extracted channel parameters were compared and verified with the 3GPP and other open-source literature [70].

TABLE IX
CHANNEL MEASUREMENTS EFFORTS FOR THE OUTDOOR ENVIRONMENTS (CONTINUED).

Frequency	**Experimental set-up**	**Remarks**
60 GHz	Ten urban locations in South Africa.	Effects of clear and rainy weather conditions on the network capacity and coverage range were measured for the two bandwidths (250 MHZ and 1.2 GHz). A reduction in coverage range was observed at 1.2 GHz due to increased noise temperature levels [71].
50-57 GHz, 67-73 GHz	Outdoor roadside, car parking, open square and street canyon environments at the Durham University campus.	-0.7cmEffects of same and cross-polarisations and antenna beamwidth on the path-loss parameters were observed [72].
28 GHz	Outdoor urban area consisting 4 - 6 office buildings, parking lot and street canyon by using ray-tracing simulations.	Effects of user body shadowing and orientations on the channel characteristics were observed and results of data-mode, talk-mode and no-user-body-mode were compared for the notch, slot and edge-patch antenna configurations of user equipment [73].
60 GHz	Two outdoor environments consisting hilly terrain with high-rise buildings, one with the presence and other with the absence of vegetation at the KSU campus in Riyadh City.	Effects of temperature drifts and solar radiation emissions on the outdoor radio links were observed during day-time and night-time. A 9.0-15.6 % increase in path loss exponent were observed during the hot, sunny weather in comparison to the night-time on the same day [74].
28 GHz	University Park Campus in the University of Southern California, Los Angeles.	Directional propagation measurements (RMS delay spreads, angular and doppler spectrums) in the presence of blockages (pedestrians and vehicles) were done for the dynamic scenario and necessity of beam direction adaptation was observed [75].
30 GHz, 90 GHz	-0.7cmHigh-speed train (HST) channel propagation measurements in the outdoor scenario at 90 GHz and inside tunnel at 30 GHz.	-0.7cmThe reflection and scattering parameters were measured at the 30 GHz for the materials of the deterministic and random objects present in the HST environment. Two outdoor HST environment with and without barriers and a tunnel were reconstructed by using ray-tracing simulations. LOS with tenth order of reflection inside of tunnel and LOS with up to third order of reflections outside of tunnel were considered for the total received energy measurements. The verification of channel model was done in terms of path-loss, shadow-fading, power delay profile and small-scale fading [76], [77].
33 GHz	Urban outdoor NLOS measurements for the trees without leaves, with leaves and in the absence of trees.	Effects of foliage attenuation on mean excess delay, RMS delay spread and coherence bandwidth were measured and verified with the ITU foliage model for the frequency range 10-40 GHz [78].

TABLE X
CHANNEL MEASUREMENTS EFFORTS FOR THE OUTDOOR ENVIRONMENTS (CONTINUED).

Frequency	**Experimental set-up**	**Remarks**
28 GHz	Outdoor to indoor (O2I) propagation measurements for the two wooden framed-double-story-dry-wall single-family units and one multi-story brick-wall office building on/near the University of Southern California.	Effects of outdoor to indoor penetration losses on the number of multi-path components, RMS delay spread, angular spread and receiver beam-diversity were observed. Building floor plan, location and surrounding structures play a key role in O2I communication [79].
32 GHz	O2I propagation measurements for the two office building (traditional and thermally efficient) via near perpendicular beam incidences through the glass windows.	Directional delay spread characteristics for the 10°, 30°, 60° and 360° receiver beamwidth were observed. Thermally efficient buildings had larger delay spread in comparison to the traditional one [80].

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